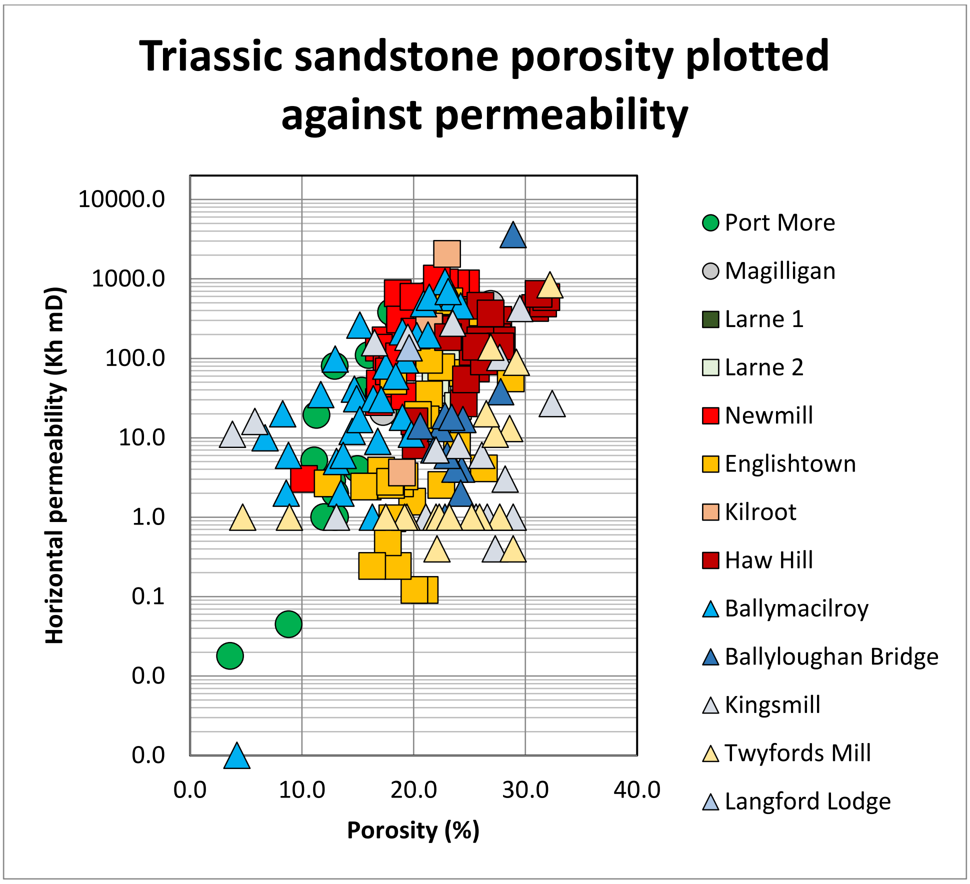
A review of geothermal reservoir properties of Triassic, Permian and Carboniferous sandstones in Northern Ireland

GSNI Report

Internal Report 19/01



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A review of geothermal reservoir properties of Triassic, Permian and Carboniferous sandstones in Northern Ireland

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This report builds on the work carried out by CSA Ltd. who produced INTERREG-funded two reports (2003, 2008) for the Department of Enterprise Trade and Investment (DETI) highlighting the potential of shallow and deep geothermal energy in Northern Ireland, and the 2009-2011 geophysical and drilling programme commissioned by GSNI and supported by the Innovation Fund. The results of the GSNI deep geothermal energy research were integral to several of the research projects carried out under the IRETHERM deep geothermal research programme (2011-2016), co-ordinated by the Dublin Institute of Advanced Studies. IRETHERM has contributed significantly to the knowledge of deep geothermal resource potential of Northern Ireland, through the acquisition of new data and the application of new processing, modelling and interpretation techniques to these new and existing data. We acknowledge here our thanks to the IRETHERM team both for these contributions and many useful discussions over the years.

This report also draws on the results from work carried out by students for their MSc and BSc projects based on studies of geothermal and reservoir properties of the Sherwood Sandstone Group, in particular Amy Chambers and Rachel Millar from the University of St. Andrews.

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Summary

This report presents the results of a review of the available porosity and permeability data for potential deep geothermal sandstone reservoirs in Northern Ireland. It is based on information from published and unpublished sources and data collected as part of a GSNI reservoir characterisation project involving a detailed petrography study borehole core and sample material by one of the authors (Dr R Raine).

The geology of the north-eastern part of Northern Ireland is characterised by a number of deep sedimentary basins largely concealed below the extensive outcrop of Palaeogene basalts covering most of County Antrim and parts of counties Londonderry, Tyrone, Armagh and Down. The Larne, Lough Neagh, Rathlin and Foyle basins contain thick sequences of sedimentary rocks of Carboniferous to Cretaceous age, including Carboniferous, Permian and Triassic sandstones which are potential hydrocarbon and/or hydrogeothermal reservoirs.

Sandstones of similar age and types are being used to produce heat in geothermal energy systems in the Netherlands, Denmark, Germany and Great Britain. There is the potential to develop similar geothermal energy systems in Northern Ireland. Geothermal energy systems can play a role in the decarbonisation of heat and are characterised by their high deliverability and availability approaching 24/7, 365 days a year. Deep geothermal energy systems involve relatively high initial capex associated with the drilling of deep boreholes so it is important to be able to predict accurately the nature and performance of the target geothermal aquifers. In particular, we are interested in the thickness, depth of these sandstones and the temperature of the formation fluids they contain, how much fluid is stored within them and how easily it can move through the rocks. This report focuses on the porosity and permeability of the reservoir rocks, i.e. their storage capacity and fluid flow characteristics.

Surface outcrops of these sandstones are very limited in extent so that most of the information about them has been derived from rock samples collected from deep boreholes. This report draws together data included from previous published and unpublished data together with the results from recent laboratory analyses and petrographic studies carried out on core and cuttings samples by GSNI geologists or by external contractors on behalf of GSNI.

Overall the results reinforce earlier observations that the Permo-Triassic sandstones are potentially productive geothermal aquifers, albeit with significant variations in porosity and permeability both within individual borehole sequences and between boreholes from the same and different sedimentary basins. The Sherwood Sandstone Group (SSG) is a prolific aquifer at shallow depths in the Lagan Valley and Newtownards Trough and, although reservoir quality generally decreases with depth, the available data indicate that some intervals within the upper part of the SSG could be productive geothermal aquifers at depths below 1500m. When the results from pumping tests in water production boreholes are compared to laboratory derived permeabilities this suggests that fracture flow is important in the SSG.

There is very limited information from the Carboniferous sandstones – mostly from outcrops, shallow boreholes and moderate depths – but some of the samples exhibit surprisingly good reservoir properties, even below 1000 m depth. However, the petrographic analysis suggests that the porosity and permeability might be expected to reduce significantly at greater depths. These are the oldest reservoirs considered and, as a result, a better understanding of the distribution of sandstones with the greatest potential for the preservation of primary porosity or creation of secondary porosity would be helpful.

The Permian outcrop in Northern Ireland is very limited in extent and most of the available information about Permian sandstones has been obtained from core samples in a relatively small number of boreholes, both shallow and deep. Permian sandstones exhibit a wide variation in sedimentary characteristics and consequently in reservoir quality, although some borehole samples yield good porosity and permeability values.

Available temperature data from deep boreholes in Northern Ireland yield geothermal gradients of about 34°C/km, 32°C/km and 28°C/km for the Rathlin, Lough Neagh and Larne sedimentary basins, respectively, significantly higher than the average (26°C/km) for Upper Palaeozoic and Mesozoic sedimentary basins in Great Britain. The geothermal gradients for the Lough Neagh and Larne basins may be underestimates because the temperatures may not have reached thermal equilibrium with the formation fluids at the time of measurement. As a result formation fluids are likely to be close to 80°C at depths of 2000 metres, temperatures suitable for large scale direct heating uses. A temperature of 97.8°C was recorded from a depth of 2565 m in the Ballinlea No. 1 well in the Rathlin Basin.

Gravity modelling has been used with seismic survey and borehole data to predict the depths of the potential geothermal aquifers in the deepest parts of the sedimentary basins. Although gravity modelling cannot give unique or definitive depth solutions, they do indicate that the Sherwood Sandstone should lie below 2000 metres depth beneath the northeast corner of Lough Neagh and below 1500 metres in the Rathlin Basin near Ballymoney and Ballycastle, with the Permian and Carboniferous sandstones at still greater depths.

Magnetotelluric (MT) surveys are a relatively low-cost geophysical method for determining the subsurface distribution of rocks with low electrical resistivity and are routinely used in exploration for deep geothermal energy resources. In Northern Ireland MT surveys have been carried out in the Rathlin Basin and the northern part of the Lough Neagh Basin that show low resistivity rocks (potential geothermal aquifers) extending down below 2000 metres depth, thus increasing confidence in the results of the gravity modelling.

The results from this review of reservoir quality, taken together with the information on temperatures, geothermal gradients and likely depths of potential geothermal sandstone aquifers, show that there are several areas in Northern Ireland where deep geothermal energy resources may be suitable for direct heating use. Heat demand mapping will indicate where in Northern Ireland geothermal energy could provide the energy source for heat networks.

A review of geothermal reservoir properties of Triassic, Permian and Carboniferous sandstones in Northern Ireland

1. Introduction

Geothermal energy is a low carbon sustainable form of energy that can be produced from the heat stored in the earth. There is potential for the use of both shallow and deep geothermal energy resources for the production of heat, and possibly electricity, in Northern Ireland. This resource potential will be described in greater detail in a separate report.

Most of Northern Ireland has widespread potential for the use of shallow geothermal energy. The temperature of the ground is similar to the air temperature but, at shallow depths of only a few metres, the temperatures are relatively stable and not significantly affected by seasonal fluctuations in air temperature – at temperatures of about 10°C – 14°C the ground is hotter than winter and cooler than summer air temperatures. Ground source heat pump (GSHP) technology uses the ground's heat energy to provide heating for domestic and non-domestic buildings via horizontal closed loop systems buried at depths of 1 – 2 metres or vertical systems installed in boreholes up to 100 metres deep. In some locations vertical open loop systems can circulate water through aquifer rocks at depths of up to a few hundred metres to provide either heating or cooling for buildings, according to their seasonal needs. The regional high quality Sherwood Sandstone aquifer could be used for geothermal heating and cooling systems in many locations within the north-eastern part of Northern Ireland, and particularly in the Greater Belfast area. Although these shallower uses (particularly the heating and cooling in permeable sandstones) are considered in this report, the main focus is on the data and reservoir quality as they may be applied to deep geothermal reservoirs.

The earth is very hot at its core and the temperature decreases from the core to the earth's surface. In the earth's crust additional heat is produced from the decay of radioactive minerals within the crustal rocks. In volcanic areas of the world very hot temperatures are found at shallow depths of a few hundred metres, hot enough to produce electricity, in countries such as Iceland, Italy and Indonesia. However, even in non-volcanic regions such as Northern Ireland, the rocks at a few kilometres depth may contain hot water that can be pumped to the surface and used to provide direct heating for district heat networks and, if hot enough, to generate electricity.

Sandstones in the subsurface of Northern Ireland, primarily those buried in Permo-Triassic basins, offer the potential for the use of hot groundwater where these sandstones are buried deeply enough and are sufficiently permeable. Most of the information about the deep geothermal potential of the sedimentary basins on Northern Ireland comes from the results of exploration for oil and gas, although these basins are relatively little explored in comparison to areas of Europe where deep geothermal energy systems are more widely developed (e.g. Paris Basin, Bavaria, the Netherlands).

In the Rathlin, Lough Neagh and Larne sedimentary basins Permian, Triassic and possibly Carboniferous sandstones have sufficient water-filled pore space and are hot enough to form a viable deep geothermal resource for direct heating applications, in those areas where they are buried to depths of more than 1 kilometre. If these rocks are buried to depths of about 3km, temperatures of about 100°C might be expected which could be hot enough for electricity generation. Some of the areas that have the best potential for deep geothermal energy resources include the area southwest (close to Dungannon) and northeast (Antrim) of Lough Neagh, the Ballymoney – Armoy - Ballycastle area, and southeast Antrim.

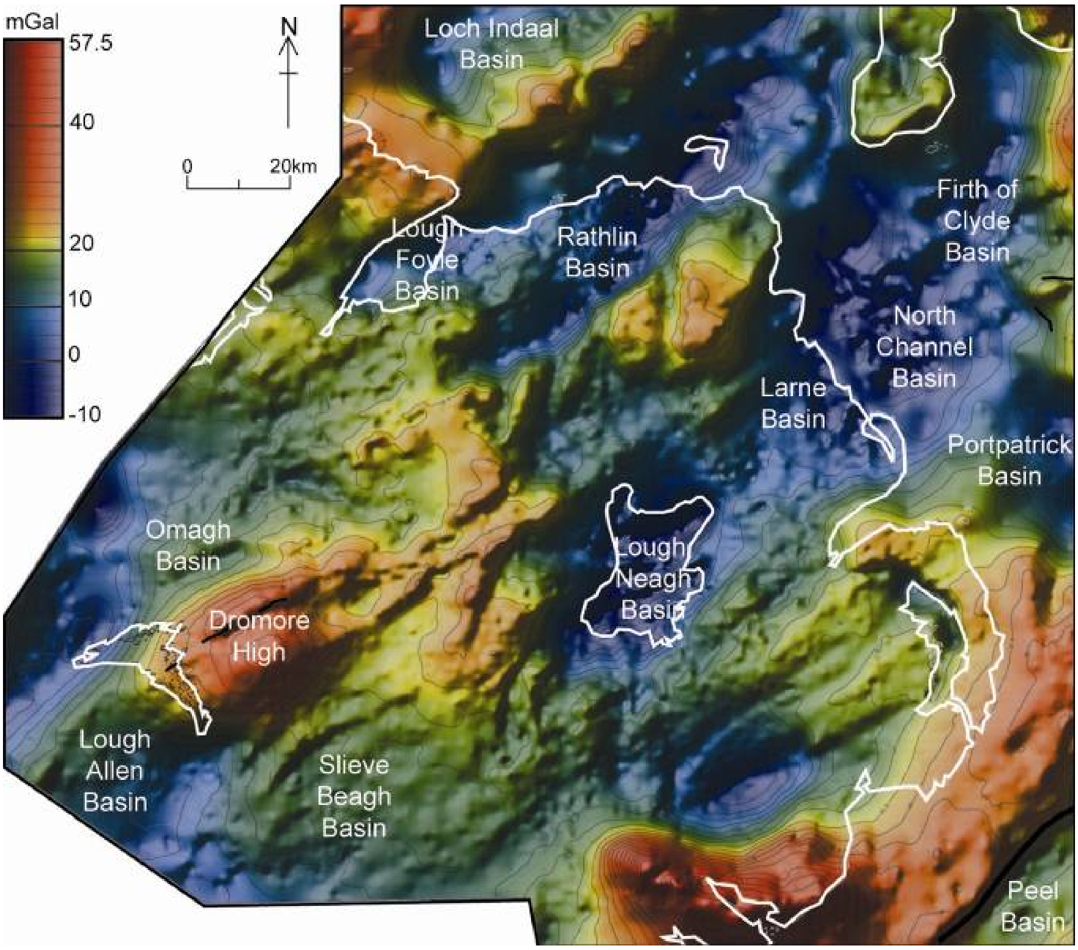

Figure 1 Shaded relief gravity anomaly map showing onshore and offshore sedimentary basins. For the most part, the gravity lows (blues and greens) correspond to sedimentary basins (modified after Reay, 2004)

The development of deep geothermal energy is in its infancy in the UK and Ireland. A UK-wide research programme was initiated in the early 1980's in response to the oil crises of the previous decade but the raison d'être of this programme was undercut by increased gas production in the North Sea and Irish Sea which satisfied a large proportion of domestic heat and power demand. The research programme resulted in the establishment of a heat network in Southampton which has remained the only deep geothermal system developed in the UK. Recently, however, the scientific imperative to reduce greenhouse gas emissions has led to changes in energy policy and a renewed interest in the potential use of geothermal energy as a low carbon energy source.

The development of deep geothermal energy depends on a range of technical, economic, social and political factors such as:

- Distribution, thickness, depth, temperature and quality of rock aquifers
- Proximity of heat demand to resource, competition with other energy sources, industry capacity, fiscal regime

- History of heat networks, public familiarity with geothermal energy
- Energy strategy, legislation & regulatory frameworks, financial instruments

Previous studies have looked at some of the technical (Kelly et al., 2005), economic (Pasquali et al., 2008) and regulatory (GTR-H, 2012) factors relevant to the development of deep geothermal energy in Northern Ireland. The two technical studies were funded by INTERREG and DETI and carried out by consultants CSA Group Ltd. And highlighted the scientific evidence for the deep geothermal energy resource potential in Northern Ireland. Subsequent research for the NIDeepGeotherm and IRETHERM projects involved the acquisition and interpretation of new geological and geophysical data which built on existing knowledge to improve our understanding of these resources. Seismic reflection surveys and deep drilling for petroleum and mineral exploration have also yielded valuable new data about the physical and thermal properties of deep aquifer rocks, and the geological structure of the Larne and Rathlin sedimentary basins.

2. Properties of deep geothermal aquifer systems

Historically, resource assessments have been carried for the Triassic Sherwood Sandstone Group as part of the UK research programme based on the data available at that time (Gale and Rollin 1986). The Permian and Carboniferous geothermal resource potential was not estimated because of a scarcity of available data for sandstones of these ages.

Downing and Gray (1986) estimated the Identified Geothermal Resource in the Sherwood Sandstone Group across Northern Ireland, at temperatures greater than 20°C, as about 523 Mtce (million tonnes of coal equivalent), a figure that would be equivalent to 2.5 billion barrels of oil, or approximately half the size of the largest UK offshore oil field. Only a small percentage of this resource could be extracted but, nonetheless, this is significant in terms of Northern Ireland's energy needs. This conservative estimate was based on very limited data and subsequent downhole measurements should allow more accurate estimates to be made.

In their 2005 study CSA Ltd. modelled temperatures at depths of 2500 metres and 5000 metres, based on data available from the GSNI archives, supplemented by new temperature measurements made in the few deep boreholes still accessible at that time. Although globally a small number of geothermal energy projects have drilled to depths of 4000 – 5000m these are typically EGS (Engineered Geothermal Systems) which often involve the hydraulic fracturing of hot crystalline rocks. For practical purposes the modelled temperatures at 2500m are more relevant to the exploitation of deep geothermal aquifers in Northern Ireland and these show a range from 65°C to 90°C for the Rathlin, Larne and Lough Neagh basins, all of which would be suitable for direct heating applications. The lower figures for the Larne and Lough Neagh basins probably reflect the unequilibrated Bottom Hole Temperatures (BHTs)[1] that they are based on and the actual formation temperatures should be higher than that. Some of the difference between these basins and the Rathlin Basin may be real, however, and may reflect differences in the basement/lower crustal rocks and depths to the Moho/crustal thickness below the basins.

Where wells are re-entered months or even years after they were drilled the temperature measurements made then are closer to the actual 'undisturbed' formation temperatures. In June

[1] BHTs are usually lower than the actual formation temperature because there is still some residual cooling from the circulation of the drilling mud at the time of measurement.

2008 the Ballinlea No. 1 exploration well in the Rathlin Basin recorded a BHT of 95^{0}C from a depth of approximately 2650 metres, confirming earlier data from the Port More borehole that this had the highest geothermal gradient of the sedimentary basins in Northern Ireland. The hole was re-entered in March 2009 and a slightly higher temperature of 97.8^{0}C was recorded at a depth of 2565 metres, although this was probably still slightly lower than the 'true' formation temperature. When further geophysical logging was carried out in 2015 the temperature log indicated that the equilibrium formation temperature would be about 100^{0}C at 2500 metres, a geothermal gradient of 36^{0}C/km.[2]

In 2009 – 2010 GSNI commissioned a research programme, with funding from the Northern Ireland Innovation Fund, looking at the geothermal potential of the northern part of the Lough Neagh sedimentary basin. Magnetotelluric (MT) and gravity surveys were carried out and existing seismic survey data were re-processed. Integrated modelling of these data provides new insights into the deep geological structure of this part of the sedimentary basin and allows Hot Sedimentary Aquifers to be mapped. The area around Antrim is considered to be an attractive target where the Permo-Triassic sandstones may be buried deeply enough to provide at least a direct heating resource. Drilling of the Permian and Triassic sandstones at Kilroot produced core samples which have been analysed for their reservoir quality and their thermal properties which will improve the modelling of the resource potential elsewhere in the Larne, Lough Neagh and Rathlin sedimentary basins. The IRETHERM research project into the deep geothermal resource potential throughout the island has built on the results from the GSNI programme and included MT surveys in the Rathlin Basin.

3. Geothermal gradients and heat flow in Northern Ireland

For the UK as a whole, heat flux and geothermal gradients are relatively low for hot sedimentary aquifers. Information given by Wheildon and Rollin (1986) suggests an average gradient of 26°C/km to depths of about 4 km. However, exceptions may occur in areas where thermally conductive geological formations (e.g. Permo-Triassic sandstones) are overlain by formations of lower thermal conductivity (e.g. Mercia Mudstone). For example, measurements from boreholes drilled to about 1700m depth in the Southampton area indicated thermal gradients of 38°C/km. Burley et al (1984) listed temperature data available for Northern Ireland - temperature gradients and heat flow calculations are generally at the upper end of the range found in Permo-Triassic basins elsewhere in the UK, although values from the Rathlin Basin appear slightly higher, at about 34°C/km.

Temperature measurements in boreholes are acquired in a number of different ways from NI wells (Bottom-hole temperatures, estimated temperatures, log temperatures, drill stem tests and equilibrium tests). Temperatures from equilibrium logs and drill stem tests are preferred for use in geothermal gradient calculations because they most closely match the undisturbed formation temperatures. However, in most cases only bottom hole temperatures obtained during geophysical logging runs are available and these can be influenced by the temperature of the previously circulated drilling mud. At shallow depths the measured temperature may be too high and, at greater depths, too low. Where there are several geophysical log runs the bottom-hole temperatures are plotted against the time since mud circulation stopped to derive an estimation of the equilibrium temperature (e.g. Barelli and Palama, 1981). The measured temperatures are also affected by surrounding topography and the residual cooling effects from the last glaciation. Topographic effects are generally small given the subdued topography surrounding the locations of most deep boreholes

[2] A permanent cement plug in the deepest part of the well meant that the 2015 temperature measurements only went down to about 2250 metres. The calculated geothermal gradient assumes a surface temperature of 10^{o}C. No corrections have been applied for residual cooling of the subsurface as a result of the last glaciation as these effects are thought to be relatively small at depths greater than 1500 metres.

in Northern Ireland but the corrections to account for the palaeoclimatic effects can be significant particularly for temperatures recorded in the top 1000 metres or so. There are standard methods to take account for these effects (e.g. Westaway and Younger, 2013) but these corrections have not routinely been applied to the NI temperature data.

The sedimentary rocks of Northern Ireland are thickest in a series of basins that formed during the Permo-Triassic. These basins have geothermal gradients that are high enough to indicate geothermal reservoirs are likely to be present at the required temperature for direct heat between 2-3km. Temperatures in excess of 100°C with potential for combined heat and power generation are more likely to be found in the Rathlin Basin which has a higher geothermal gradient.

