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A Multi-Disciplinary Investigation of Irish Warm Springs and Their Potential for Geothermal Energy Provision

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ABSTRACT

Irish warm springs are one of several target types that are being evaluated for their geothermal energy potential during the course of the academia-government-industry, island-wide, collaborative assessment of the geothermal energy potential of Ireland under the IRETHERM project (www.iretherm.ie), funded by Science Foundation Ireland. Forty-two warm springs and warm shallow groundwater occurrences have been recorded to date in Ireland. Water temperatures measured in the springs (approximately 12 °C to 25 °C) are elevated with respect to average Irish groundwater temperatures (10 °C to 11 °C). This study focuses on warm springs in east-central Ireland, which are found in the Carboniferous limestone of the Dublin Basin. Geophysical methods (controlled source electromagnetics (CSEM) and audio-magnetotellurics (AMT)) have been utilised in conjunction with time-lapse hydrogeological and hydrochemical analyses to determine the source of the heated waters at depth and the nature of the geological structures that facilitate the upward movement of the water. This has provided the basis for an assessment of the source of these thermal waters as a potential geothermal energy reservoir.

We present subsurface models derived from new geophysical data collected at St. Gorman’s Well, Co. Meath in 2013. High-resolution AMT surveys at three warm spring locations in Leinster consisted of a grid of 40 soundings recorded at approximately 200 m intervals centred on each spring. A CSEM survey (25 sounding localities with 100 m spacings along two profiles) was also carried out at one of the locations in order to provide superior resolution of near-surface features. The aim of these surveys was to identify any (electrically conductive) fluid conduit systems that may be associated with the springs and to provide an understanding of the observed association of the springs with major structural lineaments, such as the Iapetus Suture Zone that bisects Ireland.

Seasonal hydrochemical sampling of six warm spring locations commenced in July 2013. Data loggers were installed at each location to measure temperature and electrical conductivity (15-minute sampling intervals) throughout the sampling period (July 2013 – early 2015). The hydrochemical results and the data from the logger at St. Gorman’s Well are examined here in conjunction with regional rainfall and available hydrogeological information in order to establish the nature of the relationship between the hydrological cycle and fluctuations in the hydrochemistry of the spring. Further detailed hydrochemical analyses will be carried out in late 2014 to assess the age of the thermal waters. The combination of these separate strands of investigation will provide a better understanding of the location of the source aquifer for the heated waters.

1. INTRODUCTION

Ireland is located far from any active plate boundaries and is aseismic and non-volcanic. As a result, the geothermal gradient is quite low at about 25 °C/km on average in the centre of country (Goodman et al., 2004). Consequently, any geothermal energy available in Ireland is most likely to be low-enthalpy (< 150 °C). Currently ground source heat pump technology is gaining popularity and is making use of Ireland's stable shallow groundwater and soil temperatures (approximately 10 °C all year round).

Average groundwater temperatures in Ireland range from 10 to 11 °C (Aldwell and Burdon, 1984). Warm springs are therefore considered to be those natural groundwater springs where the mean annual temperature is above 12 °C. Forty-two warm springs and warm shallow groundwater occurrences have been recorded to date in Ireland (Goodman et al., 2004). The springs range in temperature from 12 °C to 24.7 °C with a small number of springs having temperatures > 20 °C. Some of the springs have been utilised in the past as therapeutic spa wells (e.g. Lady's Well, Mallow, Co. Cork (19.5 °C); Louisa Bridge Spa Well, Leixlip, Co. Kildare (17 °C)) and many more are holy wells, as is evident from their names (e.g. St. Brigid's Well, Co. Dublin (19 °C); St. Gorman's Well, Co. Meath (22°C)).

The springs occur mainly in the southern half of Ireland and form a NE-SW lineament across the centre of the island coincident with the Iapetus Suture Zone (Figure 1). This suggests that the locations of the warm springs are associated with or controlled by this feature. Massive sulphide mineral deposits in Ireland also have a close spatial relationship with the Iapetus Suture Zone. The extensive mineralisation of the Carboniferous Irish Midlands is evidence of the past operation of a giant hydrothermal system (Wilkinson, 2010).

