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Appendix 3: An assessment of the potential for subsurface CO₂ storage in the Celtic Sea Basin

Energy Programme

Commissioned Report CR/14/134

BRITISH GEOLOGICAL SURVEY

ENERGY PROGRAMME

COMMISSIONED REPORT CR/14/134

Appendix 3: An assessment of the potential for subsurface CO₂ storage in the Celtic Sea Basin

C J Vincent, K L Kirk and T C Pharaoh

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British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143

Fax 0115 936 3276

email enquiries@bgs.ac.uk

Environmental Science Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241

Fax 0115 936 3488

email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

Tel 0131 667 1000

Fax 0131 668 2683

email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD

Tel 020 7589 4090

Fax 020 7584 8270

Tel 020 7942 5344/45

email bgs london@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE

Tel 029 2052 1962

Fax 029 2052 1963

Maclea Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800

Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

Tel 028 9038 8462

Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500

Fax 01793 411501

www.nerc.ac.uk

Website www.bgs.ac.uk

Shop online at www.geologyshop.com

Foreword

This report is the published product of a study by the British Geological Survey (BGS) and was undertaken under the joint BGS and Geological Survey Ireland (GSI) Irish Sea Carbon Capture and Storage project.

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Summary

This report describes work carried out as part of the British Geological Survey (BGS) and Geological Survey Ireland (GSI) joint Irish Sea Carbon Capture and Storage (CCS) project. It focuses on a well-defined area of 2D seismic in the UK and Irish sectors of the Celtic Sea basin. The work identified 23 small closed structures within selected potential reservoir horizons with an estimated storage volume of 4 – 24 MtCO₂. After further analysis most of these closures were considered unfavourable for storage when depth, reservoir quality and seal quality were also taken into consideration. Unconfined aquifer storage could be considered in the Sherwood Sandstone Group or the Bathonian strata and Inferior Oolite Group reservoir sequence but this option would require detailed flow simulations to assess the likelihood of CO₂ reaching a natural or manmade migration pathway out of the storage complex. Unconfined aquifer storage would also be expected to require greater financial reserves to meet the requirements of the EU Storage Directive/National Competent Authority(ies) when applying for a storage licence. This is due to the enlarged size of the storage complex and consideration of secondary formations that the CO₂ could migrate into and need to be considered in contingency planning.

This study used existing data to assess the potential for storage in the northern region of the Celtic Sea basins. Additional data, including sampling, experimental testing of reservoir and seal cores, new 3D seismic and well data would need to be acquired over areas being considered for storage before any recommendations for potential storage sites could be made.

1 Introduction

This report results from work carried out as part of the co-funded Irish Sea Carbon Capture and Storage Project between the Geological Survey of Ireland (GSI) and the British Geological Survey (BGS). The project began in October 2011 and is now complete. The overall aim of this work was to create a seamless integrated knowledge resource of Ireland-UK Irish Sea CCS opportunities to facilitate informed decision making.

This project follows on from the ‘All Ireland Study’ (Lewis et al., 2008) – a high level study using publically available data to calculate the theoretical capacity for the subsurface storage of CO₂ both offshore and onshore Ireland (Figure 1). The All Ireland study identified that the North Celtic Sea Basin had potential for storage in the Greensand Group A and B sands, Wealden Sandstones and Sinemurian sandstone and that the South Celtic Sea Basin had potential for storage in the Sherwood Sandstone Group and Wealden Sandstones. The All Ireland study calculated a promising maximum theoretical capacity in the Celtic Sea Basin, but indicated that more detailed work would be needed to better understand the storage potential and risks of storage. This report summarises the results of recent investigations to achieve this.

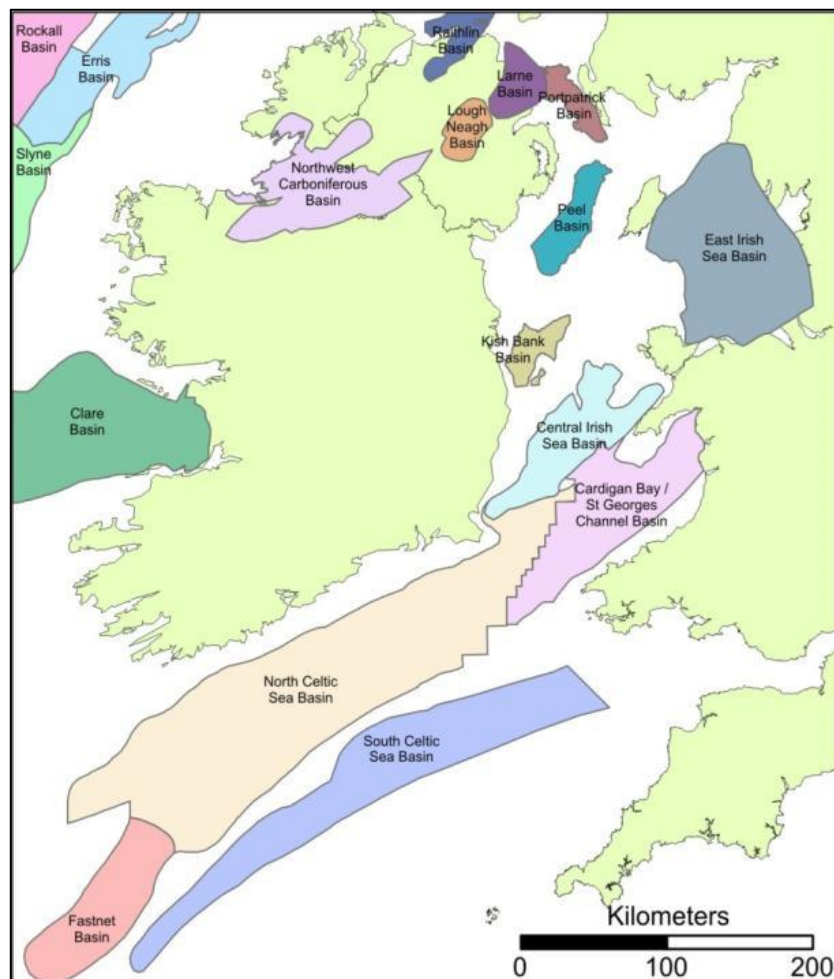


Figure 1: Sedimentary basins around Ireland

2 Regional setting and stratigraphy

The Celtic Sea Basin is a major Mesozoic basin in the Irish offshore area. The basin is divided into the North and South Celtic Sea basins. The North Celtic Sea Basin splits at the North-east end into the Cardigan Bay/St George's Channel and Central Irish Sea half-graben basins (Figure 2). Water depths vary between 90 and 150 m. The North Celtic Basin is approximately 330 km long (including the Cardigan Bay/St George's Channel extension) by 70 km wide and the South Celtic Basin is approximately 360 km long by 40 km wide.

Closure of the Iapetus Ocean during the Caledonian Orogeny (Late Silurian to Early Devonian times) resulted in a NE-SW regional structural trend. Post-orogenic extension began during the early Devonian and continued until the early stages of the Variscan Orogeny during the early Carboniferous. Convergence structures from earliest Carboniferous times follow a NW-SE trend changing to a more E-W trend for the late Carboniferous Period (Rowell, 1995). Deposition began after the Variscan Orogeny in Permian to Triassic times. The Celtic Sea Basin represents a major Jurassic – Cretaceous subsidence centre (Ziegler, 1987a). It comprises northern and southern basins which are separated by the Pembroke Ridge (Figure 2). The structural trends were set during the Caledonian and Variscan orogenies and these pre-existing lines of structural weakness were reactivated during subsequent Triassic, Late Jurassic and Early Cretaceous rifting (Rowell, 1995).

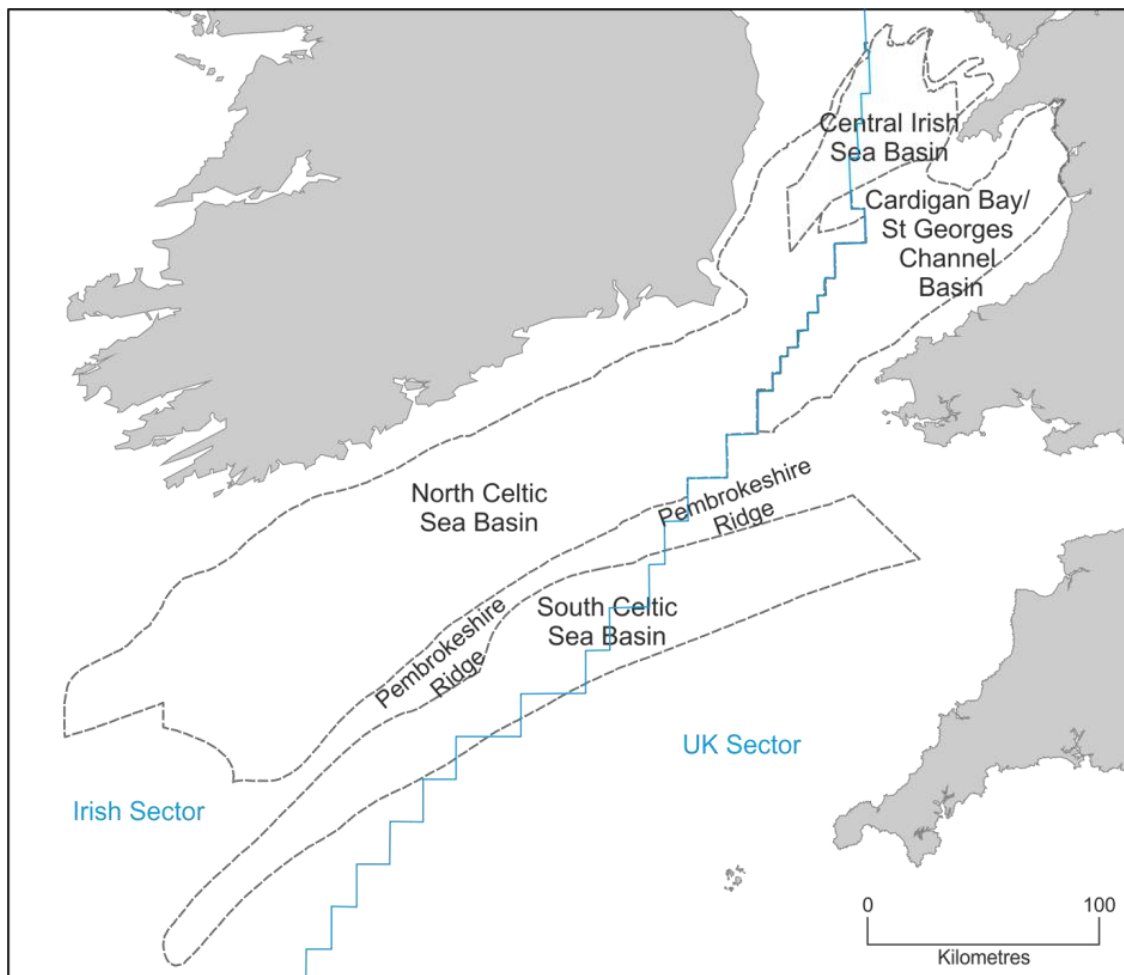


Figure 2: Map showing location of the Celtic Sea Basin

The seismic interpretation and depth conversion carried out for this report suggest that a maximum sedimentary thickness of around 11 km is achieved in the centre of the basin with strongly fault-controlled deposition of Permo-Triassic to Cretaceous sediments. The thickness and distribution of reservoir and seal formation is also controlled by periods of erosion and non-

deposition. Widespread erosional surfaces are observed at the base of the Triassic, the base of the Cretaceous and the base of Cenozoic deposits, however, locally, erosional surfaces are also observed in the Jurassic sediments where potential reservoir and seal surfaces have been removed.

The all Ireland study of CCS potential suggested good storage potential for the Celtic Sea Basin based on public-domain structural map data and several closed structures which were identified during the all Ireland study.

During this study, seismic and well data in part of the Celtic Sea Basin were assessed so as to improve understanding of the nature and extent of any potential storage structures and to assess any risks to potential storage sites.