4. Review of sandstone reservoir quality in Northern Ireland

The sandstone reservoirs in the most prospective parts of Northern Ireland for geothermal resources are the Triassic Sherwood Sandstone Group, upper Permian sandstones, lower Permian sandstones and Carboniferous sandstones. Our knowledge of the Sherwood Sandstone Group is most extensive because, although rock outcrops are restricted in Northern Ireland, it is a prolific shallow aquifer in the Lagan Valley and it has been encountered in many wells. Permian and Carboniferous rocks are less well known because they generally lie at greater depths, but they have the potential to contain aquifers at higher temperatures. A list of the most significant wells and boreholes in NI that have encountered these units is outlined in the table below.

Where the complete unit has been drilled the Sherwood Sandstone Group typically ranges from about 150 metres to 500 metres thick, with the greater thicknesses proved in boreholes from the deeper parts of the sedimentary basins. It should be noted that several of these boreholes were drilled as oil exploration wells and, as such, were located on structural highs.

Upper Permian sandstones are known only from the Lough Neagh Basin where they attain gross thicknesses of 66 – 178 m in three boreholes north of Lough Neagh. The early Permian Enler Group can reach thicknesses of over 500 metres in the Larne – Lough Neagh basins but contains non-reservoir facies conglomerates and breccias as well as sandstone units of variable reservoir quality.

Over 300 m of Carboniferous sandstones have been proved in deep boreholes from the Rathlin and Foyle basins and slightly thinner sequences in boreholes towards the western margins of the Lough Neagh Basin. In the deeper parts of the Lough Neagh and Larne basins boreholes have not penetrated Carboniferous strata.

WELL NAME	TD(m)	System at TD	Basin	Top Sherwood Sandstone Group	Base Sherwood Sandstone Group	SSG Thickness	Top U Perm sands above Mag Lst	Base U Perm Sands	UPS (upper) thickness	Top U Perm sands (under Mag Lst)	Base Upper Permian Sands	UPS (lower) thickness	Top Lower Perm	Base Lower Perm	L Perm thickness	Top Carb Sands	Base Carb Sands	Carboniferous sst unit thickness	Top Carb Sands	Base Carb Sands	Carboniferous sst unit thickness	Core analysis
Magilligan	1347	Lower - Upper Carboniferous	Foyle	581	990	409	x	x	0	x	x	0	x	x	0	990	1347	357	990	1347	357	YES
Ballinlea No.1	2684	Lower Carboniferous	Rathlin	1620	1848	228	x	x	0	x	x	0	x	x	0	2234	2621	387	2234	2621	387	
Port More	1897	early Permian	Rathlin	1317	1830	513	x	x	0	x	x	0	1845	1897	52							YES
Cross	439	Lower Carboniferous	Rathlin													8	247	239	8	247	239	
Ballymacilroy	2272	early Permian	Lough Neagh	1447	1868	421	1901	1967	66	1984	1995	12	1995	2191	196							YES
Annaghmore	1554	early Permian?	Lough Neagh	497	870	373	870	995	125	1012	1032	20	1032	1554	523							YES
Ballynamullan	1372	early Permian	Lough Neagh	700	1109	409	1109	1288	178	1317	1347	30	1347	1478	131							
Ballyloughan Bridge	556	Lower Carboniferous	Lough Neagh	0	249	249	x	x	0	x	x	0	249	319	70	319	551	232	319	551	232	YES
Edendork No. 2	364	Lower - Upper Carboniferous	Lough Neagh													3	295	292	3	295	292	
Palm Lodge No. 2	274	Lower - Upper Carboniferous	Lough Neagh													31	247	216	31	247	216	YES
Lough Nacrilly No. 4	203	Lower - Upper Carboniferous	Lough Neagh	10	86	76	x	x	0	x	x	0	x	x	0	86	162	76	86	162	76	
Elm Bush	329	Lower - Upper Carboniferous	Lough Neagh	14	113	99	x	x	0	x	x	0	x	x	0	171	291	120	171	291	120	
Brackaville	340	Lower - Upper Carboniferous	Lough Neagh													147	340	193	147	340	193	YES
Coalisland Brickpit	305	Lower - Upper Carboniferous	Lough Neagh													33	279	246	33	279	246	YES
Twyford's Mill	499	Lower Carboniferous	Lough Neagh	34	322	288	x	x	0	x	x	0	x	x	0	x	x	0	x	x	0	YES
Mire House	1231	early Triassic	Lough Neagh	1074	1231	156																
Dernagh No. 1	738	early Triassic	Lough Neagh	649	738	89																
Dernagh No. 2	940	Upper Carboniferous	Lough Neagh	597	885	287	x	x	0	x	x	0	x	x	0	931	939	9	931	939	9	
Kingsmill	377	Lower Carboniferous	Lough Neagh	8	223	214	x	x	0	343	347	4	x	x	0	x	x	0	x	x	0	YES
Soarn House	159	Lower Carboniferous	Lough Neagh							93	99	6	x	x	0	x	x	0	x	x	0	
Ballytrea	611	Lower Carboniferous	Lough Neagh	6	177	171	x	x	0	298	306	8	x	x	0	x	x	0	x	x	0	YES
Mullaghglass	759	Lower - Upper Carboniferous	Lough Neagh	183	568	385	x	x	0	731	731	0	x	x	0	x	x	0	x	x	0	
Templereagh	155	Upper Carboniferous	Lough Neagh							82	83	1	x	x	0	83	155	72	83	155	72	YES
Killary Glebe	1159	Lower - Upper Carboniferous	Lough Neagh	626	898	272	x	x	0	x	x	0	x	x	0	1040	1122	82	1040	1122	82	
Wilson's Bridge 6	142	Lower Carboniferous	Lough Neagh													81	142	61	81	142	61	
Wilson's Bridge 2	130	Lower Carboniferous	Lough Neagh													87	130	42	87	130	42	
Wilson's Bridge 5	185	Lower Carboniferous	Lough Neagh													149	185	36	149	185	36	
Wilson's Bridge 3	359	Lower Carboniferous	Lough Neagh													46	163	117	46	163	117	
Wilson's Bridge 4	111	Lower Carboniferous	Lough Neagh													62	111	49	62	111	49	
Langford Lodge	1452	Lower Palaeozoic	Lough Neagh	1143	1416	273	x	x	0	x	x	0	1416	1453	36	x	x	0	x	x	0	YES
Englishtown	107	early Triassic	Larne	26	107	81																YES
Long Kesh	91	Lower Palaeozoic	Larne	13	32	19	x	x	0	x	x	0	x	x	0	x	x	0	x	x	0	
Ballytober	1282	early Permian	Larne	565	879	314	x	x	0	975	984	9	984	1282	298							
Cairncastle 2	667	early Triassic	Larne	630	667	38																YES
Larne No. 1	1284	early Triassic	Larne	1075	1284	208																YES
Larne No. 2	2880	early Permian	Larne	968	1616	648	x	x	0	x	x	0	1823	2264	441							YES
Islandmagee	1760	late Permian	Larne	631	1257	626	x	x	0	x	x	0										
Newmill	1981	early Permian	Larne	695	1562	867	x	x	0	x	x	0	1573	1632	59							YES
Ballynure	1598	early Permian	Larne	1003	1352	349	x	x	0	x	x	0	1518	1598	80							
Woodburn Forest	2000	early Permian	Larne	586	1129	543	x	x	0	x	x	0	1203	1790	587							
Kilroot GT1	868	early Permian	Larne	255	804	549	x	x	0	x	x	0	804	868	64							YES
Avoniel	181	early Permian	Larne	16	35	19	x	x	0	x	x	0	139	162	24							YES
Belfast Harbour	522	Lower Carboniferous	Larne	32	190	158	x	x	0	x	x	0	x	x	0	x	x	0	x	x	0	
Kennel Bridge	69	Lower Palaeozoic	Newtownards										15	67	52	x	x	0	x	x	0	YES
Ballyalton No. 3	553	Lower Palaeozoic	Newtownards	7	219	212	x	x	0	x	x	0	x	x	0	x	x	0	x	x	0	
Haw Hill	183	early Permian	Newtownards	26	66	40	x	x	0	x	x	0	x	x	0							YES

WELL_NAME	TD(m)	System at TD	Basin	Top Sherwood Sandstone Group	Base Sherwood Sandstone Group	Sherwood Sandstone Group thickness	Top U Perm sands above Mag Lst	Base U Perm Sands	Thickness U Perm sands (upper)	Top U Perm sands (under Mag Lst)	Base Upper Permian Sands	Thickness U Perm sands (lower)	Top Lower Perm	Base Lower Perm	L Perm thickness	Top Carb Sands	Base Carb Sands	Carboniferous sst unit thickness	Top Carb Sands	Base Carb Sands	Carboniferous sst unit thickness	Core analysis
Magilligan	1347	Lower - Upper Carboniferous	Foyle	581	990	409	x	x	0	x	x	0	x	x	0	990	1347	357	990	1347	357	YES
Ballinlea No.1	2684	Lower Carboniferous	Rathlin	1620	1848	228	x	x	0	x	x	0	x	x	0	2234	2621	387	2234	2621	387	
Port More	1897	early Permian	Rathlin	1317	1830	513	x	x	0	x	x	0	1845	1897	52							YES
Cross	439	Lower Carboniferous	Rathlin													8	247	239	8	247	239	
Ballymacilroy	2272	early Permian	Lough Neagh	1447	1868	421	1901	1967	66	1984	1995	12	1995	2191	196							YES
Annaghmore	1554	early Permian?	Lough Neagh	497	870	373	870	995	125	1012	1032	20	1032	1554	523							YES
Ballynamullan	1372	early Permian	Lough Neagh	700	1109	409	1109	1288	178	1317	1347	30	1347	1478	131							
Ballyloughan Bridge	556	Lower Carboniferous	Lough Neagh	0	249	249	x	x	0	x	x	0	249	319	70	319	551	232	319	551	232	YES
Edendork No. 2	364	Lower - Upper Carboniferous	Lough Neagh													3	295	292	3	295	292	
Palm Lodge No. 2	274	Lower - Upper Carboniferous	Lough Neagh													31	247	216	31	247	216	YES
Lough Nacrilly No. 4	203	Lower - Upper Carboniferous	Lough Neagh	10	86	76	x	x	0	x	x	0	x	x	0	86	162	76	86	162	76	
Elm Bush	329	Lower - Upper Carboniferous	Lough Neagh	14	113	99	x	x	0	x	x	0	x	x	0	171	291	120	171	291	120	
Brackaville	340	Lower - Upper Carboniferous	Lough Neagh													147	340	193	147	340	193	YES
Coallsland Brickpit	305	Lower - Upper Carboniferous	Lough Neagh													33	279	246	33	279	246	YES
Twyford's Mill	499	Lower Carboniferous	Lough Neagh	34	322	288	x	x	0	x	x	0	x	x	0	x	x	0	x	x	0	YES
Mire House	1231	early Triassic	Lough Neagh	1074	1231	156																
Dernagh No. 1	738	early Triassic	Lough Neagh	649	738	89																
Dernagh No. 2	940	Upper Carboniferous	Lough Neagh	597	885	287	x	x	0	x	x	0	x	x	0	931	939	9	931	939	9	
Kingsmill	377	Lower Carboniferous	Lough Neagh	8	223	214	x	x	0	343	347	4	x	x	0	x	x	0	x	x	0	YES
Soarn House	159	Lower Carboniferous	Lough Neagh							93	99	6	x	x	0	x	x	0	x	x	0	
Ballytrea	611	Lower Carboniferous	Lough Neagh	6	177	171	x	x	0	298	306	8	x	x	0	x	x	0	x	x	0	YES
Mullaghglass	759	Lower - Upper Carboniferous	Lough Neagh	183	568	385	x	x	0	731	731	0	x	x	0	x	x	0	x	x	0	
Templereagh	155	Upper Carboniferous	Lough Neagh							82	83	1	x	x	0	83	155	72	83	155	72	YES
Killary Glebe	1159	Lower - Upper Carboniferous	Lough Neagh	626	898	272	x	x	0	x	x	0	x	x	0	1040	1122	82	1040	1122	82	
Wilson's Bridge 6	142	Lower Carboniferous	Lough Neagh													81	142	61	81	142	61	
Wilson's Bridge 2	130	Lower Carboniferous	Lough Neagh													87	130	42	87	130	42	
Wilson's Bridge 5	185	Lower Carboniferous	Lough Neagh													149	185	36	149	185	36	
Wilson's Bridge 3	359	Lower Carboniferous	Lough Neagh													46	163	117	46	163	117	
Wilson's Bridge 4	111	Lower Carboniferous	Lough Neagh													62	111	49	62	111	49	
Langford Lodge	1452	Lower Palaeozoic	Lough Neagh	1143	1416	273	x	x	0	x	x	0	1416	1453	36	x	x	0	x	x	0	YES
Englishtown	107	early Triassic	Larne	26	107	81																YES
Long Kesh	91	Lower Palaeozoic	Larne	13	32	19	x	x	0	x	x	0	x	x	0	x	x	0	x	x	0	
Ballytober	1282	early Permian	Larne	565	879	314	x	x	0	975	984	9	984	1282	298							
Cairncastle 2	667	early Triassic	Larne	630	667	38																YES
Larne No. 1	1284	early Triassic	Larne	1075	1284	208																YES
Larne No. 2	2880	early Permian	Larne	968	1616	648	x	x	0	x	x	0	1823	2264	441							YES
Islandmagee	1760	late Permian	Larne	631	1257	626	x	x	0	x	x	0										
Newmill	1981	early Permian	Larne	695	1562	867	x	x	0	x	x	0	1573	1632	59							YES
Ballynure	1598	early Permian	Larne	1003	1352	349	x	x	0	x	x	0	1518	1598	80							
Woodburn Forest	2000	early Permian	Larne	586	1129	543	x	x	0	x	x	0	1203	1790	587							
Kilroot GT1	868	early Permian	Larne	255	804	549	x	x	0	x	x	0	804	868	64							YES
Avoniel	181	early Permian	Larne	16	35	19	x	x	0	x	x	0	139	162	24							YES
Belfast Harbour	522	Lower Carboniferous	Larne	32	190	158	x	x	0	x	x	0	x	x	0	x	x	0	x	x	0	
Kennel Bridge	69	Lower Palaeozoic	Newtownards										15	67	52	x	x	0	x	x	0	YES
Ballyalton No. 3	553	Lower Palaeozoic	Newtownards	7	219	212	x	x	0	x	x	0	x	x	0	x	x	0	x	x	0	
Haw Hill	183	early Permian	Newtownards	26	66	40	x	x	0	x	x	0	x	x	0							YES

Table 1. Details of relevant wells that have encountered Triassic, Permian or Carboniferous sandstones. The top and base depths of these units are given. Yellow highlighted boxes indicate where there is some reservoir quality data available. The x indicates that the unit is absent in this well. Grey shading = not penetrated. Some wells do not penetrate the full thickness of a reservoir unit, so the thickness in the table may be less than the total thickness

4.1. Carboniferous reservoirs

There is very little direct information about the distribution and properties of Carboniferous sandstones at depth in the Rathlin/Foyle, Larne and Lough Neagh basins. These rocks crop out around the margins of the basins, but are yet to be proven by drilling in the deeper parts of the Larne and Lough Neagh basins. Their presence under the deeper parts of the sedimentary basins can be inferred from the interpretation of seismic reflection and other geophysical data, and is predicted from regional geological models. It is likely that there will be a thicker and more complete sedimentary succession in the basin depocentres than there is at the basin margin outcrops because of differing amounts of uplift and subsidence between the flanks and central parts of the basins. At the end of the Carboniferous the margins of the Lough Neagh Basin were subject to uplift and inversion so that the younger Westphalian strata were eroded from some fault blocks but preserved in others such as the East Tyrone coalfield. Depending on their position within the basin, fault blocks that were subject to inversion at the end of the Carboniferous then became sites of subsidence and deposition during the Permo-Triassic. It is likely that fault blocks within the central parts of the basin did not undergo as much uplift as those on the margins so that a more complete Carboniferous succession should be preserved in the central areas. However, the only direct information about potential Carboniferous reservoirs in the Lough Neagh Basin comes from the outcrops and drilling in marginal areas. By contrast, two deep boreholes in the Rathlin and Foyle basins have penetrated Carboniferous sandstones at depth and deep geothermal reservoirs of this age could be more widespread at depth.

Carboniferous sandstones are present in the Lough Allen Basin and Slieve Beagh Basin in Fermanagh, but they are interpreted to have little potential as geothermal reservoirs. Thin section studies show that the sandstones are well cemented and have suffered from burial compaction which has greatly reduced the porosity and permeability. Carboniferous sandstones record porosities generally less than 2% and rarely up to 8%, with permeabilities usually less than 0.1mD and rarely up to 1mD recorded (e.g. SCAL, 1997). Some of the hydrocarbon exploration wells in Fermanagh did experience a flow of water into the borehole from the 'Basal Clastics' (a series of sandstones that are Devonian to Early Carboniferous in age). Porosities are generally low, but water flows (23,000 litres/day estimated at McNean No. 1; 11,500 litres/day estimated at Big Dog No. 1) show that some limited reservoir potential exists. In deeper, more definitively Devonian rocks in Glenoo No. 1, water flowed from 6885' at 7,500 -190,000 litres/day and from 6907' at 115,000 litres/day (Marathon, 1966). Seibt et al. (2005) note that flowrates of about 1 million litres/day would usually be needed from a larger diameter hydrogeothermal production well.

The Carboniferous within the Larne and Lough Neagh basins crops out to the south and west of Lough Neagh (Armagh and east County Tyrone), in an isolated small outcrop on the Belfast Lough foreshore at Craigavad and a small outlier of limestone at Castle Espie (County Down) on Strangford Lough (Figures 2 and 3). The Tournaisian-aged Holywood Group comprises the lower Craigavad Sandstone Formation (140 m thick) and the overlying Ballycultra Formation (140 m thick). In Co. Down, only the Early Carboniferous is present, represented by the Holywood Group and the Strangford Group (Courceyan clastics and Brigantian carbonates). The Craigavad Sandstone Formation has received relatively little attention. The rocks are unconformably overlain by a condensed Permian succession and it is likely that there has been a significant amount of erosion of younger Carboniferous strata which may still be preserved at depth in the Larne Basin to the north but to date no boreholes have penetrated strata below the Permian.

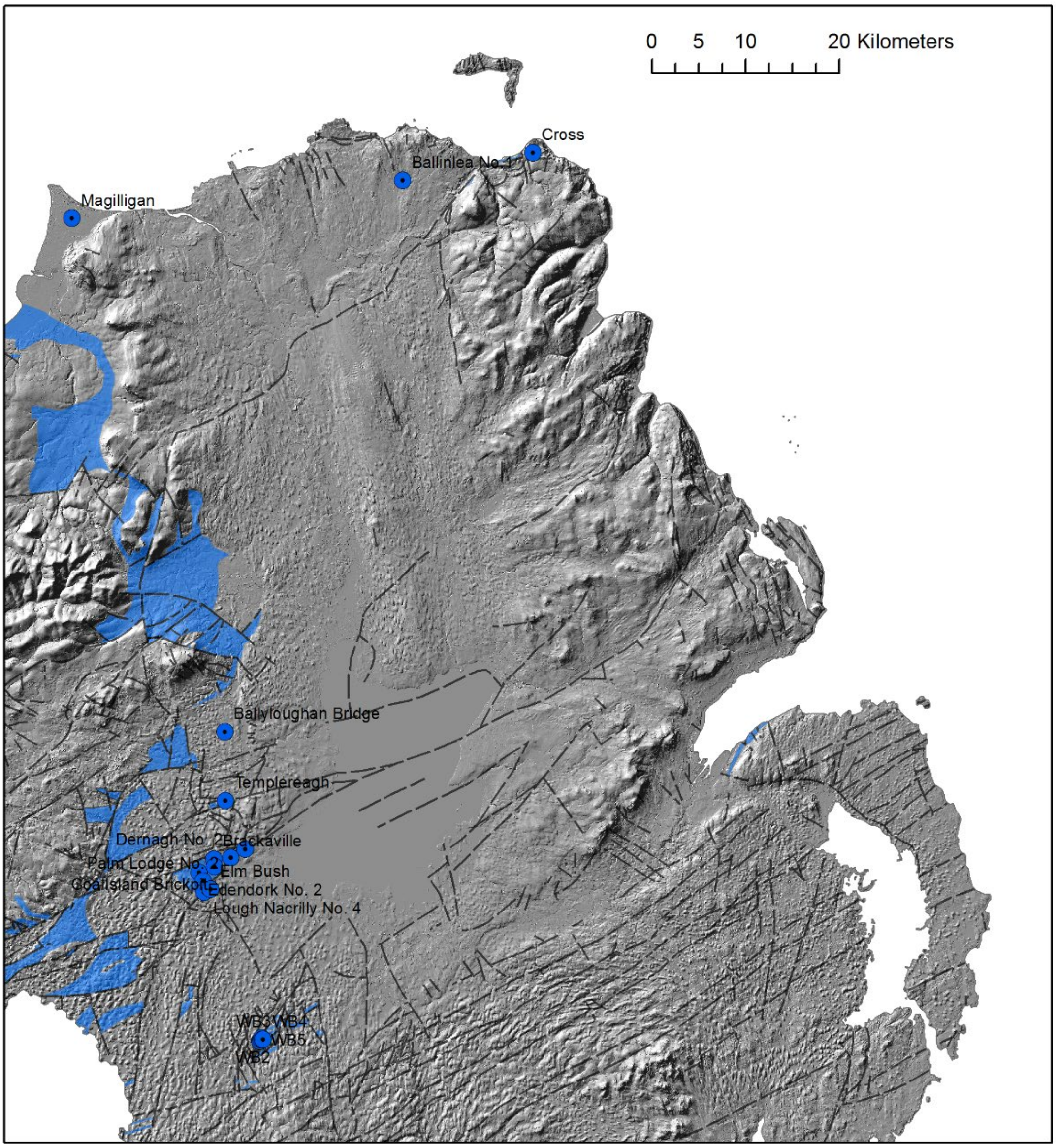

Figure 2 Distribution of Carboniferous sandstone units at outcrop (blue) with boreholes that penetrate those units from Table 1. Black dashed lines indicate faults. Grey background is shaded relief image.

The stratigraphy of the west part of the Lough Neagh Basin can be divided into five groups - the Tyrone Group, the Armagh Group, the Leitrim Group, 'Millstone Grit' Group and the 'Coal Measures' Group (Figure 3 and Mitchell, 2004). The upper (younger) three groups are not represented in the area around Armagh to the south. In the deeper parts of the basin, around and beneath the present day lough, the Carboniferous has not been penetrated, but it is likely that a more complete succession is preserved here including Westphalian rocks and more organic-rich rocks of the Leitrim Group.

The Co. Tyrone and Co. Armagh successions are separated by the Clogher Valley Fault (a southwest extension of the Sixmilewater Fault). The two successions are markedly different and the Co. Armagh succession includes strata placed in both the Tyrone Group and the Armagh Group. Northeast of Armagh, on the margin of what became the Lough Neagh Basin, the upper parts of the Tyrone Group contain a sandstone unit called the Drumman More Sandstone Formation. The sandstone is present at outcrop, but is also proved in the Wilson Bridge boreholes. It comprises up to 117 m of unfossiliferous, red and brown, non-calcareous and micaceous, medium-grained sandstones, interbedded with variegated red, purple, green and yellow mudstones. Near the base are bioturbated sandstones and thin skeletal limestones with calcareous sandstones. Other sandstones are recorded in the older Milford Mills Formation (33 m) and the Retreat Siltstone Formation (75-90 m) but these have not been assessed for reservoir quality.