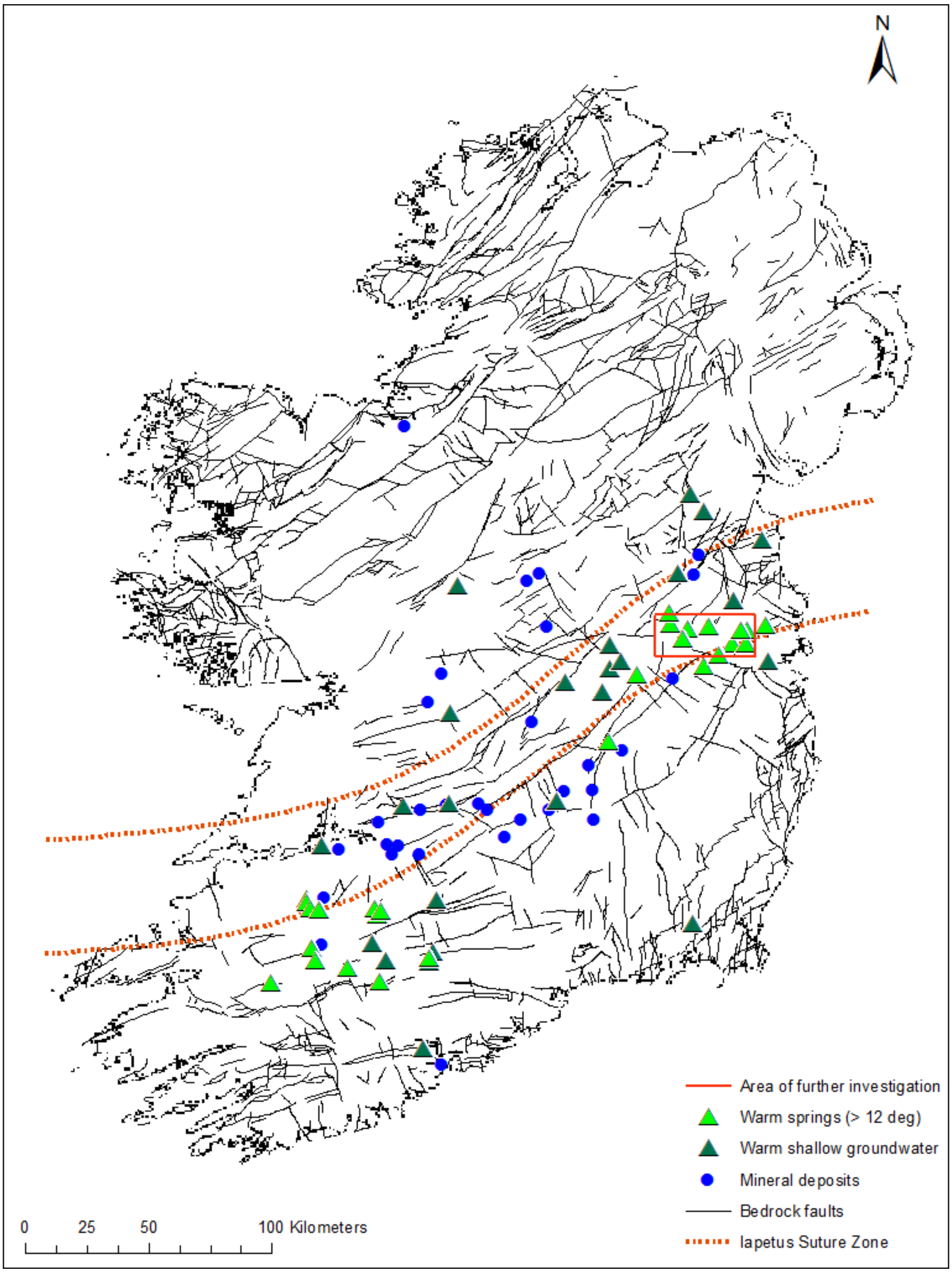


Figure 1: Irish warm spring and warm shallow groundwater locations (after Goodman et al., 2004) showing mineral deposits and the approximate trace of the Iapetus Suture Zone (after Wilkinson, 2010) . Structural geology map from the Geological Survey of Ireland (www.gsi.ie). Red box indicates area of further investigation.

There are three possible scenarios in which the warm springs or their sources may be utilised as a source of geothermal energy:

1. The warm spring water may be used directly or in conjunction with a heat exchanger for small to medium scale heating applications. In Mallow, Co. Cork, in the south of Ireland, warm water (19 °C) from the same geological structure that feeds Lady's Well warm spring is used to partially heat a municipal swimming pool. This is the only known example of such direct utilization of the Irish warm springs to date.

2. If water with higher temperatures can be located at accessible depths for drilling beneath those areas of Ireland where warm springs exist, the heat may be extracted via an open-loop circulation system and used for large- or district-scale space heating. This is currently being done in the Paris Basin, France and in Southampton, U.K.

3. There may be the potential to access waters of sufficiently high temperature for electricity generation at depths of > 3 km. Temperatures well in excess of 100 °C would be required for this.

This work builds upon previous studies on the warm springs and investigates a small sub-set of the springs in detail to determine the source aquifer of the warm waters and also to find out how the warm waters are being transmitted to the surface.

2. OBJECTIVES AND METHODS

The main aim of this project is to determine the suitability of Irish thermal springs as a geothermal energy resource. To that end, the objectives of this study are threefold:

1. To identify the source rock of the thermal waters,
2. To characterize the nature of the water circulation system at several of the springs, and
3. To investigate the possibility of deeper, warm circulation patterns which may offer higher temperature waters at depth.

To achieve these objectives, a multi-disciplinary approach has been implemented. A sub-set of six springs was chosen in the east-central part of Ireland for further investigation (the Leinster warm springs – Figure 2). These springs were chosen both for their proximity to urban centres and for their individual attributes. For example, waters from St. Gorman's Well in Enfield, Co. Meath and Kilbrook spring in Co. Kildare exhibit some of the highest temperatures in Ireland. Waters from Louisa Bridge Spa Well in Co. Kildare and St. Edmundsbury spring in Co. Dublin have the highest electrical conductivities measured in warm springs in Ireland and distinct chemical compositions.

In order to examine the geological structures feeding the warm springs, geophysical surveys were carried out at three spring locations indicated in Figure 2 (St. Gorman's Well, Kilbrook spring and St. Edmundsbury spring) using a combination of electromagnetic techniques. The methods and results of these surveys to date are discussed further in Section 4.

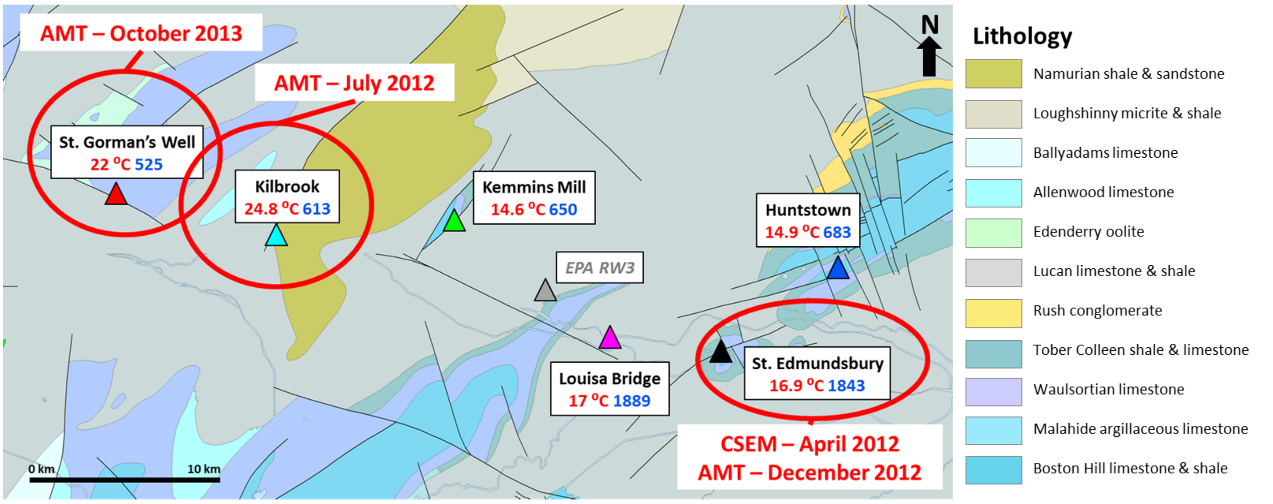


Figure 2: Geological map of the Carboniferous Dublin Basin showing warm springs that are included in the detailed hydrochemical investigation and the EPA monitoring well RW3 (cold groundwater). The maximum temperature (red) and the mean electrical conductivity in µS/cm (blue) are given for each spring. Those springs where geophysical surveys were carried out are circled in red. The legend is arranged in order of age (youngest at the top).

Detailed hydrochemical analysis has been carried out at each of the six warm springs on a seasonal basis since July 2013. The measurements will continue until autumn 2014. This chemical information is being used to provide insight into the source rocks of the thermal waters. Once data collection has finished, statistical analysis and hydrochemical modelling will be carried out using the data to identify endmembers of mixing; this in turn should inform the hydrogeological conceptual model of the warm springs. The measured parameters and findings to date are discussed in Section 5. Further detailed hydrochemical analyses will be carried out in late 2014 to assess the age of the thermal waters.