The primary reservoir targets for CO₂ storage are the Triassic Sherwood Sandstone Group (largely equivalent to the Bunter Sandstone Group in the Southern North Sea), sandstones in the Jurassic Sinemurian strata, Inferior Oolite Group, Bathonian and Callovian strata and the Lower Cretaceous B and A sands. These reservoir horizons show variable thickness across the Celtic Basin and are absent in some places due to erosion. Potential reservoir and seal horizons are outlined in Figure 3. The reservoir properties were assessed against recommendations made by Chadwick et al. (2008) for positive indicators for a storage site (Table 1) **Error! Reference source not found.** For this study, only reservoir horizons below 800 m depth were considered as this is the cautionary limit such that CO₂ is likely to be in its dense phase for efficient storage. It should be noted that within the region selected for detailed study for this report (Figure 4), the strata younger than Bathonian in age are generally too shallow for storage and have only been described for completeness within this section.

Table 1 Indicators for successful geological storage sites (after Chadwick et al., 2008).

	Positive indicators	Cautionary indicators
Reservoir efficiency		
Static Storage Capacity	Estimated effective storage capacity much larger than total CO ₂ to be injected.	Estimated effective capacity similar to total amount of CO ₂ to be injected.
Dynamic storage capacity	Predicted injection-induced pressures well below levels likely to induce geomechanical damage to reservoir or caprock.	
Reservoir Properties		
Depth	>1000 m <2500 m	<800 m >2500 m
Reservoir thickness	>50 m	<20 m
Porosity	> 20%	<10 %
Permeability	> 500 mD	<200 mD
Salinity	> 100 gl ⁻¹	<30 gl ⁻¹
Stratigraphy	Uniform	Complex lateral variation and complex connectivity of reservoir facies.
Caprock efficiency		
Lateral continuity	Stratigraphically uniform, small or no faults.	Lateral variations, medium to large faults.
Thickness	> 100 m	<20 m
Capillary entry pressure	Much greater than the maximum predicted injection induced pressure increase.	Similar to maximum predicted injection-induced pressure increase.

The youngest sediments deposited during the Carboniferous Period comprise red-brown sandstones which are at times interbedded with claystones and siltstones. Core data indicate a relatively low porosity (5 – 7%) and very low permeability (<0.01 – 0.03 mD).

The age of the Sherwood Sandstone Group sediments is not well documented, but the oldest are believed to be in the St George's Channel Basin and are of Permian age (well geological report for UK 107/01-01) and of Triassic age in the North Celtic Basin (Shannon, 1995). The Sherwood Sandstone Group was deposited in a fluvial environment and has low porosity (average 8 %) and low permeability (average 0.65 mD) and as this is not the main hydrocarbon reservoir target, few samples are available. Cores from individual sandstone bodies indicated porosities of up to 12% and permeabilities up to 7.6 mD. The Sherwood Sandstone Group is sealed by the overlying Mercia Mudstone Group deposited in a playa lake/sabkha environment, which in places includes thick evaporite deposits.

Sandstones of Upper Sinemurian age are part of the Lower Jurassic Lias Group. Kessler and Sachs (1995) describe the Upper Sinemurian sandstone interval as comprising sandstone with some siltstone, claystone and limestone deposited in a marine shelf environment. Analysis of cores available to this report indicates an average porosity of 9% (though the lithology of the Sinemurian strata in the St George's Channel Basin comprises of mainly mudstone lithologies so is unlikely to be prospective for storage). Cores from sandstone bodies in the Sinemurian sandstone indicate porosities up to 23% and permeabilities up to 198 mD. The Sinemurian strata are expected to be sealed by the overlying Lias shales/claystones deposited in a low energy shelfal environment though in some areas the overlying deposits comprise siltstones so the caprock would need further assessment to improve confidence in security of storage.

Age	Stratigraphical Group	Reservoir/seal strata
U. Cretaceous	Chalk Group	
L. Cretaceous	Greensand Group	Gault Clay A Sand
	Wealden Group	Lower Claystone B Sand
	Purbeck Group	
	Portland Group	
M to U Jurassic	Ancholme Group	Kimmeridge Clay Oxford Clay Callovian
	Great Oolite Group	Bathonian sandstones
	Inferior Oolite Group	Inferior Oolite Group reservoir sequence (Bajocian - Aalenian)
L Jurassic	Lias Group	Lias shales (Aalenian - Pliensbachian) Sinemurian sandstones
Triassic	Penarth Group	
	Mercia Mudstone Group	Mercia Mudstone Group
	Sherwood Sandstone Gp	Sherwood Sandstone Gp
Carboniferous	Westphalian	

Figure 3: potential reservoir and seal horizons of the Celtic Sea Basin

The Inferior Oolite Group sandstones of Aalenian – Bajocian age were deposited during late Aalenian to early Bajocian times in a marine shelf environment. These sandstones are generally off-white and include interbedded limestones in places. The Inferior Oolite Group reservoir sequence has an average porosity of 13% based on log analysis. Where indicated on well logs, Bajocian strata are overlain by Bathonian strata deposited in a marine shelf environment.

The late Bathonian limestone deposited on a carbonate ramp may have some reservoir potential as gas shows were identified in block 49/9 (Helvick oil accumulation, Irish Sector). Bathonian sandstones have porosities averaging 8 – 13% and permeabilities averaging 0.54 mD with individual core datapoints indicating porosities up to 16% and permeability up to 1.9 mD in porous layers. It should be noted that in places potential sealing formations have been eroded, in some areas Cenozoic and recent deposits directly overlie potential reservoir formations, placing the presence of an effective seal in doubt.

The Callovian strata, laid down in an alluvial – fluvial environment, comprise sandstone and claystone beds. Callovian sandstones generally have good porosity (average 20%) based on well data. The overlying Upper Jurassic strata, including the Oxford Clay Formation, Kimmeridge Clay Formation and Tithonian strata which comprise lacustrine/lagoonal claystones, sandstones and limestones could offer a local seal where claystone dominates. In some areas of the Celtic Sea, the Kimmeridge Clay Formation is a proven seal for hydrocarbon accumulations in other regions (e.g. Helvick oil accumulation) so it could offer an effective local seal where present. Based on the variable presence and lithology of the top seal in the Celtic Sea Basin, the seal must be examined in detail when assessing potential storage sites.

The Cretaceous B sand of Aptian – Albion age (Wealden Group to lowest Lower Greensand Group) was deposited in a fluvial-estuarine environment and shows good reservoir properties (average porosity 25%, permeability 280 mD). The B Sand is potentially sealed by the lower Claystone lowermost Lower Greensand Group. The Cretaceous A Sand of Albion age shows good reservoir properties (average porosity 17%, permeability 420 mD). The A Sand is potentially sealed by the Gault Formation and Upper Greensand Formation.

Gas and oil are produced from the Cretaceous strata (including A and B sands) and Mid - Upper Jurassic sediments (including Callovian – Oxfordian age sandstones and Late Bathonian limestones).

3 Selection of the detailed study region

The ‘All Ireland’ CCS project identified that the Celtic Sea Basin had the potential to store CO₂. The aim of this study was to look in more detail at the storage potential of the Celtic Sea Basin. Seismic and well data were obtained from the Petroleum Affairs Division of Ireland's Department of Communications, Energy and Natural Resources (PAD) with coverage across Irish waters. Additional seismic data were obtained from BGS' existing interpretation projects, along with well data obtained from the Common Data Access portal (www.ukdeal.co.uk).

The initial task in this project was to undertake seismic interpretation across the whole of the Celtic Basin, with the aim of identifying potential reservoirs and closures for utilisation as CO₂ stores. A coarse grid interpretation was produced over the whole basin to provide an overview of the potential reservoirs and the basin structure. Using the coarse grid as a guide it was decided to focus in more detail on the north region of the North and South Celtic basins adjacent to the Central Irish Sea Basin to avoid potential conflicts with ongoing oil and gas exploitation (see Figure 4 for outline of the detailed study region). In this detailed study region, the Sherwood Sandstone Group and Bathonian strata, Inferior Oolite Group and Carboniferous strata were identified as lying at suitable depth for storage (>800 m) and having broad geographical coverage so these formations were chosen for assessment in the detailed study region.

4 Data

4.1 SEISMIC DATA

There are a number of 2D seismic surveys which together extend across the northern Celtic Basin. Twenty 2D seismic surveys and one 3D seismic datasets were loaded into Petrel v10.1 (Figure 4). They largely cover the northern parts of the North and South Celtic Sea basins. The quality of these surveys is variable due to the different vintages of data.

The seismic data within the region chosen for detailed study are given in Table 2

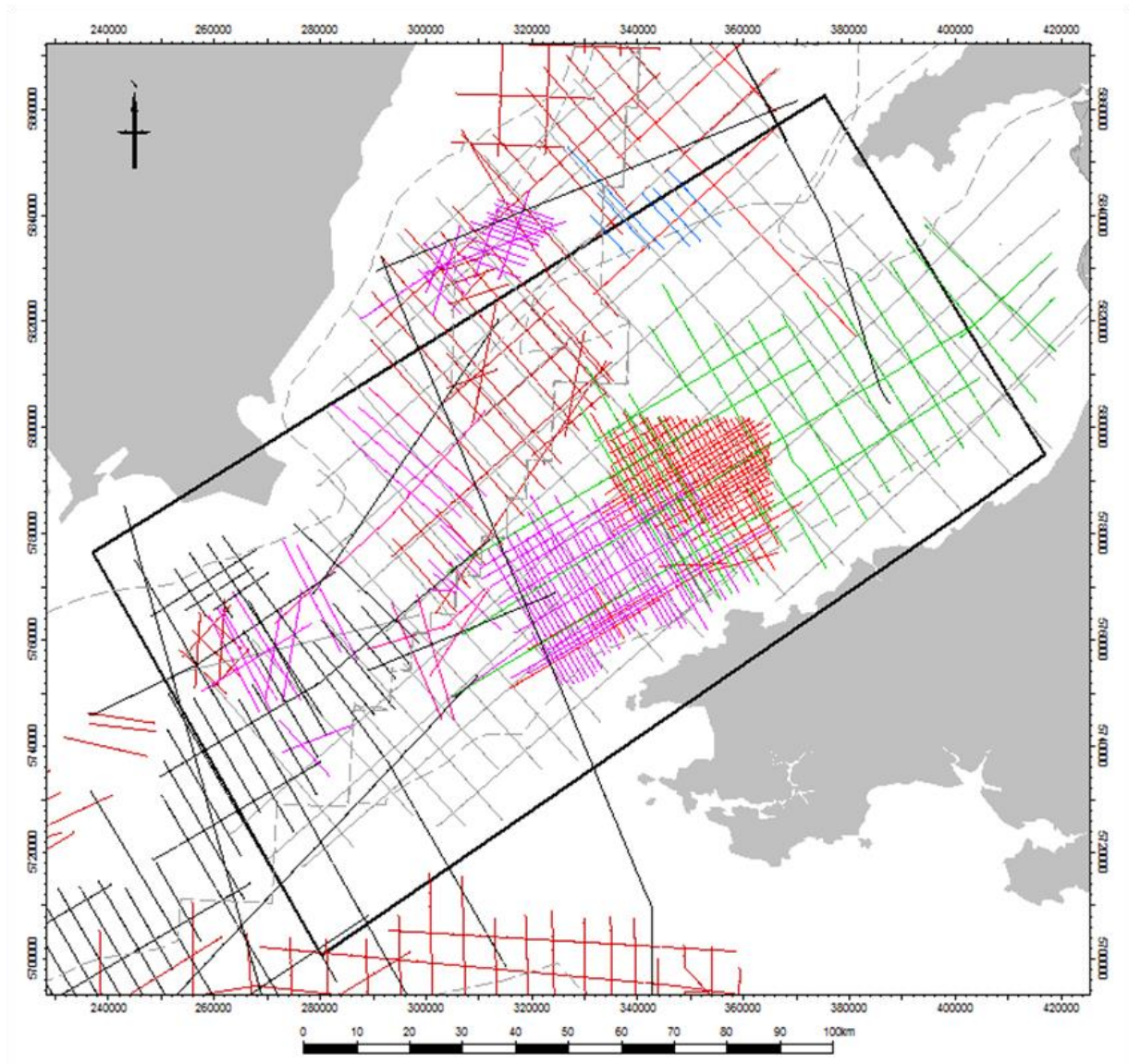


Figure 4: Location of available seismic data (coloured lines) in the region. Coastlines shown in grey (ESRI data) and basin outlines shown with dashed grey lines provided (© BGS). Black rectangle shows region of detailed study.

