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Investigation of Source and Conduit for Warm Geothermal Waters, North Cork, Republic of Ireland.

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Brecan Mooney was tragically drowned on Thursday 19 November, 2009, soon after this paper was finalized. He was only 31 years old, a professional hydrogeologist with an enormous zest for life. He was conducting this investigation in his spare time for an MSc degree in the Department of Geology, UCC.

ABSTRACT

Far from plate boundaries, with no recent volcanism or tectonism, and with geothermal gradients of <25°C/km, Ireland has few geothermal resources apart from 42 warm springs ranging in temperature from 13-24.7°C. These are concentrated in two groups, in the south-west and east central parts of the country. Recently groundwater at 26°C was encountered at a depth of 40m during routine well drilling operations near the town of Mitchelstown in the south-west, the warmest groundwater encountered to date in the shallow Irish subsurface. It is interpreted to have migrated upwards from greater depth via a steep fault structure. A research project is in progress with the aim of identifying the source aquifer and fault conduit, controlling upwards movement of the warm water, and also to assess the potential of the warm water for district heating purposes.

A major NE–SW lineament, identified on landsat images, of probable Caledonian (425-395 Ma) age, possibly subsequently reactivated during the Variscan Orogeny (295-315 Ma), passes close to the Mitchelstown well. It extends 30 km SW to the town of Mallow, where a 22°C warm spring, which formed the basis for a spa resort in the 19th century, is today being utilised with a heat pump to heat the municipal swimming pool. Geophysical surveys are being conducted to accurately delineate this structure on the ground.

A temperature survey of all water wells and springs in the Mallow-Mitchelstown area and further to the NE has been conducted. Although average groundwater temperatures in Ireland are of the order of 9-11.5°C, a number of the wells surveyed record anomalous temperatures in excess of 12°C, interpreted to represent mixing of warm deep groundwater with cooler near surface groundwater. To test this hypothesis, a programme of hydrochemical analyses has been undertaken for normal and trace components and the stable isotopes $^{18}O/^{16}O$ and $^{2}D/^{1}H$. Lower nitrate and chloride/bromide ratios and possibly higher lithium in the anomalous wells appears to differentiate the warmer water from depth from cooler near surface water with which it has mixed. This it is hoped will also fingerprint the source of the warm waters. The ultimate objective is to locate the fault conduit sufficiently accurately to make it possible to drill to intersect the fault at moderate depth in order to tap the migrating warm water where it can be utilized, and to this end it is hoped to develop a methodology which can be applied in other similar situations.

1. INTRODUCTION

Ireland is located far from any plate boundaries, and has not been subject to volcanism or tectonism in the recent past, so geothermal gradients are low (<25°C/km) (SEI, 2004), and in the south of the country, geothermal gradients are as little as 10°C/km (Goodman et al., 2004). Thus Ireland is unlikely to have any high temperature geothermal resources. Typical groundwater temperatures in Ireland vary from approximately 9 -11.5°C (Aldwell & Burdon, 1986), whilst soil temperatures are usually around 10°C. These temperatures represent the balance between solar and geothermal recharge, and radiation from the ground surface, quantified by Aldwell & Burdon (1986), and remain relatively constant throughout the year due to Ireland's temperate maritime climate. Heat can be extracted from soil and groundwater at these, seemingly low but consistent, temperatures for a plethora of uses, utilizing modern heat pump technology.

Springs, seepages and spring wells are ubiquitous in Ireland, particularly in the Dinantian limestone bedrock underlying much of the Midlands of Ireland. Exploitable geothermal resources occur in unusual geological settings where groundwater that is warmer than normal (>12°C) rises up through limestone catchments (Aldwell, 1986), discharging at the surface as low enthalpy geothermal springs. 42 of these warm springs, mainly located in Dinantian Limestone, and ranging in temperature from 13-24.7°C have been recorded (Aldwell et al. 1980; Burdon, 1983; Aldwell and Burdon 1986; Goodman et al, 2004), and are concentrated in two groups in the E and SW of the country. The earliest recorded warm spring in Ireland occurs at Mallow in the SW where the spring at Lady's Well gave rise, in the 18th and 19th Centuries, to a spa resort. Apart from this spring, which has subsequently been harnessed to heat the municipal swimming pool (O'Brien, 1987), little utilisation of these warm water energy resources has taken place, mainly because of the rural settings where most occur that in the past has limited potential options for their exploitation.

The Mallow spring has an average temperature of 19.5°C ± 2.5°C, with higher temperatures recorded in summer and lower temperatures recorded in winter, thought to reflect greater dilution of the warm water with colder water runoff during periods of higher rainfall.

The origin of these warm water resources is uncertain, but it is generally assumed that they represent deep groundwater sources brought rapidly to the surface from considerable depth by faults (e.g. Aldwell and Burdon, 1986; Murphy & Brück, 1989). Such deep circulation would be facilitated by bedrock permeability related to deep faulting. The specific factors causing deep circulation are summarised by Aldwell & Burdon, (1986) as:

- structural aspects favoring vertical over horizontal flow;
- topography leading to higher head pressures;
- increased precipitation and thus enhanced recharge;
- high infiltration; and
- karstification, particularly palaeokarst, essential for facilitation of deep circulation in Irish carbonate rocks.

Geothermal waters heated at depth in confined aquifers may reach the surface if the source aquifer is penetrated by a permeable fault zone, and if the water is under sufficiently high piezometric pressures to generate artesian conditions. The 42 warm springs in Ireland represent situations where both these conditions are met, but situations where piezometric pressures are subartesian, or where an impermeable obstacle prevents the geothermal water from reaching the surface, may be more widespread.

Two methods of investigating the existence of such resources, is by deep drilling programmes to the postulated source aquifer in favourable sites, which is generally extremely costly, or by identifying a fault structure, up which warm water has migrated, and drilling to intersect the fault at moderate depth in order to extract the warm water within it. Once a fault is identified and its location, orientation and extent delineated accurately, it may be tapped at a number of points. This represents a much less expensive option, and is the objective of the present investigation.

Sometimes geothermal waters are encountered unexpectedly at shallow levels during routine drilling operations, and represent situations where either insufficient piezometric pressures prevail, or some obstacle prevents the geothermal waters from flowing to the surface. However, the heated water has almost certainly reached shallow levels by migration up a fault intersecting the source aquifer. Regardless of whether the geothermal water penetrates to the surface, or what prevents it from reaching the surface, such heated water is an exploitable geothermal resource and should be further investigated to determine if additional heated groundwater resources exist at shallow levels where they can be readily tapped and utilised.

Recently, a well drilled for water supply purposes by Cork County Council at Johnstown in the Glanworth area of North Cork in SW Ireland, encountered moderate quantities of warm groundwater at temperatures of 23-26°C at a depth of 40m, the warmest shallow groundwater as yet recorded in the Republic of Ireland. In this investigation, we attempt to establish the source aquifer and the conduit controlling migration of this warm water towards the surface, with the intention of assessing the extent of the resource, and the potential for exploiting it. In addition, we wish to develop a methodology of investigation, which can be universally applied in other similar situations.

2. RATIONALE AND METHODOLOGY

This project is being undertaken in light of concerns over the use of fossil fuels as a means of energy supply, and the need to develop alternative clean safe inexpensive secure and renewable sources of energy. The Kyoto protocol commits Ireland to reduce CO_2 emissions to 115% of the levels in 1990 by 2012. At the present time Ireland is falling short of this target and fines will be imposed unless a concerted effort is made to reduce CO_2 emissions. The study has identified significant hydro-geothermal resources in the North Cork area that may be exploited, resulting in considerable benefits for the region.

A temperature survey of groundwater wells was carried out in and around the Mallow and Mitchelstown area. This served a twofold purpose:

- firstly as an initial screening process it would identify any more geothermal anomalies existing in the area enabling any patterns that may exist to be studied with the purpose of providing explanations for these anomalies;
- secondly, the well survey data quantifies ambient groundwater temperatures in the region which together with known aquifer productivity maps from the Geological Survey of Ireland (GSI) give an approximation of the geothermal resource in the North Cork area.

Following the well survey a 2-D resistivity study was undertaken to further characterize the bedrock aquifers in which anomalies were observed. The hypothesis is that geological structures present in the subsurface provide a conduit bringing warm water to the surface from depth in these areas exhibiting higher than average groundwater temperatures. As permeability in the Palaeozoic sediments of the Munster Basin is almost always fracture related, 2-D resistivity was a relatively inexpensive way to augment the literature search and provide some structural context in two anomalous areas that were lacking in outcrop.