Data loggers were installed in each of the six warm springs in July 2013 and have been recording temperature and electrical conductivity at 15 minute intervals. Water level loggers were also installed at St. Gorman's Well in April 2014. This data acquisition will continue until spring 2015. The hydrochemical results and the data from the loggers are examined in Section 6 in conjunction with regional rainfall and available hydrogeological information in order to establish the nature of the relationship between the hydrological cycle and fluctuations in the hydrochemistry of the warm springs.

The combination of these three separate strands of investigation – geophysics, hydrochemical analysis and time-lapse hydrogeological measurements – will provide a better understanding of the source of the warm waters and whether the structures feeding them to the surface are robust enough to withstand abstraction in the future.

3. GEOLOGICAL SETTING

In broad terms, the geology of Ireland consists of a mountainous rim of Precambrian to Lower Palaeozoic crystalline rocks that surround a lowland centre, which is underlain by Upper Devonian to Carboniferous sediments (Figure 3). The midlands of Ireland are dominated by Dinantian (Lower Carboniferous) limestones, which are overlain by glacial till deposits and therefore poorly exposed. In general, these limestones tend to have a poor primary porosity but are widely fractured and karstified. This provides important conduits and fissures for groundwater flow in rocks which have low permeability otherwise. The predominant tectonic structures in Irish geology have a NE-SW trend (Figure 1).

It can be seen from Figures 1, 2 and 3 that warm groundwater in Ireland is predominantly associated with Dinantian limestones in the east and centre of the country, and with Namurian (Mid Carboniferous) shales and sandstones in the southwest. Both the warm springs and the major metal mineral deposits in Ireland appear to be associated with the dominant NE-SW structural lineaments and these structures are probably very important in controlling regional groundwater flow (Henry, 2014).

The six springs chosen for further study in Figure 2 are all situated in the Carboniferous Dublin Basin. The Dublin Basin holds approximately 2000 m of sedimentary fill and formed in the Lower Carboniferous during a gradual marine transgression from south to north. As a result, the depositional environment within the basin gradually progresses from terrestrial and shallow marine to deep marine sedimentary facies. The basement beneath the basin is likely to be comprised of Devonian terrestrial sandstone conglomerates and Silurian metasediments. The basin fill was accommodated by movement on NE-SW oriented normal faults, whose orientation was inherited from Caledonian orogenic events (475 – 400 Ma) (Worthington and Walsh, 2011). These NE-SW faults have been present since the inception of the basin, and although they are no longer active, they may still be kept open by dissolutional processes in places, allowing water to flow from deeper units up to the surface.

Within the Dublin Basin, the Leinster springs are strongly associated with the Waulsortian limestone deposits. These limestones are massive and unbedded and are typically less prone to karstification. Structural controls on fluid flow are likely to be important in these units as any dissolution of the limestone will tend to exploit areas of fissured and faulted rock. The existence of deep dissolutional features is also likely to be controlled by prominent fault structures (Kaufmann et al., 2014). Dissolutional features in the Waulsortian limestones in the Dublin Basin have been reported at depths of 250 - 300 m (Murphy and Brück, 1989; borehole reports from www.mineralsireland.ie). It is probable that these features play an important role in the operation of deep groundwater circulation patterns and the ascent of thermal spring waters to the surface.

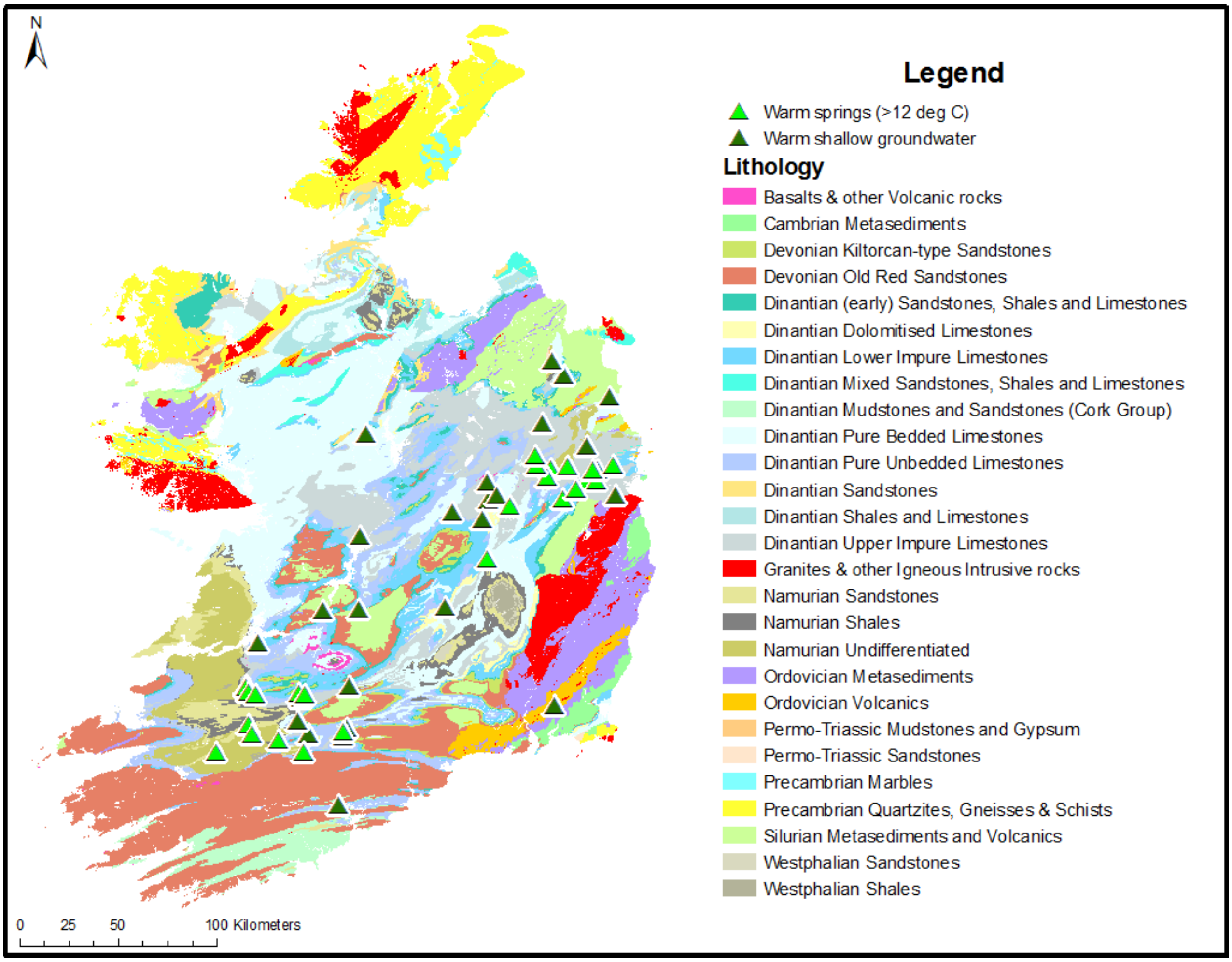


Figure 3: Geological map of Ireland (National Draft Generalised Bedrock Map) from www.gsi.ie. Spring locations are predominantly associated with Dinantian (Lower Carboniferous) limestones in the east and centre of the country, and with Namurian (Mid Carboniferous) shales and sandstones in the south-west.