Table 2: Seismic data used for detailed interpretation in part of the Celtic Sea Basin

Seismic survey	vintage
Western Geco 1983 – IS; Lines 01 – 46	1983
M89_u30; Lines 4203 – 4222 and 4802 – 4814 and 4901 – 4987 and 5001 – 5014	1989
JSM-92; several lines between 30 – 47 and several lines between CBB-02A -24A,B	1992
CB92; several lines between 02 – 45 (Irish Sector)	1992
MIL-94-u30; most lines between 01 – 74	1994
Premier P4142 1994; Most lines 01 – 29	1994
M95 – 103 – u30; most lines 04 – 12	1995
Elf Caledonia and British Gas 106962D; lines 01 – 06	1996
Marathon M96 – 106; lines Most lines 02 – 17A	1996
UK96; most lines HR18 – 55 and 01 – 22	1996
UK940; Majority of lines 01 – 70 (amplitudes)	1994
MIL94; most lines 17 – 24 (amplitudes) and 76	1994
MIL_90_100 to 104_u30	1990
BIRPS SWAT 0 to 5 and WINCH 4	1981-88
MPCR84 02 to 43; 16 lines loaded	1984
MPCE84 01 to 61; 46 lines loaded	1984
3D survey NO5003_02	1996

4.2 WELL DATA

Of the 109 wells evaluated in the Celtic Sea Basin, only 64 have geophysical well logs available and so can be used for interpretation. There are 18 wells within the detailed study area, 4 of which do not have checkshot data. An additional 13 wells near the detailed study area were also referenced. The wells in the detailed study area are named in Table 3 and detail on the availability of log data is given.

Well data quality is variable and in some cases checkshot data are not available and so the wells could not be tied in time to the seismic data to assist in the interpretation. The wells in the detailed study area are shown in Figure 5.

Table 3 Available well data

Well	Checkshot data	Composite	GR	Sonic	Density (RHOB etc)	Neutron porosity (NPHI)	Geological well report	Comments
UK 103/01- 1	Yes	✓	✓	✓			✓	Cores taken in Late Bathonian, Bajocian, Toarcian to Aalenian, Pliensbachian, Sinemurian, Hettangian strata. Terminates in Mercia Mudstone Group.
UK 103/02- 1 & 1B	No	✓	✓	✓	✓	✓	✓	Core taken in Bajocian, Sherwood Sandstone Group and Westphalian strata. Terminates in Westphalian D strata.
UK 106/18- 1	Yes	✓	✓	✓			✓	Hardcopy core log. Core taken in Sherwood Sandstone Group. Terminates in Upper Coal Measures equivalent.
UK 106/20- 1	No	✓	✓	✓				Hardcopy core logs. Core taken in Coal Measures. Terminates in Coal Measures.
UK 106/24- 1	Yes						✓	No digital logs available for project, hardcopy core logs. Core taken in Lower Oxfordian/Bathonian strata. Terminates in Bathonian strata.
UK 106/24a- 2, 2A and 2B	No		✓		✓	✓		No Composite log available. Cores in Upper Jurassic. Terminates in Mercia Mudstone Group.
UK 106/28- 1	Yes		✓	✓	✓	✓	✓	No digital logs available for project, geol field log & stratigraphical log. Core taken in MMG. Terminates in Triassic Sherwood Sandstone Group.
UK 107/01 - 1	Yes	✓	✓	✓			✓	Just outside area. Cores taken in Triassic and Permian Sherwood Sandstone Group. Terminates in Permian Sherwood Sandstone Group.
UK 107/16- 1	No	✓	✓	✓				No digital logs available for project. Cores taken in Bajocian, Aalenian and Aalenian/Toarcian strata. Terminates in Aalenian/Toarcian strata.
UK 107/21- 1	Yes	✓	✓	✓	✓		✓	No digital logs available for project, porosity estimated from logs by operator. Terminates in Toarcian strata.
IR 41/30-1	Yes	✓	✓		✓	✓	✓	Terminates in Mercia Mudstone Group.
IR 42/16- 01	Yes	✓	✓	✓	✓	✓	✓	Core taken in Sherwood Sandstone Group and Carboniferous strata. Terminates in Carboniferous strata.
IR 42/17- 01A	Yes	✓	✓		✓	✓	✓	Terminates in Visean strata.
IR 42/21-1	Yes	✓	✓	✓	✓		✓	Terminates in Lower Jurassic strata.
IR 50/10-1	Yes	✓	✓	✓	✓		✓	Core in Bathonian strata. Terminates in undifferentiated Triassic below marked Sherwood Sandstone Group equivalent.
IR 50/3-1	Yes	✓	✓	✓	✓		✓	Terminates in strata of Sinemurian – Pliensbachian age.
IR 50/3-2	Yes	✓					✓	No digital logs available for project. Core taken in Bathonian strata. Terminates in early Bathonian strata.
IR 50/3-3	Yes	✓	✓	✓	✓		✓	RFT permeability available. Terminates in Sherwood Sandstone Group equivalent.

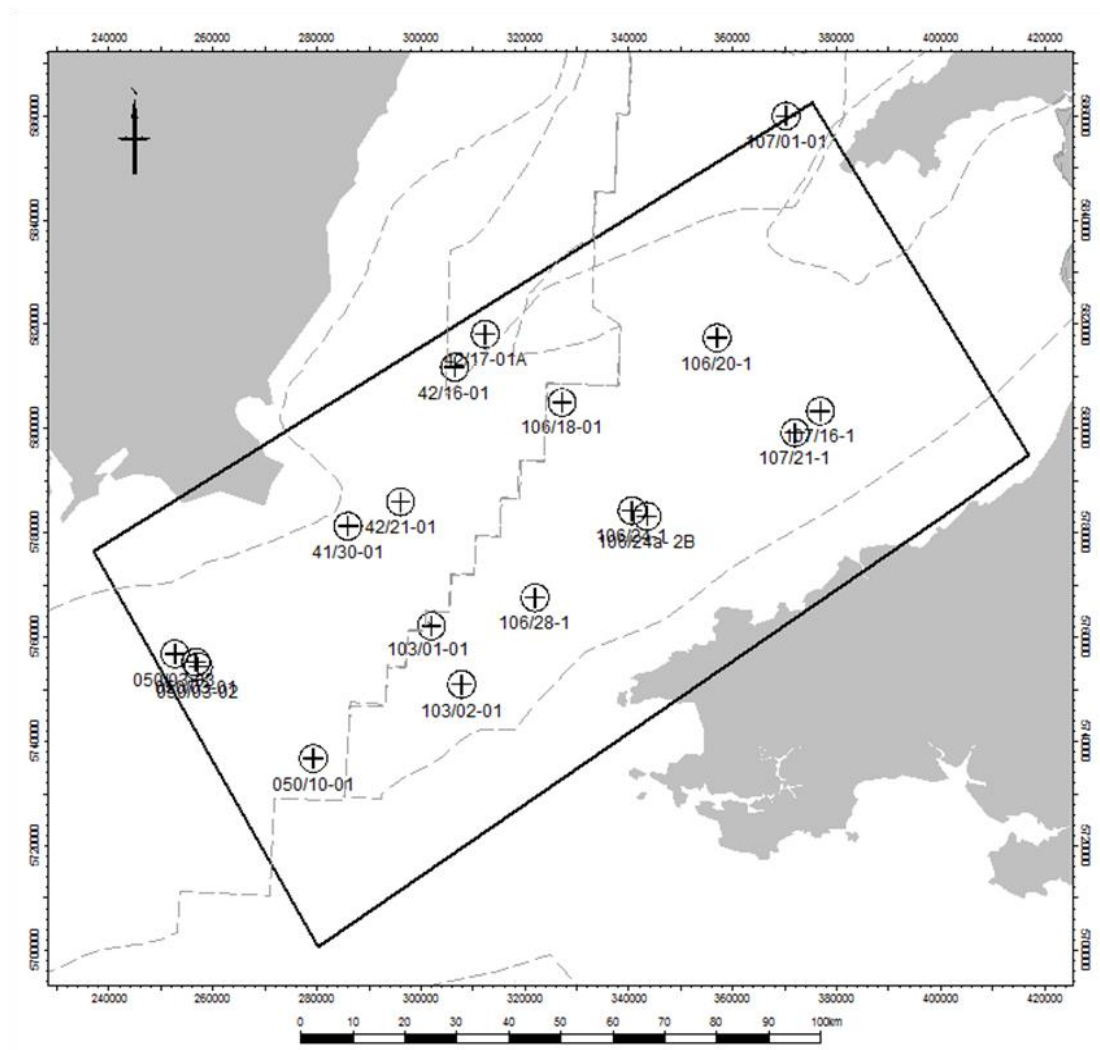


Figure 5: Map showing well locations in the detailed study area

4.3 DATA ISSUES

Issues with data quality and quantity were encountered during the data collation and interpretation phases of the project. It should be noted that the data used were collected during hydrocarbon exploration activities and as the aim of the surveys was not to collect data for geological storage of CO₂, data that would have been useful for this study were not always available. In particular, there are few porosity and permeability data on sealing horizons.

Much of the well data were collected during the 1970s and the seismic data during the 1980s to 1990s. As seismic, drilling and geophysical logging techniques have improved greatly over the last few decades, this will impact data quality and therefore confidence in the interpretation. As an indication of how seismic processing techniques have improved, two versions of one seismic survey were obtained and the version which had been reprocessed was significantly easier to interpret as the data quality was greatly improved by the reprocessing.

There are a good number of wells in the study region. However, the regional variability of lithology and large number of erosional surfaces does result in uncertainties in the interpretation. The lack of wells penetrating the deeper horizons of interest in the basin depocentres also means that the maximum depths of these horizons were interpreted from the seismic data and are not proven. The availability and format of well data were also variable, however utilising hardcopy

and digital data, a large amount of data were loaded into Petrel. Not all wells contain all required data, for example, not all wells have porosity and permeability data in the reservoir horizons and geophysical logs were not available for all wells and all horizons of interest.

As an example of data quality issues, when loading surveys in the South Celtic Sea Basin, some of the navigation data were incorrect and the lines were distorted. Issues with the navigation data were corrected in most cases. However, some lines were not loaded into the Petrel interpretation where the navigation data were of insufficient quality and it was determined that other nearby lines would give sufficient coverage.

4.4 INTERPRETATION METHOD

4.4.1 Seismic interpretation

The formations were picked based on seismic characteristics. It should be noted that seismic packages of different ages bore similar characteristics, so well control in order to differentiate between formations was extremely important.

Key horizons were picked on troughs (negative response) or peaks (positive response) on the seismic data as described in Table 4.

Table 4: Formations picked during seismic interpretation

Top of formations/strata picked in Petrel	Seismic signature
Top Kimmeridge Clay Formation	Peaks
Top Bathonian strata	Troughs
Top Inferior Oolite reservoir sequence	Peaks. Sharp peaks on sonic-velocity response (Tappin et al., 1994)
Base Inferior Oolite Group reservoir sequence	Peaks
Top Sinemurian strata	Peaks
Mercia Mudstone Group	Troughs
Sherwood Sandstone Group	Peaks
Top Carboniferous (unconformity)	Can be either peaks or troughs depending on lithologies. Often identified by angular unconformity

It should be noted that in the basin depocentres, the wells do not reach the deeper horizons, such as the top Sherwood Sandstone Group or top Carboniferous surfaces, thus in these locations, these surfaces have been picked through seismic interpretation and are not proven by wells.

4.4.2 Horizon gridding

The main time horizons picked on the seismic data were gridded on 250 m spacing and smoothed to reduce artefacts, e.g. those arising from poor ties at seismic line intersections. A set of fault polygons was then generated by intersecting smoothed fault planes with this surface.

