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Methodology in Assessment and Presentation of Low Enthalpy Geothermal Resources in Ireland

[1]Róisín Goodman, [2]Gareth Ll. Jones and [1]John G. Kelly

[1]SLR Consulting (Ireland) Ltd, 7 Dundrum Business Park, Windy Arbour, Dublin 14, Ireland. [2]Conodate Geology, 7 Dundrum Business Park, Windy Arbour, Dublin 14, Ireland.

rgoodman@slrconsulting.com, conodate@mac.com, jkelly@slrconsulting.com

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ABSTRACT

Studies were carried out in 2004 and 2005 across the island of Ireland, to develop a database and a series of index maps for the geothermal resources of Ireland. The objective of the projects was to produce a GIS-linked geothermal database, an up-to-date map series, and a report with recommendations for the next steps necessary in expanding the use of Ireland's geothermal energy from both shallow resources and the somewhat unknown deeper resources. Some of the difficulties involved in finding a best approach to such an exercise are discussed and some of the strength and weaknesses of the results of such a study are presented. However the value of carrying out such an exercise is highlighted as a first tool in geothermal resource assessment. A number of geothermal depth plans have been produced for surface, 100m, 500m, 1,000m, 2,500m and 5,000m depths. The maps may be viewed using free MapInfo-Proviewer software.

INTRODUCTION

The Geothermal Resource Map Series of Ireland study (Goodman *et al.* 2004) was performed by the CSA Group (now SLR Consulting (Ireland) Ltd.) in co-operation with Conodate Geology, Cork Institute of Technology and the Geological Survey of Ireland. It was a Public Good contract carried out on behalf of Sustainable Energy Ireland.

The goals of the study were to identify potential resources of geothermal energy in Ireland and use these to create geothermal plans of Ireland by gathering the necessary hydrothermal, geological and structural data to facilitate the production of a GIS-linked database and create a series of geothermal maps of Ireland. The work also reviewed the current status and utilisation of geothermal energy resources in Ireland and recommendations were made on best approach to future potential exploitation of the geothermal resource in Ireland in the context of International Best Practice. A later all-island study included more detailed data on Northern Ireland and was also completed by the CSA Group, under EU, INTERREG funding (Kelly *et al.* 2005).

It was expected that new data and reinterpreting Ireland's geothermal database would significantly enhance the value of the available information on Ireland's geothermal potential and provide a concise review of earlier work allowing easier integration of the available information with the European geothermal databank. The public availability of the data was emphasized as a key aspect of the work in order to increase awareness of the potential of geothermal energy in Ireland. As the first review of its kind since the 1980s it was hoped to identify strategies for geothermal energy development.

The base data presented for this study are in effect a partial data set and the methods employed to extrapolate were simple and include broad assumptions. The results are presented as a first approach to handling sparse geothermal data and as a first pass for assessing geothermal resource potential as a tool perhaps to encourage further exploration and dedicated drilling programmes to quantify the actual resources.

DATA USED FOR THE STUDY

The study started with a review of the available data sources in the relevant government departments including the Geological Survey of Ireland within the geothermal archives, the Exploration and Mining Division and the Petroleum Affairs Division. Previous studies were reviewed and data incorporated into the study – in particular the Irish Geothermal project 1981-1983 (Aldwell 1984, Burdon 1983a,b) and Murphy & Brück (1989).

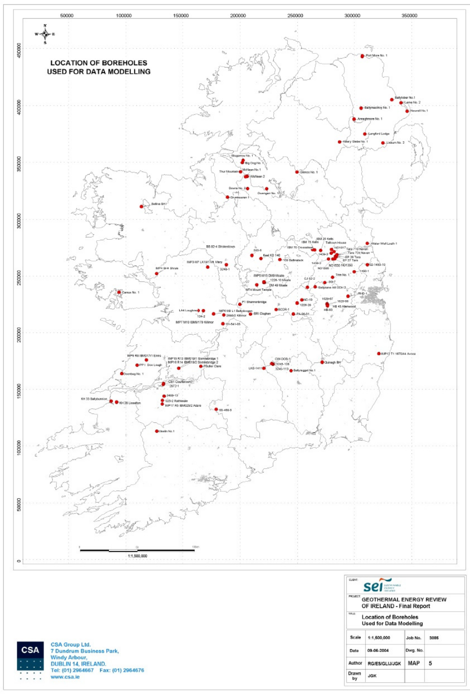

Figure 1: Borehole distribution used for the study.