4. GEOPHYSICAL SURVEYS

Audio-magnetotellurics (AMT) and controlled source electromagnetics (CSEM) were used to gather geophysical data in 2012 and 2013. The aim of the geophysical surveys was to identify any (electrically conductive) fluid conduit systems that may be associated with the springs and to provide an understanding of the observed association of the springs with major structural lineaments, such as the Iapetus Suture Zone that bisects Ireland (Figure 1). Bedrock outcrop in the Irish midlands is generally quite scarce so geophysics is necessary to gain insight into the geological structures beneath the springs.

AMT is a passive electromagnetic method that measures variations in the Earth's natural electric and magnetic fields and how the bedrock geology responds to these changes. The source fields for AMT are naturally occurring electrical discharges (lightning storms) in tropical latitudes. These waves have frequencies of >1 Hz and travel around the Earth in the space between the Earth's surface and the ionosphere. Generally, night time recordings are found to be less noisy (Garcia and Jones, 2002). For this reason, all AMT recordings for this project were made overnight to maximise the quality of the data. AMT can penetrate depths of up to 2 km if the geological conditions are appropriate. As there have been very few deep boreholes (>1 km) drilled in the Dublin Basin, a deep geophysical method such as AMT will provide valuable, inexpensive information about structures at depth.

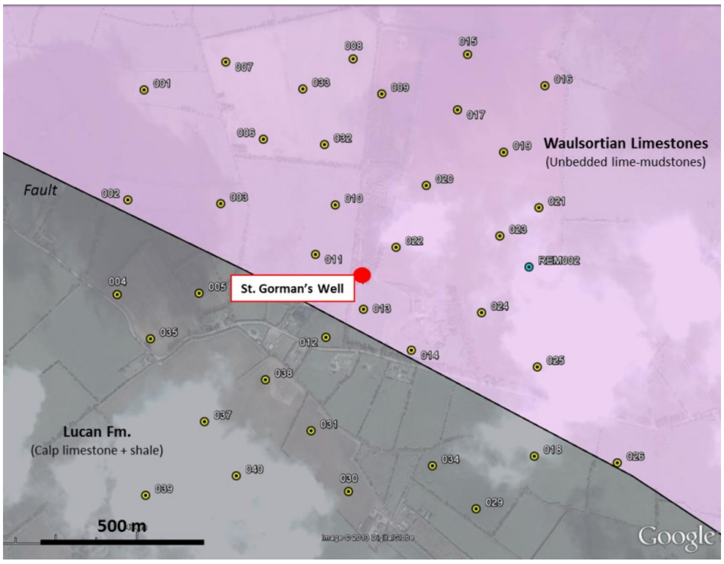


Figure 4: AMT station layout and bedrock geological map at St. Gorman's Well, Enfield, Co. Meath. Background image from Google Earth.

At each of the three AMT survey locations, 40 measurements were made in a grid approximately 1.5 km by 1.5 km with spacings of 200 m between stations. Recordings were made between 10,000 and 10 Hz. Figure 4 shows a sample layout configuration as carried out at St. Gorman's Well in Co. Meath. The data quality was found to be good at St. Gorman's Well and Kilbrook spring but poor at St. Edmundsbury spring. This is attributed to the proximity of Dublin City to St. Edmundsbury (10 km). For this reason, the survey at St. Edmundsbury was supplemented with a CSEM survey in order to overcome the ambient noise in the area and also to provide better resolution of more shallow geological features.

The CSEM method used was transient electromagnetics using a loop-loop configuration. The measurements were made using two different systems; the PROTEM system (on loan from ETH Zurich, Switzerland) made 25 measurements along two profiles using a 100 m x 100 m transmitter loop and the Phoenix system made 8 measurements along the same two profiles using a 200 m x 200 m transmitter loop. Results from this survey will not be discussed further in this paper.

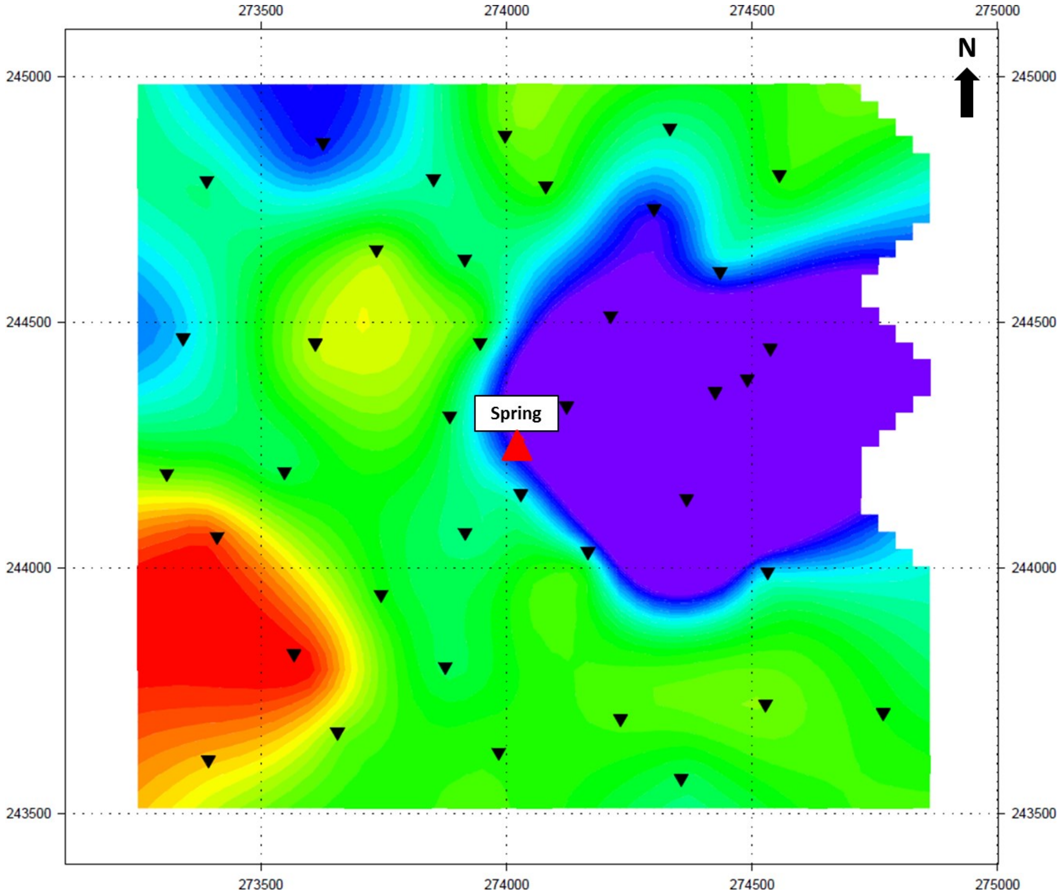
Modelling of data from all three surveys is ongoing. Preliminary results from the AMT survey for St. Gorman's Well are discussed below.