A hydrochemical analytical program was subsequently undertaken in order to further pinpoint a possible source for the thermal waters and these results are also discussed.

3. REGIONAL GEOLOGY AND HYDROGEOLOGY

Ireland generally consists of a mountainous rim composed of Precambrian to Lower Palaeozoic crystalline rocks surrounding a lowland interior largely underlain by U. Devonian to L. Carboniferous sandstone, shale and limestone (Fig. 1).

Late Palaeozoic, Mesozoic and Tertiary rocks are absent, apart from in the NE corner of the island, where they are preserved beneath the basalt plateau of the 50-60Ma Tertiary North Atlantic Igneous Province associated with the opening of the North Atlantic. However, there is evidence that they were also deposited over much of the rest of the island, but were stripped away by the intense erosion and peneplanation that accompanied the opening of the North Atlantic.

U. Palaeozoic bedrock, whilst underlying much of the interior of Ireland, is generally buried beneath a cover of Pleistocene glacial till and Holocene peat deposits, and is rarely exposed. L Carboniferous limestone, which dominates the U. Palaeozoic, is extensively karstified, but overburden deposits are relatively thick and surface expression of karst is generally absent. Thus, most of Ireland's limestone bedrock consists of buried karst.

Ireland lies within the Caledonian orogenic belt, which affected all Precambrian and L. Palaeozoic units. The Iapetus Suture, marking the collision zone of Laurentia and Avalonia, runs diagonally across Ireland from the Shannon estuary to Clogher Head, 50 km to the north of Dublin. All of the warm springs in the Irish Republic lie to the south of this tectonic line.

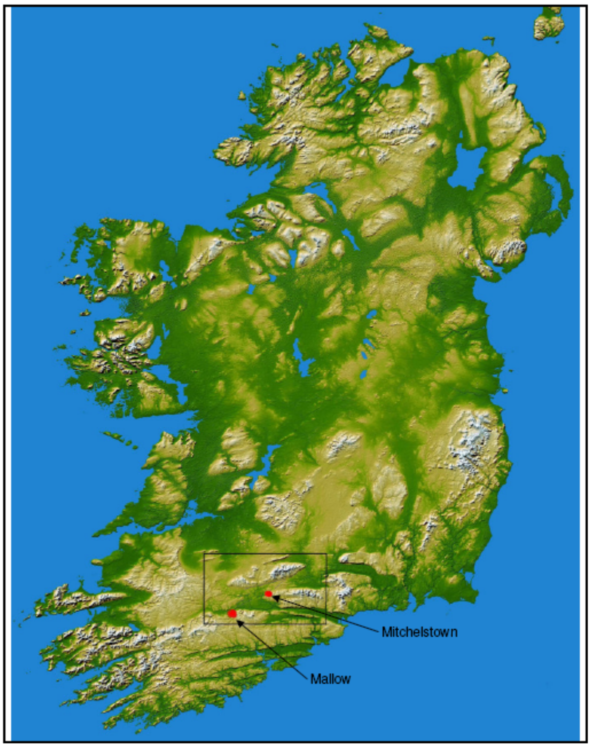

Figure 1: Relief Map of Ireland showing NE-SW trending morphology in south-central Ireland. (NASA)

The late Carboniferous Variscan (Hercynian) Orogeny affected the very south-west of Ireland, which represents the westernmost extension of the external Rheno-Hercynian Zone of the Variscan Orogenic Belt. Its northern boundary, the Variscan Front, is the Killarney-Mallow Fault Zone (KMFZ), which runs E-W, midway between the south coast of Ireland and the Shannon estuary. The southwestern group of warm springs are all situated just to the north of this tectonic boundary.

Tectonism with accompanying fault activity in the SW of Ireland can be summarized as:

- Caledonian orogenesis (c. 425–395Ma) associated with oblique sinistral closure of the Iapetus Ocean manifested by NE-SW strike–slip faulting in a transpressional regime (Phillips, 2001), and low grade metamorphism leading to complete recrystallisation of L. Palaeozoic and older rocks and complete loss of primary porosity.

- Extensional development of the Munster Basin of SW Ireland (c. 395-350Ma), related to evolution of a stretched passive continental margin, and resulting in repeated reactivation of the pre-existing NE-SW Caledonian strike-slip faults as basin bounding normal faults. This was accompanied by progressive subsidence, with deposition of thick accumulations of high porosity U. Devonian Old Red Sandstone terrestrial clastics, and subsequent marine transgression and deposition of low porosity L Carboniferous marine clastic and biogenic sediments.

- Variscan orogenesis (c. 350-320Ma) associated with N-S collision of Laurussia and Gondwana, and the formation of a very low grade fold-thrust belt in SW Ireland. The E-W Killarney–Mallow Fault has been postulated to represent the sole thrust (e.g. Landes et al. 2002), and is marked by a sharp discontinuity in deformation intensity (Gill, 1962), with almost complete loss of primary porosity of the U. Palaeozoic rocks to the south of this structure, but very weak deformation and possibly very little reduction in primary porosity to the north. NE-SW Caledonian faults are thought to have been further reactivated, some as thrusts and others possibly as strike-slip faults.

Geothermal gradients in the island of Ireland although overall relatively low, generally increase towards the NE, where a maximum of 35°C/km has been found in County Antrim (Goodman et al, 2004), due to enhancement of geothermal gradients by the Tertiary igneous activity. Low yields of relatively hot water at 88°C were encountered in the early 1980's in a borehole to 2.8 km depth at Larne to the NE of Belfast, within the Permo-Triassic Sherwood Sandstone, an aquifer widespread in Britain, but only present in Ireland in the extreme NE preserved beneath the Tertiary Basalt plateau. In the Irish Republic, conditions for generation of hot water at depth are not favourable, but the presence of 42 warm springs, indicates that aquifers do occur at depth, and that moderate geothermal resources, which could be exploitable, do exist.

4. IDENTIFICATION OF THE FAULT CONDUIT

The first task was to identify the fault conduit which has controlled the upwards migration of the geothermal waters. The borehole with the warm water at Johnstown near Mitchelstown in North Cork is located approximately 20 km to the northeast of the Lady's Well spring at Mallow and other historically mentioned, but lesser known warm springs in the Mallow area. There is a strong possibility that a relationship may exist between the two geothermal occurrences, which may have a similar source aquifer and a similar migratory path from depth. This would suggest that their upwards migration may have been controlled by a steep NE-SW Caledonian trending structure. However, the Mallow-Mitchelstown area is relatively flat with virtually no outcrop, and the geological map of this area (Fig.2) shows no evidence of a major NE-SW structure.

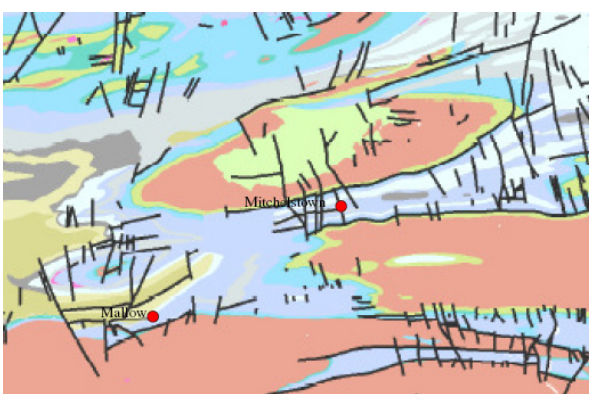

Figure 2: Geological map of area of investigation. (After Geol. Survey of Ireland (GSI) Regional Map)

A landsat map of the Mallow-Mitchelstown area (Fig. 3) emphasises the local relief, and clearly illustrates the NE to SW Caledonian trending physiography of the region. The region is transected by the E-W flowing Blackwater River, which exploits the KMFZ, and to the north of this is dominated by the Galtee Mountains in the north and the Knockmealdown Mountains in the east. A faint but conspicuous NE-SW trending lineament can be discerned emanating from Mallow in the SW and projecting northeastwards towards Mitchelstown and onwards along the southern margin of the Galtee Mountains. It appears to be one of a series of sub-parallel lineaments, which splay southwestwards from the southern margin of the Galtee Mountains. These lineaments have been referred to as the Dingle-Galtee Mountains Fault Zone (DGMFZ) (e.g. Vermeulen et al., 2000), regarded as the basin-controlling and bounding structures for the Munster Basin. It is likely that these structures have been offset by minor N-S strike-slip faults, which appear to represent late Variscan compartmental faults associated with thrust tectonics, and it is possibly truncated by the KMFZ at Mallow. Close examination of the landsat image indicates that the structure passes close to the Spa Glen in Mallow and the vicinity of the Johnstown well near Mitchelstown.