Mineral exploration companies were contacted to gather any available information from recent exploration programmes which were not yet publically available. A borehole and spring temperature monitoring programme was carried out at accessible sites. The study included geological, structural and hydrothermal analysis of the areas with potential and attempted to use these data to provide a more reliable estimate of the resources and potential. It was first reported at the Unterhaching EGC (Jones *et al*. 2007).

Data compilation

Initially as part of the study, data were compiled on heat-pump usage and groundwater temperature trends in warm springs and shallow boreholes <100m depth, a total of 80 sites. A programme of temperature monitoring was also completed for 32 open boreholes to obtain new temperature profiles. The new boreholes ranged in depth from 40m to 810m. The deepest borehole monitored was No. 01-541-03, Co. Galway in the west midlands (Figure 1).

Temperature data from 68 historical mineral and oil exploration holes ranging in depth from 300m to 2,300m (deepest borehole Drumkeeran (No. 1), Co Leitrim) were then compiled from boreholes monitored since the previous geothermal studies. Data sources included Mineral Exploration reports EMD / GSI 1970–2003a,b and Oil company reports 1970-2001a,b PAD / GSNI.

Temperature records from active oil and mineral exploration companies provided data on nine new boreholes ranging in depth from 391m to 1,550m with five holes deeper than 1000m.

New data were then combined with data from earlier studies, Aldwell 1984, 1990; Aldwell & Burdon 1980, 1984, 1986; Brock 1989; Burdon 1983a,b).

<u>Mineral Exploration Data</u>

Ireland has had a very active mineral exploration and mining sector for over 50 years and as such there has been a significant amount of shallow (50-300m) drilling in parts of the country though predominantly located in areas underlain by Carboniferous aged limestones covering much of the midlands of the country (Figure 2). Despite this exploration activity there are still many areas with sparse drilling and therefore poor geological detail at depth. Though there has been limited onshore oil and gas exploration there are few areas with boreholes deeper than 500m. As a result the data available are sporadically distributed and somewhat biased to particular lithologies.

QUALITY OF DATA

As mentioned the compiled data are heavily biased towards areas of economic interest, primarily the Carboniferous Limestone areas for metals, Carboniferous coals and the Permo-Trias Basins for hydrocarbons, halites. The maximum depth from which temperature measurements were available was 2300m with much of the data coming from shallower than 500m. Only temperature measurements from boreholes greater than 500m deep have been used to provide geothermal gradients for extrapolation to depths below 1,000m. Large areas of the country have little or no exploratory drilling; this includes granite batholiths, metamorphic areas, Namurian outliers and Lower Palæozoic and Devonian inliers. Some of the specific issues encountered in modelling geothermal gradients and extrapolating temperatures in the related to local geology are documented in the following sections.

Carboniferous Midland Basins

Though the majority of the boreholes are located in the Carboniferous Limestone, many are <300m depth and as the influence of fracturing and karst in the Carboniferous is more intense than in other units care is needed in extrapolation to depth.

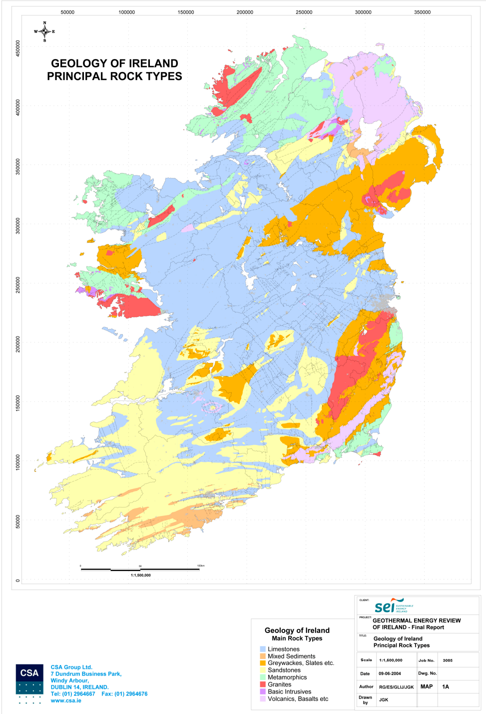

Figure 2: Ireland summary geology Basalt and Mesozoic Basins (pale purple (Northern Ireland only)), Carbonates (blue), Devonian sandstones (yellow), Lower Palaeozoic sediments (orange), Caledonian metamrphics (green), Granite (red)

Munster basin

Most of the Munster Basin with Devonian and Carboniferous clastic sediments has no deep drilling or temperature data available. One deep drillhole in the northwestern edge of this basin records very low temperatures of 33.8ºC at a depth of 1,690m (Meelin no. 1 borehole). The low gradient of 14.3°C/km recorded has influenced all modelling for this region. It is essential that more extensive information is obtained in the future to reduce the reliance on this single data point.

