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An overview of deep geothermal energy and its potential on the island of Ireland

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Summary

This paper provides a short overview of geothermal energy, including a discussion on the key geological controls on heat distribution in the subsurface, and on the different types of geothermal resource and their potential uses. We then discuss the island of Ireland as an example of the role that geothermal energy can play in decarbonising the heat sector in a region characterised by relatively low-enthalpy (temperature) resources. Significant shallow geothermal potential exists across the island via the deployment of ground source heat pumps. The geology of onshore Ireland provides relatively limited potential for deep hydrothermal aquifers with primary porosity and permeability. Therefore, deep geothermal exploration on the island is likely to be focused on fractured carbonate reservoirs of Carboniferous age, with recorded groundwater temperatures reaching 38°C at 1 km depth, or on lower permeability petrothermal reservoirs developed as Enhanced or Advanced Geothermal Systems. The exception to this occurs within Mesozoic basins in Northern Ireland where porous and permeable Permo-Triassic sandstones are preserved beneath Paleogene basalts. Geothermal potential also exists in equivalent basins immediately offshore Ireland. For example, Triassic sandstones within the Kish Bank Basin, a few kilometres off the coast of Dublin, have estimated reservoir temperatures of 20-120°C across the basin.

Introduction

Geothermal energy is thermal energy (heat) stored beneath the surface of the Earth that originates from (1) primordial heat leftover from planetary formation, (2) radiogenic heat produced by radioactive decay of isotopes within the Earth's mantle and crust, and (3) heat from solar irradiation stored close to the Earth's surface (e.g., Schubert et al., 1980; the KamLand Collaboration, 2011). The geothermal gradient between the hot core and the cool surface of the Earth means that there is a continuous transfer of heat – primarily via conduction and convection – from the Earth's interior outwards to the exterior surface as the planet cools over geologic time. The mean surface heat flows are 65 mW m^{-2} and 101 mW m^{-2} in continental and oceanic areas, respectively, with an areal-weighted global mean of 87 mW m^{-2} (Pollack et al., 1993). Within sedimentary basins, down to depths accessible by modern drilling, typical geothermal gradients are in the range of 20°C km^{-1} to 45°C km^{-1} (e.g., Gretener, 1981). Lower geothermal gradients are often observed in old stable continental cratons whilst significantly higher geothermal gradients occur in areas with active tectonism and volcanism. Heat flow tends to be highest near tectonic plate boundaries and, hence, traditional geothermal power generation has focused in areas where the geothermal heat is easily accessible, such as western USA, Indonesia, Philippines, Turkey, New Zealand, Mexico, Italy, Kenya, Japan, and Iceland (Huttrer, 2021).

A geothermal system has been described as 'any localised geologic setting where portions of the Earth's thermal energy may be extracted from natural or artificially induced circulating fluids transported to a point of use' (Moeck, 2014). There are essentially three different components of a conventional, convection-based geothermal system: a heat source, a permeable reservoir and a fluid that can transport the heat (e.g., Fanelli et al., 2007). There is a continuum of geothermal systems from high-permeability **hydrothermal** reservoirs that can produce naturally occurring geothermal fluids to low-permeability **petrothermal** reservoirs that may have limited or no natural fluid content (Figure 1). In petrothermal reservoirs, the permeability can be artificially generated, or enhanced, by creating or reactivating an existing subsurface fracture system via hydraulic fracturing in what are known as Enhanced (or Engineered) Geothermal System (EGS) or Hot Dry Rock (HDR) projects. The development of hydrothermal and EGS/HDR reservoirs typically uses a series of open-loop doublets (i.e., a pair of wells open to the rock) where heat is extracted from warm fluid produced from one well and, following heat extraction, the residual fluid is then re-circulated using the complementary injector well.

Closed-loop systems, or Advanced Geothermal Systems (AGS), can provide an alternative means of developing petrothermal reservoirs. AGS involves circulating a working fluid

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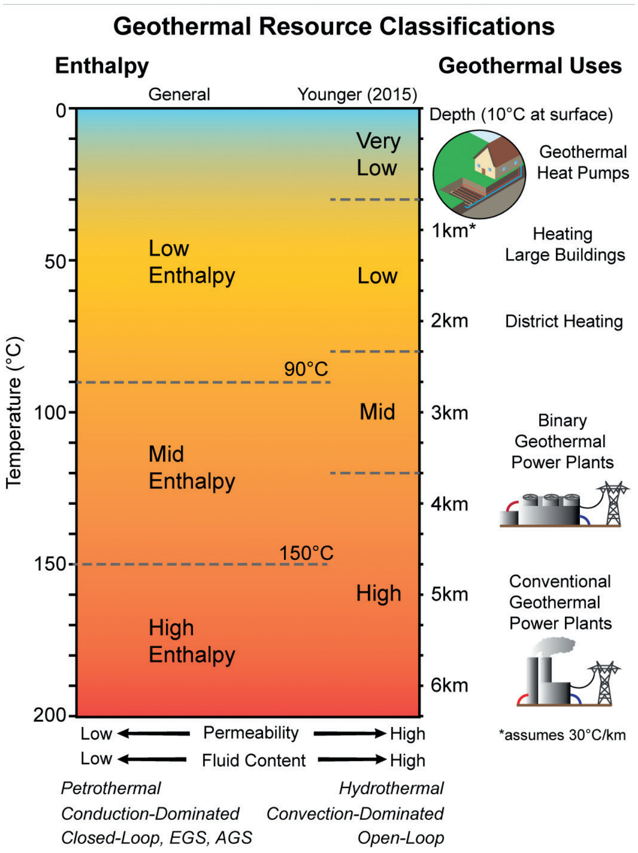

Figure 1 Simple tripartite geothermal resource classification scheme based on temperature and associated forms of utilisation (Fanelli et al., 2007; Banks, 2012). The indicative depth track assumes a surface temperature of 10°C and a geothermal gradient of 30°C km^{-1}. A discussion of the alternative Younger (2015) classification scheme is presented in GSI (2020).

down through a long, sealed wellbore and extracting the heat via conduction from the surrounding rock (Malek et al., 2021). Closed-loop systems come in various forms including co-axial, U-tube, and multilateral U-tube systems (Figure 2). Closed-loop systems have the advantage of removing the permeability risk and other potential issues with open-loop systems such as fluid loss, mineral scaling, fluid-mineral chemical reactions, and induced seismicity (Malek et al., 2021). However, the contact area between the fluid and the rock is limited to the wellbore wall, and the geothermal potential is completely dependent on the temperature, thermal conductivity and diffusivity of the surrounding rock, and the length of wellbore(s).