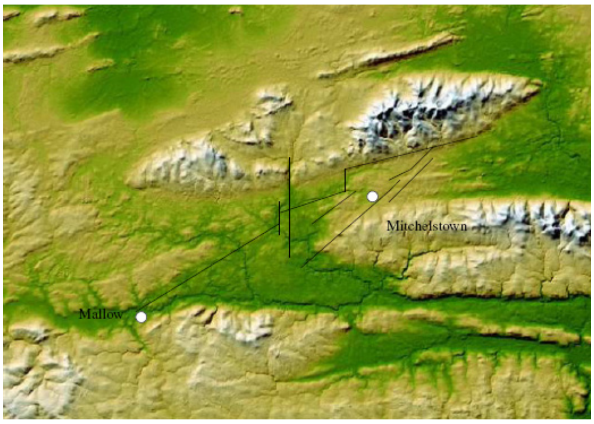

Figure 3: 1:40,000m Relief Map of investigation area with possible fault conduit lineages

To the northeast of Mitchelstown, a major steep southwards-dipping NE-SW reverse fault defines the southern margin of the Galtee Mountains inlier, and brings a sequence of steep southerly dipping U. Devonian sandstones and conglomerates in the footwall into juxtaposition with synclinally folded L Carboniferous limestones and shales. Any of these U. Devonian formations could be a candidate for the source aquifer.

In the southwest of the study area at Mallow, a number of parallel southerly-dipping E-W faults mark the KMFZ again with southerly-dipping units on their footwalls. However, most of these are siltstone/shale or limestone units, none of which would appear to be likely candidates for a source aquifer. L. Carboniferous limestones, although widely karstified in the Irish midlands are unlikely to represent the source aquifers, as karstification appears to have mainly taken place during the Tertiary, subsequent to any tectonism in Ireland, and since karstification is a relatively superficial process, it is doubtful whether deeply buried limestones would have sustained karstification.

The minor N-S strike-slip faults offset northeasterly striking geological units in the Mallow-Mitchelstown area and beyond along the southern margin of the Galtee Mountains. The Lady's Well spring at Mallow is situated in an entrenched narrow N-S valley, the Spa Glen, which exploits one of these latter faults, and many of the anomalous wells may also be located on such minor cross faults. These faults are however not interpreted to represent the fundamental fault which has controlled migration of the warm groundwater from depth, but may have provided final pathways for circulation of the warm groundwaters at shallow crustal levels.

5. GROUNDWATER TEMPERATURE SURVEY

In order to test the validity of the interpretation of the NE-SW fault conduit for the geothermal waters at Mallow and Mitchelstown, a temperature survey of groundwater wells in the Mallow-Mitchelstown area was conducted.

Shallow groundwater (<100m depth) in the southern part of Ireland typically records an annual average temperature range of 10.48-11.08^{o}C (Aldwell & Burdon, 1986) due to a balance of surface recharge, incident solar radiation and outgoing radiation from the Earths surface as mentioned earlier. Care is required in measuring groundwater temperatures in boreholes that do not have natural flow: temperatures representative of the groundwater aquifer "tapped" by the borehole must first be attained by slow purging of at least three well volumes of water from the borehole before measurement of the temperature of the boreholes should be attempted. Heat generated due to pumping also affects temperature, so it is preferable to hand purge wells with bailers and to turn off pumps in pumping wells for a minimum of 24 hours prior to measuring the temperature. Purging was not considered necessary in wells that were known to be in constant use and these wells were monitored following periods when the pump was not in use. Purging was also not required in flowing springs and one artesian well that had a constant flow.

In this study, groundwater temperatures were measured directly in the borehole using a down borehole probe. The survey was carried out in accordance with the sampling protocol of British Standard Code of Practice for Site Investigations (BS 5930: 1999).

The temperature survey has quantified the spatial distribution of groundwater temperatures in the area between Mallow, Co. Cork and Cahir, Co. Tipperary, 20 km to the NE of Mitchelstown and has compared these temperatures to normal observed groundwater temperatures within Ireland. For the purposes of this study a conservative "normal" temperature range of 10-12°C is assumed. The survey indicates that a correlation may exist between the presence of crustal faults and elevated groundwater temperatures.

Monitoring points were identified from the Geological Survey of Ireland (GSI) groundwater well database, Cork County Council records, ordnance survey maps which were particularly useful for identifying springs, and interviews with local hydrogeological consultants, drilling contractors, and with local inhabitants. A total of seventy wells were monitored between July 2006 and July 2008. Stagnant water was purged from the wells prior to measurements being taken and a sonde was employed that allowed temperature and conductivity readings to be measured simultaneously. Well locations and recorded temperatures are listed in Table 1 and on topographic and geological maps of the Mallow-Cahir area (Figs. 4 & 5). Of the 70 well temperatures recorded in the survey, 67 readings are considered accurate representations of the groundwater aquifer. Suspected surface water intrusion could not be ruled out in 3 of the wells (Nos. 30, 62 and 63) and therefore these elevated temperatures have not been included in the geothermal maps.

Table 1. Well Temperature Survey Data.

Well ID	Townland	Date	Easting	Northing	T°C	Comments
1	Leaselands	01/08/2006	555	993	12.9	Well depth 100m (Hydrogeological report available)
2	Leaselands	01/08/2006	555	993	13.1	Well depth 100m (Hydrogeological report available)
3	Kilknockan, Mallow	20/05/2006	547	996	10.9	Farm supply well
4	Annabella, Mallow	20/05/2006	544	987	10.71	Well depth 100m (Hydrogeological report available)
5	Annabella, Mallow	20/05/2006	544	987	10.62	Well depth 100m (Hydrogeological report available)
6	Annabella, Mallow	20/05/2006	544	987	10.24	Well depth 100m (Hydrogeological report available)
7	Johnstown, Mitchelstown	23/05/2006	774	111	25.9	County Council Supply Well
8	Gooldshill, Mallow	27/05/2006	552	965	11.5	Disused farm production well
9	Ballydeloughy, Kildorrery	04/07/2006	745	097	10.55	
10	Ballydeloughy, Kildorrery	04/07/2006	745	097	10.79	
11	Ballydeloughy, Kildorrery	04/07/2006	745	097	10.95	
12	Killdorrery	15/01/2006	685	100	10.9	Hydrogeological report available
13	Ballyvoddy, Kildorrery	04/07/2006	706	076	12.54	Yield Approx. 300 Ga/Hr
14	Ballyvoddy, Kildorrery	04/07/2006	706	076	10.42	(35m West of CF1)
15	Ballendangan	04/07/2006	754	091	11.22	EPA IPC monitoring well 1,000-1,200 Ga/Hr
16	Ballendangan	04/07/2006	754	091	10.92	EPA IPC monitoring well 1,000-1,200 Ga/Hr
17	Ballendangan	04/07/2006	754	091	10.85	EPA IPC monitoring well 1,000-1,200 Ga/Hr
18	Ballykenly	05/07/2006	762	075	10.46	
19	Broomhill	05/07/2006	783	118	11.21	
20	Carriganleigh	06/07/2006	792	121	10.57	500-600 Ga/Hr
21	Ballyenahan	06/07/2006	723	090	10.71	Total Depth of well 55 ft.
22	Derryvillane	06/07/2006	736	074	11.03	Total Depth of well 225 ft.
23	Derryvillane	06/07/2006	739	071	11.07	Total Depth of well 50m approx.
24	Gortnagreiga	07/07/2006	562	951	11.22	
25	Carrigaduff	07/07/2006	570	949	10.41	
26	Clogheen,	07/07/2006	573	932	11.1	Well Depth 120ft.
27	Ballinvussig Waet	07/07/2006	581	946	10.73	
28	Ballynamona Br.	07/07/2006	564	930	10.63	110 Ft. Well ORS
29	Monavooria	08/07/2006	603	985	11.49	
30	Ballymacmoy, Killavullen	08/07/2006	986	636	13.02	Dug Well, probable surface water source.
31	Ahaunboy, Killavullen	08/07/2006	633	998	11.05	400ft. Well.
32	Mallow	08/07/2006	564	986	20.01	
33	Ballygarrane Cross Roads	09/07/2006	644	025	11.79	
34	Ballyveelick	09/07/2006	643	025	10.8	Static water level 23m
35	Ballygrilihane	09/07/2006	684	031	12.53	Probable surface water source.
36	Carrigpark	23/09/2006	60957	01497	11.08	Well depth 160ft. Drilled 5 - 6 weeks previously.
37	Carrig Demesne	23/09/2006	61377	00499	12.29	Old well, not in use. Donal Turner
38	Kilcanway	23/09/2006	62546	00239	11.57	Spring.
39	Keatley's Close	24/09/2006	57891	99210	10.68	Domestic supply well.
40	Spring	24/09/2006	65003	00077	11.9	Spring.
41	Powerstown	24/09/2006	62880	04203	11.02	Domestic suply well.
42	Newberry	14/01/2007	51661	97086	12.9	7.37 pH Artesian well drilled into Limestone
43	Newberry	14/01/2007	51634	97064	12.11	Well drilled into sandstone.
44	Newberry	14/01/2006	51591	47031	12.12	7.35 pH, Natural spring in sandstone.
45	Mallow	14/06/2008	54962	01879	11.49	Domestic supply well. SWl 4.78m
46	Mallow	14/06/2008	55981	02029	11.17	Domestic supply well. SWL 2.15m Well depth 19.3m.
47		14/06/2008	56172	02367	10.84	Domestic supply well. SWL 5.9m. Well depth 35m.
48		14/06/2008	56088	04092	10.69	Domestic supply well. SWL 5.9m. Well depth 35m.
49	Ballybrack	14/06/2008	58548	03829	10.67	Domestic/farm supply well. SWL 2.3m.Well depth 40m.
50		14/06/2008	58250	02852	11.84	SWL 1.95m. Total depth 43.68m.
51		14/06/2008	58837	02209	11.68	
52		14/06/2008	57179	01312	11.26	SWL 6.50m BGL Total depth 30.48m.
53	Dromdeer, Doneraile	14/06/2008	63006	05431	10.74	SWL 6.2m BGL. Coal seams reported historically
54		14/06/2008	62512	05440	10.87	SWL 3.8m Total depth 27m.
55		14/06/2008	62270	06798	11.04	SWL 7.85m BGL
56	Doneraile	14/06/2008	63657	07384	11.54	Domestic supply well
57	Cregg	02/06/2008	R 000	770	10.82	SWL 11.00m. Domestic well
58	Cornhill, Fermoy	02/06/2008	R 022	778	11.45	Farm supply well
59	Ballyhooley South	02/06/2008	W 997	736	11.6	Domestic well
60	Kilbehenny PWS	28/07/2008	R 865	157	11.72	Spring (Farm Supply)
61	Coolagarranroe	28/07/2008	R 902	174	11.16	Domestic
62	Ballyhuroo	28/07/2008	R 961	198	18	Pond - Mainly surface water influence
63	Kilcaran GWSS	29/07/2008	R 986	217	13.56	Domestic group water scheme, surface water ingress
64	Scartnaglorane	29/07/2008	R 998	219	10.44	Farm and domestic supply well
65	Benguragh	29/07/2008	S 044	257	11.15	Farm well
66	Holy Well	29/07/2008	S 042	258	11.16	Domestic well (Dug stone lined well)
67	Benguragh	29/07/2008	S 042	256	11.39	Holy Well - Spring
68	Tarrent Concrete	30/07/2008	S 054	264	11.01	Tarrant concrete production well
69	Rossadrehid	30/07/2008	S 054	274	11.92	Domestic well
70	Rockwell College	30/07/2008	S 071	343	10.94	Rockwell College Supply well