Granites

The batholiths of Leinster, Galway and Donegal are completely untested except for a number of shallow (<150m) boreholes for which heat flow data have been measured (Figure 3). However there are few data to indicate whether these areas would be of interest for Enhanced Geothermal Systems and more data are required. One point of interest is that the Mourne Mountain Complex and Slieve Gullion Complex (Young *et. al*, 2009) on the northeast coast is known to have the highest radioactivity of any batholith in the UK and Ireland and has become the focus of deep geothermal investigation by the Geological Survey of Northern Ireland in the past year.

Metamorphic / Crystalline basement and Lower Palaeozoic basement sediments

Little data were available for the metamorphic basement which underlies most of the Ireland and is exposed in the vicinity of the Leinster Massif, within midland inliers and especially in the south-east and in the Longford-Down belt from the north midlands to the Co. Down coast.

Exposures in the north-west and west have no temperature data. However it is likely that these rocks control much of the deep geothermal potential An attempt was made during the study to produce level plans mapping the occurrence of crystalline basement at the depth studied. This was abandoned due to insufficient geological data.

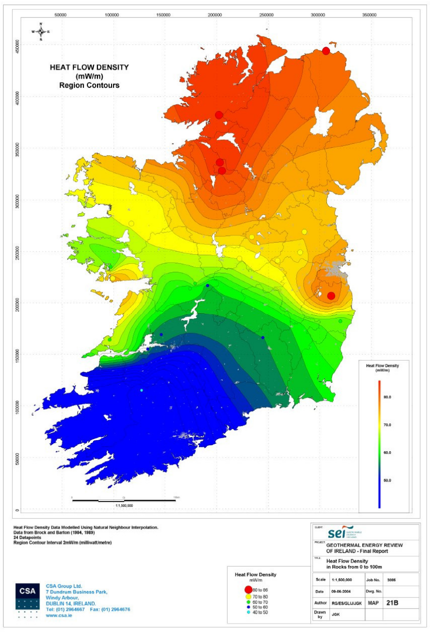

Figure 3: Modelled Heat Flow

EXTRAPOLATION OF THE DATA TO DEPTH

Once data had been compiled in excel format, a major issue with the project was how to best utilise these temperature and geothermal gradients to provide best estimates of temperatures in areas and at depths for which there were no data. It was clear that the dataset required extensive extrapolation as there were insufficient data for simple contouring of measured data at the depths for which maps were required. Extrapolation of temperature using geothermal gradient was carried out on data from all boreholes greater than 300m depth in order to provide sufficient coverage for map production.

Calculation of gradients in earlier studies often assumed a single gradient for the whole borehole and thereby resulted in conservative overall gradients in many cases due to the influence of locally depressed surface gradients due in part to surface water influx through karst and fractures. In fact looking at these same data it is apparent that in 40% of cases the gradient is seen to increase with depth (the opposite is observed in 30% of cases). The controls on these changes in geothermal gradient are complex and critically dependent on local conditions i.e. lithology, porosity and permeability and fracturing/structure.

For this study all new and historic data were reviewed and the gradient chosen in each case for extrapolation was as far as possible more representative of deeper parts of the borehole and the deeper geology.

The relationship between the measured gradients and the geology was also examined in each case and helped in choosing a preferred gradient for extrapolation. An attempt was made to categorise the likely gradients in common lithologies encountered in the drilled sequences. However this was found to be impossible with the available data though some qualitative statements can be made about the general influence of more mud rich versus more karstic or sand rich sequences. Comments on these are included in the sections below.

It is noted that in similar modelling exercise of geothermal gradients in Belgium by Vanderberghe and Fock (1989), a strict limit was placed on the depth to which data from a borehole would be extrapolated. This has not been applied in this study as the distribution of data is insufficient to give any meaningful estimate of geothermal gradient at depth without extrapolation from most boreholes available.

GIS, DATA MODELLING & MAP CONTOURING

The final database contains measured records from 75 boreholes between 300m and 2,300m depth. Of these boreholes 49 extend to a minimum of 500m depth and have been used for deeper temperature modelling. Data on many other boreholes <300m deep are available and have been used for modelling to 1000m but have not been included in deeper.