The Tyrone Group in east Co. Tyrone includes the Ballyness Formation (conglomerates and sandstones) and the Clogher Valley Formation (mudstone and limestone). These are then overlain by a number of limestone units thought to be the equivalent of the Ballyshannon Limestone Formation, with a number of mapped sandstone units collectively called the Carland Sandstone Member. Further southwest towards Benburb the upper parts of the Tyrone Group are exposed and include the Maydown Limestone Formation, Blackstokes Limestone Formation, the Carrickaness Sandstone Formation and the Blackwater Limestone Formation.

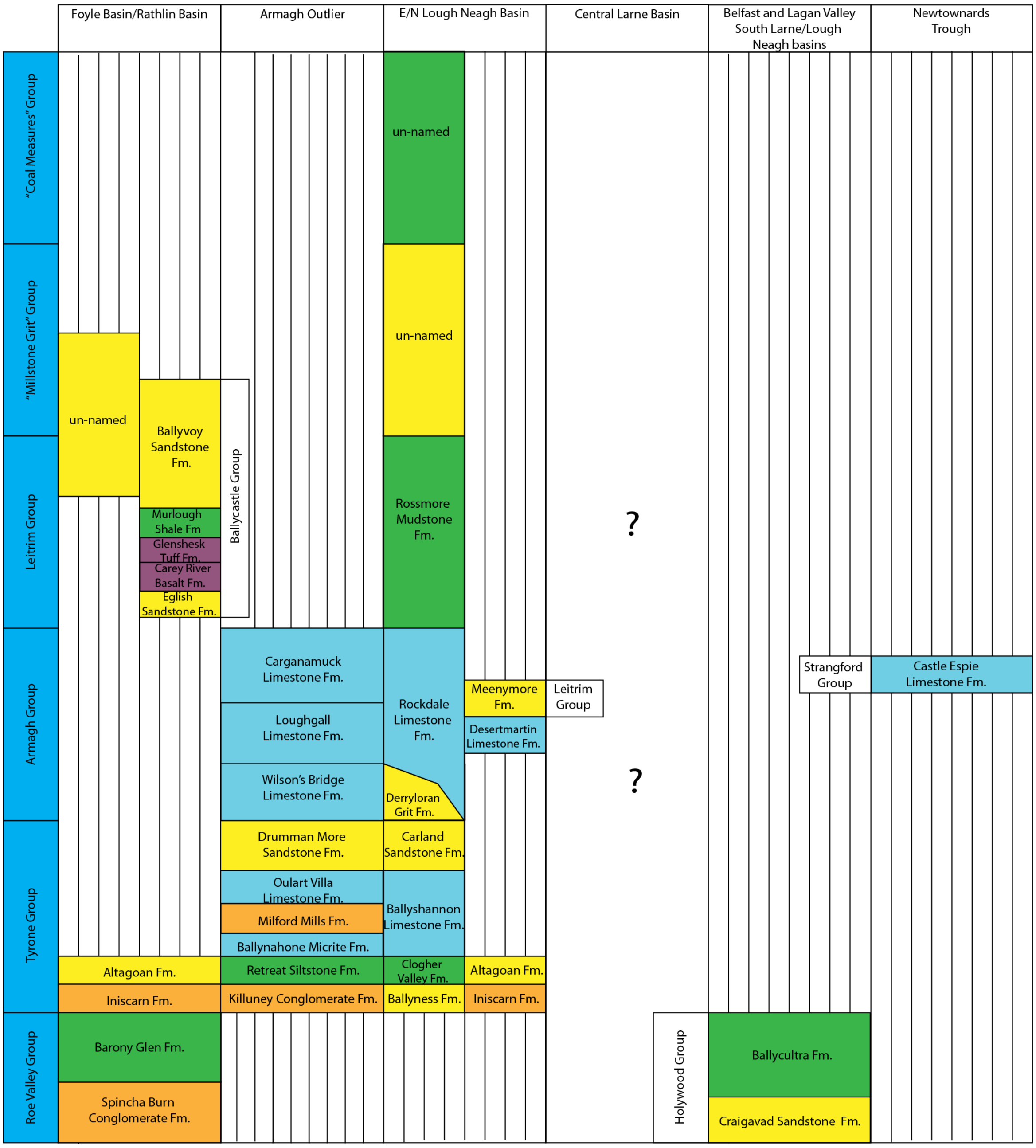

Figure 3. Lithostratigraphy of the Carboniferous rocks in the Rathlin, Lough Neagh and Larne basins. Sandstone-prone units (potential reservoirs) are shown in yellow (modified after GSNI, 1997 and Mitchell, 2004)

In the area around Cookstown, in east Co. Tyrone, sedimentation appears to have started with the Armagh Group and the oldest rocks are coarse clastic sediments. The base of the Armagh Group comprises the Derryloran Grit Formation of channel sandstones and fossiliferous marine sandstones. The overlying Rockdale Limestone Formation is Asbian and possibly Brigantian in age and, with at least part of the Derryloran Formation, in taken to be equivalent to the Desertmartin Limestone Formation. Pre-Asbian sediments in the Cookstown area were either not deposited or more probably were removed by erosion prior to the deposition of the Derryloran and Rockdale Limestone Formation (Figure 4). The Armagh Group rests on the Ordovician age Tyrone Plutonic Group. The overlying Leitrim Group comprises the Rossmore Mudstone Formation and this is overlain by sandstones, coals and mudstones of the “Millstone Grit Group” and then by mudstones, siltstones and coals of the “Coal Measures Group”.

A different stratigraphic succession is noted to the north in the area around Draperstown. This has the older Tyrone Group resting unconformably on the Slieve Gallion Granite. The succession is represented by the Iniscarn (basal breccias) and Altagoan formations (sandstone and siltstone).

On the northwest side of the southward extension of the Tow Valley Fault the Roe Valley Group represents an older succession of basal breccias and overlying mudstone, siltstone and sandstone passing upward into mudstone and limestones. The main Carboniferous reservoirs from the Rathlin Basin are the Ballyvoy Sandstone (Ballycastle Group), which is an age equivalent of the Leitrim Group and part of the “Millstone Grit” Group. This is exposed at outcrop, and proven in a series of shallow coal exploration boreholes, in the Ballycastle coalfield, and penetrated near Armoy in the Rathlin Basin by the Ballinlea No. 1 exploration well.

The Eglish Sandstone at the base of the Ballycastle Group comprises pebbly sandstones. In the Foyle Basin, only one borehole (Magilligan) penetrates the Carboniferous. There are a sequence of sandstones that are un-named, but probably equivalents of the Ballyvoy Sandstone based on their age, and have good reservoir quality in this borehole.

4.2. Permian reservoirs

The Lithostratigraphy of the Permian strata in Northern Ireland comprises a twofold division into the Enler Group (Early Permian) and Belfast Group (Late Permian), with the former generally characterised by coarser clastic lithologies and the latter by a calcareous unit ('Magnesian Limestone') overlain by finer-grained clastic rocks with evaporites (although basal breccias may occur in both groups).

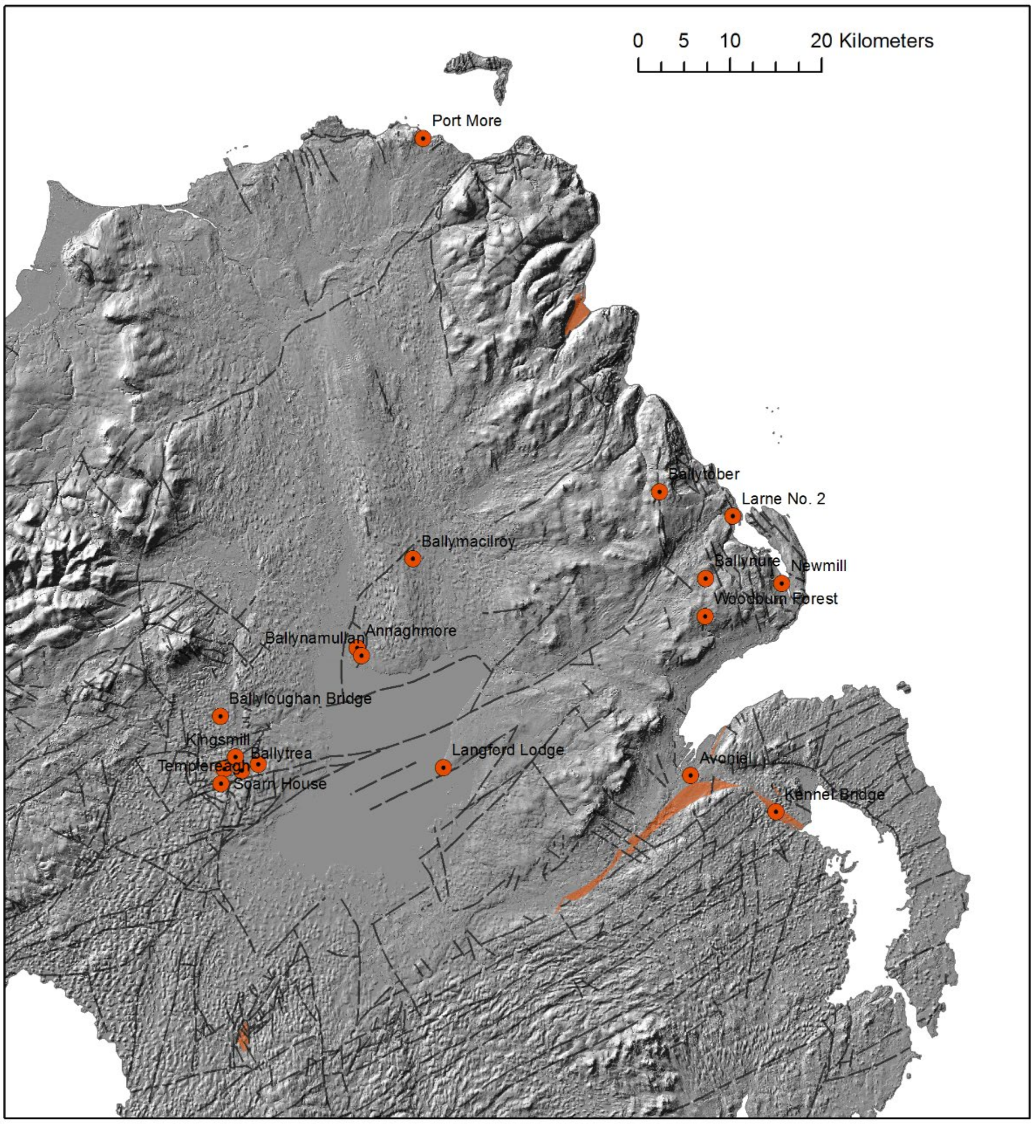

Figure 4. Distribution of Permian sandstones at outcrop and boreholes that have penetrated these sandstones. Note the very limited areas of outcrop.

Our knowledge of the Permian in Northern Ireland is hindered by the fact that there are very limited outcrops of these rocks. Only three localities contain unambiguous Permian rocks. The best locality is at Cultra on the foreshore of Belfast Lough, with other records of Permian rocks at small outliers at Armagh and a small fault section at Grange (which is no longer accessible). Apart from this, Permian rocks are available only as core samples or drill cuttings from a relatively small number of boreholes. The strata, with the exception of the Magnesian Limestone, are generally non-fossiliferous although palynology can be used to gain some insight into their relative ages and help to correlate the sequences from different boreholes (Warrington, 1995).

Around Armagh, the Permian is exposed, but only the basal sandstones are seen. They are superficially similar to the Sherwood Sandstone Group, but a carbonate was found in boreholes and represents the Magnesium Limestone, thereby placing the lower part of the Dobbin Formation and the underlying Drumarg Conglomerate Formation (purple-red bedded conglomerates and coarse grained sandstones) into the Enler Group.

However, Permian rocks are recorded in most of the deepest boreholes drilled through the basalts and older strata, although the succession is variable and the boreholes are widely spaced, resulting in a number of different local lithostratigraphical names for what may be the same, or equivalent, rock units (see Figure 5).

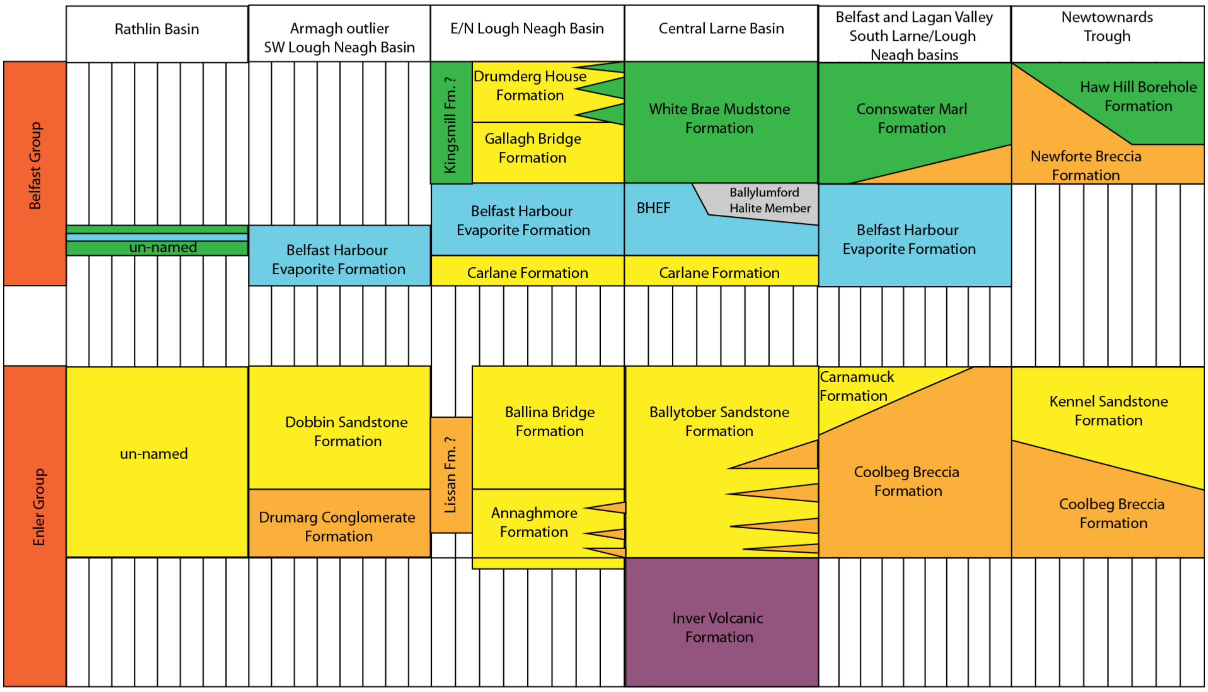

Figure 5 Lithostratigraphy of the Permian strata of Northern Ireland. Sandstone units in yellow.

The southern part of the Larne and Lough Neagh basins represents a margin along the Lower Palaeozoic Down-Longford Massif. Thicknesses are fairly consistent and in all the boreholes drilled in Belfast and the Lagan Valley there is a consistent stratigraphy. Where it rests unconformably on Lower Palaeozoic greywackes the Permo-Triassic is represented by a basal breccia or conglomerate (Coolbeg Breccia Formation or equivalent) which is up to 20m thick in the Avoniel borehole. The upper part of the Enler Group is represented by the Carnamuck Formation, with up to 45 m of brown sandstones recorded in boreholes.

The overlying Belfast Harbour Evaporite Formation (BHEF) is a carbonate and evaporite succession that is around 23 m thick. The carbonates mark the marine transgression during the Late Permian of a western extension of the Zechstein Sea known as the Bakevillia Sea. Sedimentation then returned to terrestrial deposition and in the Lagan Valley mudrocks (Connswater Marl Formation) were deposited, with up to 77 m thick recorded.

In the Larne No. 2 borehole, in the main part of the Larne Basin, the lower part of the Enler Group comprises at least 554 m of volcanic lavas, tuffs and siltstones of the Inver Volcanic Formation. The basaltic lavas have not been recorded elsewhere but variegated tuffs and tuffaceous siltstones are found in a number of deep boreholes in the Larne area. Where present the Inver Volcanic Formation is overlain by a series of sandstones of the Ballytober Sandstone Formation. Thick sandstones were encountered in Annaghmore (523 m), Ballynamullan (131 m), Ballytober (298 m) and Larne No. 2 (441 m) beneath the BHEF, but southwards towards the Down-Longford Massif these sandstones tend to thin and are replaced by breccias of the Coolbeg Breccia Formation (as observed in Newmill No. 1 where only 60 m of early Permian sandstones were penetrated above breccias and conglomerates), indicating proximity to the margin of the sedimentary basin.

The drilling of Ballynamullan and Annaghmore, north of Lough Neagh, proved a thick succession of Permian rocks with thick terrestrial sandstones below the "Magnesian Limestone" (part of the BHEF) represented by a lower Annaghmore Formation and an upper Ballina Bridge Formation. The two units are quite distinct and it is possible that the former is of Carboniferous age but no age-diagnostic flora or fauna have been retrieved from the cuttings samples. A thin sandstone that overlies these unit, called the Carlane Formation, is better placed in the Belfast Group because it appears to be a transgressive deposit from marine reworking of sandy material. This unit can be recognised in a number of the boreholes. Above the Belfast Harbour Evaporite Formation lie the Gallagh Bridge Formation and the Drumarg House Formation, two sandstone-rich units, in a departure from the more usual fine-grained mudstones of the Belfast Group.

The sandstones in the Ballyloughan Bridge borehole, in east Co. Tyrone, were previously all placed in the Triassic Sherwood Sandstone Group but may include Carboniferous or Permian at the base, and parts of the Lissan Formation are provisionally placed into the Permian pending Apatite Fission Track Analysis work being carried out by Trinity College Dublin.

In the Larne Basin seven deep boreholes penetrate rocks of Permian age, although none of these have penetrated the full Permian succession or reached older rocks. However, boreholes in the area around Larne have proved some of the greatest thicknesses of Permian rocks found so far in Northern Ireland. In Larne No. 2 the Belfast Harbour Evaporite Formation is 141 m thick and includes 113 m of pure halite (salt) towards the top, and is overlain by 66 m of the White Brae Mudstone Formation. The Permian halite appears to be restricted to a small area around Larne and the northern parts of Larne Lough and Islandmagee, although it may also extend into the offshore part of the Larne - North Channel basin system. In Islandmagee No. 1 over 180 m of very pure Permian halite was drilled during exploration to find thick salt suitable for the creation of gas storage caverns. However, in both Ballynure No. 1, 6km SSW of Larne, and Newmill No. 1, 8km SSE of Larne, no Permian halite was found. The 2015 Islandmagee No. 1 well also drilled, by far, the thickest BHEF carbonate and evaporite sequence in Northern Ireland proved to date, with at least 228 m ascribed by the wellsite geologists to this interval compared to the more usual 5 – 20 m found in boreholes elsewhere.

Permian rocks are also present in a fault bounded rift (probably originally an extension of the Larne Basin) called the Newtownards Trough. The Enler Group within the Newtownards Trough comprises a basal breccia (Coolbeg Breccia Formation) up to 247 m thick and overlying sandstone unit the Kennel Sandstone Formation, which is up to 51 m around Comber. The Belfast Group in the Newtownards Trough is represented by a return to deposition of coarse-grained breccias of the Newforte Breccia Formation (53 m thick). This unit passes upwards into the Sherwood Sandstone Group, without any Permian mudrocks, suggesting that at least part of this unit is a lateral equivalent of the Haw Hill Borehole Formation that is present further south in the Newtownards Trough; the maximum thickness recorded is 94 m. A dolomitic interval recorded in the Haw Hill Borehole may represent the Belfast Harbour Evaporite Formation.

4.3. Triassic reservoirs

There are limited outcrops of Triassic rocks in Northern Ireland and even in these areas the actual rock exposures are usually restricted to occasional stream sections. Most of the information about the Triassic succession comes from a relatively small number of deep boreholes which have been drilled in the sedimentary basins (Figure 6).

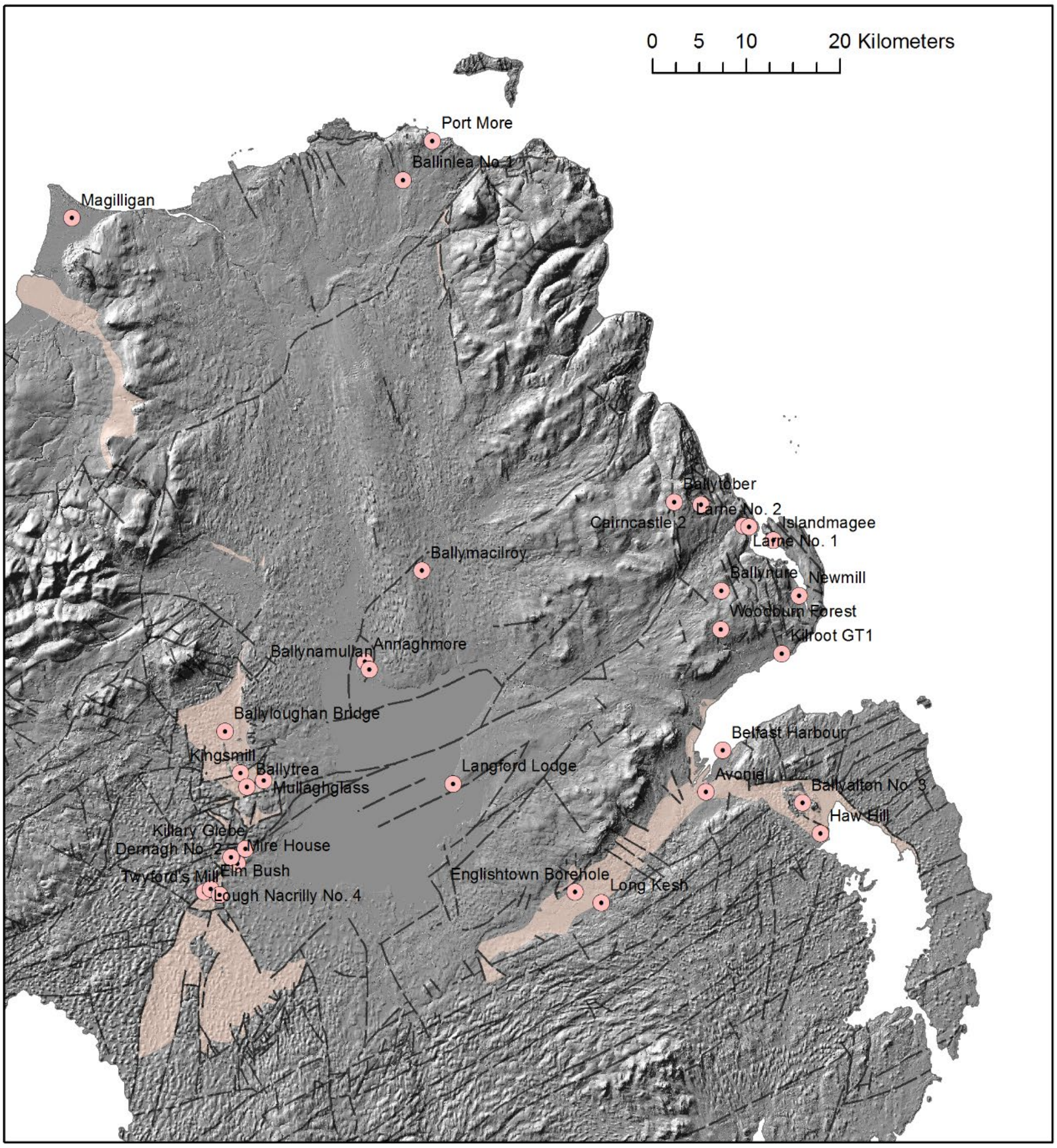

Figure 6. Distribution of the Sherwood Sandstone Group at outcrop and its subsurface occurrence in available boreholes

Little attempt has been made to revise the stratigraphy of the Triassic rocks in the Larne and Lough Neagh basins. There is a clear subdivision into a lower sandstone (Sherwood Sandstone Group), a middle mudrock unit (Mercia Mudstone Group) and a thin upper unit (Penarth Group) of mudstones and siltstones with a marine invertebrate fauna, similar to the rest of the United Kingdom (Warrington, 1995). The Mercia Mudstone Group (MMG) can contain several thick halite (salt) beds and acts as a regional caprock or seal to the underlying sandstone reservoirs. The MMG in Northern Ireland has been subdivided into a number of lithostratigraphical units, based on the Port More Borehole which was cored throughout its depth. These units were subsequently applied to the Larne No 2 borehole and have been found to be fairly consistent, although salt beds of variable thickness – apparently absent in the Rathlin Basin - are present in the Larne Basin. In terms of reservoir quality only the lowest Lagavarra Formation holds any potential as the proportion of sandstone increases downwards.