4.4.3 Depth conversion procedure

The smoothed time surface grids for each horizon were depth converted. The depth conversion used the Average Velocity procedure within Petrel. An Average Velocity Filter was created for each horizon, using the depth and Two Way Travel Time (TWTT) for the horizon in each well. The spreadsheet generated was carefully inspected for anomalous values, which were corrected or rejected. The corrected filter was then used to create an Average Velocity Surface for each horizon. The fault polygons derived were used to provide a realistic degree of structural control (typically 60%) on the resulting surface. For the Top Carboniferous and Top Sherwood

Sandstone Group horizons, three further control points were inserted into the Average Velocity Surface to improve the realism of the depth conversion. This is because of the sparse number of well provings (12-15) of these deeper horizons, and their restriction to the edges of the basin, leaving poor control of the horizons at depth in the centre of the basin. The control points were chosen at the deepest points for each horizon in the basin depocentres. Representative Average Velocity values were estimated by extrapolation from time-depth plots, and are compatible with the highest observed average velocity value for each horizon, viz. 3600ms⁻¹ for the top of the Sherwood Sandstone Group, and 3800 ms⁻¹ for the top of the Carboniferous strata. These result in depths to these horizons in the basin depocentres of 9 km or more, compatible with those previously inferred (Tappin et al., 1994). The smoothed, faulted Time Surface was convolved with the Average Velocity Surface using the Petrel Surface Calculator, to generate the final Depth Surface. The latter was checked by comparison with known well stratigraphic depths.

5 Geology of the study area

5.1 STRUCTURE

The area of interest is compartmentalised into the following major basinal elements (Figure 6). The principal depocentres are the St George's Channel Basin and the North Celtic Sea Basin, where several kilometres of Permian, Mesozoic and Cenozoic strata are preserved. Both also contain significant thicknesses of Carboniferous strata. The St George's Channel Basin is an asymmetric half-graben, founded on a basement of Caledonide origin and trend (SW-NE) and strongly controlled by the St George's Fault on its south-eastern side. This fault lies sub-parallel, and *en échelon* to the SW-NE trending Bala Fault System, and like the latter, likely originated as a Caledonide or earlier basement structure. The Bala Fault System defines the SE edge of the Cardigan Bay Basin, and its contact with the Welsh Massif. The northern limit of these basins is the St Tudwal's Arch, which extends south-westward offshore and separates the basins described above from the Central Irish Sea Basin. The structural history of the latter is described elsewhere (Kirby et al., 2012). The North Celtic Sea Basin lies athwart the Variscan Front. Its north-eastern part in UK waters has a dominantly north-east- trend and Caledonide substrate; the southern part has a more westerly trend and lying in the hanging-wall of the Variscan Frontal Thrust, has a Variscide substrate. The outline architecture and structural history of these basins is well known because of the deep seismic reflection lines which transect the region (Figure 6). However, the detailed sequence stratigraphy is poorly known because of the generally poor quality of seismic data, at least of the early vintages, and the relatively sparse number of wells.

5.1.1 Cardigan Bay Basin

Lying to the SE of the St Tudwal's Arch, the basin forms a half-graben which deepens to the south-east against the Bala Fault, and to the east, against the Mochras and Tonfanau faults. All of these faults exhibit a Mesozoic normal component of throw, but the Bala Fault has a well-documented late Palaeozoic history of movement, and origin possibly as far back as late Precambrian time (Fitches and Campbell, 1987). The fault forms the offshore extension of the Bala Lineament, comprising a number of faults such as the Tal-y-Llŷn and Bryn Eglwys, in addition to the eponymous fault (Fitches and Campbell, 1987). The Mochras Borehole (Woodland, 1971) demonstrated the presence of a thick Jurassic sequence unconformably overlain by more than 500 m of Cenozoic strata in faulted contact with the Welsh Massif. Offshore, seismic reflection data indicate the presence of a Jurassic sequence locally exceeding 2000 m in thickness. Cretaceous strata are absent. A similar thickness of Permo-Triassic strata may also include Carboniferous strata (Bullerwell and McQuillin, 1969; Dobson and Whittington, 1987). The basin is transected by the Codling Fault, a sinuous strike-slip fault, associated with gas escape structures in the near-surface Cenozoic strata.

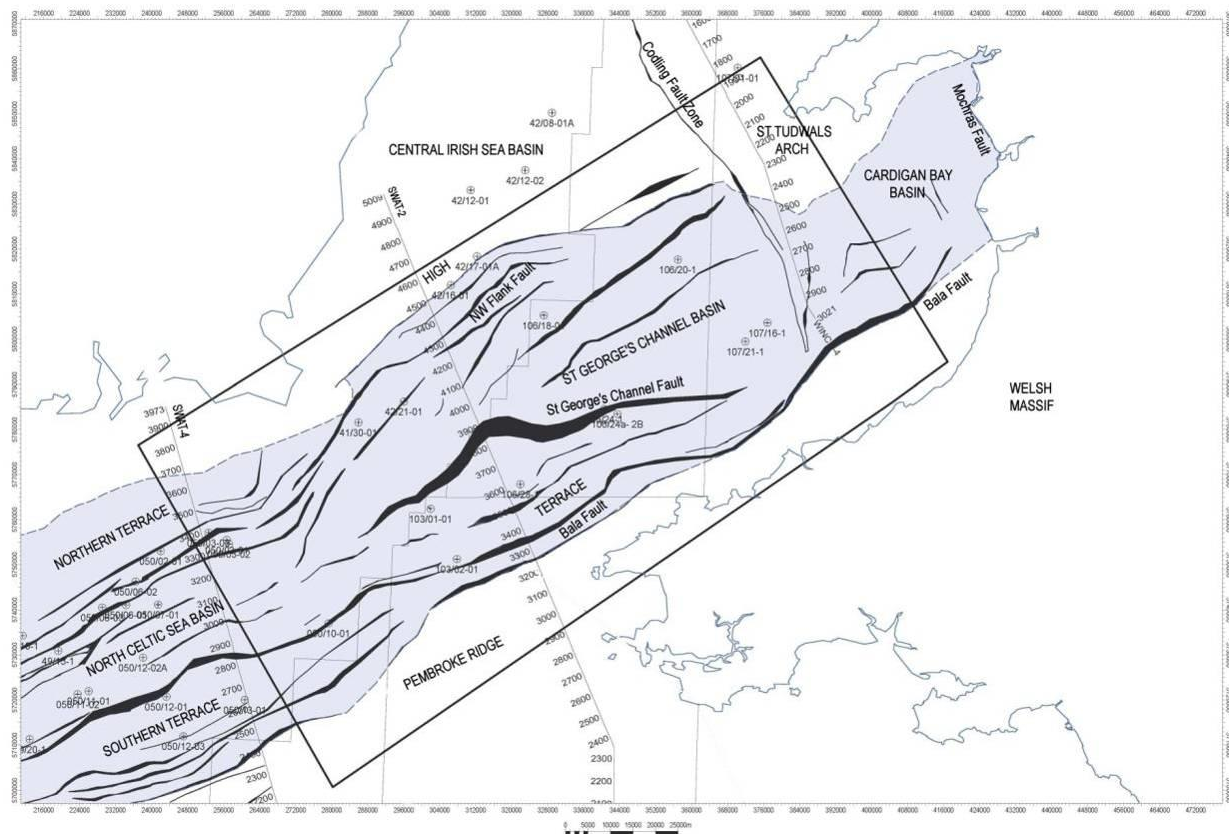


Figure 6: Structural elements of the Celtic-southern Irish Sea region. Location of key wells and BIRPS deep seismic reflection profiles referred to in the text is also shown.

5.1.2 St George's Channel Basin

This basin is one of the deepest basins in the UK offshore, with a post-Variscan sequence exceeding 7000 m, overlying up to 3000 m of undeformed Carboniferous, north of the Variscan Front. It is separated from the Cardigan Bay Basin by a saddle associated with the south-eastward extension of the Codling Fault away from the St Tudwal's Arch. The basin is compartmentalised across an axis extending north-north-west from Strumble Head, representing a possible relay-ramp or 'transfer zone' between *en échelon* elements of the St George's Fault. The eastern depocentre has the form of an asymmetrical syncline, deepest at its SE margin (Tappin et al., 1994). The western depocentre contains a similar thickness of strata, but has the form of an asymmetrical graben, thickening markedly to the south-east against the St George's Fault (Figure 7). The fault is sub-planar to slightly listric, and its throw locally exceeding 4000 m, much of which records syndepositional movement throughout Triassic and Jurassic time. The sequence has not been fully drilled by any well so the interpretation presented in Figure 7, is necessarily speculative. The presence of a thick, strongly reflective unit of evaporites within the Mercia Mudstone Group is inferred (Dimitropoulos and Donato, 1983; Dobson and Whittington, 1987). At least 4000 m of Permo-Triassic strata are present. The Jurassic sequence is equally thick. Displacement decreases to the south-east and the Cretaceous seabed crop to the west of Pembrokeshire is not affected (British Geological Survey, 2009). A prominent wall of salt is developed in the footwall of the fault, extending for at least 50 km (Tappin et al., 1994). The amplitude of the salt wall varies and locally the salt lies at very shallow depths beneath the Cenozoic, suggesting movement during the Cretaceous inversion, and possibly younger events. On the north-west flank of the basin, beyond its axial anticline (cdp4175 on SWAT -2, Figure 7) a fault with downthrow to the south-east (antithetic to the St George's Fault) also exhibits a significant Triassic syndepositional component. Displacement at the mid Jurassic level is however minimal, and lack of thickness variation across the fault suggests limited Jurassic

syndepositional throw here. Some of the throw may have been neutralised by inversion associated with growth of the axial anticline, which appears to have been a pre-Cenozoic, probably late Cretaceous event. Gentle folding of the base Cenozoic unconformity indicates a small additional Alpine component of inversion. The north-west limit of the basin is defined by the North West Flank Fault (Figure 6), reflected by a strong gradient in the Gravity Anomaly Map (British Geological Survey, 2009) on the southern flank of the Central Irish Sea Basin. The marginal high here, which brings both the basement, Carboniferous cover and the Sherwood Sandstone Group potential reservoir to relatively shallow depth (cdp 4540 on SWAT-2, Figure 7), was tested by the wells IR 42/16-01 and IR 42/17-01A in the Irish sector.

5.1.3 North Celtic Sea Basin

The northern part of this basin is delimited by the St George's Fault. It is laterally continuous to the north-east with the terrace associated with the Bala Fault, which has a Caledonide substrate. The south-west extension of the latter to the west of Pembrokeshire continues into the basin as the bounding fault of the depocentre. The appearance of Cretaceous strata, which are absent in the Cardigan Bay and St George's Channel basins, is nearly coincident with the inferred position of the Variscan Front. The basin has the form of a slightly asymmetrical, faulted downwarp apparent on the deep seismic reflection line SWAT-4 (Figure 8), most of which lies in the hangingwall of the Variscan Front Thrust, corresponding to the North Celtic Sea Reflector of McCann (1996). Extensional reactivation of the latter is considered to have played a significant part in the evolution of the basin (Cheadle et al., 1987). Syndepositional growth was greatest at the northern margin of the depocentre (cdp 3370 on SWAT-4, Figure 8), facilitated by the south-dipping listric bounding fault and several planar faults with similar polarity. This part of the basin also experienced the strongest inversion. A number of wells tested inversion anticlines in block 50/03 (Irish sector). The Northern Terrace of the graben (Figure 8) is underlain by a wedge of late Palaeozoic strata, presumed to be involved in the lowest Variscan nappes. The North-dipping southern marginal fault of the depocentre (cdp 2770 on SWAT 4, Figure 8) is the extension to south-west of the Bala Fault, and has a smaller Triassic syndepositional component but, in contrast, a larger Jurassic syndepositional component, than the northern marginal fault. As a consequence, the Jurassic sequence thickens to the south and the Triassic sequence thickens to the north (Figure 8). The late Cretaceous inversion was less severe on this margin, and the late Jurassic to Cretaceous sequence is better preserved. An inversion anticline is located close to the axis of the Jurassic depocentre (cdp 2950 on SWAT-4, Figure 8). The Southern Terrace is transitional to the Pembroke Ridge, separating the northern and southern basins of the Celtic Sea. Here the late Cretaceous postextensional 'sag' sequence, including the Chalk, with a patchy Cenozoic cover, is best preserved.