The data were uploaded to a GIS software package and data contouring was conducted using gridding software embedded within the GIS package. The GIS software used was Mapinfo and the grid modelling was conducted using a Mapinfo add-in, Vertical Mapper. Some interpolation techniques produce more reasonable surfaces when the distribution of points is truly random. Other techniques work better with point data that are regularly distributed. Highly clustered data, such as the geothermal data for the springs and boreholes, presents problems for many interpolation techniques.

Geothermal data form a particularly difficult dataset for contouring due to the highly variable distribution of the data points. The data points fall primarily within a number of data clusters (Northeast Permo-Trias, Northwest Carboniferous, North Leinster and the Mallow area) with scattered data points outside these four regions. In addition, parts of the country had no data available.

To model such a clustered dataset, it was decided to conduct the initial contouring using a variety of modelling techniques and parameters to determine which modelling technique would give the best solution. Following initial results, it was determined that natural neighbour interpolation was best suited to model the datasets and all detailed modelling was conducted using this method.

Interpolated data points

As mentioned the data distribution is highly skewed to geological regions of economic interest, and a number of geological regions contained no data. Where such regions were considered to significantly differ in properties to adjacent data-rich regions, a small number of calculated data points were inserted into the database before contouring.

STRUCTURE AND OTHER PHYSICAL CONTRILS ON GEOTHERMAL GRADIENT

Some comments are included below on the influences of local lithological changes, weathering and rock structure on geothermal gradients.

Karst development and shallow groundwater mixing

Much of the upper 200-300m of the Carboniferous Limestone in Ireland is known to have had significant karst development during periods of lower sea levels. There are indications that karstification may have reached even lower levels in some places. Many karst conduits are still operative at these depths.

In the compiled database examination of the relationship between the geothermal gradient and borehole depth indicated that the top 200-300m of most of the boreholes demonstrated mixing of surface run-off waters and shallow groundwater. This rapid percolation of surface water through deep fractures and karst had thereby disrupted the geothermal gradients at these depths. Therefore for this study only geothermal gradients from boreholes >300m were utilised for extrapolation to depths of 1,000m and only geothermal gradients from boreholes >500m were used for extrapolation to depths of >1,000m.

Insulation effect of Shale rich Units

The presence of shale layers is considered in many studies of deep geothermal potential to be important in "blanketing" deep heat and preventing it from flowing easily to the surface. Because of the abundance of shaley limestone and shales in parts of Ireland the recognition of this setting will be important in identifying deep geothermal targets.

Warmer temperatures have been recorded in some areas of the Irish midlands where there is thick limestone cover, especially in Westmeath and Offaly into east Galway. These temperatures may reflect enhancement by the insulating effect of limestones (which also have lower heat conductivity than quartz rich sediments) and the associated shale cover.

Fracture flow 'aquifers'

Most Irish rocks are strongly lithified and primary porosity is low. Permeability thus relies heavily on the secondary porosity of fracture fields. There are few true bedrock aquifers in Ireland and fracture flow predominates in porosity and permeability and hydrological connectivity.

On the other hand fracturing and deep penetrating faults are common throughout Ireland due to its position straddling the remnants of the Lower Palaeozoic Iapetus Suture, a palaeo-continental collision zone running in a northeasterly trend from Limerick to Drogheda. Variscan tectonism produced generaly east-west fractures south of the Iapetus suture. Also Tertiary joint and fracture sets were emplaced during Atlantic opening tectonism. Areas with significant fracture flow are considered important for hydro-thermal development. There are likely to be a number of very important secondary aquifers which can be considered for the development of deep geothermal projects.

It was noted in temperatures and gradients recorded in the borehole database that depressed temperatures at depth in boreholes could in some cases be attributed to possible influx of shallow ground-waters to depth along adjacent fracture zones. Similarly, warm springs or warm shallow groundwater were investigated in detail at the Mallow warm spring (O'Brien 1987) can be attributed to rapid access of deeper waters to surface along fracture zones.

These observations have influenced the choice of gradients to calculate deeper temperatures used in this study. However further investigation is required to fully quantify these effects.