In the area around the Irish Sea – offshore and onshore - the underlying Sherwood Sandstone Group (SSG) is divisible into two formations – the Ormskirk and St Bees Formations, with the latter subdivided into the Calder and Rottington Sandstone Members (Jackson et al., 1997). In Northern Ireland this subdivision has not been widely recognised although locally different lithological units have been described from the SSG in deep boreholes. For example, Naylor et al. (2003) divided the Sherwood Sandstone Group from the Lough Neagh Basin into an upper Toomebridge Sandstone Formation (226m in Ballynamullan No. 1) and a lower Drumcullen Formation (174m in Annaghmore No. 1). In general, the upper part of the Sherwood Sandstone Group in Northern Ireland is a better quality reservoir than the lower part in which the porosity and permeability may be reduced by quartz cement. Figure 7 illustrates the correlation of the Mercia Mudstone Group and a putative correlation of the local units belonging to the Sherwood sandstone group in Northern Ireland.

The top of the SSG was not penetrated in the Belfast Harbour borehole where Smith, R.A. (1986) recorded 158m of sandstone in an upper Lagan Sandstone Formation and a lower Loughside Formation. In the Rathlin Basin the lower part of the SSG is conglomeratic in the Port More borehole, reflecting the deposition of coarse sediments in alluvial fans and rivers close to the basin margin.

Ballyloughan Bridge, west of Lough Neagh, contains an unresolved unit provisionally placed in the Sherwood Sandstone Group and called the Lissan Formation. The age of this unit is possibly Permian with the lower part likely to be the Carboniferous Iniscarn Formation. This requires more work to resolve, but it is of limited geographical extent and may not be an indication of the types of facies present in the deeper basin.

From the available information there is very little systematic variation on which to subdivide the Sherwood Sandstone Group and it is predominantly a remarkably uniform unit of red and orange, variably feldspathic, fine to medium grained and locally pebbly sandstones.

The thickness range of the SSG recorded boreholes in the Rathlin and Foyle basins is 228 to 513 m. In Magilligan it is 409m thick and sits unconformably on Carboniferous sandstones. In Port More which was drilled closer to the depocentre of the Rathlin Basin (Figure 8) it is present between 1317–1830 m and overlies mudstones, sandstones and conglomerates believed to be of Permian age. The most recent deep borehole in the Rathlin Basin, Ballinlea No. 1, was also drilled near the centre of the basin, but on the flanks of a structural high, and the SSG was only 228 m thick.

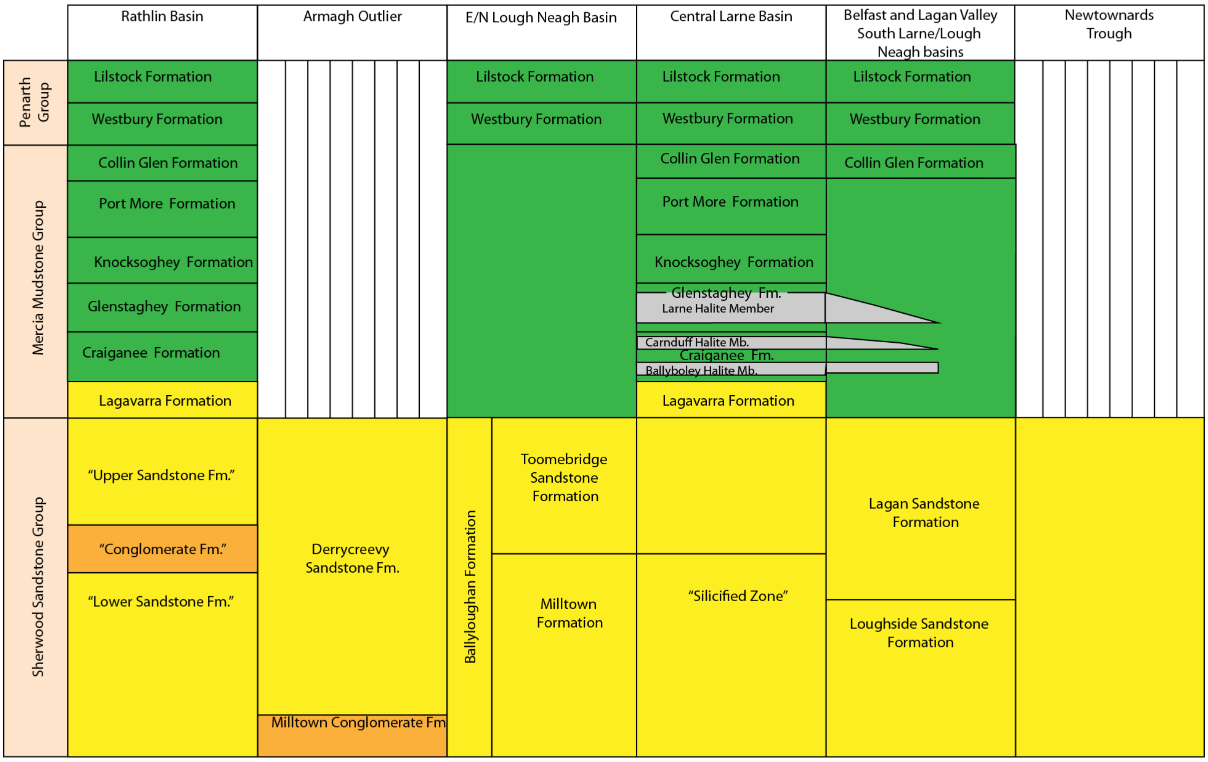

Figure 7. Lithostratigraphy of Triassic rocks in Northern Ireland.

In the Lough Neagh Basin the thickness is variable (89 m to 385 m in Mullaghglass) suggesting differential erosion following a period of uplift or differential subsidence during deposition. To the north of the Lough Neagh basin the top of the Sherwood Sandstone Group is present at depths between 497 and 1447 m and it is 373–421 m thick, reaching depths of 1868 m in Ballymacilroy. It is likely that the SSG reaches its greatest depths to the southwest of Lough Neagh and below the northeast corner of Lough Neagh itself where it may extend down to 2000 – 2200 m depth.

On the southern margin of the Larne Basin, the Kilroot Borehole proved the full thickness of the SSG as 549 m and reaching a depth of 804 m. The area north of this is less well known, but recent drilling activity in the Woodburn Forest well sought to test the Sherwood Sandstone Group as a hydrocarbon reservoir. Drilling did not encounter any oil or gas but the SSG was a similar thickness to that at Kilroot some 6km to the southeast. To the north and east the Sherwood Sandstone Group thickens markedly, such as at Newmill (868 m) and Larne No 2 (648 m), but in the Ballytober well, north of the Sixmilewater Fault, only 314 m were proven and in Ballynure No. 1, southwest of Larne, 343 m were recorded.

In the Larne No. 2 borehole it can be divided into an upper unit from 3175ft to 4113ft (285.9 m) and a lower unit from 4113ft to 5302ft (362.4 m) which is sometimes called the "silicified zone". The deepest burial depths in the Larne basin for the Sherwood Sandstone Group appear to be approximately 1600 m, in southeast Antrim.

To the south, in the Lagan Valley, the Sherwood Sandstone Formation is up to 157 m thick and is present down to depths of 190 m (Belfast Harbour Borehole). The SSG thickens into the Newtownards Trough where it is up to 212 m thick but because it is at outcrop the full thickness is not known. The Sherwood Sandstone Group reaches a maximum of about 305 m in the Belfast area (Manning et al. 1970).

4.4. Fluid flow, porosity and permeability

The storage of fluids in, and the ability of fluids to flow through, rock formations is key to the process of transferring heat to and from geothermal reservoirs. The direct measurement, or the estimation, of aquifer properties is fundamental to the prediction of the performance of the aquifer in a geothermal system.

Porosity is a measure of how much of the rock is open space. It indicates the ability of a reservoir to hold and store fluid. Mathematically, porosity is the open space in a rock divided by the total rock volume (solid + space or holes) and is expressed as a percentage of the total rock which is taken up by pore space. For example, a sandstone may have 8% porosity. This means 92 percent is solid rock and 8 percent is open space containing oil, gas, or water.

Permeability is a measure of the ease with which a fluid (water in this case) can move through a porous rock. The permeability of a rock is a measure of the resistance to the flow of a fluid through a rock. It is controlled by the size of the pores and their connectivity.

Porosity and permeability within a rock can vary on both microscopic and macroscopic scales and, although there is often a positive correlation between the two parameters, this is not always the case. For example, clay fractions can contain micropores which do not generally contribute to effective permeability. In other cases dissolution of minerals within the rock can create secondary porosity which may help to increase permeability or may be present as isolated and unconnected pore space.

On a larger scale, sedimentary structures and alternations of different rock types can lead to widely different poroperm (porosity and permeability) values within and between beds. Within beds sedimentary structures may be associated with small-scale changes in grain size perpendicular to bedding such that horizontal (bed-parallel) and vertical (bed-perpendicular) permeabilities are quite different. On a larger scale formations may consist of a succession of beds of different rock types and different poroperm characteristics.

The discussion above relates to the reservoir properties of the rock matrix itself. However, discrete structural discontinuities such as microfractures or larger fault zones may make a substantial, even dominant, contribution to the effective permeability of individual beds or sequences of beds. As a result, the different methods for the measurement of fluid flow, porosity and permeability have their own advantages and disadvantages in characterising the effective performance of a reservoir.

The most direct measurement of fluid flow and aquifer/reservoir characterisation is based on *in situ* flow and pressure testing in boreholes. In shallow wells water may be pumped at a measured rate from the reservoir interval for specified periods and the changes in water level in the production well and nearby observation wells measured to evaluate the drawdown of the water level and the subsequent recovery to the resting level. Various parameters such as transmissivity, storage coefficient, efficiency, well yield and water chemistry may be derived from pumping tests and associated sampling and analysis. Pumping tests can be expensive and are only really applicable to relatively shallow boreholes. In Northern Ireland there is a limited amount of these types of data available to GSNI, through published papers and reports deposited in the GSNI archives. Downhole flow logging using high resolution flowmeters can be used to identify and calibrate zones of flow between the borehole and the surrounding rock.

In deeper boreholes formation testing, or pressure transient testing, involves altering the reservoir pressure through the production (extraction) or injection of water and then observing the subsequent changes in pressure. Analysis of the pressure variation allows estimates of reservoir parameters to be made. The testing can range from very short stepped injection or production tests through to longer production testing over months or years. A relatively small number of deep boreholes (>500 metres deep) have been drilled in Northern Ireland and formation testing has been carried out in a smaller subset of these. In the absence of direct flow measurements and indirect estimates of in situ reservoir properties another approach is to examine rock samples in the laboratory and this has formed the basis of recent GSNI research.

The porosity of a rock sample can be determined from petrographic (microscopic) analysis or from routine core analysis. Included in the porosity values obtained from routine core analysis will be microporosity which is present within clays but largely not contributing to effective permeability. It will also include secondary porosity that is not connected to the pore network. This is why it is valuable to have thin section (petrographic) examination of samples that have been analysed for porosity and permeability. Reasons for departures from the normal relationship between the porosity and permeability can then be elucidated.

Publications containing porosity and permeability data from core analyses include the results from a series of laboratory tests carried out on core plugs from a number of boreholes on behalf of GSNI (e.g. Lovelock, 1977) and a limited number of analyses carried out for petroleum exploration companies on samples from their wells. Data sources are listed in Appendix 1. This is supplemented here by unpublished data from the GSNI thin section archive and petrographic studies.

4.4.1. Carboniferous porosity and permeability

There are relatively few data points for Carboniferous sandstones, especially from samples that have been buried to any significant depth. Surprisingly, despite being older, the Carboniferous samples often show better reservoir quality than the Permian or the Triassic, due in part to a higher degree of grain sorting and coarser grain size. Carboniferous samples may also have significant secondary porosity created through the dissolution of feldspars (how feldspathic they were at the time of deposition is unknown, but most samples are classed as quartz arenites). Carboniferous samples in the Magilligan borehole have greater amounts of quartz overgrowth, which at depth can act to stabilise a sandstone from further compaction, but eventually and with greater burial temperatures becomes a source of porosity destruction. This last point may be significant in the deeper parts of the sedimentary basins where the Carboniferous sandstones are expected to lie beneath the Permo-Triassic at depths greater than 2000 metres.

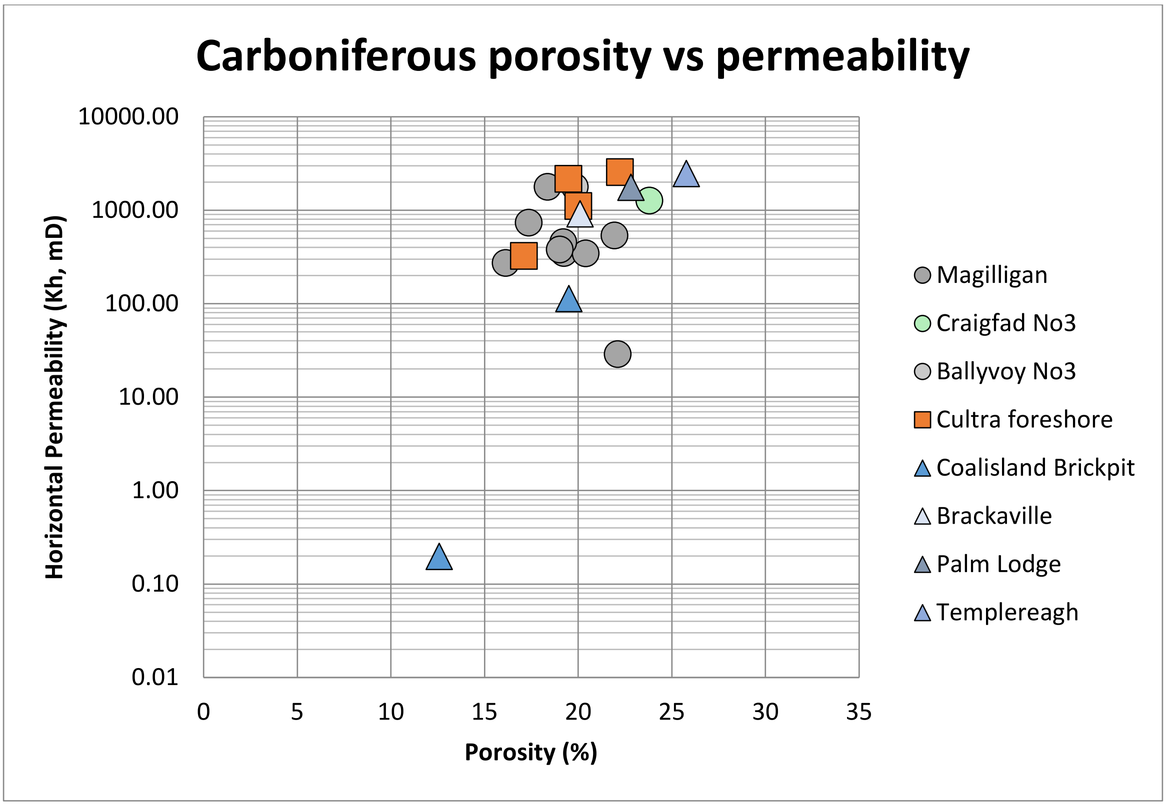

Figure 8 Poroperm (porosity and permeability) values for Carboniferous plugs from borehole and outcrop samples. Circles denote samples from the Rathlin or Foyle basins. Square symbols denote Larne basin samples and triangular symbols are those from the Lough Neagh Basin.

The data from Magilligan (depth range 1130 – 1310m) gives values of between 16.1 and 22.1% porosity (mean value of 19.3%). Permeability is 28.9-1776 mD (geometric mean of 364.5 mD).

The sample with the highest permeability shows residue of hydrocarbons in thin section, suggesting that the reservoir was once charged but it has since leaked (leakage associated with faulting or uplift). The presence of 7.9% average quartz overgrowth for the 16 samples suggest that the reservoirs may have experienced temperatures in excess of 80°C corresponding to depths of 2000 – 2500 m, but have since been uplifted to shallower depths where temperatures are closer to 35°C. The migration of oil through the sandstones may have also stopped or slowed some of the precipitation of quartz. Carboniferous samples from below 2500m are more likely to be cemented by quartz and carbonate.

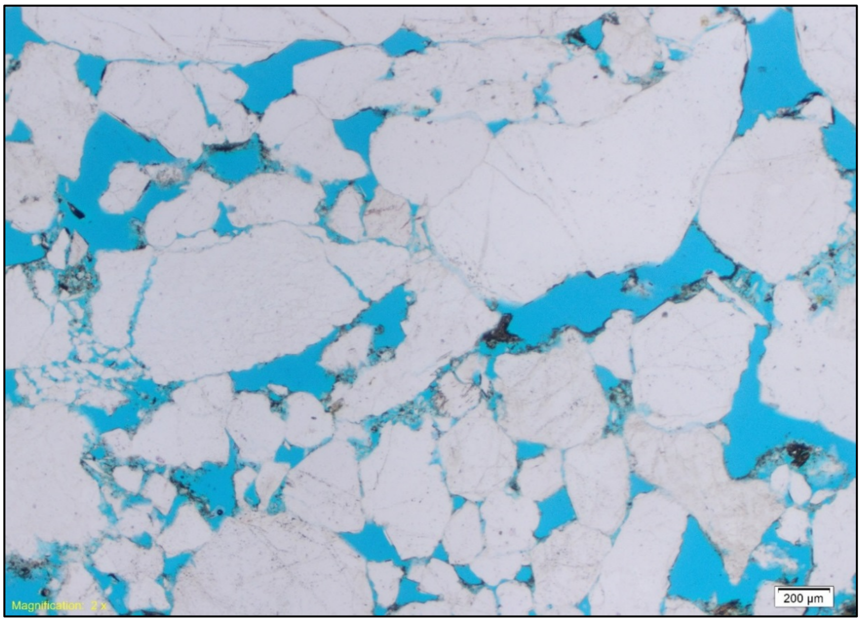

Figure 9. Thin section image showing the sandstone from 1226.52 m depth in Magilligan that had the highest permeability value of 1776 mD. Areas of porosity show as blue. The pores are open but not all connected. Large secondary dissolution pores have increased the pore volume and connectivity.

The Craigavad Sandstone Formation at the southernmost margin of the Larne Basin has high reservoir quality, based on samples taken from the outcrop on the foreshore of Belfast Lough at Cultra. Petrographically derived porosities are 5.5-7.0%, but poroperm analysis of other sandstones from the same outcrop show porosities of 17.1–20.0% and permeabilities of 323–2557 mD. The high reservoir quality is a function of grain size and weak compaction of the sandstones. However, little is known of the distribution and facies variation of this formation as it deepens northwards into the Larne Basin, or the timing of carbonate cement formation, so this good reservoir quality may not persist at depth.

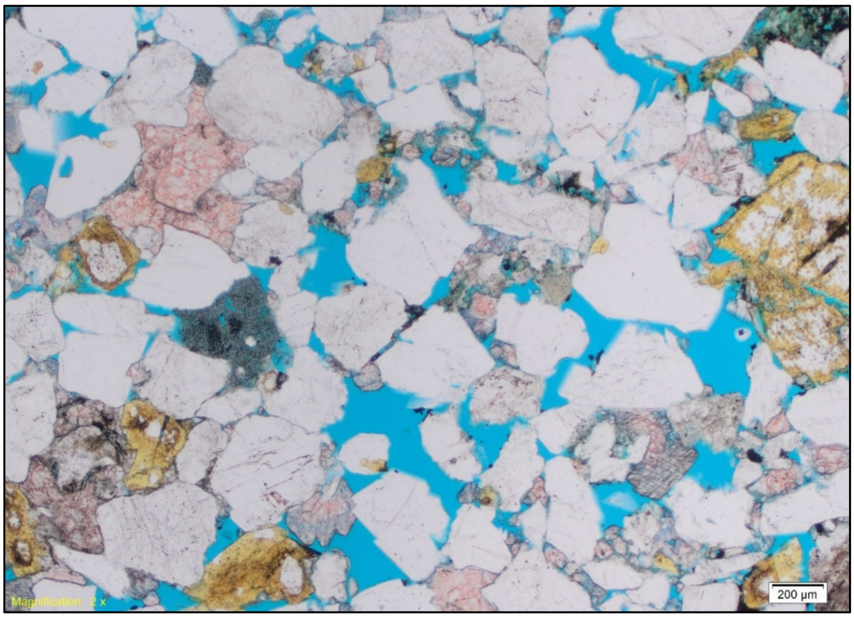

Figure 10. Photomicrograph of the Craigavad Sandstone Formation showing open and partly connected pore space. There are some areas of non-ferroan calcite that have occluded (blocked) pores.

Other potential reservoirs include the "Millstone Grit" Group recorded in boreholes to the west of the Lough Neagh Basin. So far porosity and permeability has only been measured from shallow boreholes. The deepest borehole containing the group is Killary Glebe, which is located quite close to a major fault. Parnell (1991) records petrographically derived porosity from one sample at unspecified depth of 20.8% and Parnell (1988) records porosity in thin section of 7.6% from 1120 m and 21.6% from 1125 m. GSNI thin sections from 1050 m, 1091 m and 1106.42 m have porosities between 7.0% and 9.5%. Some samples contain abundant dolomite and significant quartz overgrowth, but the presence of barite enclosed by the dolomite and the ferroan nature of the dolomite suggest that the source of the cements could be hot fluids from nearby faults rather than an indication that all the "Millstone Grit" Group sandstones at this depth and below are cemented to this degree.