A geothermal resource is an accumulation of heat energy for which there are ‘reasonable prospects for eventual economic extraction’ (Williams et al., 2010). This energy can be used for power generation or heating, and a more detailed discussion of the potential utilisation of geothermal resources can be found in Fanelli et al. (2007). Unlike mineral and hydrocarbon resources, geothermal resources are generally co-located with end use. For example, geothermal power plants will be located close to the wells that produce high temperature water or steam which can be used to drive large turbines and generate electricity. On the other end of the resource spectrum, a Ground Source Heat Pump (GSHP), or thermal exchanger, will exploit shallow, lower-temperature resources for heating (and cooling) buildings (Banks, 2012). Although the focus of this paper is on geothermal heat extraction, Underground Thermal Energy Storage (UTES) may also have an important role in decarbonisation (e.g., Kallesøe & Vangkilde-Pedersen, 2019), for example at shallow depths through seasonal storage of heat and cold within aquifers (ATES) or flooded mine workings, or as shallow storage of heat from deeper resources. UTES can also

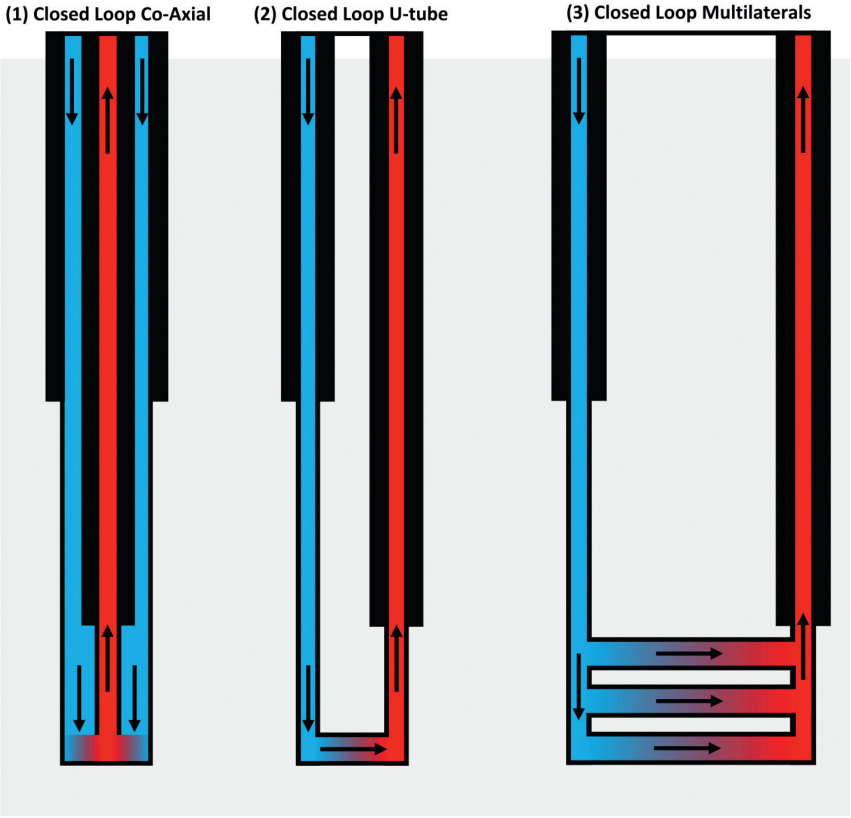

Figure 2 Different forms of closed-loop systems (modified from Law et al., 2014): (1) a co-axial system where the fluid is pumped down through an outer annulus, heating up on the way down due to contact with rock along the outer wall, after which the working fluid is circulated back up to the surface via a central pipe; (2) a U-tube system within a vertical well or where a long horizontal wellbore section has a vertical producer well and injector well on each end; and (3) a multi-lateral system which is a variation of the U-tube system but with more horizontal wellbores.