In the vicinity of the Iapetus Suture in the midlands there are numerous zones of anomalous warmer or colder temperatures and associated variations in geothermal gradient. Again the distribution of boreholes available for testing has produced some bias in the data. A zone of enhanced geothermal gradients was previously interpreted by Phillips (2001) to lie along the trend of the suture zone where it is linked with Paleogene age fault activity in the area. In this study cooler zones along the suture trend are interpreted to result from zones of fractures /joints and/or karst development, allowing localised rapid infiltration of cold water from the surface deep into the groundwater, where it reduces the groundwater temperatures.

Regional and palaeo-tectonic setting

In general, Ireland is considered to be tectonically stable. The main evidence of tectonism in recent times has been rare, small earthquakes in the Irish Sea basin and onshore in northwest Donegal and southeast Wexford. Except for small warm spring areas there are no strongly geothermally active regions. However recent work in the Irish Sea confirms the presence of some previous geothermal activity in the Irish Sea basin. Ongoing work indicates the presence of a palaeo hot-spot which may have been active during pre-Quaternary times. This palaeo hot-spot has been postulated as possibly influencing the distribution of river systems draining westward across Ireland and resulting in the formation of so called 'palaeo-channels' in the Irish midlands (Hardy 2003).

COMBINING HISTORICAL DATA WITH NEWLY MONITORED DATA

The temperature monitoring equipment used for the acquisition of new data for this study was a specially commissioned 1,000m long dual dipmetre and temperature probe which allowed easy access to borehole sites. For shallow monitoring a hand held 2m digital recorder was used.

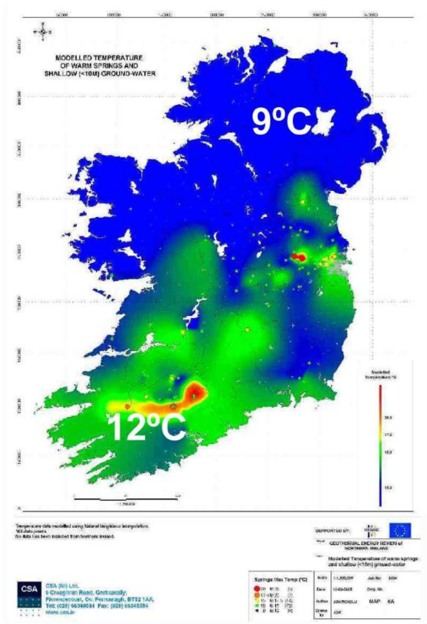

Figure 4: Modelled Temperatures at Surface indicating areas of warm springs

It is noted that temperature readings from more than five different thermometers have been used in this study. As much of the data is historical it was not possible to carry out a calibration exercise between them.

RESULTS

In a regional context, geothermal gradients in Ireland show an increase from south to north at all levels. An exception to this is the west of County Clare in western Ireland where the highest geothermal gradients in the south of Ireland are located. This trend is also evident in measured temperature data from the deeper boreholes. This regional trend is interpreted to be associated with the main structural divisions in the Irish subsurface in particular the Iapetus Suture. This is a deep crustal structural feature and marks the line of the late Silurian collision between two crustal plates which were previously separated by an ocean. Although the Iapetus Suture is over 460million years old it had a long-lived influence on sedimentation patterns and can still be seen in deep geophysical profiles of the sub-surface of Ireland (Jacob *et al.* 1985). The position and different characteristics of these plates is also seen to mark a change in the geothermal properties of these areas.

Another significant trend in the data is an east-west trend to the south of the Iapetus Suture which is observed in both the North Leinster and North Munster warm spring data sets. This is Variscan in origin and its associated structures are interpreted to be generally east-west deep penetrating faults. The Variscan deformation resulted in the formation of a number of deep inclined faults in the south of the country which control the presence of warm springs in the Cork area. It is interpreted that the thickening of the sediments in the south, as a result of compressional faulting during the Variscan, may have resulted in the presence of lower geothermal gradients due to the thickened crust. It is postulated here that some component of this low geothermal gradient in the south is also the higher conductivity of the quartz rich sediments here allowing rapid transfer of the near surface heat to the atmosphere. This is in contrast to the Northern Ireland where the interpreted presence of thinned crust underlying the Antrim flood basalts seem to control the higher geothermal values present. To the north of the Iapetus Suture a subtle north-south trend also emerges which is interpreted to be associated with a much later tectonic event of circa. Triassic age. This is seen in the Kingscourt area, Co. Cavan where there are enhanced temperatures (15ºC) near surface. The same structure at Kingscourt may also continue north and influence the Lough Neagh area in Northern Ireland where there are high temperatures at depth.