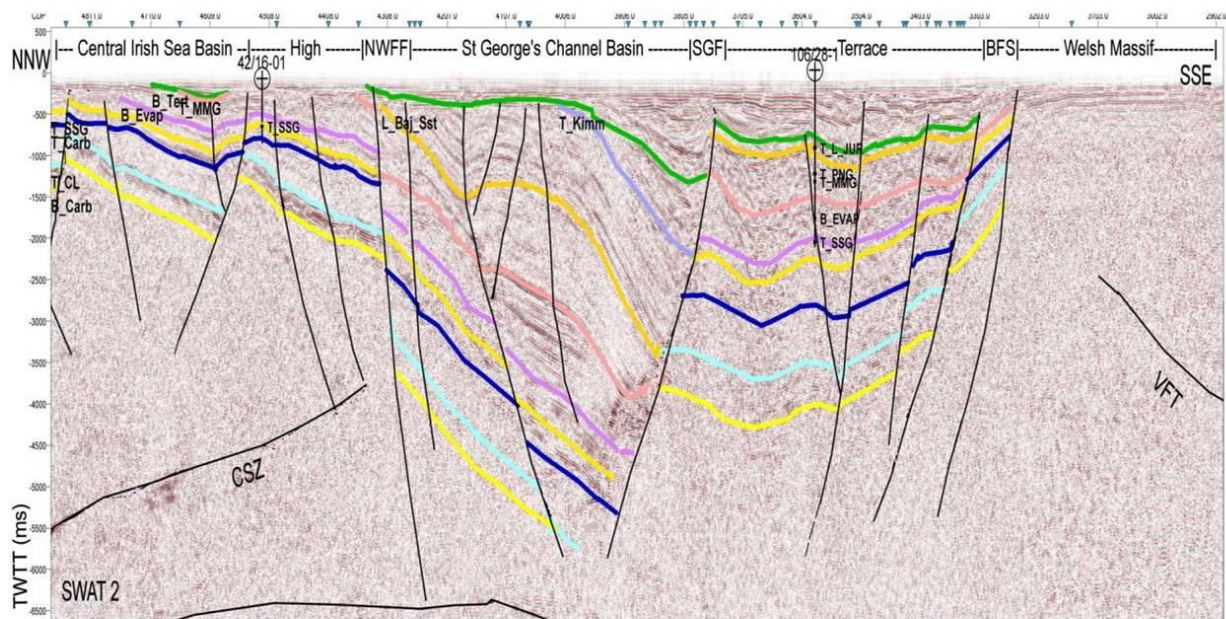


Figure 7: BIRPS deep seismic reflection profile SWAT-2 (courtesy of NERC), showing key named reflectors (mostly lower case) and well stratigraphy (upper case). Key to abbreviated structural names: NWFF North West Flank Fault; SGF St George's Channel Fault; BFZ Bala Fault Zone; CSZ Caledonian Shear Zone; VFT Variscan Frontal Thrust.

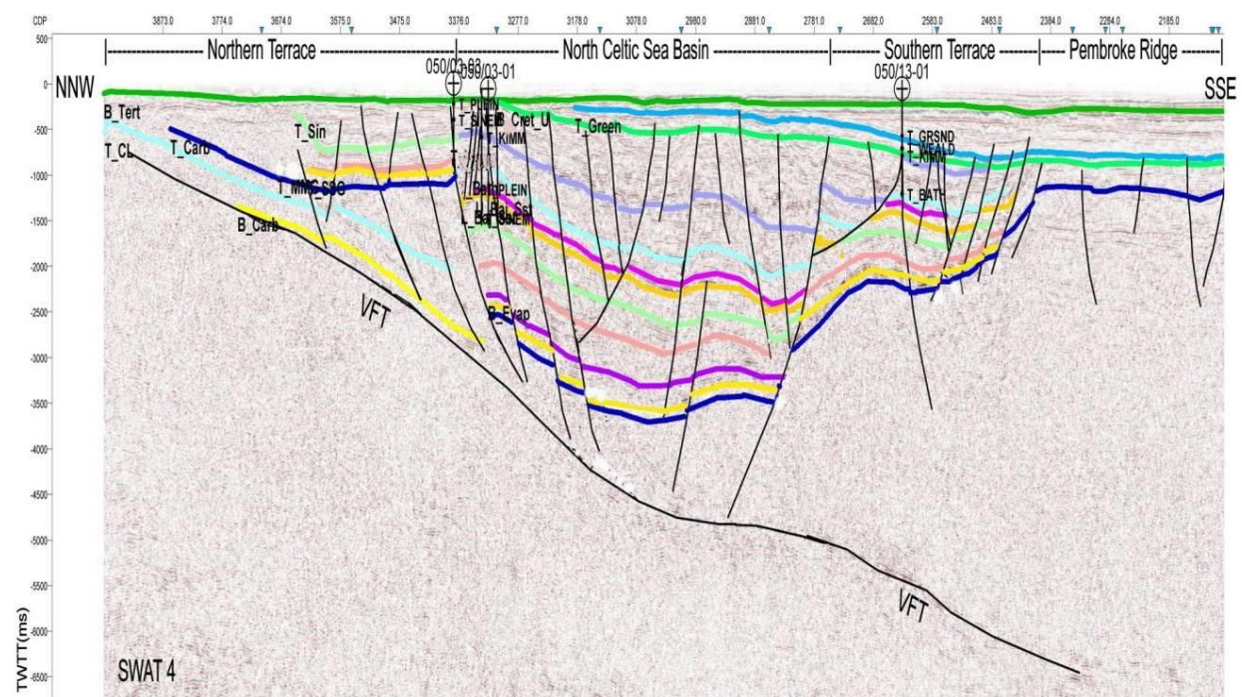


Figure 8: BIRPS deep seismic reflection profile SWAT-4 (Courtesy of NERC), showing key named reflectors (mostly lower case) and well stratigraphy (upper case). Key to abbreviated structural names: VFT Variscan Frontal Thrust.

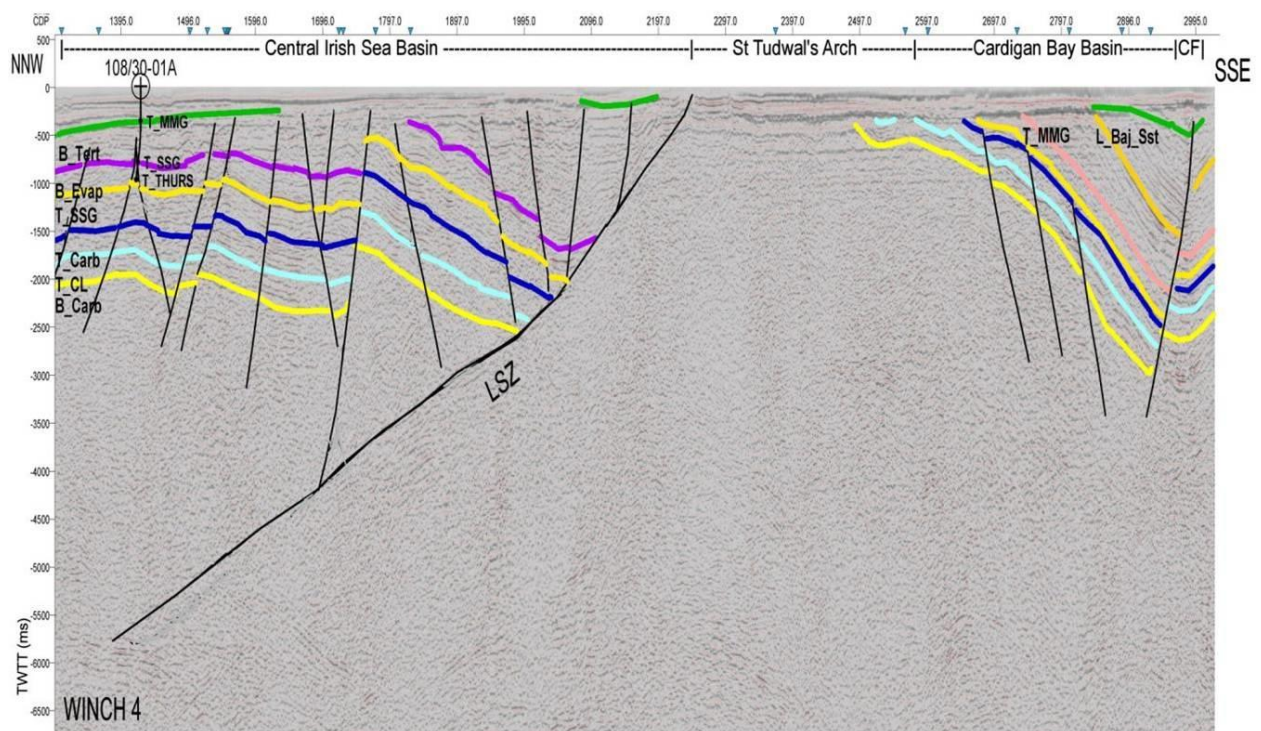


Figure 9: BIRPS deep seismic reflection profile WINCH-4 (Courtesy of NERC), showing key named reflectors (mostly lower case) and well stratigraphy (upper case). Key to abbreviated structural names: LSZ Llŷn Shear Zone; CF Codling Fault.

5.2 STRUCTURAL EVOLUTION

As described above, the detailed study region lies upon a complexly deformed basement substrate. In the north, this comprises rocks of the Caledonide Orogen, principally early Palaeozoic mudstones and sandstones deformed during the Acadian Phase of the Caledonian Orogeny, about 395 Ma. Late Precambrian rocks occur in Pembrokeshire, but are also involved in crustal lineaments on Anglesey (Mona Complex) and the adjacent mainland, where they form the crust underlying the early Palaeozoic basins. Precambrian rocks are caught up in the South Irish Sea Lineament extending from Anglesey towards Wexford in south-east Ireland, forming the boundary between the Central Irish Sea Basin and the St George's Channel Basin. North-east trending crustal lineaments such as the Menai Straits Fault System and Llŷn Shear Zone were generated during terrane accretion in latest Precambrian and early Palaeozoic time (Gibbons, 1987; Pharaoh and Carney, 2000). Other major north-east trending faults, e.g. the Bala Fault, while having an uncertain early Palaeozoic history, have demonstrable dextral strike-slip displacement late in the Caledonian Orogeny (Fitches and Campbell, 1987). The reactivation of several of these fault systems during subsequent Mesozoic extension to form basin-controlling faults is either demonstrable (Bala Fault) or suspected (St George's Channel Fault).

The Variscan Front is inferred to extend in a west-north-west direction from Pembrokeshire to south-east Ireland. It is inferred that it comprises the northern limit of large-scale thrusting and nappe formation associated with the Variscan Orogeny, at about 295 Ma. A number of these thrusts are recognised on seismic reflection data (Petrie et al., 1989; McCann, 1996), and map out with a west-north-west- or west- trend, and southerly dip, underlying the southern part of the region. In general, it is not possible to interpret the internal stratigraphy of these thrust nappes, however they likely comprise the largely clastic Devonian, and carbonate and mudrock-dominated Carboniferous sequences cropping out in the adjacent parts of south Wales and south-east Ireland. The Variscan thrusts were reactivated during Permian to Mesozoic extension. The

northern part of the region lay in the largely undeformed foreland of the Variscan Orogen. Here seismo-stratigraphic principles have been used to define and map picks which are believed to be associated with the top of the Carboniferous limestone (Visean) and the top of the Caledonian basement.