4.1 St. Gorman's Well

For the AMT data from St. Gorman's Well, 1D smooth resistivity models were calculated from the Berdichevsky invariants of the AMT impedance data (Berdichevsky and Dimitriev, 2008) using Occam inversion (Constable et al., 1987). These models indicate the presence of a resistive bedrock unit in the NE of the survey area and a more conductive unit to the SW (Figure 5A). There is a sharp contrast/boundary between the two units which is oriented NW-SE. This compares favourably with the published geological map of the area which shows the presence of a faulted contact between the Waulsortian limestone to the NE and Lucan Formation limestone to the SW (Figure 4).

1D cross-sectional models of the area show the resistive bedrock unit (interpreted as the Waulsortian limestone) extends to a depth of at least 600 m beneath the spring (Figure 5B). The contact between this resistive unit and the more conductive bedrock to the W and SW (interpreted as the Lucan Formation limestone) is sharp and appears to be vertical at depths greater than 100 m. The 1D AMT models are in agreement with borehole logs from the SG8 geothermal borehole which was situated near to the spring (Murphy and Bruck, 1989). These logs show Waulsortian limestone bedrock from a depth of 50 m below ground level to the final depth of 513 m. Preliminary 3D modeling of the data also supports the presence of the sharp vertical boundary between resistive and conductive bedrock, however this work is still in progress.

A:



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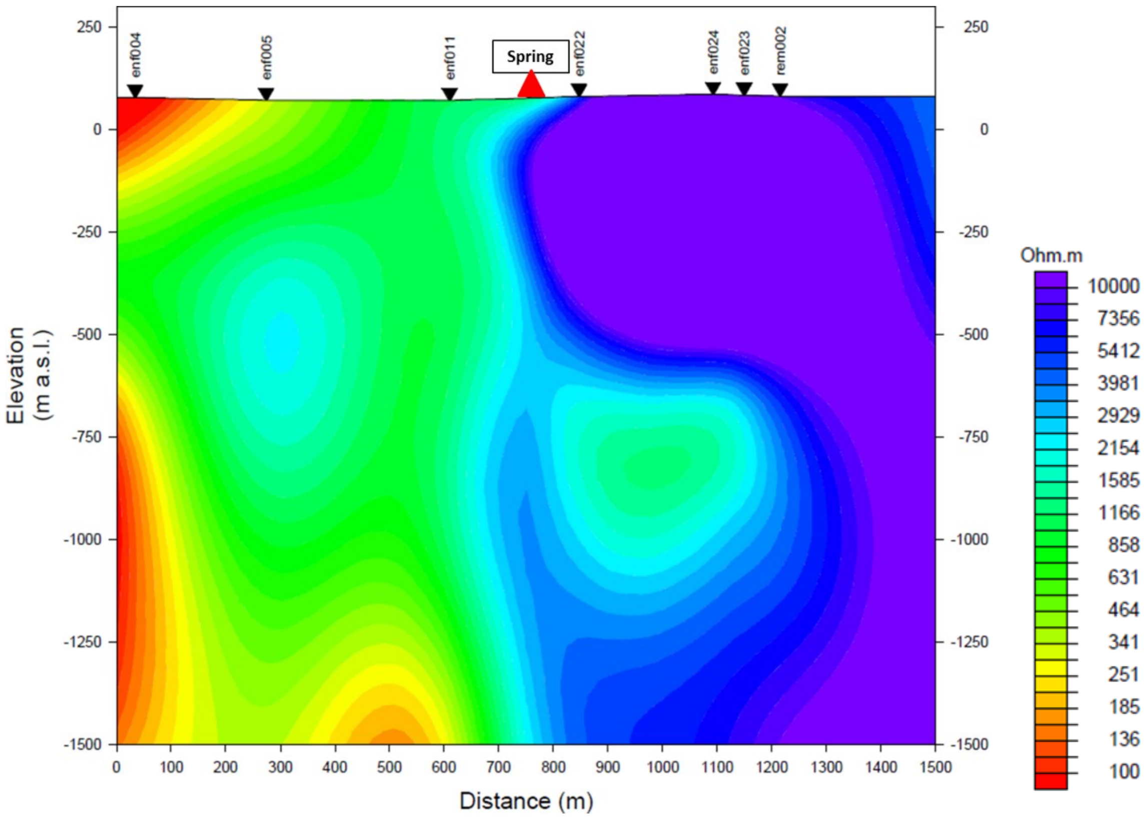

Figure 5: 1D Occam resistivity models of St. Gorman's Well AMT data. A: Constant elevation slice at 200 m below sea level (approx. 280 m depth). Irish National Grid coordinates. B: Cross section taken from W to E through the centre of the spring (vertical exaggeration 0.75).

5. HYDROCHEMICAL ANALYSIS

Irish warm springs tend to have a dominantly meteoric hydrochemical signature (Burdon, 1983a; Mooney et al., 2010). This implies that the thermal spring waters are mainly composed of waters that are recently recharged from rainfall events. However, there are hydrochemical traits in some of the springs that, along with their elevated temperatures, hint at a deeper source rock for the waters (e.g. the high electrical conductivities seen in Louisa Bridge Spa Well and St. Edmundsbury spring). Thus, whatever water is available to sample at the spring mouth is likely to be a mixture of at least two groundwaters from different sources (e.g. the deeper circulating water and the recent recharge water).

A seasonal hydrochemical sampling programme of the six Leinster warm springs in Figure 2 was implemented in July 2013 and is set to run until autumn 2014. The purpose of this programme is to measure the major, minor and trace hydrochemical constituents of each warm spring in order to:

- chemically fingerprint the waters and see how they compare to each other and to average groundwater compositions;
- provide information on how the hydrochemistries of the springs vary throughout the year;
- provide information on the distinctive geochemical characteristics of the source rock; and
- provide information on how much mixing has taken place between the thermal waters and younger, cooler, meteoric recharge.