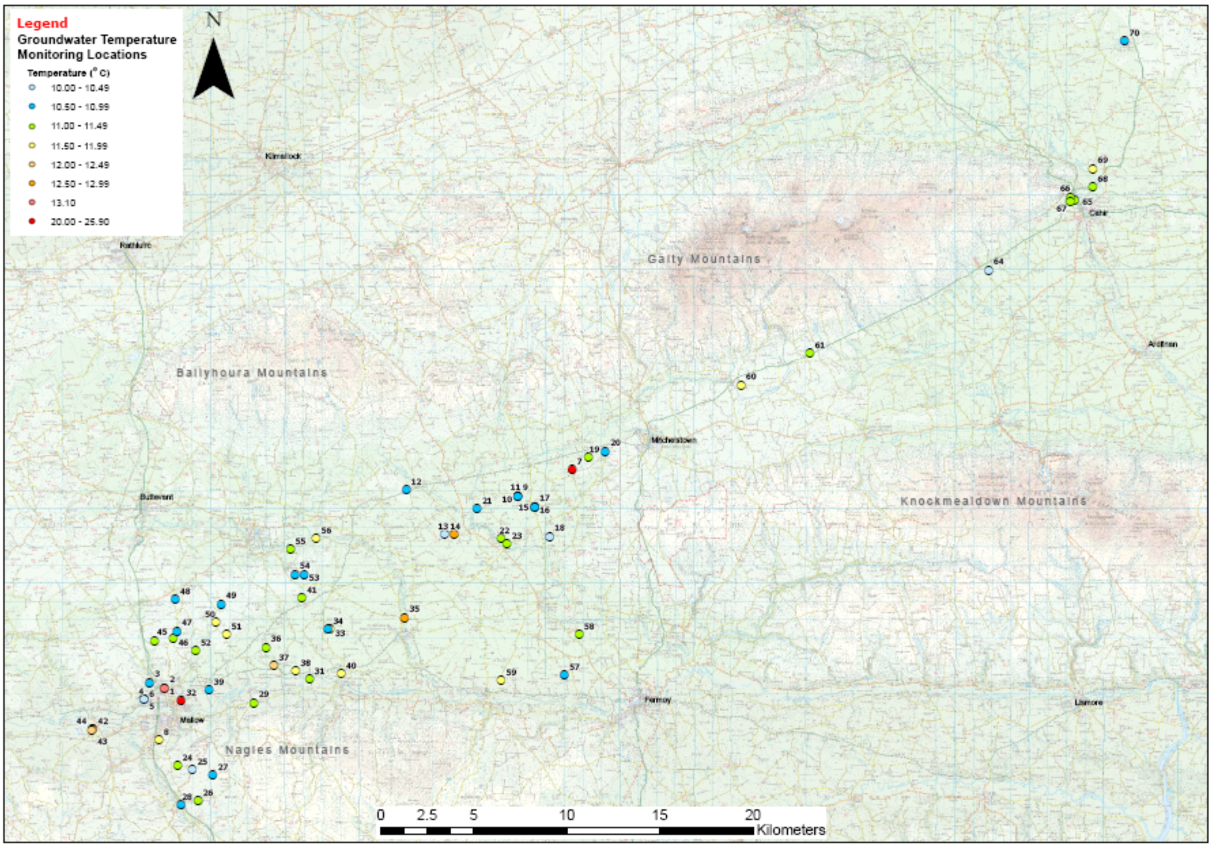

Figure 4: Well Temperature Survey Data Plotted on Ordnance Survey of Ireland Regional Map