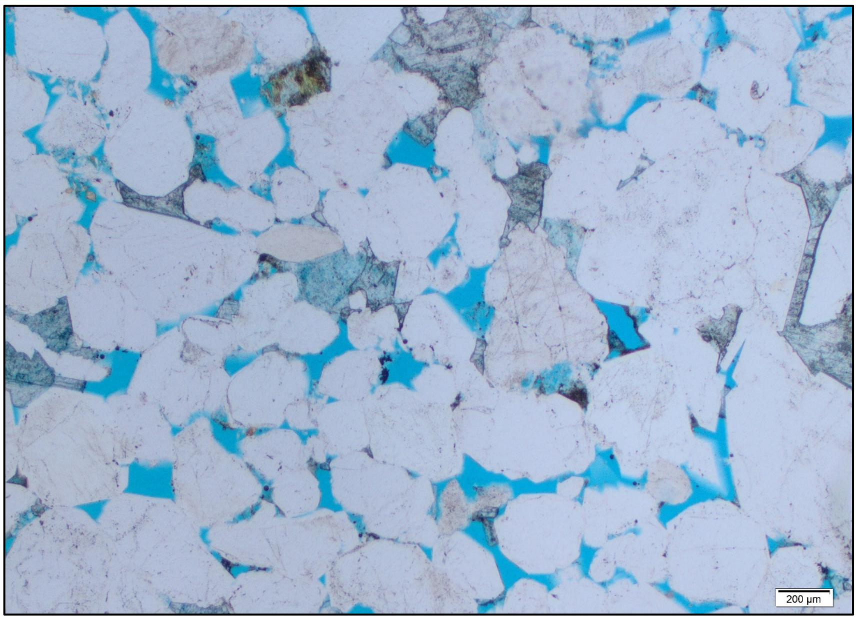

Figure 11. Killary Glebe No. 1. Photomicrograph of sandstone from 1091 m depth. Pore throats are blocked by syntaxial quartz overgrowth and ferroan dolomite. The sandstone shows weak to moderate compaction.

In the Rathlin Basin, the Port More borehole did not reach the Carboniferous, but porosity and permeability readings for samples from the uplifted Ballycastle coalfield show that the Ballyvoy Sandstone Formation has good reservoir quality (porosity 23.8%, permeability 1266mD and porosity 19.8%, permeability 1782mD from Craigfad No. 3 and Ballyvoy No. 3, respectively). This reservoir quality is unlikely to be preserved at depth as thin sections from the same unit in the Ballinlea No. 1 borehole, on the Rathlin Basin side of the Tow Valley Fault, suggest that the porosity is much reduced by cementation. Ballinlea samples from around 2470–2496 m depth contain porosity of 3.5–8% and the permeability is likely to be much reduced at this depth. Quartz overgrowth in the samples is 8.5–18.5% and carbonate is locally up to 16%, but in many samples it is <1%, so the distribution of cements needs further study. It should also be noted that the section cored may not be representative of the full Ballyvoy sandstone section in Ballinlea No. 1, as porosities derived from analyses of geophysical logs identify some non-cored intervals with higher porosities.

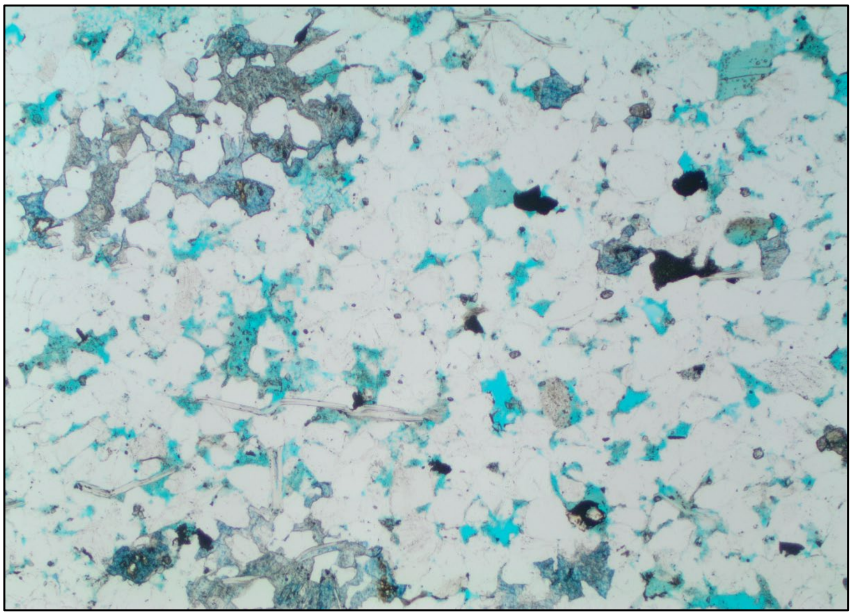

Figure 12. Photomicrograph of a thin section from 2478.85 m depth, showing cementation by quartz and ferroan dolomite. Ballyvoy Sandstone Formation, Ballinlea No. 1.

The Drumman More Sandstone Formation, south and west of Lough Neagh, does not have any core analysis, but thin sections from shallow boreholes suggest it is a porous and permeable sandstone. Petrographic samples have 12-19.5% porosity.

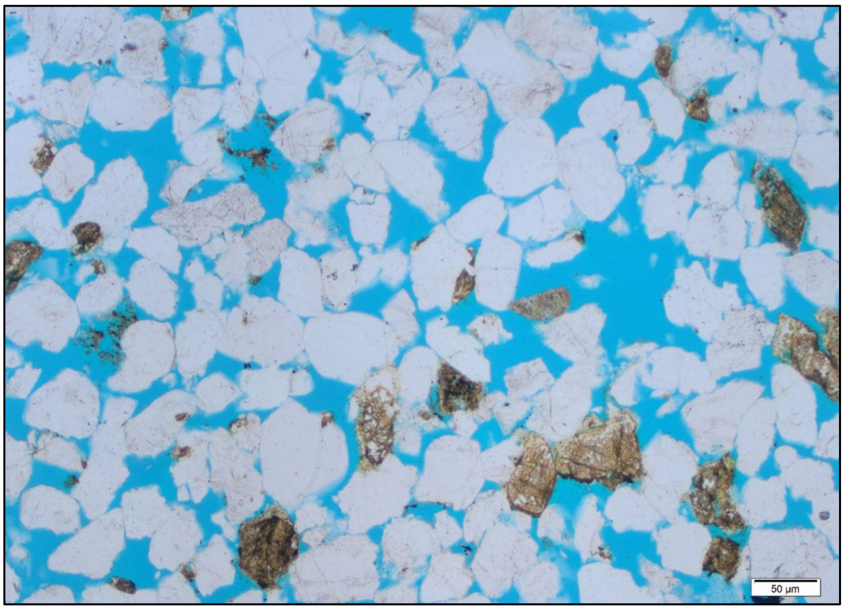

Figure 13. Thin section photomicrograph of a sandstone from the Drumman More Sandstone Formation in Wilson's Bridge BH5 at a depth of 159.5 m. Note the extensive and well-connected pore space (blue).

4.4.2. Permian porosity and permeability

As described above, the Permian is not well represented either in surface outcrop or by rock cores from deep boreholes so that there are limited core analyses from Permian sandstones. However, Figure 14 shows that the data follow a clear trend of permeability increasing with porosity, as expected. Although the analyses from Larne No. 2 and Port More core samples show low permeabilities the data from other wells record permeabilities that would be classified as moderate to good reservoir quality.

It is notable that the analyses from the Annaghmore No. 1 well, in the Lough Neagh Basin, do not follow the normal porosity – permeability trend, having lower than expected permeabilities for the porosities determined from the sidewall cores. One possible explanation for this is that the sidewall cores (SWCs) – small plugs cut directly from the borehole wall using a downhole tool - have experienced some disaggregation of the outer sand grains during retrieval of the tool from the borehole that has led to higher porosities being measured whilst the central part of the SWCs have been unaffected leading to 'true' horizontal permeabilities being measured.

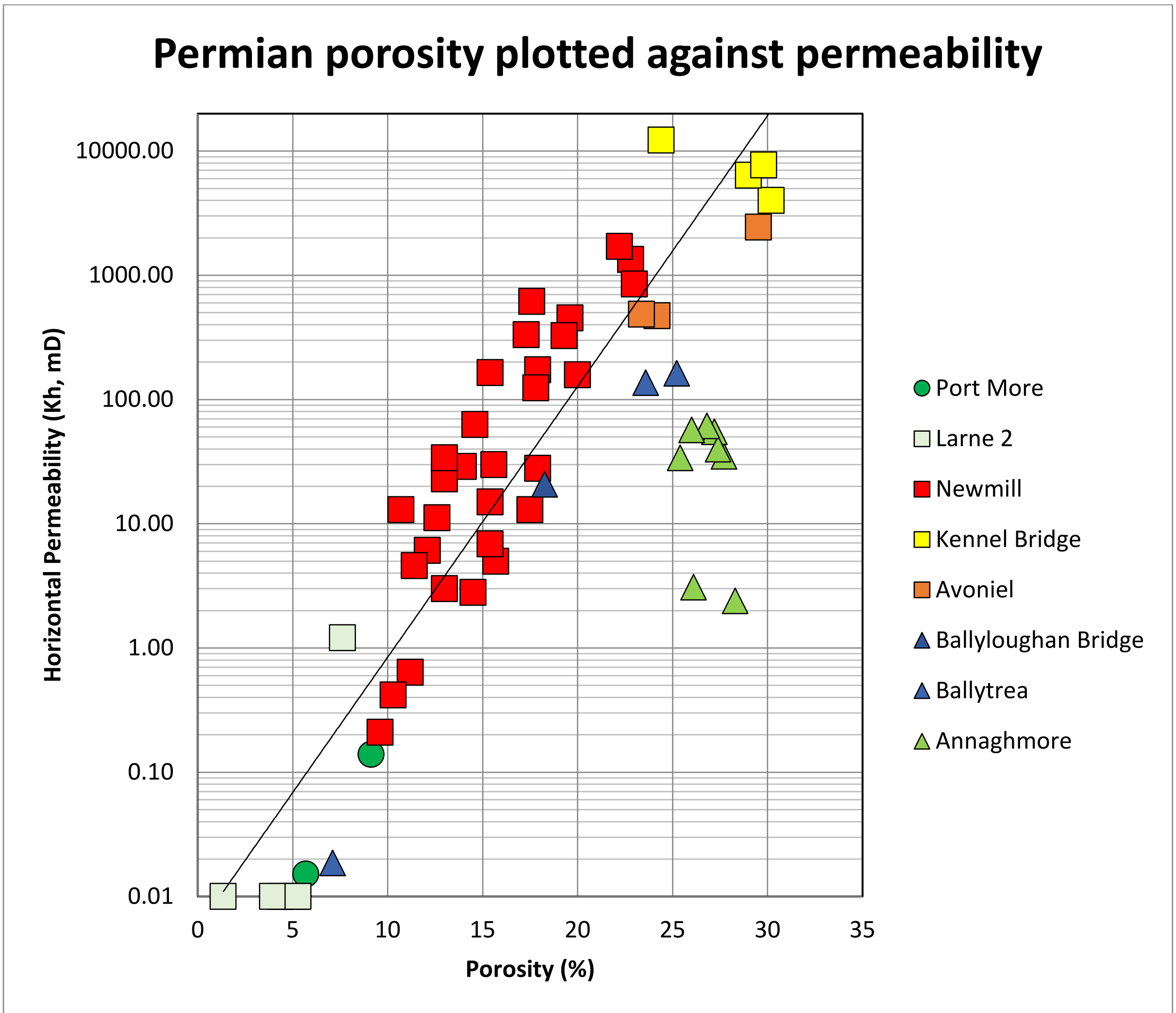

Figure 14. Poroperm values for Permian core plugs. Circles denote samples from the Rathlin or Foyle basins. Square symbols denote Larne Basin samples and triangular symbols are those from the Lough Neagh Basin. Note: Trend line excludes Annaghmore No. 1 sidewall core data (green triangles)

The Permian sample database is dominated by samples from the Carnamuck Sandstone Formation in Newmill No. 1 where a high number of measurements were taken over an interval of 30ft (1574.20-1583.35 m RKB). Porosities of 9.6 - 23.0 % (mean value of 15.58%) and permeabilities of 0.21 to 1705 mD (geometric mean of 30.94 mD) were recorded (CoreLabs in Marathon 1971).

Sadly the core from which the measurements were taken has been lost, but GSNI sampled cuttings for petrography at 5170' (1575.82 m), 5200' (1584.96 m), 5250' (1600.2 m), 5290' (1612.39 m) and 5350' (1630.68 m). On examination the range in the reservoir quality is interpreted to be caused mainly by variable levels of post-compaction ferroan dolomite and subordinate anhydrite cement that has occluded the porosity. There is minor pore-bridging clay in some samples.

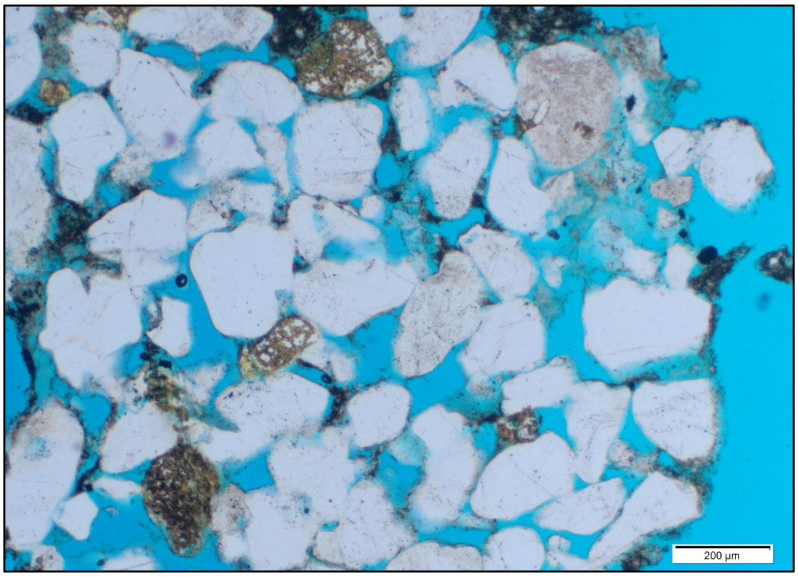

Figure 15. Photomicrograph of a cuttings sample from the Ballytober Sandstone Formation in the Newmill borehole. (1584.96 m depth). In this sample, pores are open and moderately connected, but permeability may be reduced by illite clay (showing as dark trails of very small grains between much larger quartz grains) that locally bridges pores.

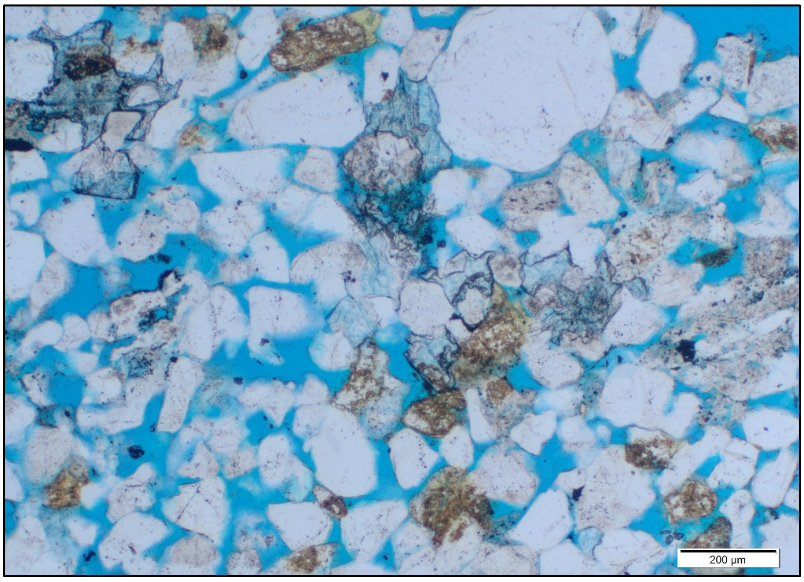

Figure 16. Photomicrograph of a cuttings sample from the Ballytober Sandstone Formation in the Newmill borehole (1600.2 m depth). In this fragment of sandstone there is partial occlusion of pores by dolomite (semi-translucent grains often with darker rims and internal patches).

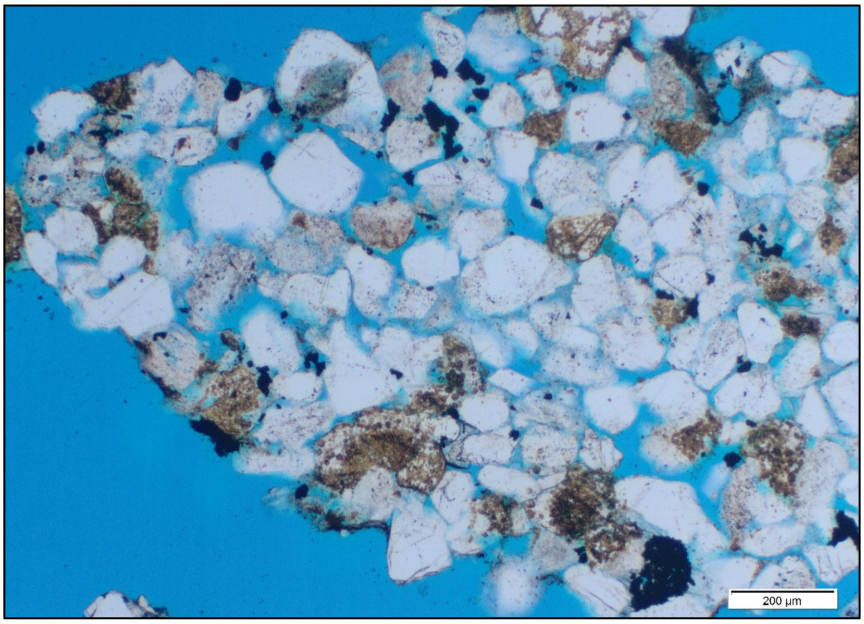

Figure 17. Photomicrograph of a cuttings sample from the Ballytober Sandstone Formation in Newmill at 1612.39 m depth. The sandstone has open and well-connected pores.

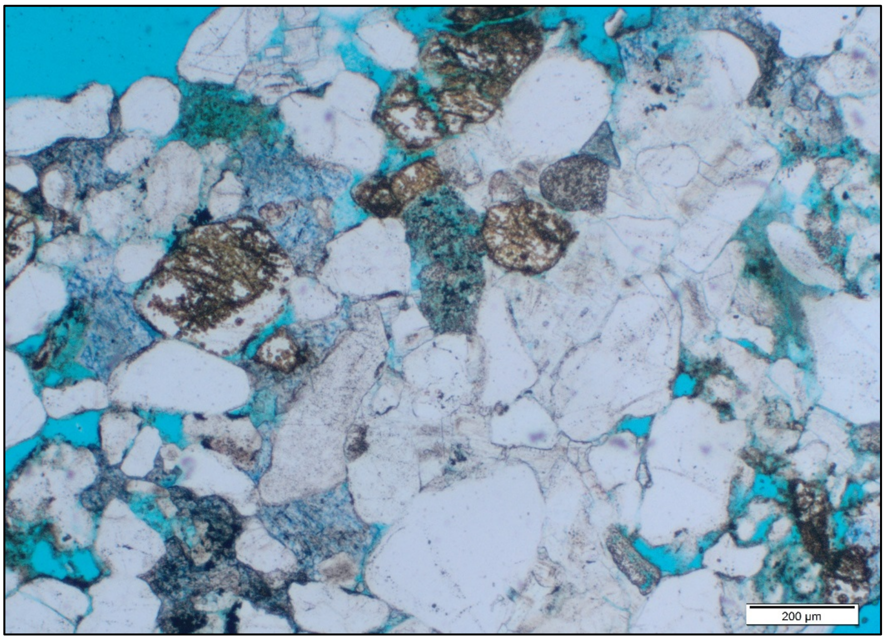

Figure 18. Photomicrograph of a cuttings sample from the Ballytober Sandstone Formation in the Newmill borehole at 1630.68 m depth. Some sandstone fragments such as this are almost completely occluded by clay, ferroan dolomite and anhydrite.

There are a number of Permian sandstone formations that have reservoir potential, but for which there are few reservoir quality data points.

The Carlane Formation is a generally thin unit of clean, well sorted sandstone and has been recorded in Ballynamullan, Annaghmore, Ballymacilroy, and possibly in Larne No. 2. This is the unit that contained a small amount of gas in the Larne No. 2 borehole. It occurs immediately below the Magnesian Limestone and is cautiously interpreted as marking the onset of the marine transgression.

The sandstones beneath the Belfast Harbour Evaporite Formation in east County Tyrone may be an equivalent of this unit as they are well sorted and contain trace fossils indicative of marine transgressive deposits and are therefore part of the Belfast Group. The sample analysed from the Ballytrea borehole had low reservoir quality, but cuttings samples and logs show that reservoir quality may be better in the subsurface (Figure 19).

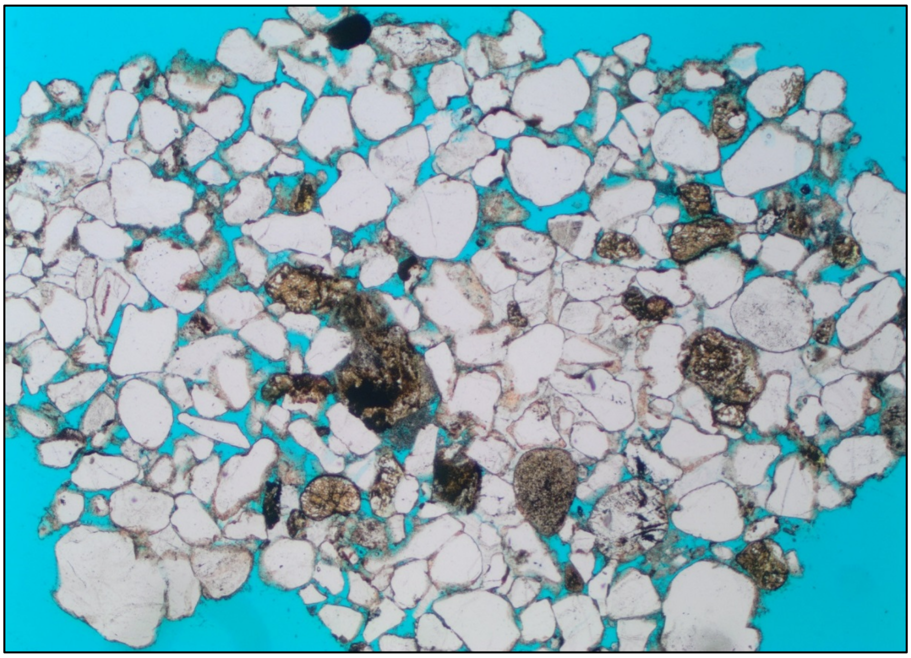

Figure 19. Photomicrograph of a cuttings sample from the Carlane Formation in Ballymacilroy at a depth of 1990 m. Some anhydrite cement is present, but the sandstone is well sorted and porous.

There are no cores from the early Permian Ballina Bridge or Annaghmore formations which were penetrated in the Annaghmore and Ballynamullan boreholes. Cuttings suggest that there are significant intervals of porous sandstone, but dolomite and clay cements may reduce permeability.