Temperature of shallow (<100m) groundwater & warm springs

Ireland is fortunate in having a temperate-wet climate continuously recharging large volumes of relatively warm water in the subsurface. From this study groundwater is defined as having temperatures over 12ºC in the south of the country and over 9ºC in the north of the country (Figure 4). Allen & Milenic (2003) and Davis (2003) delineated buried shallow, high-flow aquifers in Cork, which have been, and are being, exploited by several major projects such as the Glucksman Art Gallery (Gondwe *et al.* WGC2010).

Warm spring and enhanced shallow groundwater temperatures vary from just above normal to a maximum of 23.5ºC, as observed in a borehole at Glanworth Co. Cork (Mooney *et al.* WGC2010). This study has confirmed that the areas with the most abundant warm springs are the Mallow area in north Co. Cork and the Dublin/Meath/Kildare area.

Of most importance in the distribution of warm springs is the presence of deep tapping structures such as the Carboniferous Basin bounding, Blackrock-Rathcoole fault at the north side of the Leinster Granite in south Co. Dublin and the thrust fault at the north side of the Devonian in Mallow (Mooney *et al.* WGC2010).

Temperatures and geothermal gradients at 500m

At 500m depth a number of hot-spots are present in west Clare, north-west Cavan, north Antrim and east Tyrone where values range from 25ºC-27ºC. Generally more elevated values are present throughout the midlands as compared with the west and south where values are mostly in the range of 17ºC-19ºC. There is some degree of bias due to the relative abundance of data in the more central areas. However despite this bias, it is interpreted that there is some division in deep geothermal activity, from the colder temperatures and lower geothermal gradients in the south to the warmer temperatures and higher geothermal gradients in the north. This feature becomes better defined at deeper levels.

Temperatures and geothermal gradients at 1,000m

The results of temperature contouring at 1,000m are included on Figure 5. The borehole temperature map at 1,000m depth has been modelled from measured and calculated temperatures in 72 boreholes. The modelled data have been produced from boreholes that reached 1,000m together with temperatures calculated from geothermal gradients in boreholes that reached 300m. Some similar patterns of warmer temperatures and geothermal gradients as seen at 500m are also seen at this level, as some of the data have been directly extrapolated from the gradients present at 500m depth.

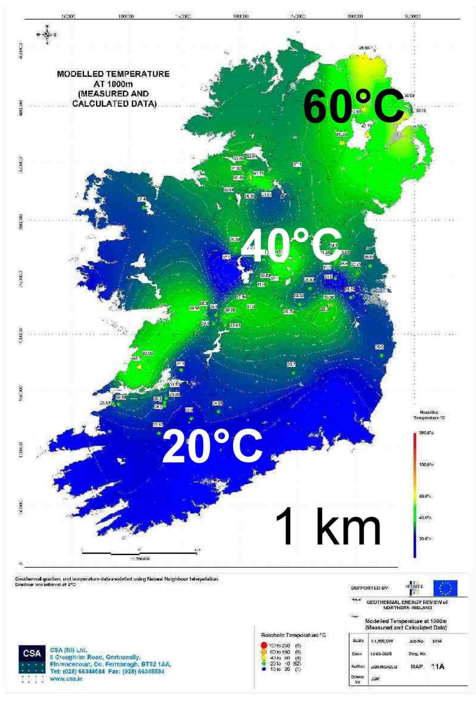

Figure 5: Modelled Temperatures at 1,000m

Generally at 1,000m, gradients in the south of the country are 10ºC – 15ºC/km and range from 20ºC–30ºC north of the Iapetus Suture line. Highs in geothermal gradients of around 35ºC/km are recorded in the more anomalous zones and represent the areas of most potential in any further investigation and testing of deep geothermal gradients

The areas showing the higher geothermal gradients are in the Antrim, northwest Cavan/Fermanagh and Clare areas. The presence of the Iapetus Suture becomes more strongly defined at this depth and generally creates a separation between the north and south midlands. Temperature ranges between 22ºC–28ºC to the south to 37ºC–46ºC to the north of this line. There are still some zones of anomalously low temperatures in areas underlain by potentially karstified limestones which may be the result of deep circulation of cold groundwater from surface along fractures.