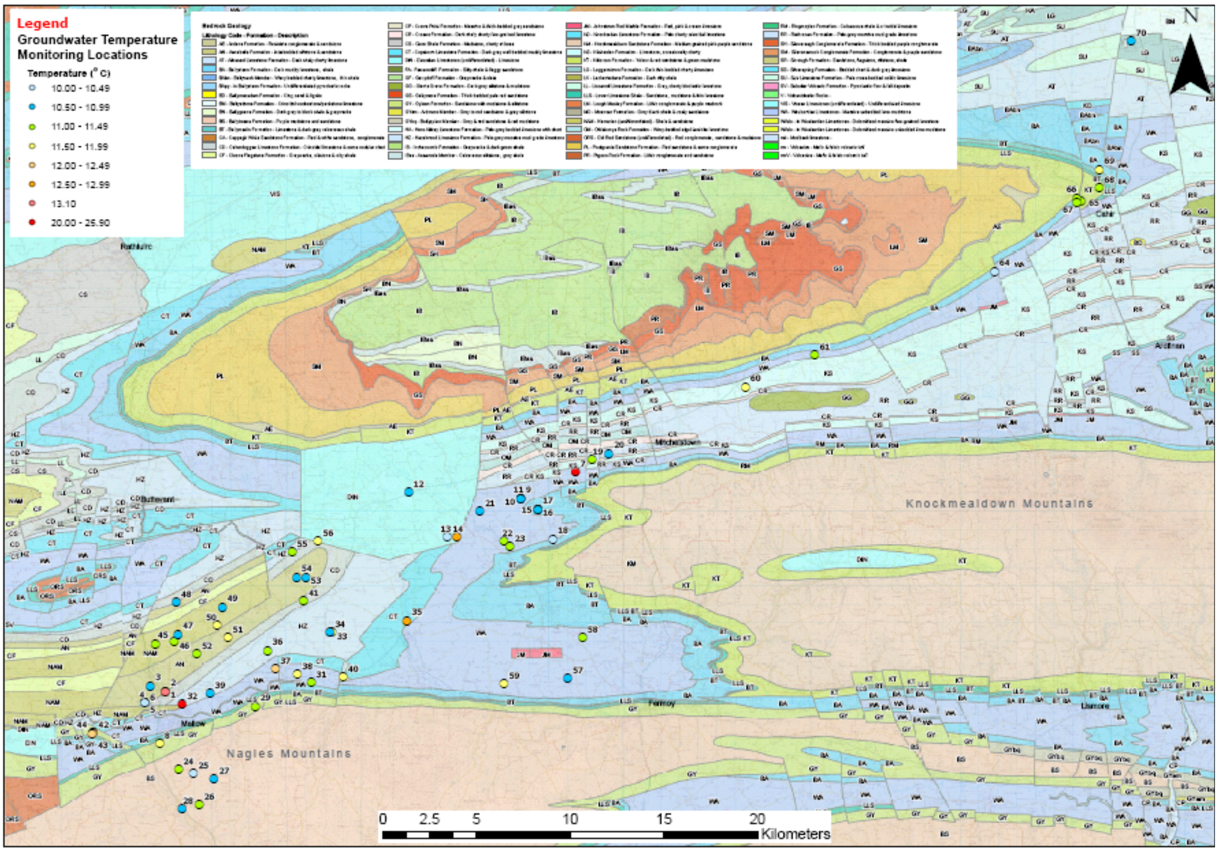

Figure 5: Location and Temperature of Wells Plotted on the GSI Regional Bedrock Geology Map

Of the remaining 67 wells, 57 (85%) had temperatures that fell within the conservative "normal" range. Temperatures of 10-10.5ºC were recorded by 4 wells (Nos. 14, 18, 25 and 64); 21 wells (No.'s 3, 4, 5, 6, 9, 10, 11, 12, 16, 17, 20, 21, 27, 28, 34, 39, 47, 48, 49, 53 and 70) recorded temperatures of 10.5-11ºC; 24 wells (No.'s 15, 19, 22, 23, 24, 26, 29, 31, 36, 41, 45, 46, 50, 52, 54, 55, 57, 58, 59, 61, 65, 66, 67 and 68) gave temperatures of 11-11.5ºC and 8 wells (No.'s 8, 33, 38, 40, 51, 56, 60 and 69) gave temperatures of 11.5-12ºC. None of the wells surveyed recorded temperatures below the normal range for groundwater in Ireland.

The remaining 10 wells (15%) recorded temperatures that exceed the normal range for Irish groundwater of 10-12ºC. Temperatures of 12-12.5ºC were recorded by 3 of the wells (No.'s 37, 43 and 44). Four of the wells (No.'s 1, 13, 35 and 42) recorded temperatures of 12.5-13ºC; One well (No. 2) gave a temperature of 13.1 ºC. Two wells (No. 7 and No. 32, Spa House Mallow and the Johnstown County Council Well) recorded temperatures in excess of 20ºC.

The topographic map (Fig. 4) shows that the wells with the anomalous temperatures are strung out in a NE-SW linear trend and are spatially related to a line projecting from Mallow to Mitchelstown. This represents the location of the lineament identified on the landsat map, the postulated conduit controlling upwards migration of the geothermal waters.

Given a geothermal gradient of around 10^{o}C/km for this part of Ireland (Goodman et al, 2004), the observed maximum temperatures of 22°C at Mallow and 26^{o}C at Johnstown, would reflect groundwater from depths of ca. 1,100m and ca. 1,500m respectively, assuming normal surface temperatures of 11°C for this region. Should dilution be a significant factor, the warm groundwater may have circulated from greater depth.

Of the 70 wells surveyed and listed in Table 1, a significant proportion (15%) recorded temperatures in excess of 12°C. The GSI has classified warm springs as springs recording temperature in excess of 13°C, but this does not necessarily mean that all springs with temperatures below this level represent shallow circulating meteoric waters of surface origin. If the range of shallow groundwater temperatures in Ireland is less than 11.5°C, then the wells in excess of 12°C must contain a component of warmer water.

The volume and temperature of warm spring waters reaching the surface, depends on the porosity and permeability of the source aquifer and fault conduit, and on the geothermal gradient. The higher the geothermal gradient, the greater is the likelihood of encountering high temperature groundwater resources at shallow depth. However, if the fault conduit intersects other aquifers at shallower depths, groundwater from the shallower aquifers will cool the warmer groundwater as it migrates up the fault, to the extent that it may be reduced to normal shallow groundwater temperatures. In much of SW Ireland, karstified deposits of the Waulsortian Limestone Formation at shallow depth, may be the source of cooler groundwaters which reduce the temperature of deep warm groundwaters during their upwards migration. It is possible that all of the warm water springs in SW Ireland may be sourced from a single deep aquifer, but that the circulating warm groundwaters have been differentially affected by cooler waters during their upwards migration, accounting for the range in temperatures of these springs. Indeed many well waters with temperatures in the 'normal' range of groundwater may have a component of warm groundwater that has been so diluted by cooler waters at shallow levels that the temperatures have been lowered to below 12°C.

Figs. 6 and 7 illustrate the location and temperature of wells on the GSI regional aquifer classification and aquifer vulnerability maps. The purple areas on Fig. 7 indicate limited knowledge of the depth to bedrock due to a subsoil cover usually in excess of three metres. Thick deposits of Pleistocene glacial overburden, which blankets much of Ireland, may have buried a NE-SW trending structure in the underlying bedrock.

Thus the temperature survey of water wells carried out between Mallow and Mitchelstown indicates anomalous temperatures along a NE-SW trend suggesting the possible presence of a buried Caledonian-aged fault. The thick clay–rich overburden in the Mallow-Mitchelstown area may have blanketed this structure and acted as a confining layer, preventing geothermal waters from penetrating to the surface. Intersection of minor N-S compartmental faults of Variscan age with this fundamental fault may have aided some of the geothermal waters to reach the surface as at Mallow and at Johnstown, and elsewhere may also have provided pathways for groundwater migration.

6. GEOPHYSICAL INVESTIGATIONS

In areas of poor to non-existent outcrop such as the Mallow-Mitchelstown area, geophysical techniques are powerful and essential tools in gaining a reasonable understanding of the bedrock geology. Geophysical investigations also play an important role in identifying aquifer systems and outlining aquifer configurations under varying hydrogeological conditions. In addition, geophysical surveys can be very useful in delineating accurately the location of buried faults.

Surface electrical resistivity surveys utilising the vertical electrical sounding (VES) technique has proved particularly useful for groundwater studies due to its simplicity and cost-effectiveness. A well-planned, non-invasive, geoelectrical investigation is capable of mapping aquifer systems, confining layers (i.e., clay formations), depth and thickness of aquifers, and groundwater quality (Jha et al., 2008).

A limited preliminary electrical resistivity survey was undertaken involving the acquisition of vertical geoelectrical soundings across two profiles in the study area. The locations of the profiles took into consideration data acquired during a literature search and also data from the well temperature survey. The profiles were thus conducted in areas where elevated groundwater temperatures had been identified during the well survey and therefore where there was the possibility of a buried Variscan-reactivated Caledonian structure affecting groundwater circulation and migration.

The two traverses were undertaken adjacent to the Johnstown borehole and in the Carrig Demesne area on the outskirts of Mallow adjacent to one of the anomalous wells and relatively close to the Spa Glen and Lady's Well. The geolectrical soundings and the interpreted geophysical profiles are presented in Fig. 8.