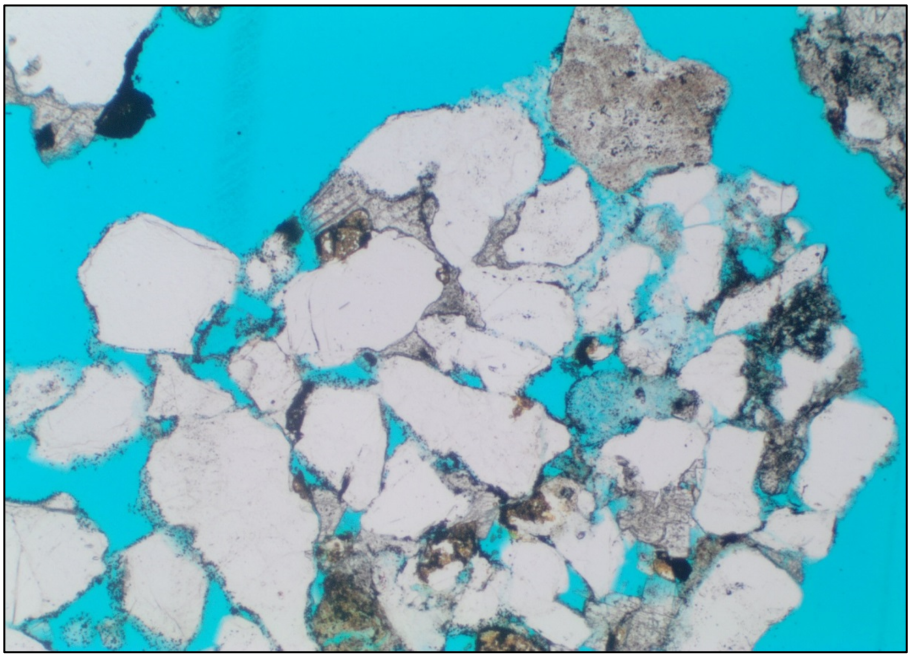

Figure 20. Cuttings sample from the Ballina Bridge Formation in Annaghmore, 1231.39 m depth.

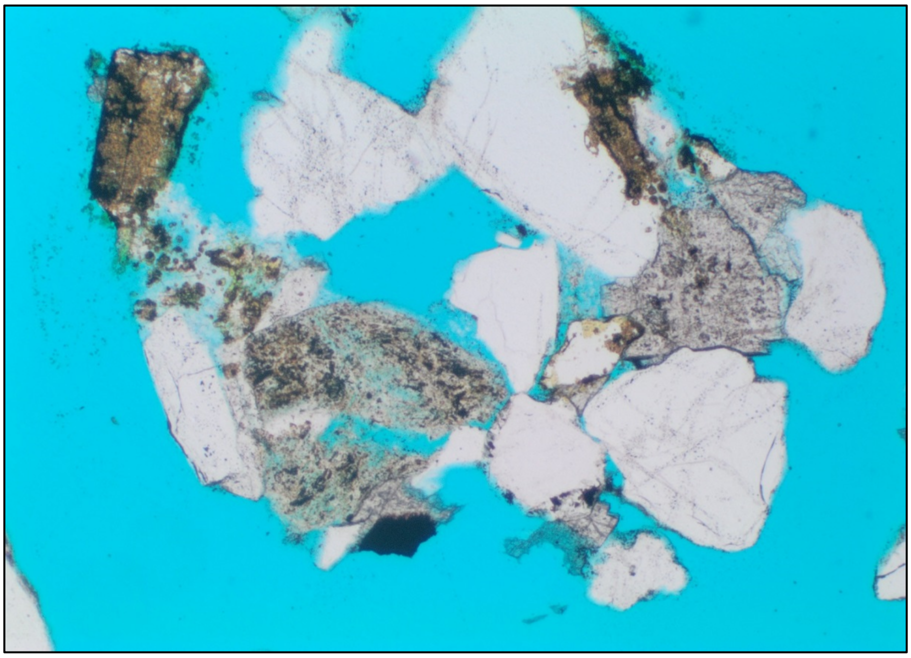

Figure 21. Photomicrograph of a sandstone fragment from the Annaghmore Formation in Annaghmore, 1432.56 m depth. The sandstone contains large unoccluded pores, but some intergranular dolomite cement.

The Permian rocks sampled in the Ballytrea, Ballyloughan Bridge and Avoniel boreholes are interpreted to have higher porosity and permeability because they are from shallow depths and may not have been as heavily compacted as other samples. The values from Avoniel come from the Lower Permian, but the highest reading comes from a sandstone within the Coolbeg Breccia Formation (a unit that for the most part has very low reservoir quality).

The reservoir quality encountered in the Permian in Larne No. 2 was disappointing, but based on petrography it is not interpreted that the samples are heavily compacted but rather that they have been the subject of increased cementation. There may be hope for less cemented reservoirs at a similar depth elsewhere, as suggested by the results from the cores cut in Newmill No. 1 to the south. The location of the Larne No. 2 borehole close to the major Sixmilewater Fault (mapped at surface and evident on seismic sections) and other faults, deduced from geophysical data, running through Larne Lough may be significant for the introduction and circulation of formation fluids and increased cementation. The mineralogy and geochemistry of the volcanoclastic sediments associated with the Permian basalts (present only) in Larne No. 2 may also have influenced the type and intensity of cementation in the overlying sandstones. The Neutron porosity averages 9% (Downing et al. 1982) so it is likely that cementation for one reason or another has affected most of the Lower Permian Sandstone at this location.

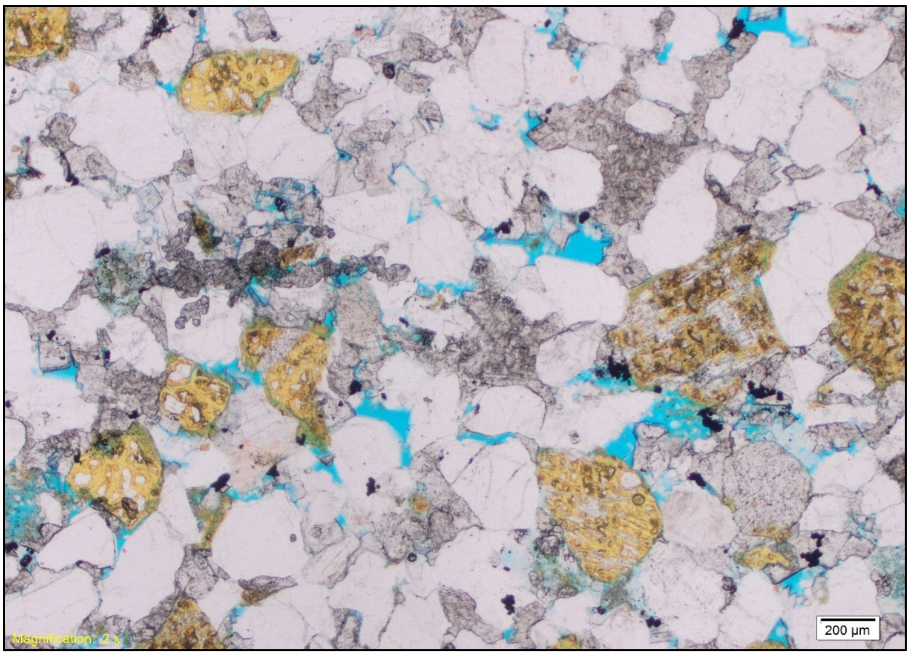

Figure 22. Thin section photomicrograph from the Ballytober Sandstone Formation in Larne No. 2. The porosity is occluded by feldspar overgrowth, non-ferroan dolomite and then syntaxial quartz overgrowth. Anhydrite then appears to have further occluded the porosity. 1834.44 m. This sample is taken 6 cm above the plug that gave values of 7.63 % and 1.21 mD. Values of porosity loss through cementation are 37.5%, while 4.69% of initial porosity is interpreted to have been lost through compaction. Image taken in plane light.

The porosity and permeability in the Kennel Bridge borehole is likely to reflect the shallow burial of rocks in the Newtownards Trough. Horizontal permeability up to 12.27D is recorded in one sample at 61.3 m depth. Plugs from a variety of orientations were analysed over a 13 m interval of core, yielding a geometric mean of 2827 mD.

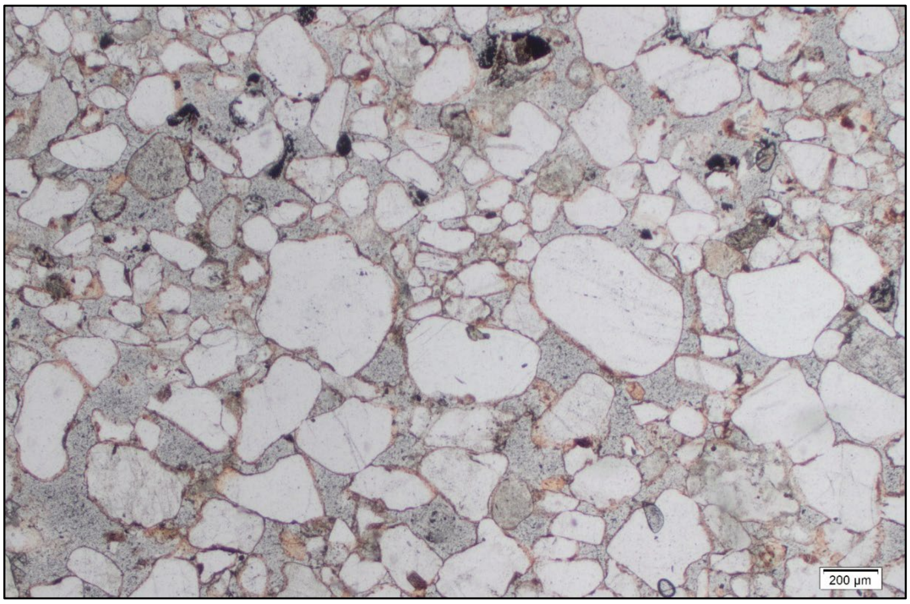

Figure 23 Thin section photomicrograph showing the Kennel Bridge sample from 61.3 m. There is much variation vertically in the porosity as a result of the mixed grain sizes, but highly porous laminae comprise loosely compacted and coarse grained, uncemented quartz grains. There is very little carbonate cement in the sample. Taken in plane polarized light. NI4191.

The thick Permian volcanic section encountered in the Larne No.2 borehole contains lavas, tuffs and, at the base, volcanic sandstones, all of which have negligible reservoir quality.

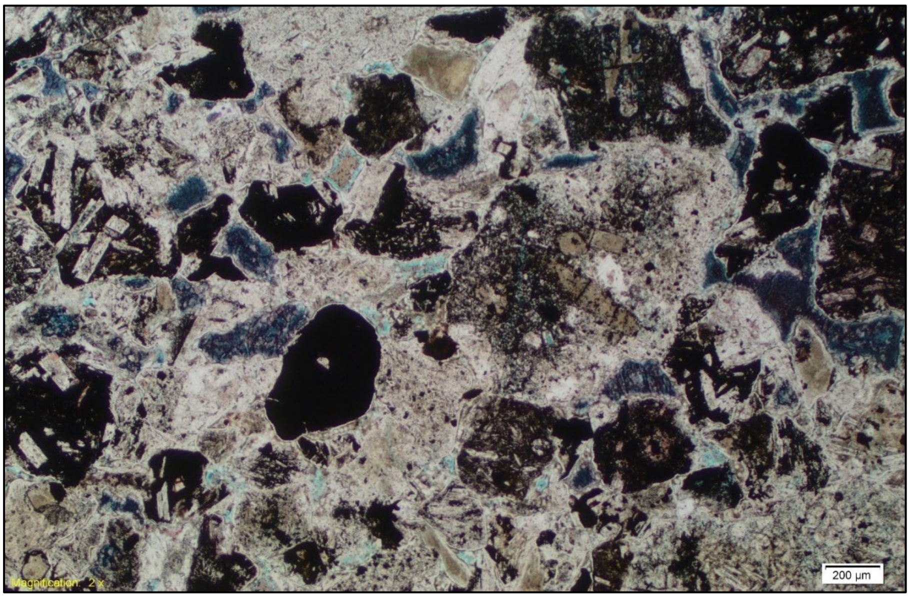

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Figure 24. The terminal core (2871.1-2880.2 m) taken in the Larne No. 2 borehole comes from a unit of volcanic sandstones at the base of the well. Although porosities of 1.35-5.15 were recorded, permeability was consistently <0.01 mD. The thin section image from 2875.1 m shows that the porosity is entirely as microporosity, explaining the low permeability. Pore space has been cemented with silica and ferroan calcite.

In the Rathlin Basin only two samples from the Permian in the Port More borehole have been analysed petrographically.

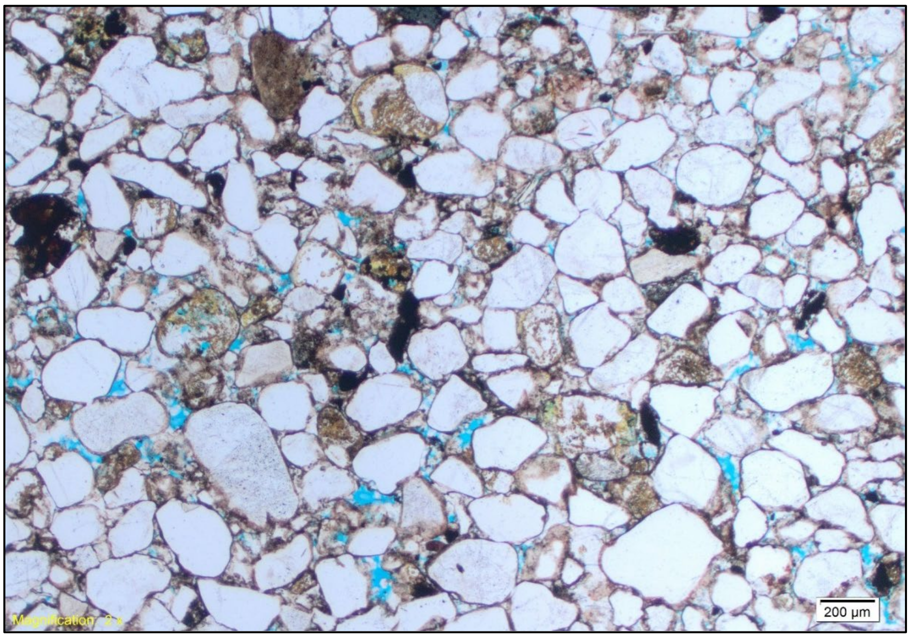


Figure 25. Photomicrograph of a thin section from 1838 m depth in the Port More borehole. The sample comes from the Belfast Group and contains a proportion of rounded grains as is typical of the Upper Permian sandstones elsewhere. This sample contains partly dissolved anhydrite cement that has reduced the porosity and permeability. Porosity is 5.7% and permeability is 0.015 mD.

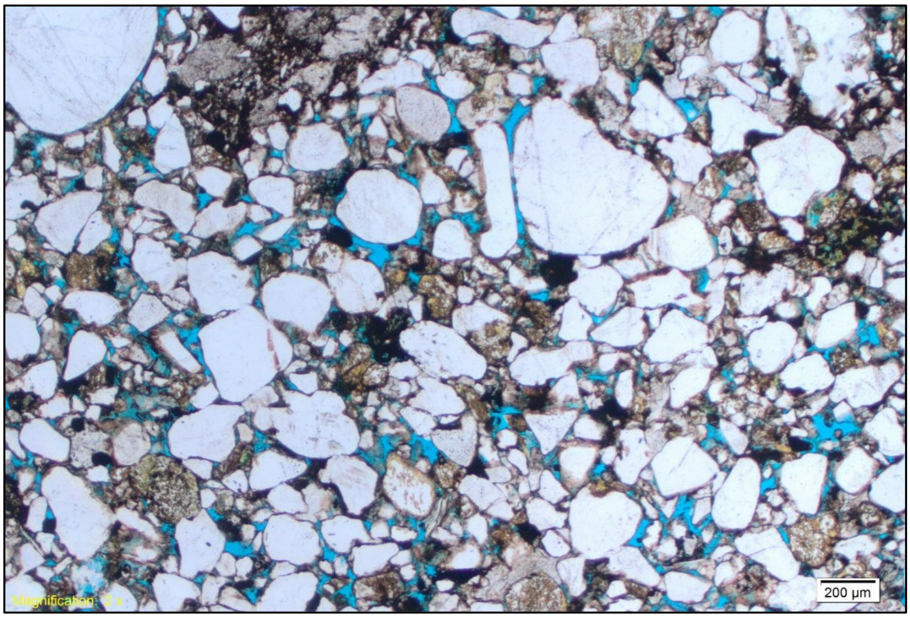


Figure 26. Photomicrograph of a thin section from Port More (1883.66 m depth) from the Enler Group also has low porosity and permeability of 9.13% and 0.14 mD. These low values are caused by poor sorting, and the presence of dolomite and anhydrite cements.

4.4.3. Triassic porosity and permeability

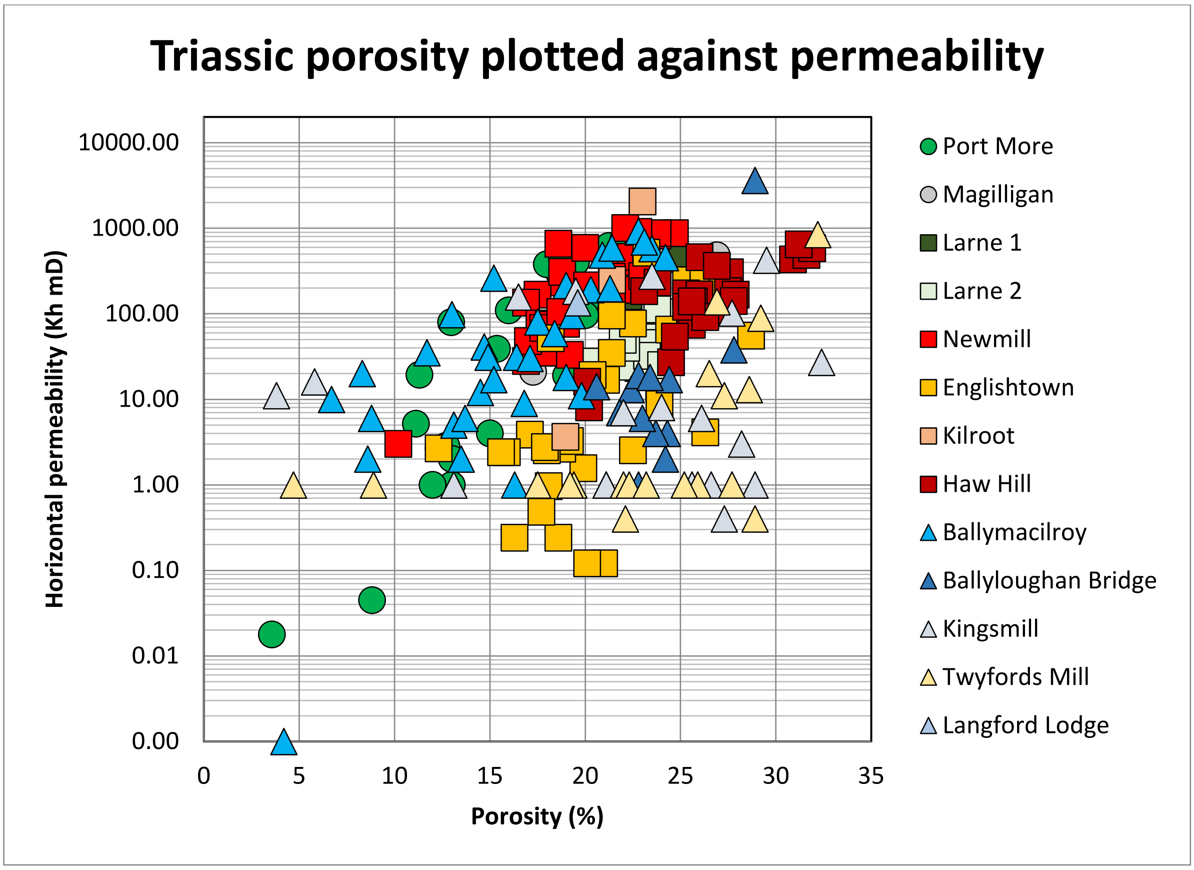


Figure 27. Porosity versus permeability for horizontal plugs from the Sherwood Sandstone Group. The circles show boreholes in the Rathlin and Foyle basins. Square symbols indicate wells from the Larne Basin and Newtownards Trough and triangles denote borehole samples from the Lough Neagh basin.

The Triassic Sherwood Sandstone Group has been cored in many wells and there is a wealth of poroperm data for this unit. Much of the variation between samples of a single well is a function of detrital clay content and grain size. Commonly when samples are selected, only the cleanest samples are chosen for petrography and poroperm analysis. This means that the poorer quality reservoir intervals are often not represented. Differences between wells appears to be a function of the depth of burial. Samples from the shallow Haw Hill, Twyford's Mill and Kingsmill boreholes all show higher porosity values. Port More and Ballymacilroy samples are more permeable but less porous than those from Larne No.1 and No.2 suggesting some variation between basins. This is possibly due to the presence of anhydrite in the Larne samples and indicative of the more evaporitic depositional environment that characterised the Larne area. Average porosity values range from 16.73 in Port More to 27.58 in Twyford's Mill. Average permeability varies from 6 mD to 226 mD between boreholes although some boreholes have only a few samples taken from a short interval. Across the whole Sherwood Sandstone Group, as sampled and analysed, there is an average porosity of 21.3 % and average permeability of 40.5 mD.

		Porosity				Permeability			
Basin	**Well**	**Min**	**Max**	**Average**	**Number**	**Min**	**Max**	**Average**	**Number**
Rathlin	**Port More**	3.58	23.35	16.73	25	0.02	727	49.1	24
Foyle	**Magilligan**	12.32	26.90	21.04	5	2.65	518	78.2	5
Lough Neagh	**Ballymacilroy**	4.20	24.20	16.16	33	0.001	919	33.6	37
	Kingsmill	19.50	32.40	25.56	15	0.40	424	23.5	13
	Twyfords Mill	22.10	32.20	27.58	10	0.40	842	11.9	9
	Ballyloughan Bridge	20.60	28.90	23.94	12	2.00	3607	19.5	13
Larne	**Larne 1**	21.41	25.60	23.99	7	78.0	438	226	7
	Larne 2	20.49	24.03	23.12	19	13.4	112	42.8	19
	Newmill	10.20	24.70	19.77	30	3.00	1005	167	30
	Englishtown	15.60	28.70	21.07	29	0.12	280	6.03	32
	Kilroot-1	18.97	23.01	21.13	3	3.63	2057	123	3
Newtownards Trough	**Haw Hill**	20.10	31.90	26.19	26	8.00	644	142	25

Table 2 Summary of porosity and permeability data for the Sherwood Sandstone Group.

4.5. Anisotropy of permeability

In sandstone reservoirs the permeability will vary depending on the direction in which it is measured and the difference is generally most marked between the bed-parallel and bed-perpendicular directions. Often, but not always, there is more variation in grainsize and mineralogy across beds and in a vertical direction than laterally within beds, and this variation can give rise to variations in permeability. For this reason it is useful to take both horizontal (bed-parallel) and vertical (bed-perpendicular) core plugs and make measurements on both.