The full suite of hydrochemical analytes, methods of measurement and detection limits are provided in Table 1.

Major ion analyses from October 2013 and January 2014 have been plotted on a trilinear Piper diagram in Figure 6 alongside representative "cold" groundwater from July 2012 (samples collected from the EPA RW3 sampling borehole in Co. Kildare). There were no samples collected for St. Edmundsbury spring in January due to flooding of the site. In general, the following conclusions can be drawn from this exploratory analysis:

- the overall composition of the individual spring waters sampled in 1982 (results from Burdon, 1983a) is similar to the samples recovered in 2013 and 2014;
- the overall composition of the individual spring waters is similar whether collected in dry (October) or wet (January) periods;
- most of the warm springs and the representative "cold" groundwater samples are of a predominantly calcium bicarbonate composition – this is typical for Irish groundwater sourced from limestones (Burdon, 1983a); and
- Louisa Bridge Spa Well and St. Edmundsbury spring plot towards the sodium chloride side of the plot indicating that these waters have a distinct chemical composition that is atypical for groundwater sourced from limestones in Ireland.

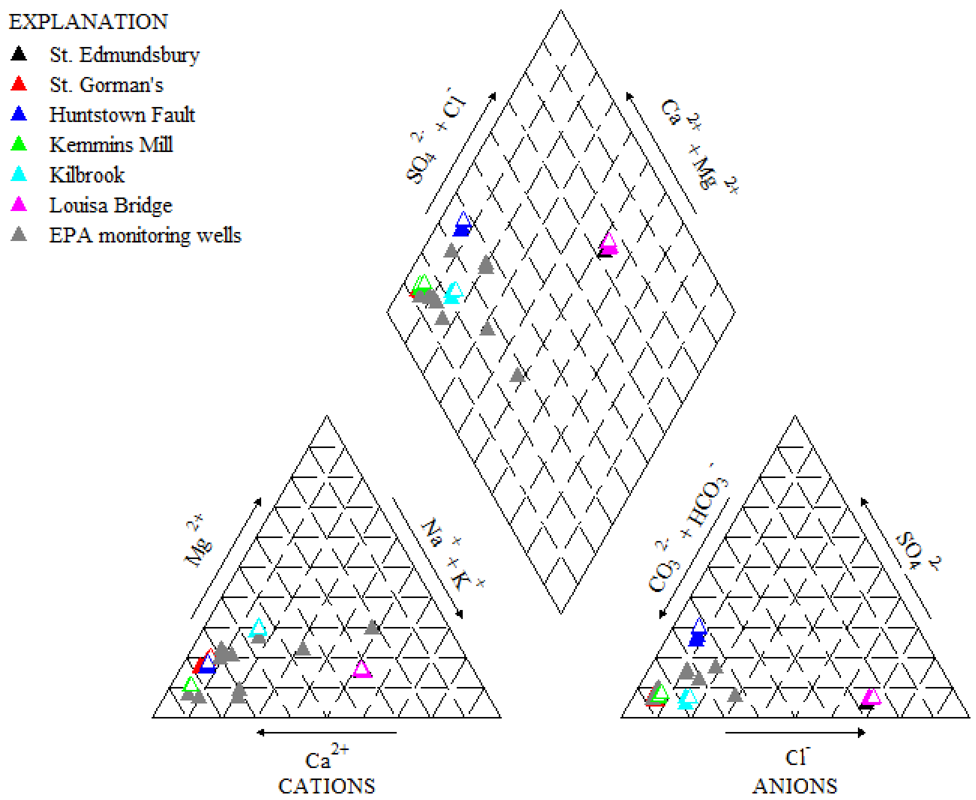

Figure 6: Piper diagram of hydrochemical analyses from October 2013 (closed symbols) and January 2014 (open symbols). Cold groundwater samples taken from EPA monitoring borehole RW3 in July 2012 (grey triangles).

Table 1: Major, minor and trace analytes, detection limits and methods of measurement.

Analyte	Units	Detection limits	Method of analysis
pH	pH units	0	Titralab
Conductivity	uS/cm @20	25	Titralab
Alkalinity	ppm CaCO3	10	Titralab
Ammonia	ppm N	0.007	Spectrophotometry
Ammonium	ppm NH4	0.009	Spectrophotometry
Nitrate	ppm N	0.12	Spectrophotometry
Phosphate	ppm P	0.009	Spectrophotometry
Chloride	ppm	2.6	Spectrophotometry
Sulphate	ppm	1	Spectrophotometry
Silica	ppm	1	Spectrophotometry
Bromate	ppb	1	Ion chromatography
Fluoride	ppm	0.1	Ion chromatography
Ag	ppb	0.05	ICP-MS
Al	ppb	1	ICP-MS
As	ppb	0.5	ICP-MS
Au	ppb	0.05	ICP-MS
B	ppb	5	ICP-MS
Ba	ppb	0.05	ICP-MS
Be	ppb	0.05	ICP-MS
Bi	ppb	0.05	ICP-MS
Br	ppb	5	ICP-MS
Ca	ppm	0.05	ICP-MS
Cd	ppb	0.05	ICP-MS
Ce	ppb	0.01	ICP-MS
Cl	ppm	1	ICP-MS
Co	ppb	0.02	ICP-MS
Cr	ppb	0.5	ICP-MS
Cs	ppb	0.01	ICP-MS
Cu	ppb	0.1	ICP-MS
Dy	ppb	0.01	ICP-MS
Er	ppb	0.01	ICP-MS
Eu	ppb	0.01	ICP-MS
Fe	ppb	10	ICP-MS
Ga	ppb	0.05	ICP-MS
Gd	ppb	0.01	ICP-MS
Ge	ppb	0.05	ICP-MS
Hf	ppb	0.02	ICP-MS
Hg	ppb	0.1	ICP-MS
Ho	ppb	0.01	ICP-MS
In	ppb	0.01	ICP-MS
K	ppm	0.05	ICP-MS