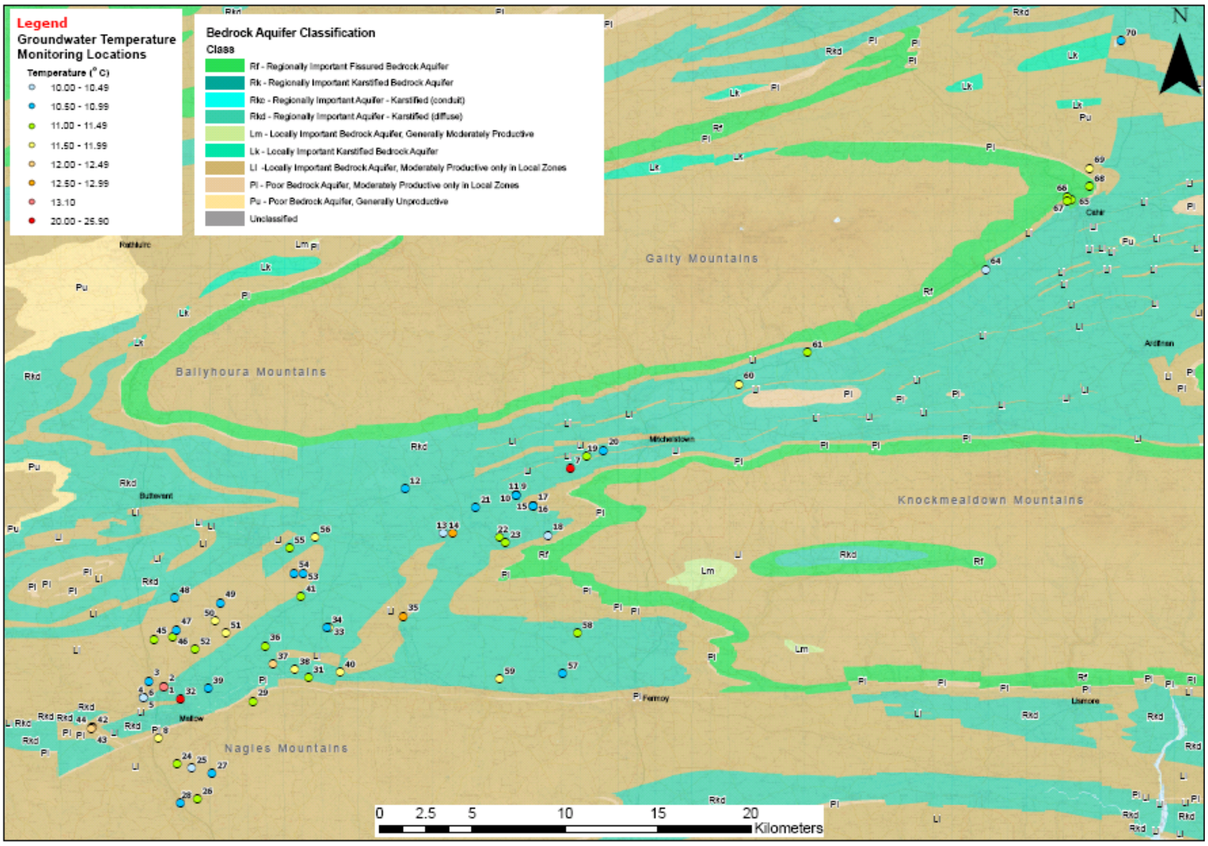

Figure 6: Location and Temperature of Wells Plotted on GSI Regional Aquifer Classification Map

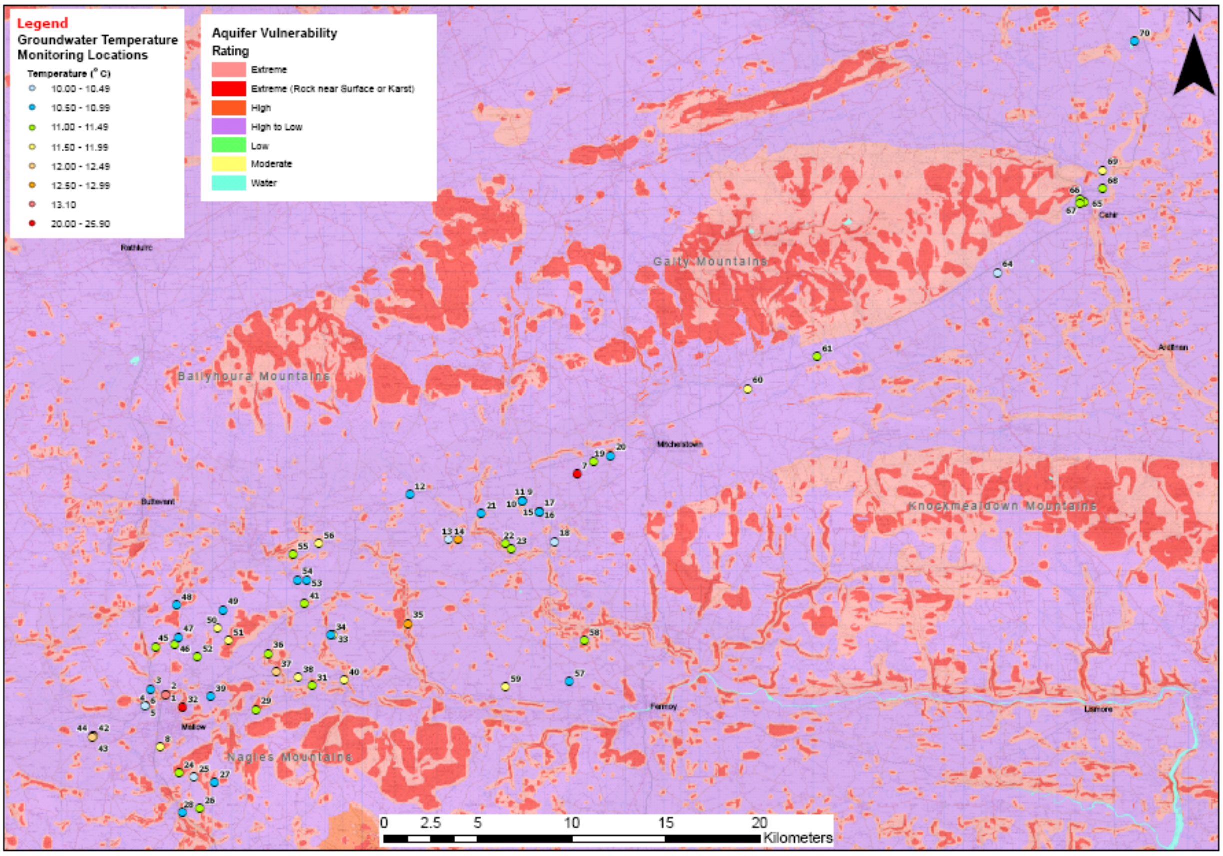

Figure 7: Location and Temperature of Wells Plotted on GSI Regional Aquifer Vulnerability Map