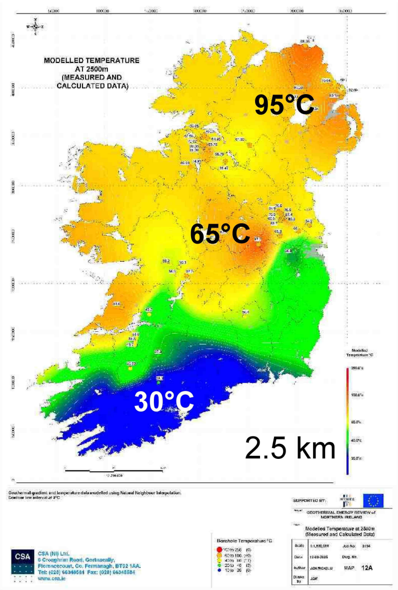

Figure 6: Modelled Temperatures at 2,500m

Temperatures and geothermal gradients at 2,500m

The results of temperature contouring at 2,500m are included on Figure 6. The borehole temperature map at 2,500m depth has been modelled from two measured and 47 calculated temperatures from geothermal gradients in 49 boreholes that reached a minimum depth of 500m. As most of the temperatures here are calculated, more caution must be used in the interpretation. Additional caution is necessary also as most measured data are from the Carboniferous, while at a depth of 2,500m in the midlands the predominant rock-type is interpreted as Lower Palaeozoic in age and is a quartz rich sequence compared to the limestones of the Carboniferous. The map shows a similar division in temperature values across the Iapetus Suture from Drogheda to Limerick with 'hot-spots' in the Kildare, Navan and north Cavan areas in the Republic of Ireland and in the east Tyrone and north Antrim areas of Northern Ireland. Temperatures vary from a range of 28ºC to 45ºC in the south to a range of 64ºC to 97ºC in the north (with a max of 101ºC).

This partly also applies to the Lough Allen Basin, in the north midlands (where the basin is either Lower Palaeozoics or Dalradian metamorphics with variable thicknesses of Old Red Sandstone facies between the basement and the Carboniferous sequence), in the Larne, Lough Neagh and Rathlin basins, total sedimentary sequence thicknesses exceed 3,000m for the Permo-Triassic alone, with unknown thicknesses of Carboniferous or older sediments overlying the basement rocks in these areas.

Temperatures and geothermal gradients at 5,000m

Borehole temperature modelled contours at 5,000m depth are presented on Figure 7.

The temperatures presented on this map have been modelled using temperatures calculated only from geothermal gradients in boreholes that reached 500m. The unavailability of data at depths below 5,000m means the temperatures presented are of necessity only an indication of the possible temperatures that may be encountered at this depth. The patterns of 'hot spots' are the same as for the map for 2,500m, since the data on the 5,000m map are extrapolated from the data at 2,500m. The models show a similar division in temperature values across the Iapetus Suture from Drogheda to Limerick with 'hot-spots' in the Kildare and Navan areas of the Irish Midlands and in the Lough Allen, Larne, Lough Neagh and Rathlin basins.

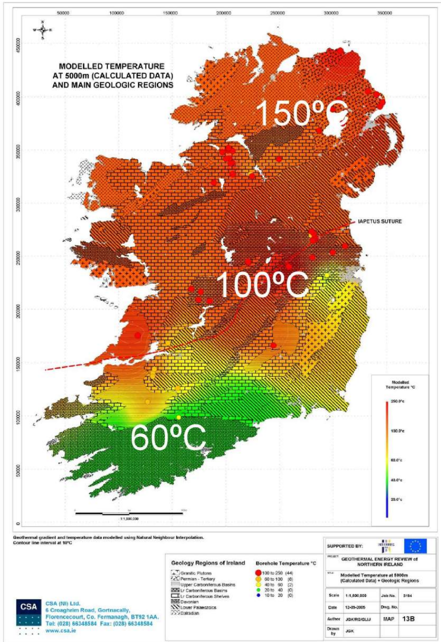

Figure 7: Modelled Temperatures at 5,000m

At 5,000m the background temperatures in the southern parts of Ireland are in the range of 60ºC - 75ºC while they are significantly higher in Northern Ireland, with values of 115ºC - 165ºC in the Lough Allen Basin, 115ºC - to 150ºC in the Larne and Lough Neagh Basins and a potential 180ºC in the Rathlin Basin.

TEMPERATURE VARIATION AND HEAT FLOW

Heat flow density measurements from four sites have been added to a previous database and modelled (Figure 6). Heat flow can change with depth and can also result in lower geothermal gradients where it results in high transmissivity of heat to the surface resulting in more rapid cooling of the surface of the crust. Therefore data on measurements of heat flow need to be applied with caution.