Analyte	Units	Detection limits	Method of analysis
La	ppb	0.01	ICP-MS
Li	ppb	0.1	ICP-MS
Lu	ppb	0.01	ICP-MS
Mg	ppm	0.05	ICP-MS
Mn	ppb	0.05	ICP-MS
Mo	ppb	0.1	ICP-MS
Na	ppm	0.05	ICP-MS
Nb	ppb	0.01	ICP-MS
Nd	ppb	0.01	ICP-MS
Ni	ppb	0.2	ICP-MS
P	ppb	10	ICP-MS
Pb	ppb	0.1	ICP-MS
Pd	ppb	0.2	ICP-MS
Pr	ppb	0.01	ICP-MS
Pt	ppb	0.01	ICP-MS
Rb	ppb	0.01	ICP-MS
Re	ppb	0.01	ICP-MS
Rh	ppb	0.01	ICP-MS
Ru	ppb	0.05	ICP-MS
S	ppm	1	ICP-MS
Sb	ppb	0.05	ICP-MS
Sc	ppb	1	ICP-MS
Se	ppb	0.5	ICP-MS
Si	ppb	40	ICP-MS
Sm	ppb	0.02	ICP-MS
Sn	ppb	0.05	ICP-MS
Sr	ppb	0.01	ICP-MS
Ta	ppb	0.02	ICP-MS
Tb	ppb	0.01	ICP-MS
Te	ppb	0.05	ICP-MS
Th	ppb	0.05	ICP-MS
Ti	ppb	10	ICP-MS
Tl	ppb	0.01	ICP-MS
Tm	ppb	0.01	ICP-MS
U	ppb	0.02	ICP-MS
V	ppb	0.2	ICP-MS
W	ppb	0.02	ICP-MS
Y	ppb	0.01	ICP-MS
Yb	ppb	0.01	ICP-MS
Zn	ppb	0.5	ICP-MS
Zr	ppb	0.02	ICP-MS

The data from October 2013 and January 2014 were used to calculate saturation indices for several of the typical rock-forming minerals using PhreeqC and the llnl.dat database (Parkhurst and Appelo, 2013). The saturation indices for dolomite are plotted with temperature in Figure 7. In October, at the end of the dry season, the hydrochemistries of St. Gorman's Well, Kilbrook spring, Louisa Bridge Spa Well and St. Edmundsbury spring indicate equilibration and a slight super-saturation with respect to dolomite. This suggests dolomite is likely to be a major mineral in the source rock. All of the spring waters become less saturated with respect to dolomite during the winter recharge. St. Gorman's Well and Kilbrook spring both have the greatest variation in both saturation with respect to dolomite and in temperature. For both of these springs, temperature increases over the winter months as the waters simultaneously become less saturated with dolomite. This suggests that the waters either have a different source rock, a different pathway to the surface or a shorter residence time in the dolomite-rich bedrock in the wet season when regional recharge is greatest.

Further detailed hydrochemical analyses will be carried out in late 2014 to assess the age of the thermal waters.

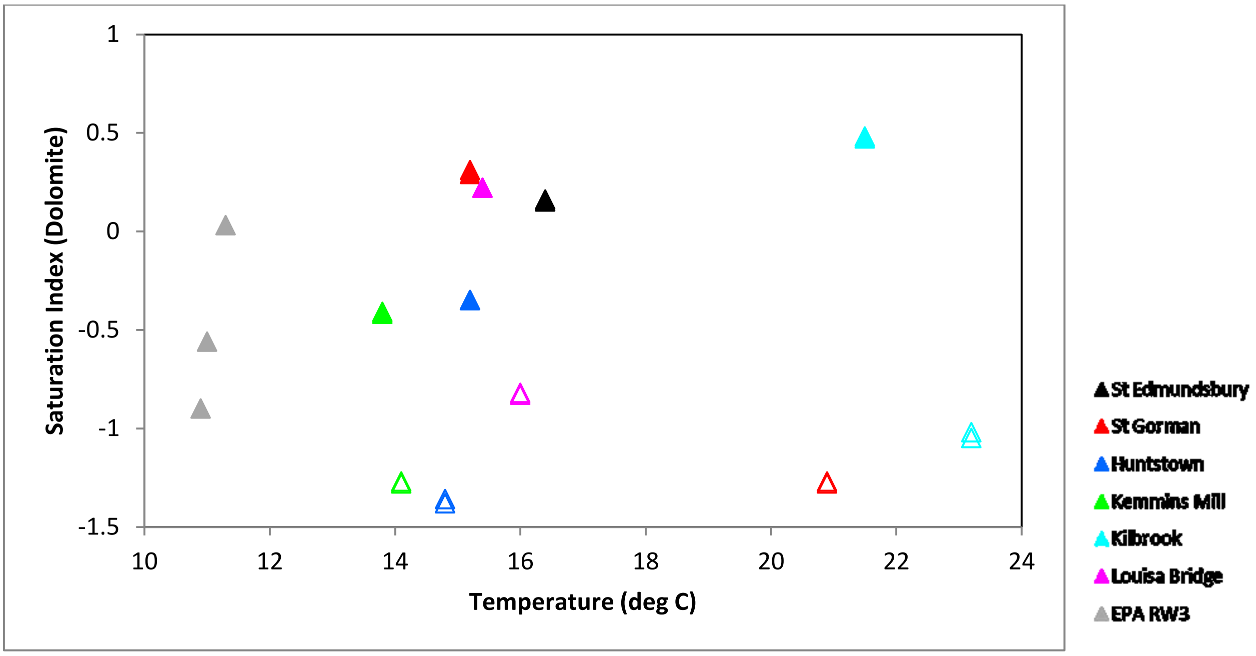

Figure 7: Temperature and saturation indices for dolomite calculated for Leinster warm springs from samples taken in October 2013 (closed symbols) and January 2014 (open symbols) using PhreeqC. Cold groundwater samples taken from EPA monitoring borehole RW3 in July 2012.

6. TIME-LAPSE HYDROGEOLOGICAL MEASUREMENTS

Combined temperature and electrical conductivity loggers were installed at each of the six warm spring locations in July 2013 and set to record at 15-minute sampling intervals. The measurements will continue until early 2015. The loggers are calibrated regularly. The temperature data is reliable but the electrical conductivity data in some of the locations is made noisy by algal or bacterial growths on the sensors (e.g. Huntstown Fault, Kilbrook Spring).

The logger results for St. Gorman’s Well are presented in Figure 8 along with daily rainfall data (for 2013 only) from the nearest weather station at Dunsany, Co. Meath (approximately 20 km away). This spring is ephemeral, with outflow usually appearing in late autumn/winter and drying up again in the spring. The logger is installed in a borehole 20 m west of the spring pond and the borehole has artesian flow during the winter months while the spring pond is full. The spring does not appear to respond quickly to rainfall events and so appears to be insulated from near-surface recharge processes. The temperature decreases gradually from early October until December, reaching average values for “cold” Irish groundwater (approximately 11 °C) in November and December. This is evidence of mixing of the thermal waters with cooler meteoric waters after the onset of autumnal recharge in October.

The temperature of the spring increases very sharply in winter (from 12 to 19 °C in the space of 6 hours on December 23rd 2013) and peaks in March. This suggests the presence and annual activation of deep, heating circulation patterns that are influenced by an increased influx of meteoric water in winter. The fluctuations in temperature and chemistry before and after this event are markedly different. Before, the graph has semi-diurnal fluctuations attributed to tidal influences on the confined aquifer (Burdon, 1983a) and after, these fluctuations are largely absent. This is attributed to the flow from the borehole becoming artesian at this time.