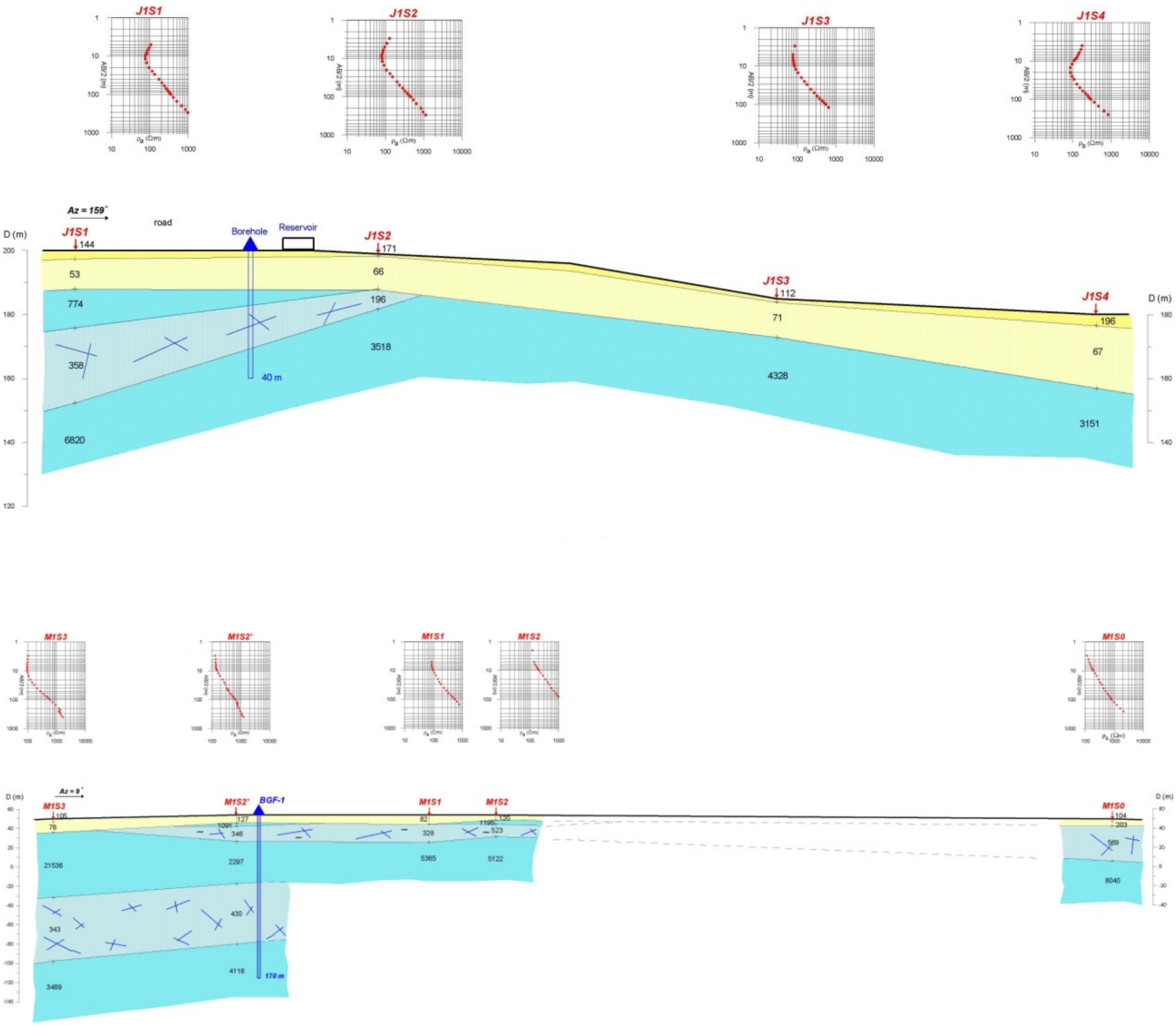

Figure 8: Diagrams of the Geoelectrical soundings and the geoelectrical geophysical profile in the area of the well at Johnstown, Mitchelstown (Well Survey Reference No. 7) (top) and Sean and Liz Turner's well, Carrig Demesne (Well Survey Reference No. 37)

The interpretation of electrical resistivity data from the Johnstown borehole indicates karst permeability in a fracture/conduit zone dipping approximately 30° south of the borehole location and for the Carrig Demesne locality, two sub-horizontal conduit zones running beneath the well. This interpretation of the geo-electrical data supports the hypothesis that thermal waters are travelling laterally along karst structures having circulated to some great depth via fault related conduit permeability.

A further geophysical project to delineate the precise location and orientation of the fault conduit is planned for Autumn 2009. The intention is to conduct a series of NW-SE traverses at 1-2 km intervals across the postulated line of the fault utilising a combination of the electrical resistivity lateral mapping technique and the electromagnetic VLF method. This it is hoped will confirm the presence of the fault, and enable any future drilling programme seeking to tap into and exploit a warm water supply along the line of the fault to make a more informed selection of borehole sites.

7. GEOCHEMICAL INVESTIGATIONS

Geochemical investigations were undertaken in order to fingerprint the warm geothermal waters, with the hope that distinctive hydrochemical characteristics may be established, allowing the source aquifer and the circulatory pathway of the warm waters to the surface to be distinguished. Similar exercises have been successful in identifying source and pathways of geothermal waters elsewhere (e.g. Andrews *et al*. 1982).

Major Ions

A survey conducted by Burdon (1983), ascertained that in general the ionic content of Irish warm spring waters is typical of Irish groundwater as a whole. This could be interpreted as an indication that most Irish warm springs water have mixed with cooler near-surface groundwater during their ascent to the surface

The chemistry of the Lady's Well spring at the Mallow Spa was investigated by University College Cork over the period September 1981-January 1983 (Brück et al, 1986). The results of this study indicates that the water is of calcium bicarbonate type and similar to the local groundwater in the limestone aquifers. The main differences are slightly lower calcium, bicarbonate, and nitrate concentrations in water from Lady's Well. Further geochemical analyses of 10 representative samples of both thermally anomalous and normal wells and springs were undertaken to augment the existing knowledge base as part of this study (Table 2). Temperatures listed in Table 2 were those taken during sampling, and are lower than those in Table 1, as sampling took place in winter when rainfall was greater and water table levels higher.

Earlier observations were confirmed during this study, with all ten of the samples analysed for major ions recording calcium bicarbonate type water characteristic of the local limestone aquifers. Generally the trend was for thermally anomalous wells to have slightly lower levels of all three of the ionic parameters of calcium, bicarbonate and nitrate.

Nitrate

In this intensely farmed area, the presence of nitrate in groundwater reflects an anthropogenic origin and indicates recent recharge of the shallow groundwater within all of the wells in the study area. However, concentrations of nitrate are significantly lower in the thermal wells indicating less mingling of the thermal waters with more recent shallow groundwater (Table 3).

The lowest concentration of nitrate was observed in the well which recorded the highest temperature, the Johnstown well (Table 1, No. 7), followed by three other thermal wells and springs: the Sugar Factory spring, the Sugar Factory artesian well and the Lady's Well, Mallow (Table 1; Nos. 44, 42 and 32), whilst the next two lowest values also were recorded by wells which exhibited anomalous thermal values in the original survey. The remaining four wells, which exhibited normal groundwater temperatures during the original survey exhibited significantly higher concentrations of nitrate. These results suggest that due to its anthropogenic origin nitrate is a useful indicator of mixing of geothermal water with shallow cooler recently recharged groundwater, and that the higher the value of nitrate in the geothermal water the greater the degree of dilution of the geothermal water by shallow groundwater.

Table 2. Ionic Composition of Wells.

Well Survey Ref. No.	**7**	**32**	**42**	**44**	**37**	**21**	**13**	**59**	**33**	**19**	**Units**
Sampling Date (d.m.2009)	31.01	24.01	24.01	07.02	08.02	07.02	07.02	07.02	31.01	31.01	mg/l
Temperature	23	17.5	12.1	11.2	11.2	11.1	10.9	10.8	10.4	10.35	°C
Sulphate	12.08	18.13	14.11	11.24	14.22	11.19	6.15	10.64	13.31	11.19	mg/l
Chloride	16.5	24.2	19.2	17.7	18.7	42.7	21.3	16.4	25	42.7	mg/l
Flouride	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	0.7	<0.3	<0.3
Nitrate as No_3	4	10.8	12.5	5.5	18	60	19.9	32.9	48.8	60	mg/l
Ortho phosphate as PO_4	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	mg/l
Total Alkalinity as $CaCo_3$	164	192	200	180	176	132	236	236	300	132	mg/l
Calcium -dissolved	60	85	80	72	85	59	110	120	129	59	mg/l
Magnesium - Dissolved	14	10	12	10	6	16	8	6	7	16	mg/l
Potassium - dissolved	1	1	1	2	5	1	1	4	2	1	mg/l
Sodium - dissolved	12	15	12	12	11	17	9	10	11	17	mg/l
Iron - dissolved	<0.02	<0.02	<0.02	<0.02	<0.02	0.022	<0.02	<0.02	<0.02	<0.02	mg/l
Manganese - dissolved	<0.002	<0.002	<0.002	<0.002	<0.002	0.019	<0.002	<0.002	<0.002	<0.002	mg/l
Nickel - dissolved	<0.002	<0.002	<0.002	<0.002	<0.002	0.009	<0.002	<0.002	<0.002	<0.002	mg/l
Copper - dissolved	<0.007	<0.007	<0.007	<0.007	<0.007	0.016	<0.007	<0.007	<0.007	<0.007	mg/l
Lithium - dissolved	0.006	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	mg/l
Strontium - dissolved	0.086	0.110	0.219	0.198	0.071	0.078	0.054	0.069	0.086	0.097	mg/l
Bromide	18	10	8.8	3.3	2.5	6.9	2.5	2.9	5.9	6.9	mg/l
Silica	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	mg/l
HCO_3	200	234	244	219	215	161	289	288	366	161	mg/l
CO_3	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	mg/l

Table 3. Concentrations of Nitrate in the Study Area.

Well ID (Shallow Well Survey Reference)	NO_3^-
Johnstown Well (7)	4
Spa House (32)	10.8
Sugar Factory Artesian Well (42)	12.5
Greencore Spring (44)	5.5
Padraig O`Brian (33)	48.8
Richard Coughlan (19)	52.5
James Kennedy (21)	60
Ballyvoddy (13)	19.9
Sean and Liz Turner (37)	18
Carey Ballyhooley (59)	32.9

Table 4. Chloride/Bromide Ratios.