Where this has been done in Northern Ireland the Sherwood Sandstone Group shows a range of anisotropy between Kv/Kh. One sample with an anisotropy value of 8 is likely to be a fractured plug (this has not been plotted) but, surprisingly, there are many samples with higher permeability in vertical plugs. This may result from vertical mm-scale grain size changes or small fractures or channels in the rock. It would suggest that bed-parallel mica and detrital clay laminae are not a major barrier to vertical flow for the most part. Most plugs are anisotropic especially those from boreholes in East Tyrone. This may be because the Sherwood Sandstone there is more laminated with fines or that they represent a part of the stratigraphy not sampled in the other cores. Core plugs from Larne No.1 and No.2, Ballymacilroy, and Port More appear less anisotropic.

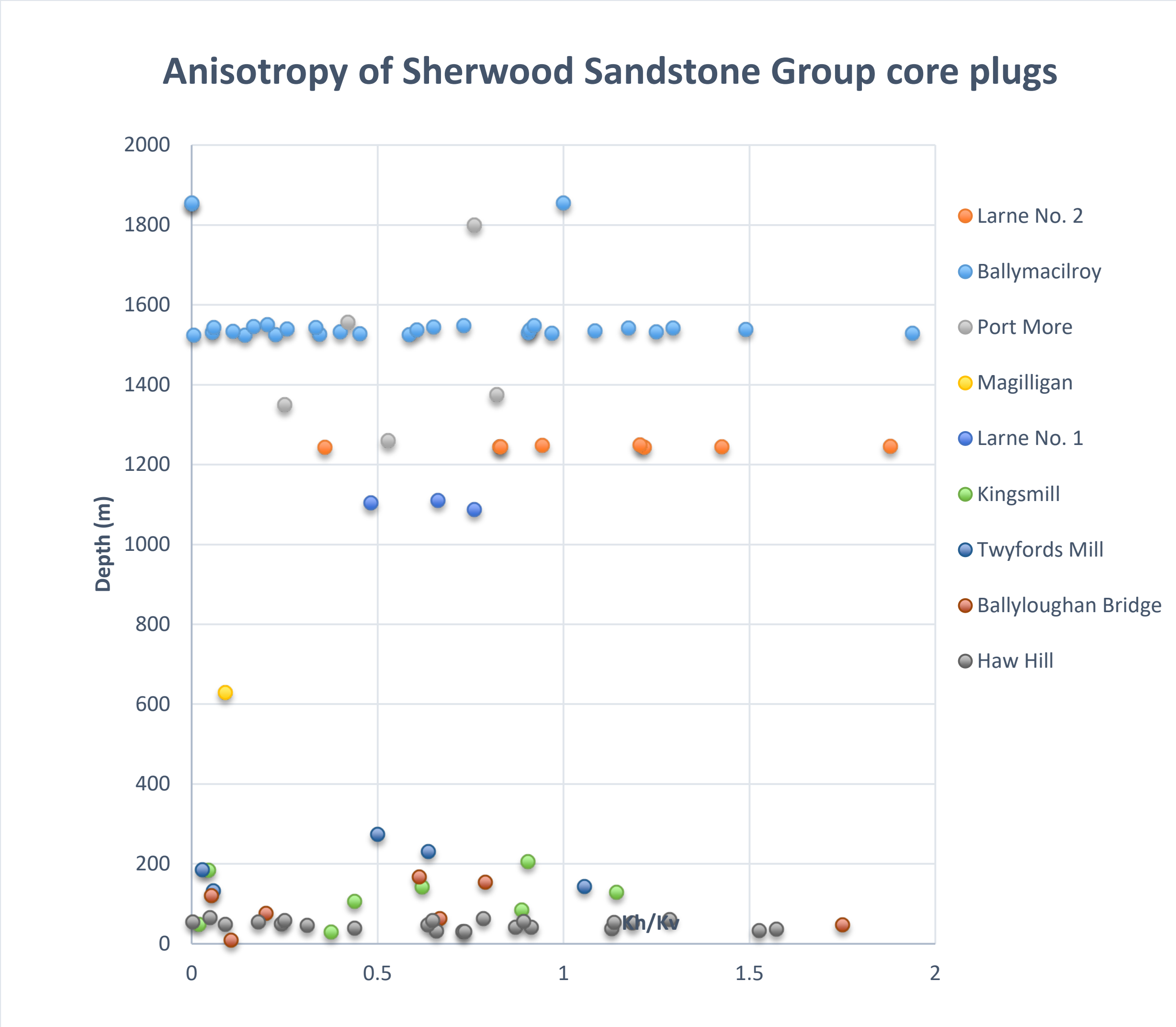


Figure 28. Anisotropy of core plugs from the Sherwood Sandstone Group. The distribution of data points reflects the narrow range of depths cored in individual boreholes

4.6. Transmissivity

The transmissivity is a measure of the rate of flow through an aquifer (or reservoir) per unit width which takes into account the thickness of the aquifer. It is usually defined as the product of the hydraulic conductivity and the thickness, expressed in units of m^2/day (or Dm – Darcy metres). A major BGS report on the physical properties of major aquifers in England and Wales (Allen et al., 1997) gives a mean transmissivity of 189 m^2/d, an interquartile range of 90 to 436 m^2/d and a maximum of 5200 m^2/d, from measurements of Permo-Triassic sandstones at 763 sites. These aquifers would be described as having moderate to high potentiality, according to the table below.

Transmissivity value (m^2/day)	Potentiality description
<5	Negligible
$5 < T < 50$	Weak
$50 < T < 500$	Moderate
$T > 500$	High

Table 3. Classification of aquifer potentiality based on transmissivity values

Transmissivity can be calculated from pumping tests in shallow boreholes or derived from intergranular permeability measured in borehole core. If the two values are similar it can be inferred that the transmissivity of the aquifer is adequately characterised by the intergranular permeability.

In the Newtownards Trough pumping tests yielded a total transmissivity value of 522 m^2/d and a laboratory derived intergranular permeability of 0.09 m/d for the Sherwood Sandstone in the Haw Hill borehole. The saturated thickness of the aquifer in this borehole is 37 m, suggesting a transmissivity of 3 – 4 m^2/d based on the permeability value. From this it can be inferred that intergranular permeability alone cannot account for the pumping test performance and that fractures probably make a large contribution to the total transmissivity of the Sherwood Sandstone aquifer at this location (Robins, 1996).

During the Lagan Valley hydrogeological study (Bennett, 1976) aquifer evaluation tests were carried out in a number of boreholes and transmissivity and storativity values derived. Transmissivity ranged from 30 to 195 m^2/d, based on SSG intervals 91 – 122 m thick. In the Englishtown borehole core samples at 3 m intervals were analysed for porosity and permeability. Porosity ranged from 20 – 27% and 15 – 21% in the upper 50m and lower 57 m of the borehole and intergranular permeability ranges from 10^{-1} m/d to 10^{-4} m/d in certain zones of the upper and lower parts of the hole, respectively, with a mean effective value of 10^{-2} to 10^{-3} m/d for the whole sequence. However, using a dynamic saturated aquifer thickness of 82 m, the test transmissivity values equate to a hydraulic conductivity[3] of 3×10^{-1} m/d, i.e. one to two orders of magnitude greater than the measured intergranular permeability. Here again, it may be inferred that flow through fractures (and/or flow through unsampled thin highly permeable layers) are major components of the total flow through the aquifer.

Examples of similar non-matrix (fracture) contributions to transmissivity in the Sherwood Sandstone Group has been noted by Lovelock (1977) from boreholes elsewhere in the UK, so it is reasonable to assume that this is the case for the SSG across Northern Ireland. However, there is little information about the extent and persistence of fractures at depths greater than the intervals in shallow water wells on which pumping tests have been carried out. Drill Stem Tests (DSTs) provide direct information

[3] For practical purposes the intergranular permeability of an aquifer is equivalent in magnitude to the hydraulic conductivity where the latter refers to the flow of water through that aquifer.

on aquifer performance at greater depths but have rarely been run in Northern Ireland boreholes (see section 4.7).

In the Sherwood Sandstone Group the measured permeabilities from borehole cores are lowest in the area west of Lough Neagh and appear to increase towards the east, with transmissivity increasing from 20 m^2/d to 150 m^2/d, due to better sorting, slightly coarser grain size and less induration.

In the Larne No. 2 geothermal exploration borehole the base of the primary target, the Sherwood Sandstone Group, was shallower than expected and was above the 60°C isotherm. The overall transmissivity of the sandstone is about 9 Dm. The Lower Permian sandstones are in the temperature range 60–70°C, but they are heavily cemented with low porosities; the permeability does not exceed a few millidarcies and the total transmissivity is only about 0.5 Dm. The transmissivity in the Sherwood Sandstone of the Ballymacilroy borehole is 18 Dm with a temperature of 62°C.

Smith (1986) regarded the Permian as tight, and as a unit with more uncertainty of facies distribution, so it was not considered in geothermal resource estimates for the UK. However, the Permian has a subcrop in a small area SE of Belfast where shallow boreholes show porosities of 25%-30% and in pumping tests the Permian sandstones have transmissivities about 120 m^2/d. This value is in line with what would be expected from the lab-derived permeabilities and implies that fracture or fissure flow is not an important factor in these aquifers (Smith 1986), at this location.

4.7. Drill-stem tests (DSTs)

Drill-stem tests have only been attempted in Northern Ireland at Ballymacilroy (Burgess 1979) and at Larne No. 2 (Downing et al. 1982).

In Ballymacilroy this comprised two successful tests on a Sherwood sandstone interval (1534–1549 m depth) and on a relatively open sandstone ascribed to the Upper Permian (1902–1920 m). There was also an unsuccessful test on the Permian sandstone immediately below the Belfast Harbour Evaporite Formation which failed when the soft sandstone caved. This interval included the Carlane Formation which is known to contain soft sandstones probably representing reworking of the underlying Enler Formation during the onset of the marine transgression associated with the Belfast Group.

The results of the Sherwood Sandstone Group test are assumed to be representative of the upper 215 m thick aquifer by correlation with the petrophysical logs and the 72 mD estimate of bulk field permeability, suggesting transmissivity of about 15 Dm for this interval. Below this the permeability of the Sherwood Sandstone Group decreases significantly but an intermediate interval could contribute a transmissivity of several Darcy-metres to a geothermal production well.

The total thickness of open Upper Permian sandstone, including the test interval, is about 45 m thick and has an estimated transmissivity of around 3 Dm.

In Larne No. 2, two successful tests were conducted in the Sherwood Sandstone Group (between 4420 and 4452 ft. (1347.2 and 1356.9 m) and between 4580 and 4632 ft. (1395.9 and 1411.8 m). They indicate low transmissivity values that agree with the low permeability measurements made in this borehole. It suggests that the topmost interval is the most open aquifer in the Sherwood Sandstone Group and contributes around 7 Dm to a total transmissivity of 8 Dm for the whole group.

Interpretation of geophysical logs from Newmill suggests that the Sherwood Sandstone Group is of similar reservoir quality to that found in Ballymacilroy – i.e. better quality than in the nearby Larne No. 2 borehole. A tripartite division of the Sherwood Sandstone Group can be made, based on physical properties, into an upper relatively open (or permeable) sandstone, an intermediate unit and a lower tight (or low permeability) sandstone unit. The same division is found in the Killary Glebe borehole, southwest of Lough Neagh, where the thicknesses of the units are 60 m, 90 m and 86 m, respectively.

In Larne No. 2 the Lower Permian (Enler Group) sandstone interval has an estimated transmissivity of 0.5 Dm from the logs and core. The results of the gas-lift pumping test from the Lower Permian sandstone and the volcanic sequence below give comparable estimates of transmissivity. The Newmill well is located relatively close to the southern margin of the Larne sedimentary basin where the early Permian sedimentation was dominated by deposition of coarse poorly sorted clastics in an alluvial fan setting.

The difference in Sherwood Sandstone Group reservoir quality between Larne (poor) and Ballymacilroy and Newmill (moderate to good) was attributed by Smith (1986) to their different relative locations within the sedimentary basins. However, the internal geometry of the Larne and Lough Neagh basins is not well known because of the scarcity of deep boreholes and the difficulty in obtaining good quality seismic reflection data from below the basalts. The geographical variation in reservoir quality requires more study as it will have an impact on the geothermal prospectivity, although the fact that the area immediately around Larne seems unique in its basin setting and history (thickest salts including Permian salt, Permian volcanism) should reflect more positively on the rest of the basin. The interpretation of other geophysical data such as magnetotellurics (MT) and gravity, calibrated against borehole data, could improve our understanding of the causes of this variation in reservoir quality.

4.8. Fractures

Apart from the comparisons between transmissivities calculated from pumping tests and those derived from permeabilities measured in the laboratory, little work has been done to investigate the role of fractures in reservoir sandstones in Northern Ireland. Geophysical logging suites run in deep boreholes have only rarely included imaging tools for the direct detection of fractures. In the Larne No. 2 geothermal borehole both a 4-arm dipmeter and a fracture finder/microseismogram tool were run, providing some information on the occurrence and nature of fractures present. Unfortunately, the similarities in salinity between the salt-saturated drilling mud and the saline formation fluid precluded the detection of open fractures using the resistivity or self-potential logs.

Using a combination of the gamma, neutron porosity and density logs, three units can be identified within the SSG of the Larne No. 2 borehole. The uppermost unit (968 – 1252m) has higher average porosity and lower density, the middle 'silicified zone' (1252 - 1335m) has lower porosities and higher density, and below 1335m there is a series of thin beds of shales and siltstones, some with anhydritic cements, showing higher densities and lower porosities within the dominant sandstones. A number of intervals, nineteen in total, were identified throughout the SSG where readings suggestive of fractures were interpreted from both tools. The caliper log which measures the diameter and eccentricity of the hole showed significant enlargement of the hole and caving, which may indicate fracturing in an east-west direction, within the uppermost unit. Where such caving occurs neither the fracture finder nor the dipmeter would be expected to yield reliable data, so these fractures would be additional to those intervals mentioned above.

Although these are very limited data from one borehole, they do indicate the presence of fractures within the Sherwood Sandstone Group at substantial depths which could make a significant contribution to fluid flow through the reservoir.

5. Variation in porosity with depth

Some 499 data points are available from the poroperm measurements of samples from across Northern Ireland. They include samples from the Rathlin and Foyle basins, the Larne basin, the Lough Neagh basin and the Newtownards Trough. The porosity readings have been plotted by depth in Figure 29. Although based on a limited number of wells, particularly for the deeper strata, and from different units (some of which may have been buried more deeply in the past but are now at shallower depths), some general observations may be made. Most striking are the horizontal trends – these reflect the variability in porosity measurements made on samples from individual core runs – i.e. there can be a great variation in porosity within a single core run over a depth interval of 10 metres or so. Although this might be expected from the data at shallow depths, where many more wells were sampled covering different parts of the SSG succession, it is also apparent for data from deeper cores. Overall, however, the data show the expected trend of decreasing porosity with increasing depth reflecting the effects of compaction and cementation. Between the depths of 1500 m to 2000 m, where reservoir temperatures may be high enough for direct heat applications, porosity values tend to be within the range of 10%–20%, although there are some higher values. The values from the Larne Basin are skewed by the atypically poor reservoir properties found in the Larne No. 2 borehole. Below 1500 m in the Rathlin Basin there is a much greater variation in porosity values. The Lough Neagh Basin lacks many data points from depths greater than 1500 m but, at 1500m, the porosities in Ballymacilroy are higher than equivalent sample depths in the Rathlin and Larne basins. This suggests that where the target reservoirs in the Lough Neagh Basin are deeper than this they may still contain significant porosity, although this may be confined to certain ‘sweet spots’ rather than throughout the sandstone reservoir units.

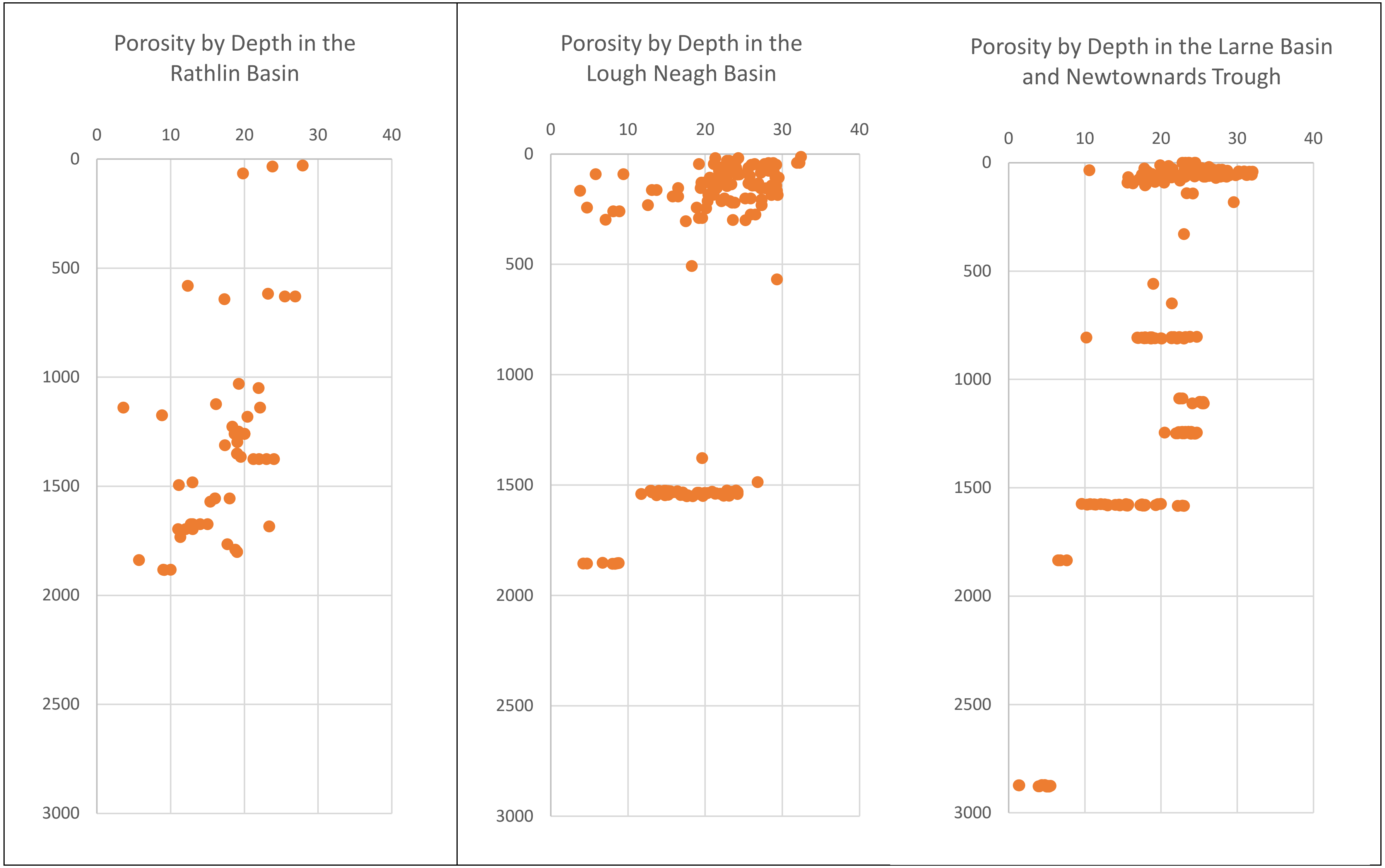


Figure 29. Porosity vs Depth measured from deep borehole samples

6. Geothermal gradients and the depth range of sandstones

6.1 Geothermal gradients

Geothermal gradients and heat flows within the Larne, Lough Neagh and Rathlin sedimentary basins are slightly above the average for Permo-Triassic basins in the UK which are usually quoted as 26°C/km and 52 mW/m^2, respectively (e.g. Busby 2010). The highest geothermal gradient is recorded in the Rathlin Basin whereas the other basins show significantly lower values (Table 4). Some of the difference may be the result of the borehole temperatures in the Larne and Lough Neagh basins being measured before the cooling effects of the drilling mud worn off, leading to an underestimation of the temperatures in the potential geothermal sandstone reservoirs. In the Rathlin Basin temperature measurements were taken in Port More and Ballinlea No. 1 several months or years after drilling was completed and, therefore, the temperatures were closer to the actual formation temperatures. However, the higher geothermal gradient calculated for the Rathlin Basin is believed to be real and is possibly the result of the Moho (the base of the crust) shallowing in a north-westerly direction towards the NW Atlantic Ocean, an effect suggested on the WINCH deep seismic reflection profile which runs offshore from the Hebrides through into the North Channel.

Basin	Rathlin	Lough Neagh	Larne
Gradient (°C/km)	35+/-2	32+/-2	28+/-2
Data source	Ballinlea & Port More temperature logs	Killary Glebe	Larne No. 2
Comments	Approximates equilibrium formation temperature at TD; logs run months or years after drilling	From temperature log; excludes anomalously high 55.2°C BHT; probably well below equilibrium temp.	Using calculated equilibrium temperature at 2876m (close to TD)

Table 4. Geothermal gradients estimated from deep borehole temperature readings

The temperatures in the Sherwood Sandstone, Permian and Carboniferous sandstones will depend on their depths and the geothermal gradient, such that the highest temperatures should be expected where they are deepest. However, there is often a general trend of decreasing reservoir quality with increasing depth, albeit that this may be influenced by other factors such as original composition, sedimentary facies and burial history, so that there is a trade-off between heat capacity and deliverability.

6.2 Depths of potential geothermal sandstone reservoirs

The depths of the potential geothermal reservoirs can be measured directly from deep boreholes but there are very few of them and they have usually been drilled as oil or gas exploration wells and, therefore, have been located on structural highs rather than in the deepest parts of the basins. In most areas seismic surveys are carried out to gain an understanding of the sub-surface geological structure but, again, there is relatively sparse seismic data and it is of insufficient quality and extent to enable the sedimentary basins to be fully mapped. However, other geophysical measurements can be used to model the sub-surface structure, with the well and seismic data providing control points and calibration for these models.

Figure 30 shows one such model where the gravity anomaly data have been used to derive a 3D model yielding estimates of the depth to the base of the Permo-Triassic rocks across the Antrim Plateau, including the Rathlin, Lough Neagh and Larne sedimentary basins. Although the model indicates clearly where the deepest parts of the basin are located, the interpretation of gravity data alone does not yield unique solutions and the resultant models are subject to uncertainties where the sedimentary basins have complex geological and tectonic histories and the sedimentary infill has a wide variation in density. This is the case with the concealed basins of Northern Ireland which have been subjected to repeated periods of subsidence and uplift and the main low density sedimentary sequence is overlain by a variable thickness of high density basaltic rocks, on which there may be localised basins of very low density clays and lignite of the Lough Neagh Clays Group. For example, the 3D model indicates that the deepest part of the Lough Neagh basin is situated under the northeast corner of the present-day lough which is most probably the case. However, the maximum depths to the base of the Permo-Triassic here – over 4 km – may be overestimated because gravity effect of the near-surface Lough Neagh Clays Group (which have very low densities) has not been fully reflected in the model.