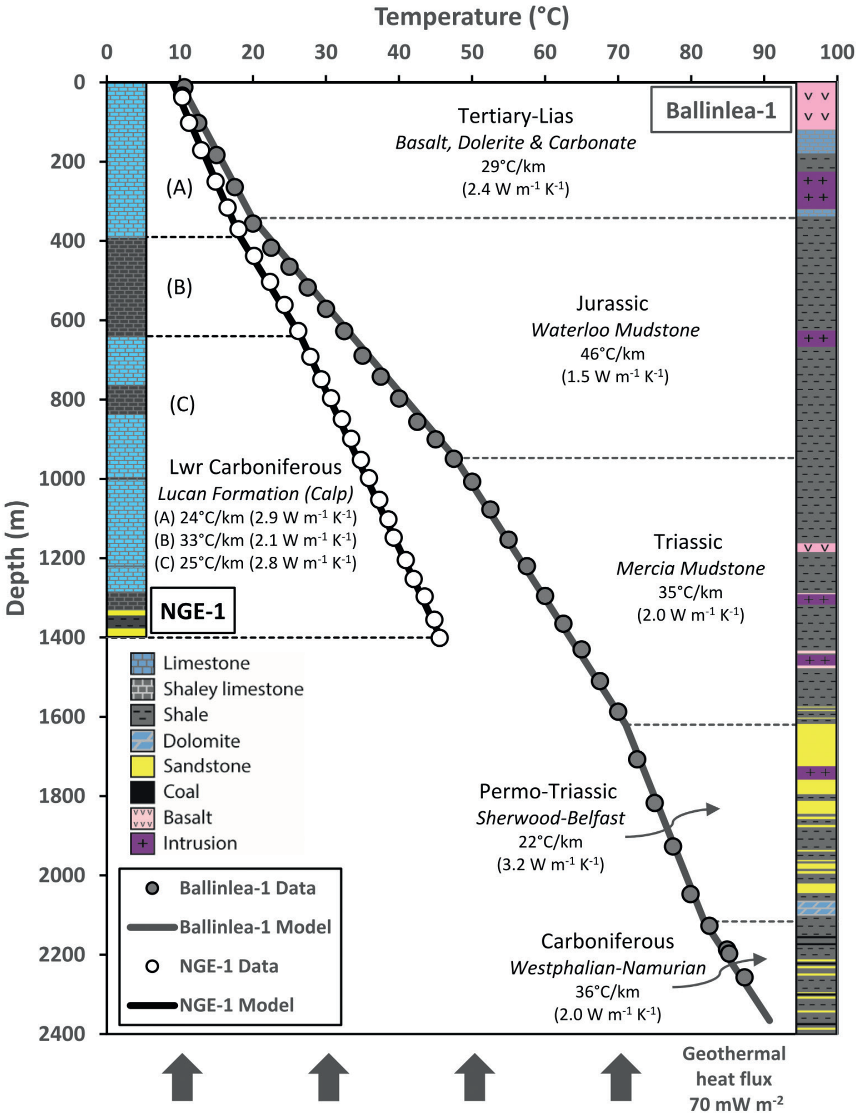

Figure 3 Temperature data from two onshore wells: NGE-1 in the Republic of Ireland, and Ballinlea-1 in Northern Ireland (see locations in Figure 6). The temperature data is stabilised in both cases. The Ballinlea-1 well was drilled in 2008, and the temperature data were acquired just before the well was plugged and abandoned in 2015. The NGE-1 well was also drilled in 2008, and the temperature data were collected circa 2.5 months later in early 2009. Both wells intersected significantly different stratigraphy with a predominantly mud-dominated Mesozoic-Cenozoic section in Ballinlea-1, and a carbonate-dominated Carboniferous section in NGE-1. Each well was split into a number of thermal layers defined on the basis of a break-in-slope in the temperature profile. Assuming a heat flow of 70 mW m^{-2}, the average estimate for onshore Ireland from Mather et al. (2018), the thermal conductivity of each thermal layer was estimated via modelling calibrated to the observed temperature data. These thermal conductivity estimates were also compared with published estimates from similar stratigraphy (see Figure 4), and the estimates for the Lower Carboniferous limestones in NGE-1 are consistent with the typical values of 2.8 ± 0.5 W m^{-1} K^{-1} noted in Mather et al. (2018). These data demonstrate the significant control that stratigraphy has on the vertical geothermal profile.

help to decarbonise energy systems with a significant contribution from renewable sources, because TES can provide flexible storage of excess energy for later use in heating, cooling, or electricity generation (Maruf et al., 2022).

Geothermal resources are considered renewable with significantly lower carbon dioxide (CO_2) emissions than power generation from fossil fuels (e.g., Rybach, 2003). While there is a carbon footprint associated with the installation of a geothermal system, technological improvements are continually being made to reduce this impact (e.g., electric drill rigs). Geothermal systems require careful management during abstraction to ensure sustainable development. Exploitation of an individual system could become unsustainable over time if (1) the rate of geothermal fluid extraction from the system exceeds the fluid recharge rate, and/or (2) the system falls to an unusable temperature because the heat extraction is occurring at a greater rate than the natural replenishment (Banks, 2012). In the first case, fluids can be re-injected into an open-loop system to allow greater sustainability of the fluid-driven resource; this is not an issue in closed-loop systems that do not utilise a natural geothermal fluid. In the second case of temperature depletion, this issue will be more pronounced in petrothermal and closed-loop systems because the natural energy recharge occurs only via thermal conduction, which is a relatively slow process across the rock units.

Herein, we provide a short review of the geological controls on geothermal anomalies, and the different types of geothermal resources. We then move on to discuss the island of Ireland as an example of the potential role that geothermal energy can play in decarbonising the heat sector in a region characterised by relatively low-enthalpy (temperature) resources. Finally, we provide a preliminary assessment of the geological factors that are likely to impact on the deep (i.e., at depths in excess of circa 500 m) geothermal potential of Ireland.

Geological controls on geothermal anomalies

Banks (2012) noted the following as examples of geological controls on high-temperature geothermal anomalies:

- **Divergent plate margins:** High heat flows and geothermal gradients are often present in extensional plate margins due to the presence of thinned crust and a relatively shallow asthenosphere or due to the presence of magma at shallow depth. Examples include mid-oceanic ridges (e.g., Iceland), or continental rifts (e.g., the East African Rift and the Rhine Graben).