The post-Variscan evolution of the region was dominated by extension of the continental crustal plate ('Pangaea') established by the Caledonian and Variscan orogenies. Thick synextensional sedimentary sequences were deposited in a succession of complex fault-bounded basins in north-west Europe. Episodes of extension and subsidence were punctuated by pulses of regional uplift and minor local inversion. This process eventually led to the propagation of sea-floor spreading into the North Atlantic region by mid Cretaceous (Aptian) times. Subsequently, post-extensional shelf sequences were deposited unconformably upon the syn-extensional strata, overlapping the margins of the rift basins. Closure of the Tethyan Ocean basin to the south of Pangaea occurred throughout Cretaceous times and ended in Cenozoic times with the climactic pulses of the Alpine Orogeny. These events were reflected in the rift basins by phases of inversion and erosion, resulting in variable preservation of the original rift fill.

During Permian and Triassic times, east-west directed extension driven by lithospheric tensional stresses, led to the extensional reactivation of the structural template in the basement, and the rapid subsidence of the Cardigan Bay, North Celtic Sea and St George's Channel basins. Coarse clastic sequences were succeeded by mud-dominated strata as the relief of the surrounding massifs was reduced. Invasion of the sea through intramontane basin systems and the hot, sub-equatorial climate resulted in restricted marine circulation, hypersaline conditions and the development of evaporitic sequences which would later play an important role in basin evolution. Unlike in the East Irish Sea and likely the Central Irish Sea basins (Shannon, 1991; Jackson et al., 1994), only very limited seismo-stratigraphical evidence is found for the preservation of Permian strata within the region. Permian strata are likely to be thin, comparable to the 70 m of undated, presumed Permian mudstone and sandstone proved by the wells UK 93/6-1 in the South Celtic Sea Basin, and UK 103/02-1 in the St George's Channel Basin. They have not been proven so far in the Cardigan Bay or North Celtic Sea basins, perhaps because these basins were initiated in late Permian or early Triassic times (Shannon, 1991; Ziegler, 1981). Triassic strata are believed to comprise the majority of the Permo-Triassic sequence. The thickness of the Sherwood Sandstone Group may exceed 600 m in the depocentre of the St George's Channel Basin. The Mercia Mudstone Group includes a significant proportion of evaporite strata. Salt within these strata was subsequently mobilised and a prominent salt wall (Figure 7, SWAT-2) developed in the footwall of the St George's Fault which extends for at least 50 km of its length.

During Early Jurassic times, a further pulse of extension resulted in renewed subsidence of the basins, with marine incursion across the low-relief landscape consequent upon late Triassic thermal-relaxation subsidence and erosion. The Cardigan Bay Basin has probably the thickest Jurassic sequence of any UK basin. In mid Jurassic (Bajocian–Bathonian) times, subsidence was interrupted, particularly over basin margins, by localised thermal doming associated with magmatism in the North Sea (Dobson and Whittington, 1987), the so-called 'mid-Cimmerian' event (Ziegler, 1990). A number of sandy units were fed into the basin as a result of erosion of the rejuvenated surrounding massifs. Subsidence resumed across the whole region in late Jurassic times, greatly increasing the area of deposition. In early Cretaceous times, sea-floor spreading propagated northwards from the Central Atlantic region (Morocco) towards Iberia and Newfoundland. The rotation of Iberia imparted a strong north-south extension to the region, resulting in local intense rift-extension. In addition, the area was subjected to regional thermal uplift driven by lithospheric heating, reflected in the 'late-Cimmerian' event (Ziegler, 1987b; 1990). The marginal massifs and shelves were uplifted and eroded, perhaps by as much as 3000 m (Van Hoorn, 1987) and coarse clastic sediment was funnelled into very localised depocentres in rift basins such as the North Celtic Sea Basin, where it forms the Wealden non-marine sequence.

Following the onset of sea-floor spreading during mid Cretaceous (Aptian) times, a regime of post-extensional shelf subsidence was established across the region, and Albion to Cenomanian strata (Greensand and Chalk) were deposited unconformably upon the 'late-Cimmerian' erosional surface. The lack of terrigenous material in the Chalk suggests that it was laid down over much of the region (Tucker and Arter, 1987), including the surrounding massifs. Unfortunately, subsequent 'Laramide' inversion and erosion in latest Cretaceous time (resulting from early Alpine compression) has destroyed evidence for such deposits in the basins lying to north of the Variscan Front. In the North Celtic Sea Basin, erosion was most severe on the north-west margin. Upwarping of the basin depocentre and reversal of the basin margin faults are indicative of crustal shortening and true basin inversion (Tucker and Arter, 1987).

In early Cenozoic times there was a return to regional thermal-relaxation subsidence and clastic deposition. The clearest evidence for Cenozoic normal faulting is on the St George's and Bala faults. Up to 1500 m of Cenozoic strata are preserved in the St George's Channel Basin. Significant uplift of the Welsh Massif may have occurred at this time (Dobson and Whittington, 1987), associated with movements on the marginal faults of the Cardigan Bay Basin, i.e. the Mochras and Tonfanau faults. The north-west trending Sticklepath and West Lundy fault zones lying to south of the region, within the domain floored by Variscan basement, show sinistral strike-slip movement and are associated with localised pull-apart basins (Holloway and Chadwick, 1986). The Codling Fault within the region also has a north-west trend and was certainly active during Cenozoic times. It however lies entirely within the Caledonide domain with a dominantly south-west trending structural grain. Its precursor is therefore most likely associated with early Carboniferous rifting in the Irish Sea Basin.

In latest Oligocene to early Miocene times, a pulse of crustal shortening related to the 'Helvetic Phase' of Alpine collision resulted in uplift and minor basin inversion within the region, corresponding to the main structural inversion of the onshore Wessex Basin (Lake and Karner, 1987; Chadwick, 1993). Uplift was most pronounced south of the Variscan Front, and both the North (SWAT-4, Figure 8) and South Celtic Sea basins experienced gentle upwarping of their depocentres and reversal of their marginal faults. As a consequence, the post-extensional late Cretaceous strata are better preserved on the Pembroke Ridge than in the basins. North of the Variscan Front, inversion was more limited. A number of unconformities are present within the Cenozoic strata of the St George's Channel Basin. The antithetic fault of the St George's Channel Basin was reversed and a prominent inversion anticline developed (SWAT-2, Figure 7). Dextral reactivation of the strike-slip fault zones accompanied inversion. Locally along the footwall of the St George's Fault, mobilisation of salt has caused deformation of the overlying early Cenozoic strata, indicating that movement continued into the Helvetic Phase.

5.3 STRATIGRAPHICAL SUMMARY

5.3.1 Stratigraphical history of the northern region of the Celtic Sea Basin

The oldest rocks penetrated by wells in the North and South Celtic basins are of Visean age. The rocks of interest for geological storage of CO₂ are of Carboniferous and Permo-Triassic to Jurassic age and the main reservoir formations and caprock formations are described briefly here and more details are given in sections 6 and 7. Older rocks of Precambrian to Silurian age outcrop on both sides of the Irish Sea and a brief description of these strata is included here for completeness.

During Precambrian to early Palaeozoic times the detailed study region lay to the north of the Gondwana landmass on the southern edge of the Iapetus Ocean. The oldest rocks are represented by Precambrian intrusive and metamorphic rocks which can be observed outcropping in small pockets in south Wales and on the east Irish coast. Early Palaeozoic rocks are present on both sides of the Irish Sea in Wales and on the east coast of Ireland. These comprise intrusive and extrusive igneous rocks as well as sedimentary strata.

During the early – mid Cambrian Period, the northern part of the North Celtic Basin and the St George's Channel/Cardigan Bay basins (subsequently referred to as the northern North Celtic Basin for convenience) most likely lay within the Welsh Basin. During the early Cambrian Period, deposition of shallow-marine conglomerates, sandstones and siltstones occurred across the northern North Celtic Basin. The central part of the North Celtic Basin lay on the Midlands Platform and shallow shelf sediments were deposited in this region. To the south of the Midlands Platform lay the landmass of Pretannia (Gibbons, 1983). Outcrops of Cambrian turbiditic sands and hemipelagic mudstones are present in North Wales, deposited in the Welsh Basin during this time (Tappin et al., 1994). During the late Cambrian, shallow-water siltstones, grits and mudstones were deposited across the Welsh Basin region (Rushton, 1974; Turner, 1977). In contrast, the most southern part of Wales and most likely the central North Celtic Basin experienced uplift during latest Cambrian to earliest Ordovician times. In South Wales, this uplift resulted in an erosional unconformity at the base of the Tremadoc age strata (Tappin et al., 1994; Bassett, 1980).

During latest Cambrian to early Ordovician times, subduction began along the northern margin of Gondwanaland. Back-arc spreading resulted in the formation of a marginal basin and the separation of the Welsh Basin and southern Britain from Gondwanaland. Extensive volcanism occurred in the Welsh Basin during the Ordovician Period. Ordovician age sediments are penetrated by BGS borehole 72/60 in the Bristol Channel where they comprise cleaved, grey, micaceous mudstone (Tappin and Downie, 1978). As the Caledonian Orogeny progressed, the Welsh Basin and most likely the northern North Celtic Basin were uplifted and shallow shelf marine strata were laid down during the late Tremadoc and early Arenig epochs. During the late Arenig Epoch a marine transgression (Tappin et al., 1994; Woodcock, 1990) resulted in deposition of marine sandstones, siltstones and mudstones in the northern parts of the Welsh basin until late Caradoc times. These marine sedimentary strata are interspersed with subaerial volcanic deposits. During late Caradoc to early Ashgill times the 'soft' (i.e. with no major orogenesis along the collision suture) collision of Eastern Avalonia with Laurentia (Pickering et al., 1988) resulted in an unconformity which can be traced across much of the Welsh Basin. The Midlands Platform was established during the early Ordovician Period. This platform covered the southern end of South Wales and most likely part of the central North Celtic Basin. Thus South Wales and most likely part of the central North Celtic Basin were emergent with deposition of continental sediments during the Arenig stage until the Llandeilo stage. During the Caradoc stage, as the region subsided, turbidites were deposited in the north of the Welsh Basin and most likely the northern and central parts of the North Celtic basins (Tappin et al., 1994). Shelfal limestones and shelly facies were deposited across part of central Wales and probably part of the northern North Celtic basins (Tappin et al., 1994).

During the Silurian period, the three depositional regions established at the end of the Ordovician persisted (Tappin et al., 1994): Deposition of basinal sediments continued in the northern North Celtic Basin (with turbidites, greywackes and mudstones deposited in the middle of the Welsh Basin and deposits becoming increasingly coarse towards the margin of the basin where fan and deltaic deposition occurred (Tappin et al., 1994; Wood and Smith, 1959; Kelling and Woollands, 1969)). Limestone and shelly facies deposition occurred across part of central Wales as sea levels rose during the late Llandovery and Wenlock and as a result increasing areas of shelf were inundated. Towards the end of the Silurian period, uplift allowed shallower marine sediments to be deposited in the Welsh Basin. The uppermost Silurian strata are of continental origin (Tappin et al., 1994).

During latest Silurian to early Devonian times, the Welsh Basin was uplifted and infilled. The main period of deformation due to the Caledonian Orogeny occurred during this time. The 'hard' (i.e. when regional deformation patterns are set) collision between Avalonia and Laurentia resulted in the cessation of subduction along the Iapetus Suture Zone, and the closure of the Iapetus Ocean (Tappin et al., 1994; Pickering et al., 1988). The region then lay on the southern margin of Laurentia. St George's Land covered much of north and central Wales (Tappin et al.,

1994) and the northern North Celtic Basin. Uplift of St George's Land resulted in erosion and redeposition of these clastics as the Old Red Sandstone in an alluvial plain environment occurred across southern Wales and most likely part of the central North Celtic Basin. A fluctuating shoreline lay in the Bristol Channel and the 'mid-Devonian landmass' separated this environment from the southern region where mainly marine basinal deposits were laid down. It is uncertain whether South Wales and Devon were part of the same basin (Tappin et al., 1994; Freshney and Taylor, 1980) but contemporaneous deposits were laid down in Devon during the early Devonian Period.

During the mid-Devonian Period, deposition is believed to have been mainly restricted to the Bristol Channel and deposits are absent in South Wales. The oldest first Upper Devonian strata in South Wales are of Frasnian age and of aeolian/fluvial origin. These are then overlain by strata of late Famennian age showing a marine transgression with deposits of marginal marine and shallow shelf origin. Upper Devonian age rocks are not believed to be widespread in South Wales (Tappin et al., 1994). Devonian strata are penetrated by a few wells, including UK 103/21-1 in the Cardigan Bay Basin.