Well ID (Shallow Well Survey Reference)	Cl^-	Br^-	Cl^-/Br^- (Molar)
Johnstown Well (7)	16.5	18.00	2.066002
Spa House (32)	24.2	10.00	5.454244
Sugar Factory Artesian Well (42)	19.2	8.80	4.917425
Greencore Spring (44)	17.7	3.30	12.08867
Padraig O`Brian (33)	25.0	5.90	9.550084
Richard Coughlan (19)	30.6	4.10	16.82119
James Kennedy (21)	42.7	6.90	13.94755
Ballyvoddy (13)	21.3	2.50	19.20255
Sean and Liz Turner (37)	18.7	2.50	16.85857
Carey Ballyhooley (59)	16.4	2.90	12.74574

Chloride/ Bromide Ratios

The thermally anomalous groundwater samples have much lower Cl^-/Br^- ratios than groundwater from the other shallow wells sampled during this survey (Table 4). This relationship is possibly due to:

- chemical characteristics of the source aquifer host rock
- longer residence time for the thermal waters in the source aquifer, resulting in a greater degree of substitution of Br^- ions for Cl^- ions through groundwater interaction with the host rock
- temperature conditions in the source aquifer
- chemical characteristics of the host rocks encountered during accent from depth
- degree of mixing with shallow groundwaters during accent

The similar ratios for Lady's Well, Mallow and the Sugar Factory artesian well in Mallow suggests a similar history for the groundwater at these locations. The lower Cl^-/Br^- ratio for the well at Johnstown correlates with its higher temperature and possibly indicates a longer residence time or less dilution of thermal waters with more recent shallow groundwaters. The Cl^-/Br^- ratio thus shows a correlation with groundwater temperature and may provide a fingerprint for the source aquifer. However, the numerous possible explanations for the lower Cl^-/Br^- ratios make it difficult to categorically assign it as an indicator of the hydrochemical characteristics of the source aquifer.

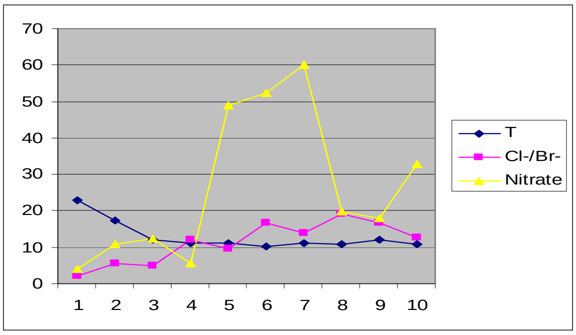

Fig 9: Negative correlation of T°C with [Cl^-/ Br^-] & NO_3^-

Lithium

The trace element Lithium was detected above the laboratory detection limit of 0.005mg/l in just one of the samples, the thermal well at Johnstown, with a concentration of 0.006mg/l. This is regarded as significant as the Johnstown well gave the highest temperature value in the groundwater temperature survey and probably reflects the least diluted geothermal water in the North Cork area. The lithium value in this sample may thus reflect a compositional characteristic of the source aquifer, which has not been obscured by dilution.

Isotopic and Gas Analyses

Isotopic and gas analyses from Lady's Well showed 4HE x 107 at about 170 and Tritium (TU) of 11. Aldwell interpreted these results as reflecting deeper circulation and longer residence time than usual for Irish groundwater. (Aldwell, 1996).

Table 5. Isotopic Composition of Groundwater in N. Cork.

Well ID (Shallow Well Survey Reference)	Sampling Date	δ²H(‰VSMOW)	δ18O(‰VSMOW)
Johnstown Well (7)	31/01/2009	-40.5	-6.48
Spa House (32)	24/01/2009	-39.7	-6.19
Sugar Factory Artesian Well (42)	24/01/2009	-39.6	-6.28
Greencore Spring (44)	07/02/2009	-40.0	-6.22
Sean and Liz Turner (37)	31/01/2009	-38.9	-6.16
Holy Well (39)	25/01/2009	-39.2	-6.25
Richard Coughlan (19)	07/02/2009	-41.6	-6.62
James Kennedy (21)	07/02/2009	-37.5	-6.18
Carey Ballyhooley (59)	31/01/2009	-39.3	-6.28
Jerry McSweeney (25)	24/01/2009	-39.7	-6.73
Leaselands 1 (1)	07/02/2009	-38.2	-6.12
Leaselands 2 (2)	07/02/2009	-40.0	-6.30
Ballyvoddy (13)	07/02/2009	-38.2	-6.23
Ballyvoddy (13)	07/02/2009	-38.2	-6.23
River Blackwater (n/a)	24/01/2009	-38.7	-6.57
Local Precipitation Sample (n/a)	04/03/2009	-50.7	-9.20

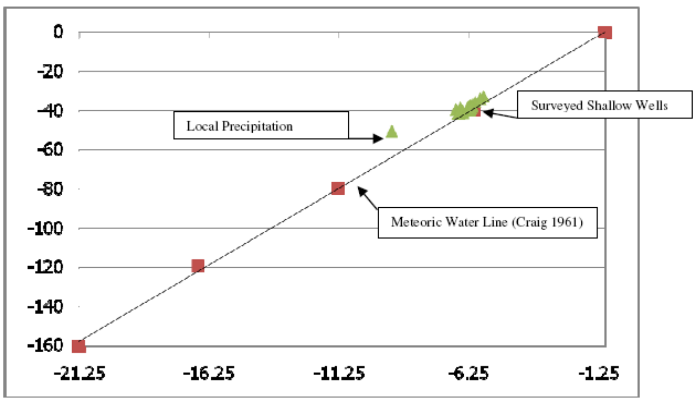

Figure 10: Plot of δ²H (‰ VSMOW) (y axis) against δ¹⁸O (‰ VSMOW) (x-axis)

Fifteen samples of thermally anomalous and normal groundwaters from the North Cork wells and springs have been analysed for hydrogen ($^2D/^1H$) and oxygen ($^{18}O/^{16}O$) isotopes together with a sample of surface water from the River Blackwater at Mallow and a rainwater sample taken in Cork city (Table 5). The hydrogen and oxygen isotopic compositions of the thermal waters demonstrate that it is of meteoric origin. The isotopic compositions lie close to the worldwide meteoric water line (Fig. 10) and the ratios are very similar to those for other shallow groundwater in the region, analysed at the same time.

All of the wells cluster together along the right side of the global meteoric water line. The local precipitation sample, taken in Cork City, consisted of a mixture of rainwater and snow and plots to the left of the meteoric water line relative to the shallow well and River Blackwater samples.

Geothermometry

Geothermometers allow us to calculate the temperature at which ground water equilibrated chemically with the rocks within its aquifer (Henley et al. 1984, Domenico & Schwartz, 1998). They are used widely in geothermal exploration, as they can indicate the presence at depth of hot water. Unfortunately they cannot be applied in this study for various reasons. Firstly, the temperatures of the North Cork wells are too low for use of the alkaline geothermometer and unrealistic results were obtained. Secondly, the various Si^{4+} geothermometers could not be applied, as Si^{4+} was not detected above the laboratory detection limit in any of the samples from the study area.

CONCLUSIONS

North Cork contains an abundant groundwater resource in its bedrock aquifers. The consistent 10-12°C temperature of this resource throughout the year, make it an ideal source for water based heating, cooling, or heating and cooling systems using heat exchanger and heat pump technology. Anomalous areas of elevated groundwater temperatures have hitherto been explained as representing groundwater that has circulated to deep levels and traveled to the surface again via fault related conduit permeability. A shallow borehole temperature survey has verified this relationship.

Landsat imagery indicates the presence of Caledonian aged NE–SW trending structures in the region, likely to be responsible for the deeper circulation and longer residence times of the thermal groundwater. The minimum depth of circulation is 1100m in Mallow and 1,500m in Johnstown, with greater depths likely considering heat loss during the ascent of the groundwater and potential mingling of deeper sourced thermal water with the cooler shallow groundwater.

2-D Resistivity surveys in areas with anomalous temperatures indicate extensive karstification of shallow limestone bedrock aquifer enhancing the permeability for horizontal flow of groundwater. These horizontal structures intersect deeper vertical structures.

Geochemical analyses indicate that all of the groundwater is of meteoric origin and is of a calcium bicarbonate type, typical of groundwater in carbonate aquifers, indicating that the thermal and non-thermal waters have chemically equilibrated with the host carbonate bedrock aquifer. Trends of chloride, bromide and nitrate ionic concentrations suggests that the thermal waters have a longer residence time than the groundwater exhibiting temperatures more typical of Irish groundwater.

It is anticipated that this study, will encourage the use of these ubiquitous low enthalpy hydro-geothermal energy resources in the North Cork area, as an economically viable and environmentally sound alternative to fossil fuels. It is recommended that further research be undertaken which will identify specific projects where the low enthalpy hydro-geothermal resources that have been identified can be harnessed for the benefit of all stakeholders in the study area. There is a case for local government to lead the way, as private developers can sometimes be slow to adapt to innovative new technologies; investment in successful flagship projects will reap economic and environmental benefits and provide the example for private entrepreneurs to follow suit.

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