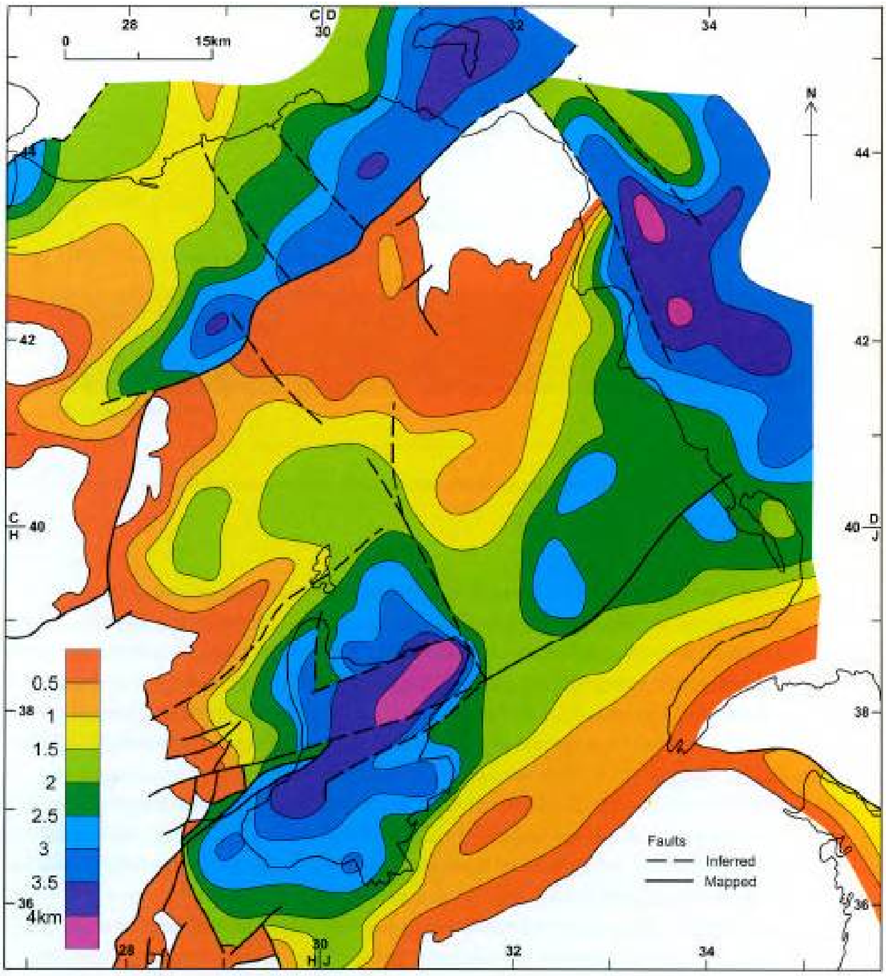


Figure 30. Depths to the base of the Permo-Triassic rocks of Northern Ireland, based on gravity modelling (Reay, 2004). Note: The greatest thicknesses shown may also reflect the presence of Carboniferous sedimentary rocks near the base of the sedimentary basins.

Nonetheless, the gravity model can be used with seismic data to extrapolate from known depths in wells to predict the depths of the sandstones in other locations. Table 3 gives estimates of the depth ranges for the Sherwood Sandstone Group and early Permian sandstones at four locations within the Lough Neagh (Antrim, Washing Bay), Rathlin (Ballymoney) and Larne (Ballylumford) basins, respectively. Although Ballymoney is in the basin with the highest geothermal gradient it is near Antrim where these geothermal reservoirs may be at their deepest. The results from the Annaghmore No. 1 well, near Toomebridge, also suggest that the early Permian sandstones in this part of the Lough Neagh Basin may have good reservoir potential at depths where temperatures greater than 80°C might be expected. The deepest parts of the Lough Neagh basin appear to beneath the SW and NE corners of the present-day lough so that a well drilled from south of Antrim town and deviating beneath Antrim Bay may be a suitable test of deep geothermal energy resources in this area. An alternative location worth investigating would be southwest of Lough Neagh, near Coalisland, where the sedimentary succession is downthrown to the east by the Drumkee and Killeen Faults. Here the SSG would be the primary target with deeper Carboniferous sandstones a secondary objective. Permian sandstones are expected to be thin in this area.

Location	Basin	Sherwood Sandstone		Permian/Carboniferous Sandstones	
		Top	Base	Top	Base
Antrim	LNB (NE)	2200	2650	2900	3200
Ballymoney	RB	1500	2000	2100	2300
Ballylumford	LB	650	1200	1700	2100
Washing Bay	LNB (SW)	1300	1700	1800	2300

Table 5. Predicted depths to Permo-Triassic geothermal reservoirs at selected locations (modified after Pasquali et al. 2008). Depths in metres below surface, estimates +/- 100m. Lower aquifer at Ballymoney may include Carboniferous sandstones which may be thicker than estimated here. Lower aquifer at Washing Bay is Carboniferous. Antrim depth estimates have been recalculated from inspection of seismic line UNR91-06. Lower aquifer interval at Ballylumford may include some non-productive rocks.

Deep boreholes provide direct measurements of the depth and temperature ranges for the potential geothermal sandstone reservoirs. These values must be considered as conservative, however, because most boreholes have been drilled on the flanks of the basins or, if they were hydrocarbon exploration wells, on structural highs within the basins. Figure 31 illustrates this point, showing the depth range of the different sandstone units found in boreholes across the three sedimentary basins.

In the Lough Neagh Basin, for examples, most of the borehole data comes from coal exploration boreholes drilled on the margins of the basin south or west of Lough Neagh. Of the deeper boreholes three were drilled north of the Lough (Ballymacilroy, Annaghmore and Ballynamullan), one on the eastern shore (Langford Lodge) and one to the southwest (Killary Glebe) – but none of these were drilled in the deepest parts of the basin. Similarly, only three deep boreholes have been drilled in the Rathlin Basin (Magilligan, Port More and Ballinlea No. 1) but these are all located well away from the basin-bounding faults near where the deepest sedimentary sequence may be expected (from the interpretation of seismic and gravity data). By way of contrast, the Larne No. 2 geothermal exploration borehole was drilled in one of the depocentres of the Larne Basin but the Permo-Triassic sequence here was atypical with thick salt beds, relatively poor quality sandstone reservoirs and a thick Permian volcanic sequence. The background to Figure 31 is shaded light and dark pink to show the predicted depths where the reservoir fluids are predicted to be below 60°C and 90°C, respectively, in the three basins.

Although this shows that the Rathlin Basin has the highest geothermal gradient (and this believed to be a real effect), the geothermal gradients in the other two basins may be underestimated because the measured well temperatures used to derive them may not have reached equilibrium with the formation water temperatures. It should be noted that the equilibrium temperature at the bottom of the Ballinlea No. 1 well (2650m) is estimated to be about 100°C +/-2°C from an extrapolation of the temperature log run in 2015. The End of Well temperature log run in 2008 recorded maximum temperatures of 95°C but a higher temperature of 97.8°C was recorded at 2565m on re-entering the well for testing in March 2009, and the 2009 temperature log recorded values that were more than 5°C higher than those at the same depths on the original log, down to the top of the cement plug at 2257m depth.

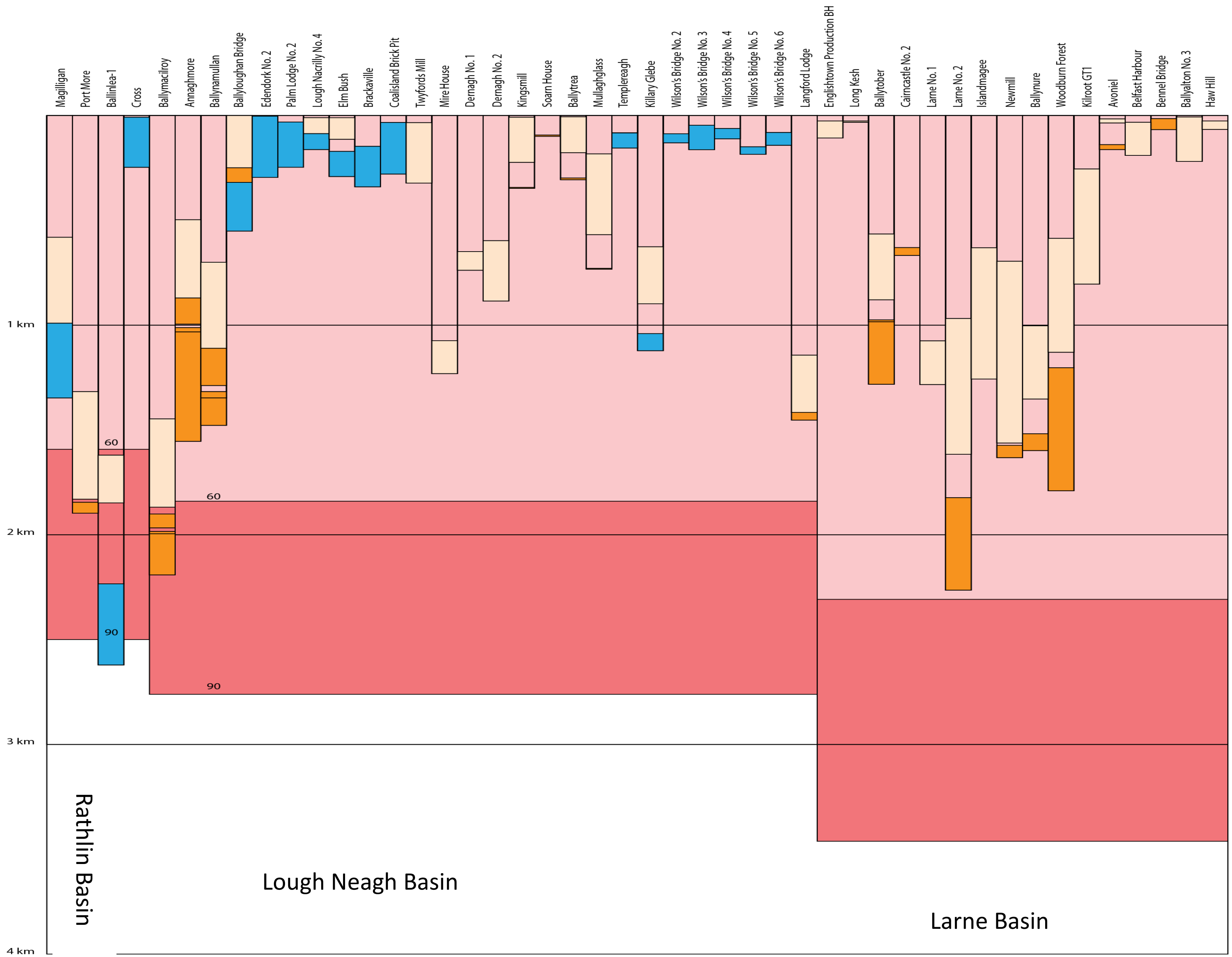
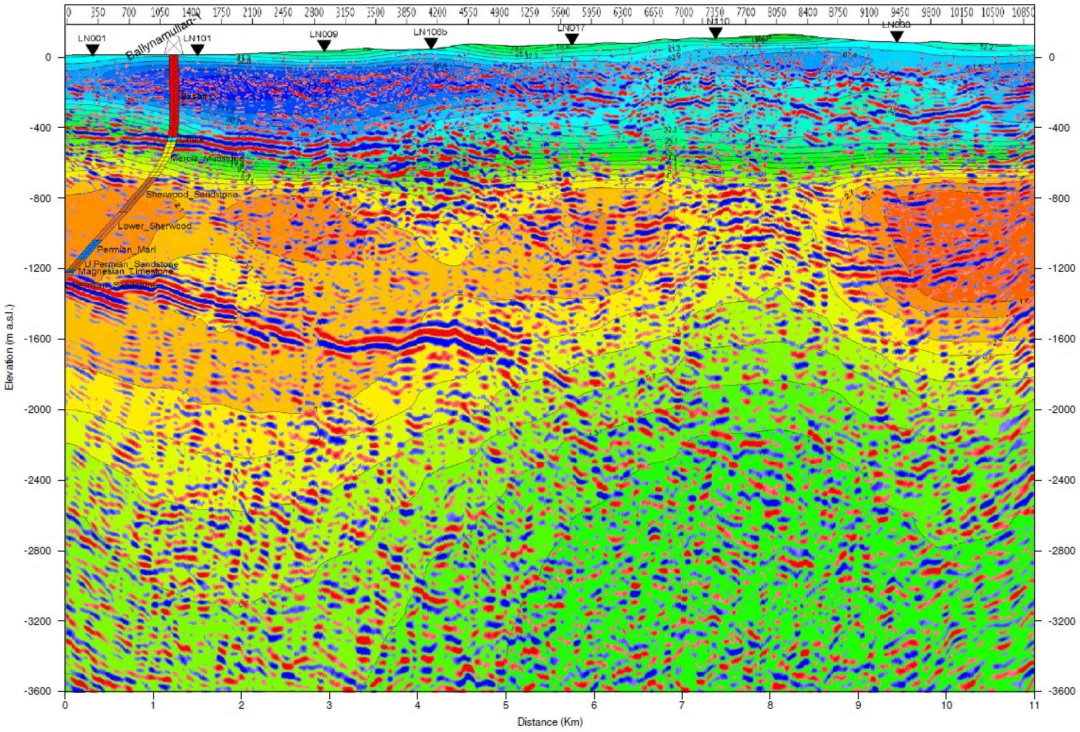


Figure 31. Measured and estimated depths and temperatures for Carboniferous (blue), Permian (dark orange) and Triassic (light orange) sandstones in the Rathlin, Larne and Lough Neagh sedimentary basins (Left to Right). Note: the deepest parts of the basins are undrilled, with the exception of the Larne basin where Larne No. 2 reached TD at 2880 metres in Permian volcanics.

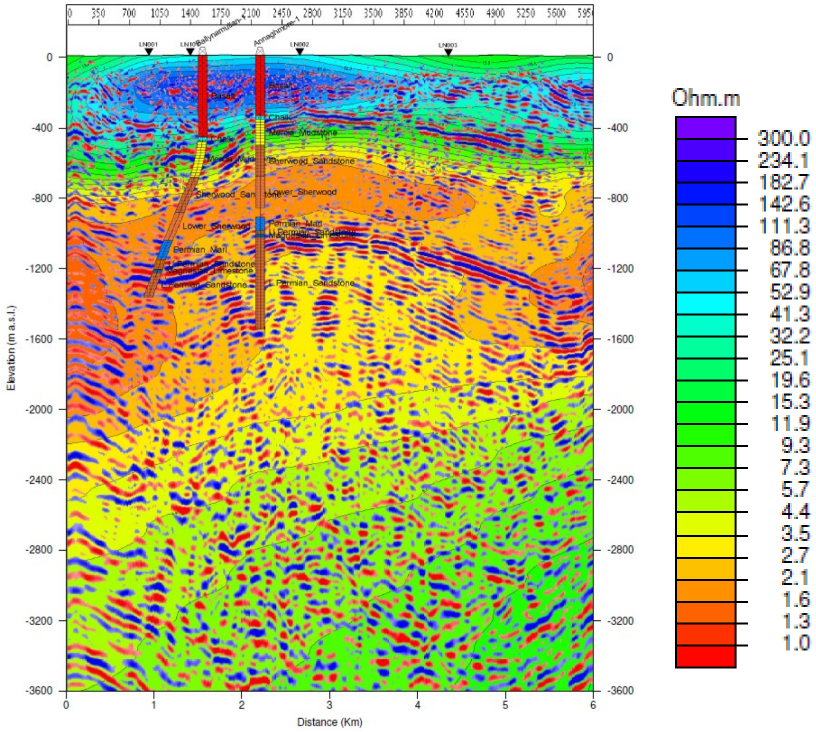
The results from an MT (magneto-telluric) survey across the area between Toomebridge and Randalstown north of Lough Neagh, commissioned by GSNI in 2008, have been modelled using 3D inversion techniques (Geosystem 2009) to show the subsurface distribution of low resistivity values – i.e. the presence of permeable reservoir rocks. The results of the 3D modelling were presented both as N-S and E-W 2D cross-sections and as depth slices at 500 metre intervals. In addition to this Geosystem produced overlays of re-processed 2D seismic lines on 3D MT inversion data, with well control in places.

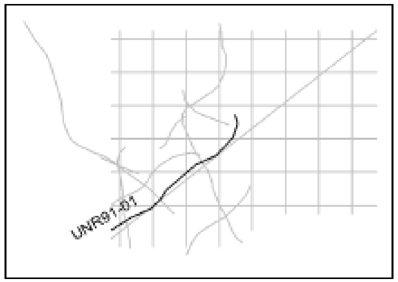
Figure 32 illustrates two of the combined seismic and MT displays for seismic lines UNR91-01 & 02, which pass close to the Annaghmore and Ballynamullan exploration wells. There is a good correlation between the low resistivity layers from the MT models (orange to yellow colours) with the Triassic Sherwood Sandstone Group and the Upper and Lower Permian sandstones proved in the wells and interpreted on the seismic sections. A strong reflector, corresponding to the Magnesian Limestone, separates the intervals containing the Upper Permian and Lower Permian sandstones, but the orange to yellow low resistivity layers extend both above and below this reflector, suggesting that both sandstone intervals contain potential geothermal reservoirs. It is also noteworthy that, although the Annaghmore and Ballynamullan wells were drilled on the crest and flank of a structural high respectively, line UNR91-02 suggests that the conductive sandstone layers deepen further southwards, towards Lough Neagh, as predicted from the gravity anomaly data. With a station spacing of approximately one MT station per 1.5 km^2, the 3D magnetotelluric model does not have the spatial resolution of a seismic reflection survey. However, the MT survey data can be used to extrapolate the subsurface geological structure derived from seismic data into areas where this data is not available, and it can be used to derive information about the electromagnetic properties of the rocks within sedimentary basins. It can be considered to be a cost-effective reconnaissance exploration tool for deep geothermal energy resources.

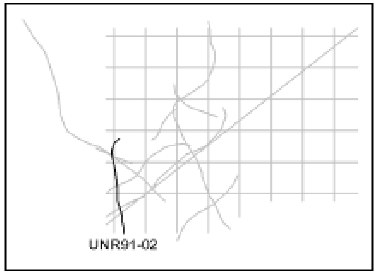
SW SEISMIC LINE UNR91-01 NE



S SEISMIC LINE UNR91-02 N







Vertical exaggeration 2

Vertical scale range: 0 (mean sea level) – 3600 m; tick interval 400m

Horizontal scale range: 0 – 11km (UNR91-01), 0 – 6km (UNR91-02); interval 1km

Annaghmore & Ballynamullan wells projected onto section (slight mismatch for deviated Ballynamullan well)

Figure 32. Depth-converted PSTM Seismic sections displayed on 3D Magneto-telluric (MT) blind inversion data (from Geosystem, 2009)

7. Conclusions

The review of published and unpublished poroperm data available to GSNI show that Carboniferous, Permian and Triassic sandstones have variable, but good, reservoir potential. Pumping test results from shallow water production boreholes in the Permian Enler Group and Triassic Sherwood Sandstone Group (SSG) aquifers in the Lagan Valley and the Newtownards Trough show that these sandstones can be prolific aquifers. Commercial enterprises such as Coca Cola and the Diageo Group have demonstrated that the Sherwood can sustain significant abstraction rates.

Analyses of core samples from deep boreholes, together with detailed microscopic examination of the petrography of these sandstones, indicate that good reservoir properties extend to depth. The petrographic studies help to elucidate the diagenetic history of the rocks, revealing the sequence of cement precipitation and dissolution that can lead to initial reduction and subsequent increases in porosity and permeability, respectively. As expected there is a general decrease in porosity and permeability with depth but the data indicate that reservoir intervals with good poroperm values are still present at depths of 1000 to 1500 metres. The upper part of the Triassic Sherwood Sandstone Group appears to be the most promising reservoir although Carboniferous sandstones in the Rathlin Basin show evidence of secondary porosity that increases their potential. The Permian Enler Group sandstones show a greater variability in thickness and lithologies, probably as a result of deposition in more proximal sedimentary environments. In places, however, high porosity and permeability values are recorded from the Permian at shallow depths in the Newtownards areas and occasionally from core material in deep boreholes (e.g. Newmill No. 1) so it may be a valid secondary target.

The geographical variability in the aquifer properties of the Sherwood Sandstone is still quite poorly understood and it would be useful to acquire more production data from existing abstraction sites, particularly large users who are likely to monitor aquifer performance on a continuous or regular basis.

There is a relative lack of borehole data on which to base structural depth and thickness maps of the potential geothermal reservoir units so these data should be supplemented by geophysical data. Seismic reflection data, the geophysical data type most commonly used for subsurface geological mapping is sparse and data quality is moderate to poor where thick basalts overlie the sedimentary basins. However, magnetotelluric (MT) surveying is a low cost geophysical method which can provide useful 1D, 2D and 3D models of subsurface electrical conductivity which can be used to differentiate reservoir and non-reservoir rock units. MT survey data in the northern part of the Lough Neagh Basin shows good correlation with co-located 2D seismic reflection data and can be used to extrapolate depth models into areas without seismic data, with a reasonable degree of confidence. It is recommended that the available geophysical data (including from relatively recent seismic, MT, gravity and aeromagnetic surveys) are integrated with borehole data to produce 3D geological models of the sedimentary basins, building on the existing National Geological Model.

Other parameters pertinent to the prediction of geothermal aquifer potential are the geothermal gradients and the thermal conductivities of the reservoirs themselves and the overlying rock strata. Thermal conductivities can be measured directly on core samples using specialist equipment and such data are generally restricted to values derived from a small number of selected samples only. A more systematic programme of thermal conductivity measurements could be integrated with analysis of borehole temperature logs to produce thermal conductivity – depth models. Where the temperature log data is of sufficient quality and other pertinent information is available, it may be possible to provide more accurate estimates of the equilibrium temperatures and, thus, be able to model the geothermal gradients with greater confidence. Corrections for the effects of topography and palaeoclimate can also be applied where appropriate.

The geothermal energy resource potential of deeply buried sandstone units has been recognised for many years and this study has brought together new and existing data about the reservoir quality of these rocks. The next stages in the development of geothermal energy systems in Northern Ireland should probably involve a three-pronged approach – the deployment (and monitoring) of shallow aquifer heat pump systems, the continued characterisation and modelling of deep geothermal reservoirs and the development of a demonstration project involving the use of a deep geothermal aquifer to provide a direct heating source to a heat network. As this would be the first deep geothermal energy project in Northern Ireland it would be unrealistic to expect the private sector to instigate it and take on the entirety of the commercial risks involved. Some financial support from funding sources such as INTERREG and a government-backed insurance scheme to cover technical risks (such as are operated in France, the Netherlands and Denmark) would be required.

8. Recommendations

The following recommendations are proposed as a result of this study:

1. GSNI carries out an integrated study into the geological structure of the Rathlin, Lough Neagh and Larne sedimentary basins. This study would use existing geophysical and borehole data to produce detailed 3D models of the deep geothermal reservoir targets.
2. A systematic programme to measure the physical properties of rock units in Northern Ireland relevant to the characterisation of geothermal reservoir potential. This would include new measurements of thermal conductivity and analysis of existing log and production data.
3. GSNI to work with DfE Energy to secure inclusion of geothermal energy (shallow and deep) into new energy, sustainability and decarbonisation strategies. Scope the potential for deployment of shallow geothermal energy systems in the public estate (government departments, Housing Executive, InvestNI).
4. GSNI to engage with Local District Councils (e.g. Antrim, Mid-Ulster) and potential end-users to explore their appetite for involvement in a pilot/demonstration deep geothermal energy and heat network project. Heat demand mapping should help identify major users of heating and cooling. Partners to investigate funding sources.

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