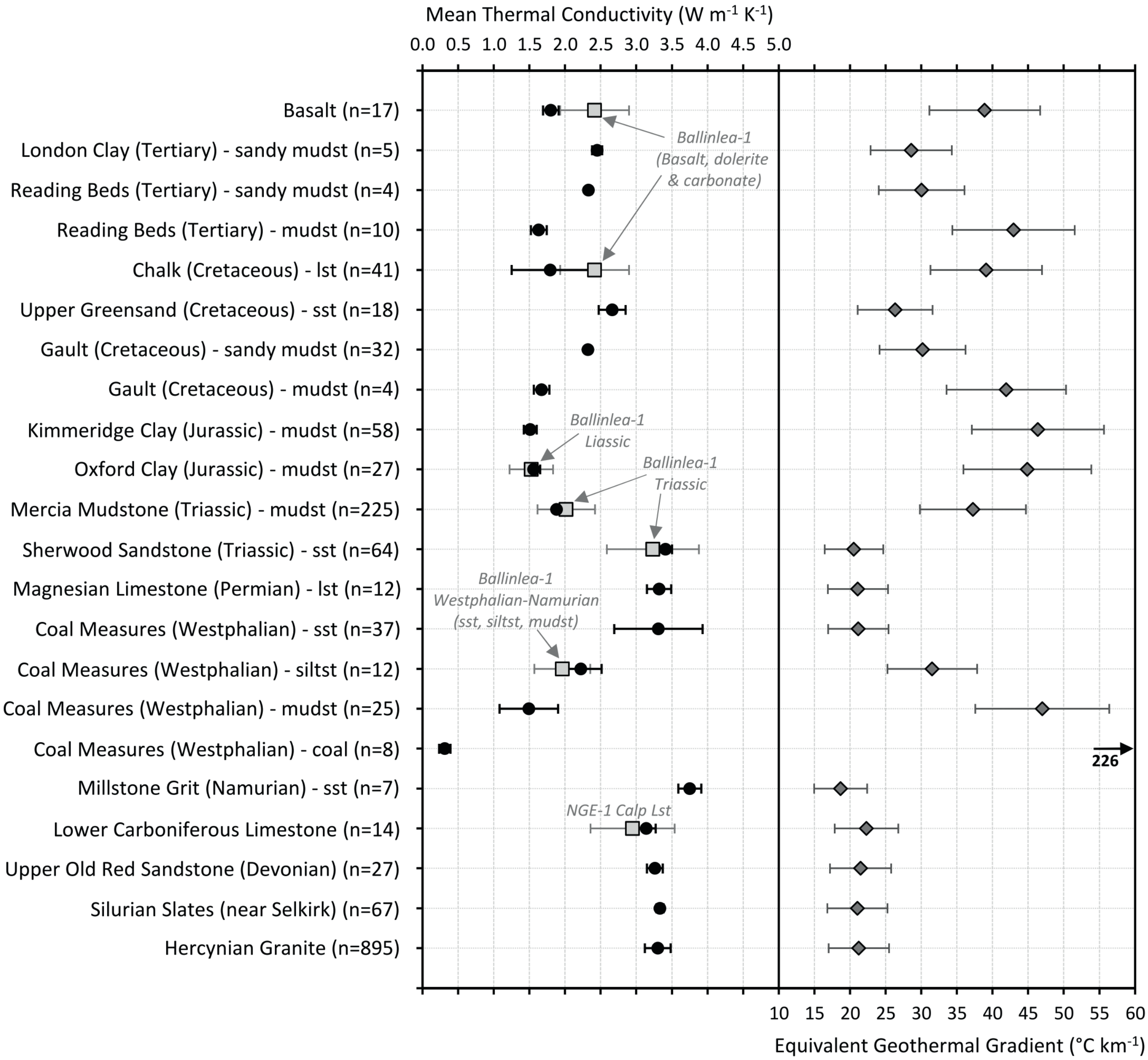

Figure 4 Thermal conductivity data for selected lithologies in the United Kingdom from Banks (2012) and references therein. The black dots indicate the mean thermal conductivity value with the error bars representing the standard error (Banks, 2012). The grey diamonds and associated error bars illustrate the equivalent geothermal gradient for each thermal conductivity value, using Fourier's law and assuming a heat flow of 70 ± 14 mW m^{-2}, the mean surface heat flow for the island of Ireland (Mather et al., 2018). The light-grey squares plot the estimated thermal conductivities for the main thermal layers in the Ballinlea-1 and NGE-1 wells from broadly similar stratigraphic sequences (Figure 3) with the error bars reflecting the uncertainty range (± 14 mW m^{-2}) associated with the mean heat flow estimate. The Ballinlea-1 and NGE-1 estimates are generally consistent with the data from Banks (2012) with higher conductivities observed in sandstones and carbonates and lower conductivities observed in mudstones. Abbreviations: mudst – mudstone; lst – limestone; sst – sandstone; siltst – siltstone; n – number of determinations.

- **Convergent plate margins:** Linear magmatic belts, with associated volcanic centres on the surface, occur at convergent margins due to partial melting that occurs above the subducting slab of oceanic crust. Examples include the Andes, Mexico, Japan, the Philippines, Indonesia, and New Zealand.
- **Hot spots:** In some intra-plate settings, volcanic hot spots form above mantle plumes where warm material rises from the deep mantle up to the base of the lithosphere. These can occur in oceanic (e.g., the Hawaiian Islands) or continental (e.g., Yellowstone) settings and are also associated with anomalously high heat flow.

However, Banks (2012) also noted that more modest geothermal anomalies may be found outside these specific tectonic settings and relate to one or more of the following:

- **Thermal blanketing or insulation:** If there is a constant heat flux from the Earth's interior, rock layers with lower thermal conductivity will be associated with higher geothermal gradients. This relationship is described by Fourier's law (Fourier, 1816)

$$q = -k\frac{\mathrm{d}T}{\mathrm{d}z}$$

where q is heat flow, k is thermal conductivity, and $\frac{\mathrm{d}T}{\mathrm{d}z}$ is the temperature gradient. Consequently, anomalously high temperatures, for a given depth, will occur beneath thick layers of rock with low thermal conductivity (Figures 3 and 4). Examples include the low-enthalpy geothermal systems in Paris (France) and Southampton (England) where permeable reservoirs are situated below a thick section of low-conductivity mudstones or limestones (Banks, 2012).

- **Internal radiogenic heat production:** Granites are often associated with higher internal heat production due to radioactive decay of uranium, potassium, and thorium. The highest geothermal heat flux in Great Britain is associated with Variscan granites in Devon and Cornwall, SW England, that have internal radioactive heat production of up to 5 µW m^{-3} (Banks, 2012). Another area of higher-than-average heat flow occurs in the north of England and is underlain by Caledonian granites with internal radioactive heat production in the range of 3.3–5.25 µW m^{-3} (Wheildon and Rollin, 1986).
- **Vertical groundwater flow:** Advective heat transfer to shallow depths can also occur when deep, warm groundwater flows upwards to the surface along permeable fault zones or rock layers. Examples include thermal springs at Bath, Buxton, and Matlock in England where faulting allows the flow of deep groundwater from Carboniferous limestone up to the surface (Banks, 1997; Brassington, 2007).
- **Recent uplift and exhumation:** Geothermal anomalies can occur in areas with active, or recent, rock uplift where there has been insufficient time to allow for thermal re-equilibration. Conversely, rapid burial of cold sediments in subsiding basins can lead to anomalously cool temperatures. An example of such a transient effect is the Pleistocene glaciation in Europe where rapid burial beneath thick ice is thought to have lowered the temperature of rocks down to a depth of at least 300 m (Wheildon and Rollin, 1986; Šafanda and Rajver, 2001; Mather et al., 2018). Post-glacial isostatic rebound would have the opposite effect of uplifting rock from greater depth. Therefore, in Europe, there is an additional consideration that the area is still recovering thermally and isostatically from the Pleistocene glaciations (Banks, 2012).

Types of geothermal resources and uses

One common classification scheme for geothermal resource is based on the enthalpy (i.e., heat content) of the natural or injected (working) geothermal fluid that transports the heat from the reservoir to surface (e.g., Fanelli et al., 2007; Banks, 2012). Although the subdivisions are somewhat arbitrary and can be subdivided further, the resources can be broadly classified as high-enthalpy, mid-enthalpy, and low-enthalpy based on their temperature and associated forms of utilisation (Figure 1).

- **High-enthalpy (>150°C):** High-enthalpy resources are commonly used for electricity generation with 150°C being the lower limit for conventional geothermal power plants. Water can exist as a liquid at temperatures above 100°C under subsurface conditions and, hence, high-enthalpy resources can be either water-dominated or vapour-dominated (or dry steam) systems. To drive steam turbines, water-dominated resources need to be flashed to steam via pressure reduction at surface, whereas dry steam resources can be used directly.
- **Mid-enthalpy (90–150°C):** Mid-enthalpy resources can be used for electricity generation in binary power plants with 90°C being the approximate lower limit. In binary plants, heat is transferred from the geothermal fluid to a secondary working fluid that has a lower temperature of vaporisation (i.e., boiling point). Thus, the secondary fluid is vaporised and can be used to drive the turbines.
- **Low-enthalpy (<90°C):** Low-enthalpy resources have a temperature below what is required for power generation. However, these lower temperature resources can be utilised for a wide variety of direct use applications including district and space heating (and cooling), industrial heating processes, horticulture (e.g., greenhouse and soil heating), aquaculture (e.g., fish farming), and recreation (e.g., swimming pools). See Fanelli et al. (2007) for a more detailed discussion.