University College Galway looked at heat flow figures across Ireland (Brock 1989, Brock & Barton 1984, 1988a,b 1989). This suggests that there is very low heat flow in the south with very high values in the north-east, plus a hot spot south of Dublin. The caveat concerning restricted data points applies to this map also and in particular the restriction of the data points to intrusive bodies only as there have been no studies of heat flow in the sedimentary or metamorphic lithologies in Ireland.

Potential for Enhanced Geothermal Systems or Hot Dry Rock

Clearly definable geological controls are difficult to evaluate in relation to geothermal gradients within deeper levels of the sub-surface in Ireland.

From the data reviewed in this study it is apparent that considerable uncertainty remains in estimating temperatures at depths of 2,000m or greater. However, results of this review indicate a number of areas with the potential for high temperatures up to >150ºC at a depth of 5,000m. These areas are the north-western part of Cavan / southwest Fermanagh, and northern Antrim / Londonderry. Measured data in both these areas show temperatures of 57ºC in Cavan at 2,000m and 63ºC in Antrim at 1,500m depth, indicating overall geothermal gradients between 24ºC/km and 35ºC/km. In parts of north County Meath there are geothermal gradients of 25-30ºC/km at 1,500m depth, which is also encouraging.

CONCLUSIONS

It is concluded that there is justification for extrapolation of data as carried out in this study as the study provides a necessary database as an initial baseline of geothermal data.

The modelling approach was successful at the production of a set of maps and a data base for future update with the caveat of the importance of stating the assumptions used to improve future evaluation.

In the case of shallow resources, warm spring data and surface/shallow groundwater temperatures across Ireland show two main anomalous zones with temperatures between 15ºC and 21ºC and a significant Variscan east-west structural trend. Outside of these areas, average shallow groundwater temperatures vary regionally from 12ºC in the south to 9ºC in the north of the country.

The major deep geothermal trends observed in this study are a regional increase in temperatures from about 18°C in the south to 26°C in the north at a depth of 500m and from 28°C – 45°C in the south to 64°C – 97°C to the north at 2,500m depth. The maximum temperature measured on the island of Ireland is 87.7ºC in Larne No. 1 at 2,882m depth. Indications of the potential for temperatures in the region of 150°C at 5,000m depth are present in Northern Ireland.

The highest recorded geothermal gradient at 1,000m in the republic is 28.4ºC/km and is located in the vicinity of north Co. Meath in the Navan area. Data from Northern Ireland indicates that the highest geothermal gradients in both the Republic of Ireland and Northern Ireland are located in the Lough Neagh to Ballycastle/Antrim area, e.g. 35.9°C/km seen in Portmore no. 1. This is interpreted as the result of thinned crustal rocks underlying the Antrim Flood Basalts.

Modelled temperatures at depths of 500m to 5000m show a consistent NE-SW break across the centre of Ireland with higher temperatures in the north-central and north of the country.

Though only indicative, these results show the potential for significant geothermal sources with possible applications in commercial developments. Further definition of the exact profile and extent of the geothermal sources and quantification of the resources requires additional data. In particular deep areas around the periphery of the island remain untested.

The study was followed by government initiatives to look at geothermal resources (O'Neill & Pasquali 2007a,b; Jones *et al.* 2007a), followed by private investment in exploratory drilling projects and later by investigative drilling by the Geological Survey of Northern Ireland of exploratory geothermal boreholes.

When fractured or karstified the Waulsortian limestone records cold temperatures unless adjacent to large deep faults, as karst/fracturing allow relatively cold surface water to penetrate deep into the groundwater.

Carboniferous and shale rich rocks act as good insulators and geothermal gradients are relatively low where fracturing is absent. This results in the presence of relatively low temperatures even in the more northerly parts of the Carboniferous basin where the regional geothermal gradient is high.

Intrusive complexes in Carlingford in Co. Louth and south Co. Down have been identified as having the highest radioactivity levels of granites in Ireland and therefore have the potential for high geothermal gradients at depth. However no data were available to test this hypothesis in this study.

REPORT AND DATA ACCESS

The CSA Geothermal report and appendices, may be downloaded as pdf files from the SEI's website at: www.sei.ie or on the following link: www.sei.ie/Grants/Renewable_Energy_RD_D/Projects_funded_to_date/Geothermal_Energy/ .
Alternatively go to "Funded Programme" then "RE RDD" and select "Projects Funded to Date". The Geothermal Resource Map is found in "Geothermal". If you wish to work with the temperature maps, they are very large files and it is better to request SEI to send a free CD.

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