During late Devonian to early Carboniferous times, the stress regime changed from compressional to tensional and the southern margin of St George's Land was progressively submerged during a major marine transgression. In South Wales, the Dinantian strata mainly comprise carbonate shelf deposits. The north part of St George's Land remained emergent. Deep seismic data interpretation of Tappin et al. (1994) suggests the presence of offshore north-west trending Dinantian basins; Kish Bank, Central Irish Sea and St George's Channel basins which are bounded by north-west dipping faults following Caledonian structural trends. The presence of Dinantian age sediments in the Central Irish Sea Basin is inferred from the presence of these rocks along strike in Anglesey (Tappin et al., 1994). The St George's Channel Basin formed along the offshore extension of the Bala Fault and Dinantian strata have been identified on the basis of palynology in well IR 42/17-1 (geological well report). Seismic reflection data in this region show the Dinantian sequence thickening south-eastwards towards the controlling St George's Fault (Figure 7). Devon and the southern part of the North Celtic Basin remained emergent (Tappin et al., 1994). During Namurian times, the stress regime became compressional again due to the continued collision of Laurentia and Gondwanaland. In the southern North Celtic Basin, Tappin et al. (1994) predict deposit of shelf sediments graduating to paralic sand/mud across the central and northern North Celtic Basin. As compression continued through the Namurian Period, St George's Land was uplifted and clastic sediments carried southwards were deposited as beach sands in central South Wales interbedded with subordinate marine mudstones (Hartley and Warr, 1990). These largely beach deposits transition into marine mudstones further south (Tappin et al., 1994). In West Wales, deltaic deposits are reported. These layers are overlain by the Upper Shale Group which covers a greater area and comprises fluvial deltaic and littoral sandstones interbedded with basinwide marine bands (Tappin et al., 1994). Regional compression continued into the early Westphalian Stage. In South Wales, fluvio-deltaic sands of early Westphalian age are interspersed with marine bands (Oguike, 1969 as referenced in Tappin et al., 1994). This is overlain by mid Westphalian deltaic sands and silts with thick and extensive coals on low-lying, swampy, alluvial, coastal plains subjected to infrequent marine incursions (Kelling, 1974) believed to continue across the northern North Celtic Basin (Tappin et al., 1994). During the late Westphalian Stage, formation of the Variscan Mountains (across Devon and most likely extending into the central North Celtic Basin) resulted in uplift across the central North Celtic Basin, with thrust fault deformation identified in this region. Sediments sourced from the Variscan Mountains led to deposition of fluvial sands which northwards pass into paralic sands across the northern North Celtic Basin (Tappin et al., 1994). Progressive uplift from the south led to the continued retreat of the basin northwards and at the climax of the Variscan Orogeny, during Stephanian times, the northern North Celtic Basin was subaerially exposed.

During early Permian times, the final phase of the Variscan Orogeny led to the consolidation of northern Europe into the supercontinent of Pangaea.

After the Variscan Orogeny, east-west regional crustal extension (Tappin et al., 1994) led to rapid subsidence of northern North Celtic Basin along lines of structural weakness with a northeast-southwest trend. The Cardigan Bay Basin, St George's Channel Basin, North Celtic Basin and Central Irish Sea Basin as observed today began to form. Thickness estimates of the Permo-Triassic sediments are tentative in the basin depocentres as no wells penetrate to the Carboniferous. Cardigan Bay Basin forms a half-graben which deepens to the south-east with locally up to 2 km of Permo-Triassic sediments (though this estimate may include some Carboniferous strata; Tappin et al., 1994). St George's Channel Basin is separated from Cardigan Bay basin by a low relief 'saddle'. The eastern part forms an asymmetric, faulted syncline and the western part forms a south-easterly deepening asymmetric graben. It is thought the Permo-Triassic sequence is in places more than 4000 m thick but no wells penetrate the whole sequence (Tappin et al., 1994). The North Celtic Basin lies to the south of the Variscan front and formed *en-echelon* with the St George's Channel Basin. A salt wall formed by migrating salt is present along much of the fault separating the St George's Channel Basin from the North Celtic Basin. During the early Permian, basement massifs were uplifted and eroded providing a source of clastic material which accumulated along the margins, passing into finer grained deposits with some evaporite layers basinward. In the North Celtic Basin the Permo-Triassic sequence is strongly fault controlled and locally in excess of 3000 m thick, but generally less than 2000 m thick (Tappin et al., 1994). Permian-Triassic sediments are dominantly non-marine redbeds.

Further uplift during the early Triassic led to a second episode of coarse clastic deposition. During the Triassic Period, deposition became more widespread and extended outside the basin confines established during the Permian Period. Permian strata are identified in the St George's Channel Basin in well UK 107/01-01 where they comprise sandstone with minor claystone and siltstone with volcanics, overlain by Triassic sandstones with thin claystone and siltstone beds. Tappin et al. (1994) note that the Sherwood Sandstone Group is finer grained offshore compared to onshore, perhaps reflecting a more distal depositional environment.

During the mid-late Triassic, the Mercia Mudstone Group was laid down in marginal marine conditions. The transition from the Sherwood Sandstone Group is conformable in basin centres but towards the basin margins, the Mercia Mudstone Group onlaps onto older sediments. Deposition was dominated by fine grained mudstones, siltstone, mudstone and evaporites which can be correlated between basins. Coarser deposits are reported along the basin margins (Tappin et al., 1994). The dominantly fine grained sediments suggest a subdued hinterland basinal environment of deposition some distance from the sediment source which resulted in the relatively coarse deposits in southern Wales. By analogy with the Cheshire Basin as described in Arthurton (1980) and Tappin et al. (1994) suggested that the finer-grained, clay-sized material was transported in dust storms, and the coarser, silt- and sand-grade sediment by water. In the St George's Channel Basin, the Mercia Mudstone Group comprises a lower deposit composed of calcareous mudstones and siltstones with some sandstone beds and anhydrite nodules overlain by well-developed evaporite deposits which are in turn overlain by variably calcareous claystones that are silty and sandy in places. The youngest beds of the Mercia Mudstone Group were laid down in extensive semi-permanent lakes. Some marine influence is observed on the youngest mudstones and by the mid-late Rhaetian Stage, when the Penarth Group was deposited, marine conditions were established. The marine incursion occurred from the south (Tappin et al., 1994). The Penarth Group comprises shale, claystone, siltstone and dolomite in St George's Bay Basin and claystone, limestone with minor dolomite and sandstone in the North Celtic Basin.

Early Jurassic times were characterised by regional extensional stresses due to thermal relaxation following on from the Permo-Triassic lithospheric thinning which resulted in basin subsidence along bounding faults (Tappin et al., 1994). The marine transgression observed at the end of the Triassic continued. Jurassic deposits were laid down in sub-tropical conditions and generally rest

conformably on the Triassic strata. Deposition continued in the basins that were established during Permian-Triassic-times or even earlier. The Lias Group strata are of Hettangian, Sinemurian, Pliensbachian, Toarcian and early Aalenian age. The Lias Group comprises fossiliferous mudstones with a variable carbonate content, interbedded with argillaceous limestones, siltstones and, more rarely, fine-grained sandstones. The Lias Group sequence thins towards the Pembroke Ridge. The Blue Lias Formation (Hettangian – Sinemurian) at the base of the Lias Group is interpreted as a shallow-marine deposit in the St George's Channel Basin where it comprises of cyclic alternations of limestone and shale. This is overlain by the Charmouth Mudstone Formation (Sinemurian to Pliensbachian) and the Dyrham Formation, Beacon Limestone Formation and Bridport Sands Formation. In the North Celtic Sea Basin, the Hettangian to Sinemurian strata includes arenaceous material: Around well IR 41/30-01 the Lias sequence is described as the Liassic limestone formation (Hettangian), Liassic marl formation (latest Hettangian to earliest Sinemurian), Liassic sandstone (early Sinemurian) and part of the Liassic shale (late Sinemurian to Aalenian) in the composite log.

In the North Celtic Sea Basin, the Middle Jurassic (Aalenian to Callovian stages) strata comprise mostly sandstone and limestone with claystone identified in some areas. The formations are the Inferior Oolite Group (Aalenian to Bajocian), Great Oolite Group (Bajocian to Bathonian), Kellaways Formation and Oxford Clay Formation (Callovian). The most complete sequence was recorded in well IR 50/10-01 where the Middle Jurassic includes part of the Liassic shale, an early Bajocian sandstone, Bathonian sandstone and Bathonian limestone. In the St George's Channel Basin, the Middle Jurassic strata comprise mudstone, siltstone and limestone with some sandstone beds. Evaporites are sometimes present. The Middle Jurassic strata are about 1000 m thick in the deeper parts of the St George's Channel where sedimentation may have been continuous, but on the basin margins there is evidence of uplift and erosion (Tappin et al., 1994). During the mid-Jurassic, subsidence was interrupted, particularly over basin margins and a significant hiatus in deposition occurred which is believed to be the result of a period of magmatic thermal uplift is identified as the mid-Cimmerian Unconformity (Bajocian to Bathonian age) (Tappin et al., 1994).

The Upper Jurassic strata include the upper part of the Portland and Purbeck groups. The earliest Upper Jurassic sediments identified in the St George's Channel Basin are the upper part of the Oxford Clay Formation which comprises silty mudstone, overlain by the West Walton Formation and the Amptill Clay Formation both comprising calcareous mudstone interbedded with sandstone (well 106/24-01; Tappin et al., 1994). The Oxfordian strata are less well defined in the North Celtic Sea Basin, but where present comprise claystone, sandstone and limestone. The sandstones are interpreted as fluviodeltaic, coastal-plain sand bodies (Tappin et al., 1994). Kimmeridgian strata comprise mudstones interbedded with limestones and sandstones with some lignite beds. The greatest thickness recorded of the Kimmeridge Clay Formation in the St George's Channel Basin is over 950 m, identified in well UK 106/24-01 (Tappin et al., 1994). The Kimmeridge Clay Formation is interpreted as having a lagoonal or overbank origin. The Kimmeridge Clay Formation is frequently absent from wells in the North Celtic Sea Basin, having been removed by erosion. Where present, it comprises claystone, sandstone and limestone. The Tithonian strata are not as well defined, in some wells they are divided into the Portland and Purbeck groups and in other wells, only Tithonian facies (Prev. Portlandian) are recorded. The Tithonian strata comprise mudstone with variable carbonate content and some interbedded sandstones in St George's Channel Basin with limestone beds are recorded in some wells at the top of the sequence. The Purbeck facies comprises mudstone and siltstone with a basal limestone where present.

Sedimentation resumed across most of the basins during the late Jurassic due to thermal relaxation. Basin subsidence along faults continued and the area of deposition widened (Tappin et al., 1994).

The stress regime changed during the early Cretaceous due to initiating plate tectonic processes as sea-floor spreading penetrated northwards from the Central Atlantic region towards Newfoundland and Iberia. A series of well-defined basins emerged in which mainly continental clastics, derived from the uplifted basin margins, were deposited (Tappin et al., 1994).

According to Van Hoorn (1987), uplift associated with Cimmerian events was initiated in the south-west of the South Celtic Sea Basin in Mid- to Late Jurassic times, and thereafter propagated north-eastwards during the Early Cretaceous period. The basins were affected by regional thermal uplift which resulted in the late Cimmerian unconformity being present across much of the Irish Sea region. The 'late-Cimmerian unconformity' is a good example of an unconformity associated with the transition from extensional phases of basin evolution (Tappin et al., 1994). The extensional stress regime altered to a north-south orientation. Local depocentres developed with normal fault controlled deposition. Basin margins appear to have undergone erosion or a period of non-deposition, for example Van Hoorn (1987) estimated that over 3 km of sediment had been removed from the southern margin of the South Celtic Basin during late Cimmerian deformation. Salt intrusion also contributed to erosion where it caused uplift, for example, along the southern margin of the St George's Channel Basin (Van Hoorn, 1987).