Role of geothermal for decarbonisation

The Irish Government has committed to halving carbon emissions by 2030 and achieving net-zero greenhouse gas emissions by 2050 relative to pre-industrial 1990 levels, as part of the 2021 Climate Action Plan (DECC, 2021a) and in accordance with the Climate Action and Low Carbon Development (Amendment) Act. Similarly, legislative commitments to net zero by 2050 have been passed in Northern Ireland with the bill at the final stage. Ireland's energy-related CO_2 emissions can be attributed to three broad emission categories: heat, transport, and electricity generation (SEAI, 2020). According to the recent 2022 National Heat Study, Ireland's cumulative heat-related emissions currently amount to 38% of total energy-related CO_2 emissions, or 24% of the total national greenhouse gas emissions (SEAI, 2022). These emissions are derived from the combustion of fossil fuels for heating in residential and commercial buildings, as well as indirectly from electric heating.

Heat-related emissions are up 12% since 2014 and are continuing to increase (SEAI, 2022). The application of renewable heating and cooling in Ireland is the lowest in the EU at only 6% (Eurostat, 2022), and has historically been limited by a lack of binding targets for renewable heat at national and EU levels. A proposed amendment to the Renewable Energy Directive (EU) 2018/2001 seeks to enforce an indicative target of 1.1% increase per annum for renewable heating and cooling (European Commission, 2021). This, coupled with a ban on new oil and gas boiler installations (DECC, 2021a), places Ireland under increased pressure to transform its renewable heat sector. In Northern Ireland, total energy-related emissions have fallen by 25% since 1990, largely driven by the increase in renewable power generation. Energy-related emissions accounted for 59% of the total emissions in 2019, with the heat sector constituting 38% of this (NISRA, 2019).

Ireland is not located near any plate boundaries or active volcanic centres. As such, published estimates for mean surface heat flow across the island are 67 mW m^{-2} (range of 52–87 mW m^{-2}) based on 18 measurements (Brock, 1989), and 70 ± 14 mW m^{-2} based on paleoclimate-corrected present-day heat flow estimates (Mather et al., 2018). A similar range of 59–81 mW m^{-2} is observed in the Celtic Sea basins off the south coast of the island (Corry and Brown, 1998). These estimates are consistent with the 61–77 mW m^{-2} range that is typical for dominantly Phanerozoic continental crust (Pollack et al., 1993). The observed onshore geothermal gradients are also generally in the typical continental range of 20–35°C km^{-1} (Figure 5),

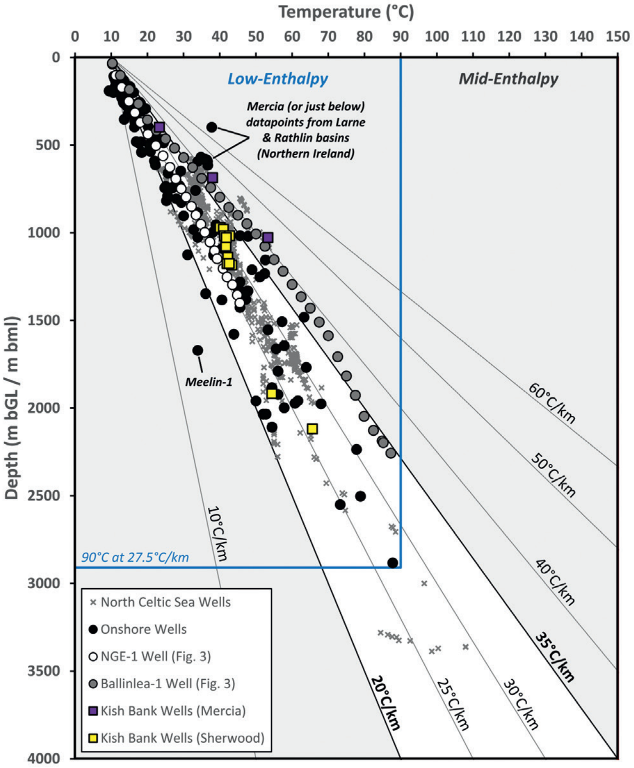

Figure 5 Temperature versus depth plot illustrating data from the offshore North Celtic Sea and Kish Bank basins, and from onshore Ireland including the data from the NGE-1 and Ballinlea-1 wells (see Figure 3). See well locations in Figure 6. The majority of data plot within the typical 20°C km^{-1} to 35°C km^{-1} range for continental crust. All the North Celtic Sea datapoints are based on formation tester data which are considered more reliable than bottom hole temperatures measured during wireline logging operations. However, the onshore database contains a mixture of data types because formation tester data are not generally available. Consequently, some of the outlier data points (e.g., Meelin-1) may be erroneous if the bottom hole temperature had not yet stabilised at the time of measurement. The highest confidence data comes from temperature surveys acquired long after drilling operations have ceased – for example, the data from NGE-1 and Ballinlea-1. Data sourced from the Geological Survey of Northern Ireland (GSNI) and the Department of Environment, Climate and Communications (DECC) in Ireland.

with temperatures of 38°C recorded at depths of 1 km within boreholes in the Dublin Basin (i.e., a gradient of 28°C km^{-1} assuming a surface temperature of 10°C). Hence, any geothermal resources in Ireland are expected to be low-enthalpy (Blake et al., 2015) – unless drilling to depths greater than ~2.5 km – and most of the future focus of geothermal energy across the island is likely to be on decarbonising the heat sector (GSI, 2020; Government of Ireland, 2021; Raine and Reay, 2021). For example, one of the conclusions of Ireland's 2022 National Heat Study is that district heating has the potential to provide as much as 50% of building heating demand in the future (SEAI, 2022). There is also significant potential for shallow geothermal utilisation in Ireland (Abesser et al., 2022; Pasquali et al., 2022), with 94% of Ireland's land mass classified as either 'suitable' or 'highly suitable' for shallow geothermal heat pump applications (see Appendix D in SEAI, 2022). As a step towards realising this potential, a draft geothermal policy statement was published in December 2021 that sets out the approach to regulating the exploration for, and development of, geothermal energy as a natural resource in Ireland (DECC, 2021b).