The sudden rush of warmer yet hydrochemically less evolved water (lower electrical conductivity, lower saturation with respect to dolomite) indicates the influence of an entirely separate flow system. Seasonal regional recharge raises the regional water table, bringing other fracture-flow systems into play and activating deep-seated circulation patterns which heat the incoming water. The fact that the hydrochemistry is less evolved indicates that the meteoric waters have had a shorter residence time in the aquifer.

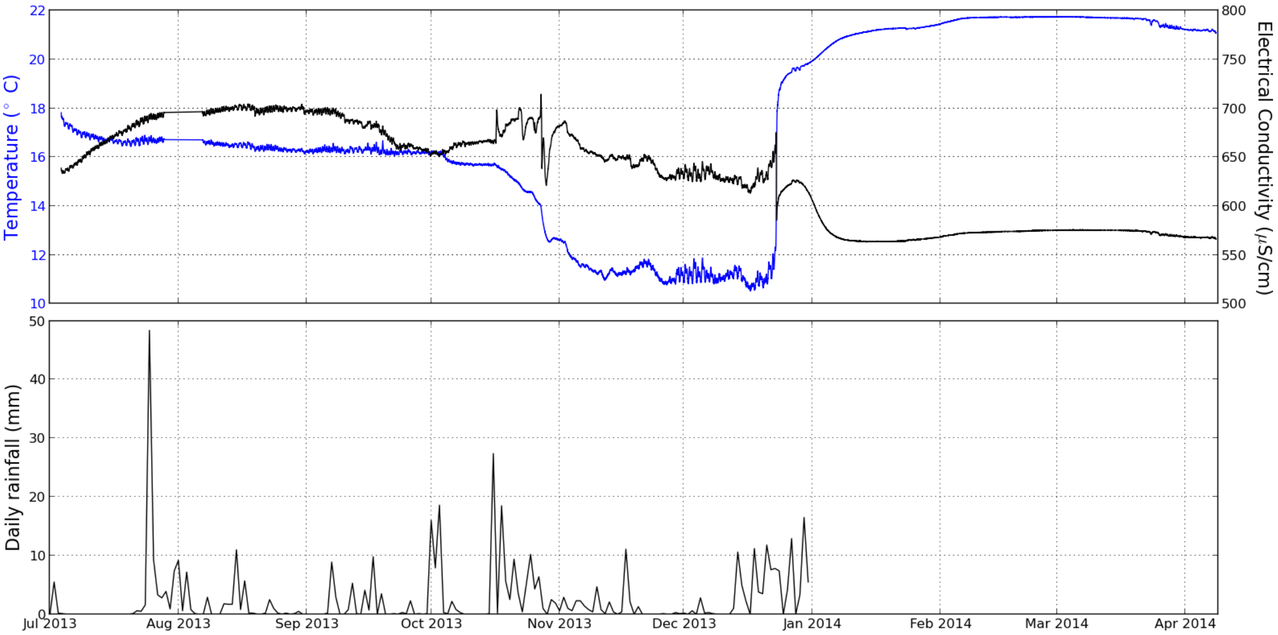

Figure 8: Time-lapse temperature and electrical conductivity measurements for St. Gorman's Well, Co. Meath (15 minute sampling rate) alongside daily rainfall values from Dunsany, Co. Meath (data from 2013 only, from Met Éireann).

7. DISCUSSION

In order for a warm spring to be most useful as a geothermal resource, ideally the deep source rock and warm water feeder structures should be located and targeted for abstraction. In this investigation, the combination of several separate strands of inquiry has increased understanding of the complex natural systems that are warm springs.

- The warm springs have seasonal variations in temperature. Significantly higher temperatures in winter (St. Gorman's Well, Kilbrook spring) indicate an activation of deep, heating circulation heating patterns with the onset of seasonal recharge. Lower temperatures in winter would indicate that the thermal waters are diluted by the influx of cooler meteoric waters (St. Gorman's Well before the activation of deep circulation patterns). If the spring was to be used directly as a geothermal energy resource, this would dramatically affect the energy yield between autumn and winter.
- It is likely that dolomitised Carboniferous Waulsortian limestones are an important source rock or storage unit for the thermal waters. This is supported by geological mapping, geophysical survey results at St. Gorman's spring, hydrochemistry (saturation indices) and borehole logs in the region of St. Gorman's Well.
- These limestones have been shown to have dissolutional features (evidence of karstification) at depths > 250 m (Murphy and Bruck, 1989). Such deep karstification would allow for rapid and deep circulation of meteoric recharge waters, which would be heated at depth and then circulated to the surface. Karstification conduits would also allow for hydrostatic piston flow processes that would explain the unusual, rapid increase of temperature seen at St. Gorman's Well in December 2013. If an average geothermal gradient of 25 °C /km is assumed, then in order for meteoric waters of 10 °C to be heated to almost 22 °C as seen at St. Gorman's Well, this would require circulation patterns of at least 500 m (assuming that heating of the water is instantaneous and no heat is lost as the water travels to the surface).

8. CONCLUSIONS

A combination of disciplines has been applied to the Leinster group of warm springs in Ireland to assess their potential as a geothermal energy resource as part of the IRETEHRM project. In this paper we take the case of one of the warmest springs in Ireland, St. Gorman's Well (maximum temperature of 22 °C), as an example of how our multi-disciplinary investigation has so far yielded useful information about the thermal water's provenance. It is hoped that in the case of all the warm springs studied under this investigation, this information will enable potential users of the springs' energy to better position their exploratory drillholes or abstraction wells in the future.

The AMT survey at St. Gorman's Well has imaged a significant vertical fault in the bedrock which the warm spring water is probably using to migrate to the surface. The chemistry of the thermal water indicates that it has been in contact with dolomitised Waulsortian limestone bedrock which the AMT survey and exploratory drilling in the area has shown to extend to depths > 500 m. Examination of time-lapse measurements of the spring's temperature and chemistry in conjunction with regional rainfall data has shown a very dynamic and complex system in operation. The spring's temperature peaks in winter when recharge is highest and the electrical conductivity of the spring water is lowest. This suggests that rapid and deep circulation patterns are activated by influx of meteoric recharge each year. The time-lapse measurements also indicate the interaction of several different flow systems.

Future work for this project will include:

- principal component analysis of the warm spring hydrochemical analyses;
- age dating of thermal spring waters;
- hydro-geochemical modelling to work out the degree of mixing of meteoric waters with deep thermal waters; and

- advanced 3D modelling of geophysical data to better constrain models of the geological structures at three spring locations.

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