Onshore geothermal potential in Ireland

The surface geology of Ireland can be described in general terms as a central lowland of Paleozoic (mostly Devonian and Carboniferous) sediments surrounded by a rim of Precambrian to Lower Paleozoic crystalline rocks, with Late Paleozoic to Cenozoic basins in the northeast of the island (Figure 6). A major crustal boundary called the Iapetus Suture Zone runs NE-SW across the central part of the island, and this zone records the closure of the Iapetus Ocean by Late Silurian time and development of the Caledonian orogeny (Chew and Stillman, 2009). Many of the other basement terranes are oriented along this Caledonian trend and several large Caledonian granitic bodies (i.e., Leinster, Galway and Donegal granites and the Newry granodiorite) were emplaced around the end of the Silurian and early Devonian. Lower Paleozoic rocks are unconformably overlain by the Devonian Old Red Sandstone (Graham, 2009), followed by a mixed clastic and carbonate succession of Carboniferous rocks (Sevastopulo and Wyse-Jackson, 2009; Sevastopulo, 2009; Mitchell and Somerville, 2011). Carboniferous strata constitute almost half of the bedrock geology of Ireland (Figure 6) and generally comprise limestone-shale sequences displaying an increase in shale within the deep basinal facies of Carboniferous sub-basins (e.g., Dublin, Shannon and Munster basins). Lower Carboniferous limestones tend to have poor primary porosity but are widely fractured and karstified and constitute important groundwater aquifers (Kelly et al., 2015).

In the northeast part of the island, in Northern Ireland, the basement geology is characterised by the same Caledonian trends, but the area was subsequently subjected to rift basin development where thick sedimentary packages were deposited during the Permian and Triassic periods (Simms, 2009). These basins also acted as depocentres for Upper Triassic to Lower Jurassic sediments and Cretaceous carbonates. Further tectonic movement during the Paleogene and Neogene periods has preserved sequences of Paleocene lavas and Oligocene clays (Figure 6). Permo-Triassic sandstones in this area provide aquifers with higher primary porosity and permeability compared to the fractured aquifers of the rest of onshore Ireland.

Several geological controls on geothermal anomalies were discussed above including lateral variation in thermal conductivity, internal radiogenic heat production and geothermal fluid circulation or advection. Figure 3 demonstrates the important control that stratigraphy has on the detailed thermal structure of the subsurface, even within a single well. It is noteworthy that areas with preserved mud-dominated Mesozoic and shale-dominated Carboniferous strata are likely to be characterised by higher temperatures for a given depth compared to areas with limestone-dominated Carboniferous strata (Figure 3). This is because mudrocks and shales tend to have the lowest thermal conductivities (Figure 4) and hence act as a thermal blanket with relatively high geothermal gradients. Lateral variations in heat flow across Ireland may be superimposed on this. Mather et al. (2018) proposed that heat flow may change across the Iapetus Suture Zone with mean surface heat flow of 65 ± 14 mW m^{-2} for Avalonian lithosphere to the southeast and 73 ± 14 mW m^{-2} for Laurentian lithosphere to the north west. This crustal control on thermal structure has been supported by additional geophysical studies (Mather and Fullea, 2019).

The Caledonian and Paleogene granitic rocks of onshore Ireland are the most likely candidates for elevated radiogenic heat production. Estimates of average heat production rate (HPR) for the Caledonian granites, including the Leinster, Galway and Donegal granites, have a range of 1.5–3.3 µW m^{-3}, but with notable outliers for the Costelloe Murvey and Carnsore granites at 6.3 µW m^{-3} and 6.4 µW m^{-3} respectively (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 HPR for the Mourne Mountains Complex are also higher – 6.6 µW m^{-3} and 7.8 µW m^{-3} for the western and eastern magmatic centres, respectively (Yarr, 2013) and a more recent overall estimated average of 6.8 µW m^{-3} (Willmot Noller et al., 2015). By comparison, the Variscan Carnmenellis granite, which is a major target of geothermal activity in Cornwall, SW England (Ledingham et al., 2019), has an estimated HPR range of 3.4–5.3 µW m^{-3} (Beamish and Busby, 2016). Mather et al. (2018) noted that the highest surface heat flow points in Ireland (90–100 mW m^{-2}) reside above granite bodies.

In terms of advection, groundwater temperatures in Ireland are generally circa 10–11°C (Aldwell and Burdon, 1986), but 42 warm shallow groundwater and warm springs have been documented across the country (Goodman et al., 2004). The temperature of the springs ranges from 12°C to 24.7°C, and the warm groundwater tends to be associated with Carboniferous limestones (Blake et al., 2021). The structural architecture of the Carboniferous in Ireland, and the associated major base metal deposits, are controlled by NE-SW to E-W trending structures (Johnston, 1999) and these structures still play an important role in groundwater flow (Henry, 2014; Moore and Walsh, 2021), either by offsetting and compartmentalising groundwater aquifers or by localising along-fault karst development and groundwater flow. High groundwater flow rates and higher-than-average groundwater temperatures are, however, usually associated with NNW- and NE-trending Tertiary strike-slip faults (Dunphy, 2003; Moore and Walsh, 2013, 2021; Blake et al., 2021), which are dilatant structures developed and karstified at shallow depths (usually < 1km), and may also be critically stressed under the present-day stress regime, particularly in the case of NNW-trending structures.

Aside from karstified zones and localised areas of enhanced natural fracturing (e.g., along faults), the subsurface geology of onshore Ireland has relatively limited potential for hydrothermal aquifers with primary porosity and permeability. Therefore, a significant focus of deep geothermal exploration is likely to be concentrated on fractured carbonate reservoirs or on technologies such as EGS or AGS that can be used to target lower permeability petrothermal reservoirs. The main exception to this is in Northern Ireland, where clastic aquifers of the Permo-Triassic to early Jurassic strata are preserved beneath the Paleogene basalts and

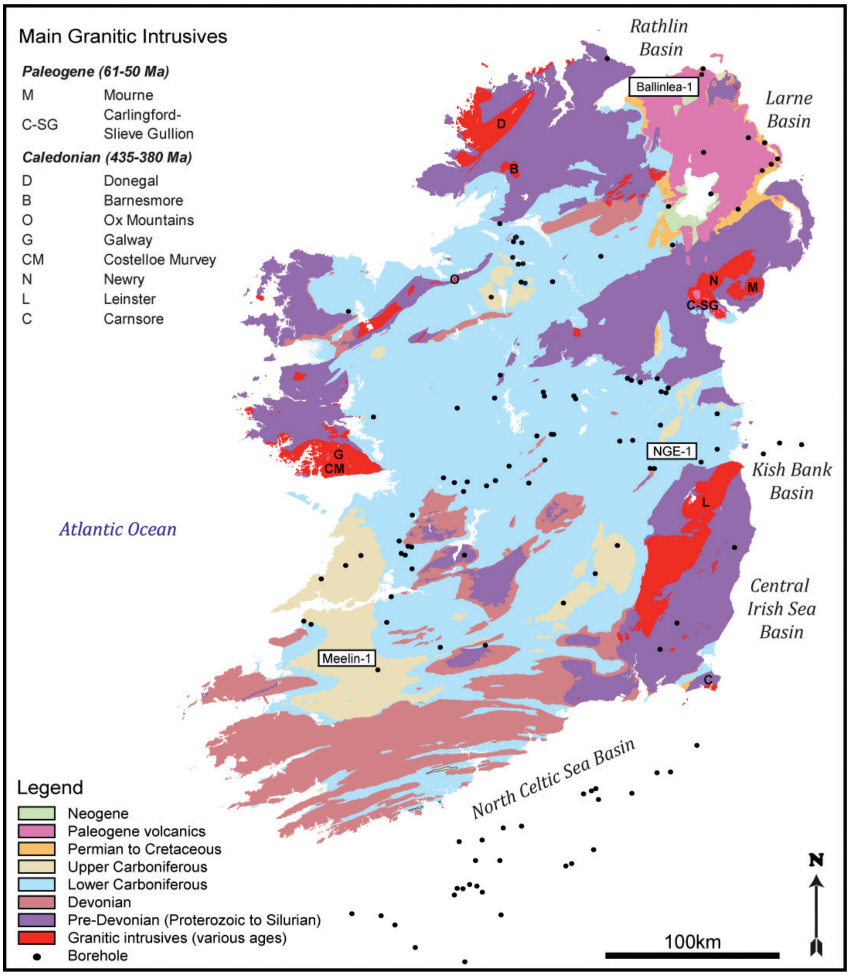

Figure 6 Simplified geological map of the island of Ireland based on bedrock geology maps from the Geological Survey of Ireland (GSI) and the Geological Survey of Northern Ireland (GSNI). The black dots represent the locations of the wells used for the temperature database plotted in Figure 5.

provide an additional onshore target for geothermal energy (Raine and Reay, 2021).

Offshore geothermal potential in Ireland

Offshore geothermal projects have been proposed in regions with anomalously high heat flow such as offshore Iceland and Italy (e.g., Karason et al., 2013; Paltrinieri et al., 2022), and in areas where high-temperature water is being co-produced with petroleum (e.g., Auld et al., 2014; Gluyas et al., 2019), and advances are also being made with long-distance (>10 km) heat transmission (see review in Kavvadias and Quoilin, 2018). Ireland is surrounded by numerous offshore Mesozoic to Cenozoic sedimentary basins, and the stratigraphy and thermal regimes are relatively well-constrained due to past hydrocarbon exploration drilling (Naylor and Shannon, 2009; Merlin Energy Resources Consortium, 2020). Although the offshore is not currently a focus area for geothermal activity in Ireland, a brief introductory discussion is included here because of: (1) the general lack of laterally continuous permeable hydrothermal targets onshore, (2) the presence of thick permeable aquifers in the offshore near major urban centres, and (3) the greater understanding of the offshore in terms of subsurface imaging and architecture. Basins adjacent to urban centres include the North Celtic Sea (Cork), Kish Bank (Dublin) and Larne (Belfast) basins. The concept is illustrated here with the Triassic of the Kish Bank Basin, within 5–40 km offshore Dublin in water depths of 15–75 m (Figure 6).

The Kish Bank Basin has been interpreted as a remnant of a larger Permo-Triassic basin system known as the Greater Irish Sea Basin (Dunford et al., 2001). The stratigraphy includes Carboniferous silts, sands and coal measures, Permian sandstones and claystones, the Triassic Sherwood Sandstone Group, the Triassic Mercia Mudstone Group (containing mudstone and evaporites), and thin Cenozoic strata (Lunula Group to Brython-Glacigenic-Demetae Groups). Three of the wells drilled in the Kish Bank Basin penetrated thick water-bearing sandstone packages in the Triassic (Figure 7) with average porosities of 14–18%. Observed drawdown mobilities of 3–359 mD/cP were measured during a Repeat Formation Tester (RFT) survey in the 33/17-2A well, which is consistent with permeability estimates of 5-100 mD based on analogues from the East Irish Sea Basin (SEAI, 2008).

The geothermal gradients in the Triassic sandstone, with respect to seafloor at an assumed temperature of 10°C, are estimated between 23-32°C km^{-1} based on maximum recorded bottom hole temperatures (Figure 7). There is a strong lithological control on the detailed thermal structure of the basin with higher gradients observed in the Mercia Mudstone Group and lower gradients in the underlying Sherwood Sandstone (see onshore example of this in Figure 3). The measured reservoir temperature in the Sherwood Sandstones in the three wells ranges from 40 and 66°C at depths of 970-2120 m below the seabed (Figure 8). The depth of the top Sherwood Sandstone Group in the Kish Bank Basin varies between 250 and 3250 m below seabed (SEAI, 2008) and hence the formation water temperature could be expected to vary from 20 to 120°C across the basin. The Triassic sandstones of the Kish Bank Basin represent an example of a potential low- to mid-enthalpy offshore hydrothermal resource that could provide additional renewable anchor loads to support the local district heating pipeline network in Dublin city centre, currently planned to distribute waste heat from the Dublin Waste-to-Energy Facility at Poolbeg in Dublin Bay (DCC, 2020).

Conclusion

A geothermal resource is the thermal energy (heat) that can be extracted at an economically accessible depth and used for power generation or heating. One common classification scheme for geothermal resources is based on the enthalpy of the geothermal fluid: high-enthalpy (>150°C) resources for electricity generation in conventional geothermal power plants, mid-enthalpy (90-150°C) resources for electricity generation in binary power plants, and low-enthalpy (<90°C) resources that can be utilised for a wide variety of direct use applications including district and

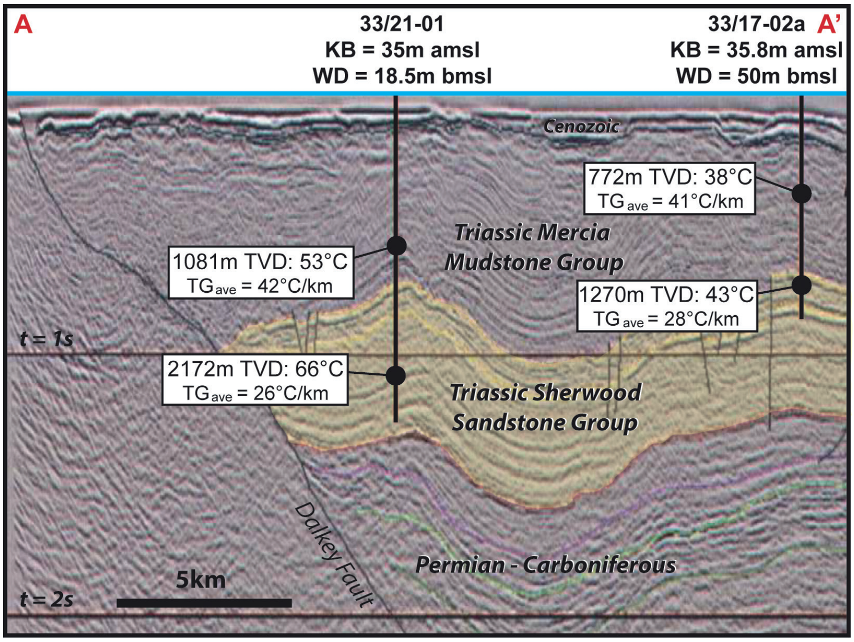

Figure 7 Cross-section of the Kish Bank Basin nearshore to Dublin (modified from Dunford et al., 2001). Section line shown in Figure 8. The Triassic Mercia Mudstone Group, consisting of shales and evaporites, overlies the Triassic Sherwood Sandstone aquifer, estimated to be >1000m thick. Well 33/21-1 and well 33/17-02a recorded temperatures of 53°C and 38°C, respectively, in the Mercia Mudstone Group. Assuming a seafloor temperature of 10°C, these temperatures indicate elevated average geothermal gradients of 41-42°C km^{-1} in the Mercia Mudstone in the Kish Bank Basin. Conversely, maximum recorded temperatures in the underlying Sherwood of 66°C and 43°C, in the same two wells respectively, indicate lower average geothermal gradients of 26-28°C km^{-1} with respect to surface (i.e., the local geothermal gradient within the Sherwood itself is likely to be even lower). This observation of higher gradients in the Triassic Mercia versus the underlying Sherwood sandstone is like that observed in the Ballinlea-1 well in Northern Ireland (Figure 3). KB = kelly bushing, WD = water depth, TVD = true vertical depth, TGave = average temperature gradient with respect to surface assuming a seafloor temperature of 10°C, amsl = above mean sea-level, bmsl = below mean sea-level, t = two-way time.

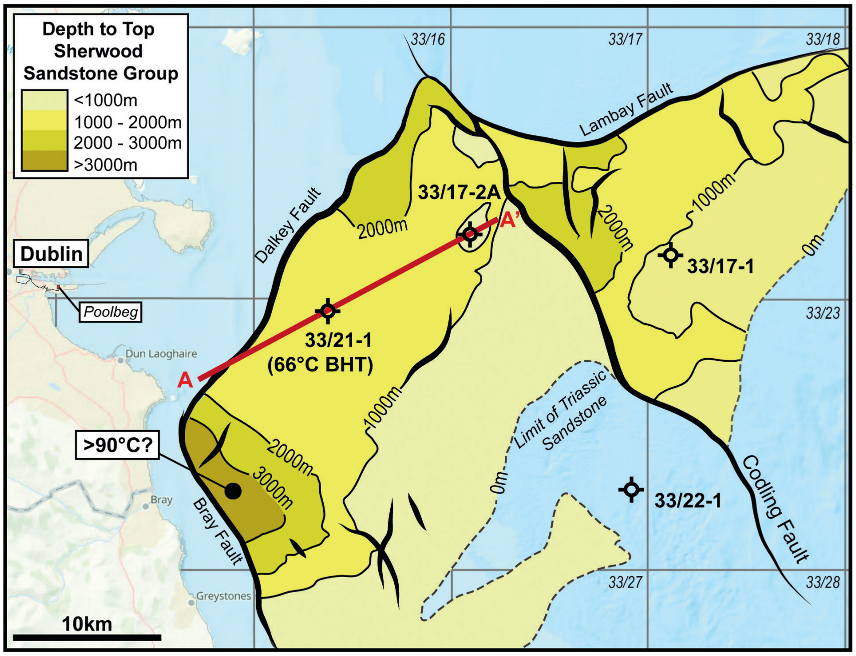

Figure 8 Simplified depth map for Top Triassic Sherwood Sandstone in Kish Bank Basin (structure map adapted from Dunford et al., 2001). Temperatures towards the depocentre close to Dublin may extend up to mid-enthalpy (>90°C) window between 2.7 and 3.2 km below mudline within the Triassic Sherwood Sandstone, assuming a seafloor temperature of 10°C and an average geothermal gradient of 25°C km^{-1} and 30°C km^{-1} respectively. The reservoir could be more than 1 km in thickness so the mid-enthalpy window could in effect cover a broader area. Further modelling is required to constrain temperatures, reservoir quality and heat resource potential. Heat resource from this basin could be brought onshore locally towards Bray (<5km) or plumbed into district heating network at Poolbeg. MRT = maximum recorded temperature, TVD = true vertical depth.

space heating (and cooling). In general, Ireland is characterised by typical geothermal gradients of ~20–35°C km^{-1} and, hence, geothermal activity will primarily focus on low-enthalpy uses such as heat.

The significant potential of Ireland's geothermal resources to decarbonise its heat sector in line with its climate targets is recognised. However, the lack of high-quality geoscientific data is a major barrier to development of the sector at present. Ireland's shallow geothermal resources are well understood, and ground source heat pumps can be readily deployed across much of the island to provide low carbon heating and cooling.

There is a continuum of deep geothermal systems from high-permeability hydrothermal reservoirs that can produce naturally occurring geothermal fluids to low-permeability petrothermal reservoirs that may have little or no natural fluid content. The geology of onshore Ireland is mostly characterised by Carboniferous and older rocks with relatively limited potential for hydrothermal aquifers with primary porosity and permeability development. Consequently, deep geothermal exploration on the island is likely to be concentrated on fractured or karstified carbonate reservoirs or on technologies such as EGS or AGS that can be used to target lower permeability petrothermal reservoirs. The onshore exception to this is Northern Ireland where clastic aquifers in the Permo-Triassic are preserved beneath Paleogene basalts. Additional geothermal potential exists in the shallow-water near-offshore basins of Ireland. As an example, thick, porous and permeable Triassic sands are present in the Kish Bank Basin with an estimated temperature range of 20–120°C across the basin.

To fully understand Ireland's geothermal potential, it is imperative that more data are acquired. Further planned research includes: (1) building and adding to the temperature and heat flow database for Ireland, (2) development of a 3D subsurface model for onshore Ireland, (3) building and adding to the thermal conductivity database to assess lateral and vertical variability and impact on thermal structure, (4) developing geological models for permeability prediction in the subsurface, (5) building an in-situ stress database for Ireland to aid in fracture permeability prediction, EGS resource evaluations and wellbore design, and (6) reviewing potential for hydrothermal clastic reservoirs in the near-offshore, including reservoir quality prediction for the Triassic sandstones in the Kish Bank Basin. The acquisition of static temperature surveys in old deep wells and national seismic acquisition programmes would also significantly add to our understanding of the thermal properties and structure of the subsurface in Ireland.

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