Progressive shallowing resulted in the spread of fluvial and deltaic conditions across the Celtic Sea Basin. Deposition of the Purbeck facies and Wealden Group was mainly confined to discrete basins (Tappin et al., 1994). Purbeck facies were deposited in the North Celtic Sea Basin as a sequence of marl with sandstone intervals and thin limestone stringers deposited in lagoonal conditions. The Purbeck facies is not proven in the South Celtic Sea Basin. Purbeck facies are overlain (unconformably) by Wealden Group strata (Valanginian to Aptian). In the North Celtic Basin, the Wealden Group comprises a thick sequence of non-marine sediments. A thinner sequence is preserved in the South Celtic Sea Basin. These facies comprise sandstones, mudstones with some coal beds deposited in marginal-marine, alluvial and fluvial/deltaic environments (Tappin et al., 1994).

Regional post-extensional shelf subsidence began during Mid-Cretaceous (Aptian) times and Upper Cretaceous strata were deposited on the late Cimmerian unconformity south of the Variscan Front. During the Albian Stage, the continental/marginal environments were gradually replaced from the west by marine conditions, and an interbedded sequence of sands and clays of Gault and Greensand facies was deposited. Calcareous mudstones and siltstones were deposited at the base of the Chalk Group as marine conditions became fully established. Finally, during latest Cretaceous times, from the Cenomanian to the Maastrichtian stages, chalk was deposited (Tappin et al., 1994).

Regional uplift (roughly synchronous with the Laramide uplift in the Southern North Sea) and a eustatic fall in sea level at the end of the Cretaceous period resulted in erosion across much of the region. In the St George's Channel Basin, erosion was quite severe. In the North Celtic Sea Basin, all Middle and Upper Cretaceous sediments were removed (assuming they were in fact deposited here; Tappin et al., 1994).

Uplift occurred during earliest Cenozoic times, the dating of this is poorly constrained. The oldest Cenozoic sediments are of possible early Oligocene age and were deposited pene-contemporaneously with the final phases of this uplift (Tappin et al., 1994). This was followed by a regional thermal relaxation regime (still during early Cenozoic times) when deposition of clastic sequences took place. Strike slip fault movement on the Cardigan Bay Basin led to the development of local fault-bounded sub-basins. Offshore Cenozoic sediments are only sampled by a few wells, but Tappin et al. (1994) were able to identify a lower, coarse-clastic section and an upper, finer-grained section within which lignite is commonly present. A pulse of crustal shortening and minor basin inversion occurred during Oligocene to Miocene times. The North and South Celtic Sea basins both experienced some upwarping of their depocentres and local reversal of basin margin faults. The impact was limited in the St George's Channel Basin which

experienced local uplift of the basin depocentre and reversal along some faults (Tappin et al., 1994).

5.4 HYDROCARBON RESOURCES

In the centre of the North Celtic Sea Basin, gas and oil are produced from a number of fields. The Kinsale Head gas field (Irish blocks 48/20 & 25 and 49/16 & 21) produces gas from the A Sand (Albian) and B sand (upper Wealden Group). Ballycotton (Irish Block 48/20) produces gas from the A Sand, Barryroe (Irish blocks 48/23-24 & 28-29) produces oil from the basal Wealden Group sands and Sevenheads (Irish blocks 48/23-24 & 28-29) produces gas from the B Sand (Lansdowne, 2014).

Gas has been discovered in the A sand at Galley Head (IR 48/18-1) and in the B Sand at Old Head (Irish blocks 49/23-2Z), Schull (IR 57/2-3), Carrigaline (IR 48/24-4) and Ardmore (IR 49/14-1). Gas has been tested in well IR 57/9-1 and in lower Jurassic sediments in well IR 63/10-1. Oil has been discovered in Albian strata and Wealden Group sediments in Baltimore (IR 48/19-2) and well IR 48/20-3. Oil has been tested in the Wealden Group in Nemo (IR 49/14-1), Galley Head (IR 48/18-1) and the Albian strata in well IR 48/26-1. Oil shows were identified in well IR 48/22-1A. Oil was identified in Hook Head (IR 50/11-1, 3 & 4), Dunmore (IR 50/6-1) and well IR 49/9-4 in lower Cretaceous sediments (Lansdowne, 2014).

The Dragon Prospect in UK Block 103/1 had gas shows in the Upper Jurassic Callovian to mid-Oxfordian sandstones (Providence Resources Plc., 2012), however the gas accumulation was judged insufficient to warrant a commercial development as it was believed the faults had not sealed the field sufficiently (Marathon Oil Company and Summit Petroleum, 1993). Drill stem tests carried out in the Helvick oil accumulation in Irish block 49/9 indicated oil flows from the Late Bathonian marine limestones and Callovian to Oxfordian sandstones (the Main Sand is of Callovian age) (Caston, 1995).

The presence of hydrocarbons indicates that potential reservoir-seal pairings are present in part of the North Celtic Sea Basin. However, the presence of economic reserves could also potentially lead to a conflict of interest if CO₂ storage operations were to impinge unfavourably on hydrocarbon exploitation activities, for example, through CO₂ unintentionally migrating into an oil reservoir or through the pressure footprint reducing oil recovery at some boreholes.

6 Reservoir and seal interpretation

The horizons listed in Table 5 were identified as key horizons based on their expected reservoir and sealing properties. Detail on their stratigraphical characteristics and the results of depth-converting the seismic to produce model surfaces for key horizons are given in this section and detail on lithology of the reservoir and seal horizons is given in Section 7 and Appendix A.

Table 5: key reservoir and seal horizons

Reservoir horizon(s)	Seal horizon(s)
Callovian sandstones, Great Oolite Group and Inferior Oolite Group sandstones and limestones (Bajocian – Aalenian)	Oxford Clay and Kimmeridge Clay formations
Sinemurian sandstones	Uppermost Lias Group
Sherwood Sandstone Group	Mercia Mudstone Group
Carboniferous sandstones	Mercia Mudstone Group

Correlation of the wells across the study area indicated great variation in lithology, reservoir and caprock quality. Generalised well lithologies and well logs are shown in Figure 20, Figure 21,

Figure 22 and Figure 23. A brief description of the reservoir lithologies described from composite logs, wells cuttings, cores and geological reports is given here.

The Carboniferous lithology and reservoir quality is variable as is to be expected from the wide range of depositional environments. Sandstone layers of varying thicknesses are noted in all the wells which reach Carboniferous strata. The Sherwood Sandstone Group generally contains sandstone layers though in a few instances, it comprises more argillaceous strata or conglomerate. It may be possible to target promising reservoir layers if a sufficiently large closure can be identified where the Sherwood Sandstone Group mainly comprises sandstone.

The Sinemurian strata have very variable lithology, in the St George's Channel Basin they mainly comprise mudstone and claystone. However, in the rest of the study area, there are more porous and permeable sandstones noted, particularly around IR 41/30-01 in the North Celtic Sea Basin.

The Inferior Oolite Group and Bathonian strata have potential reservoir layers in sandstones and/or limestones. It is worth noting that around wells IR 41/30-01 and IR 42/21-01 in the North Celtic Basin the Inferior Oolite Group reservoir sequence contains significant amounts of sandstone. However, confirmation that the overlying seal is of sufficient quality would be required.

Assessment of seals within the study area was complicated by the large number of unconformities which have resulted in an incomplete geological sequence in many areas, particularly on the basin margins.

The potential seal for the Carboniferous strata and overlying Sherwood Sandstone Group is the shales and evaporites of the Mercia Mudstone Group. This strata is likely to form an effective seal. The Mercia Mudstone Group reaches thicknesses of over 1300 m in the study area based on well data. The lithology of the Mercia Mudstone Group is generally consistent and always contains mudstones and claystones, with evaporites of varying thickness present in many wells. It should however be noted that the Mercia Mudstone Group is calcareous in some areas and silty in other areas so the seal above potential storage sites would need to be considered in detail.

The potential seal for the Sinemurian strata comprises argillaceous strata of Lower – Middle Jurassic age. The lithology of these strata is quite variable ranging from mudstone/claystone to siltstone. The sealing potential would need to be assessed on a site by site basis. The Middle to Upper Lias strata can reach thicknesses of up to 300 – 400 m as proven by wells in the detailed study area. It is worth noting that in some places potential sealing formations have been removed by erosion which could potentially allow injected CO₂ to migrate out of Sinemurian and older reservoir layers. If the seal above the Sinemurian is insufficiently impermeable then CO₂ will migrate into the overlying Bathonian and Inferior Oolite Group strata thus the sealing ability of the uppermost seals remains critical in many cases even if Sinemurian sandstones are chosen as a storage reservoir.

Potential sealing horizons for the Bathonian strata and Inferior Oolite Group reservoir sequence could be found in the interbedded mudstones and siltstones of the Middle to Upper Jurassic and younger deposits. The seals and lithologies overlying the Bathonian and Inferior Oolite Group strata vary both in thickness and in lithology rapidly over short distances so a detailed study would be required for any potential storage site. For example, in well UK 106/20-01, Bathonian–Inferior Oolite Group strata are overlain by a thick sequence (over 800 m) of Cenozoic sandstones, siltstones and mudstones which are unlikely to form an effective seal. The lithology of the Jurassic and younger seals is variable such that more detailed work would be needed to ensure any potential storage sites offer secure storage since the seals these strata are critical to security of storage.

As assessment for hydrocarbon potential has focused on potential reservoir rocks, the sealing formations have not been fully explored. In some well geological reports comments have been made on the expected sealing ability of argillaceous formations but these formations generally were not assessed in terms of porosity and permeability. More detailed work would be required to characterise the caprocks associated with potential reservoirs of the Celtic Sea including acquiring new primary data from cores.

6.1 CARBONIFEROUS RESERVOIR SEQUENCE

Carboniferous strata are proven in wells around the basin margins. The age of Carboniferous strata varies from Visean to Stephanian. All the wells which penetrate Carboniferous strata have sandstone layers indicated in the geological well reports/composite logs. In particular, in well UK 106/20-01, the Westphalian strata contain a high proportion of sand, but most other wells Carboniferous strata only appear to contain isolated sand layers.

The lithology of the Carboniferous strata is highly variable due to the wide range of depositional environments. The environment of deposition ranged from carbonate shelf to deeper water offshore basins, to emergent areas of non-deposition during the Dinantian stage (Tappin et al., 1994) during a tensional stress regime. Visean limestones (overlain by late Westphalian strata) are proven in well IR 42/17-01A on the basin margin.

During Namurian times, as the stress regime changed to compressional, more regions became emergent and in the southern North Celtic Basin, Tappin et al. (1994) interpret a deposition of shelf sediments grading to paralic sand/mud across the central and northern North Celtic Basin. Clastic beach deposits of Namurian age are also described by Tappin et al. (1994).

Early Westphalian strata are expected to comprise fluvio-deltaic sands interspersed with marine bands overlain by mid Westphalian deltaic sands and silts with thick and extensive coals deposited on low-lying, swampy, alluvial, coastal plains subjected to infrequent marine incursions (Kelling, 1974). During the late Westphalian, uplift led to erosion and sediments sourced from the Variscan Mountains were deposited as fluvial/paralic sands.

Wells indicate that Westphalian strata comprise siltstones, sandstones and claystones (wells 50/03-03, IR 42/16-01, UK 106/20-1 and UK 103/02-01, IR 42/17-01A). Well IR 42/17-01A penetrates the base of the Westphalian strata and over 900 m of Westphalian strata are proven. The other wells which reach Westphalian strata (IR 50/03-03, IR 42/16-01, UK 106/20-1 and UK 103/02-01) did not reach the base of the Westphalian strata.

In well IR 42/16-01, 526 m of Stephanian strata are proven which comprise non-marine red-brown to grey siltstones and sandstones with minor limestones, dolomites and coals.

The modelled top Carboniferous surface is shown in Figure 10. Based on the seismic interpretation, the top Carboniferous depth reaches up to 11,000 m in the basin centre. Where Carboniferous strata are penetrated by wells, the depth to top of these strata varies from 548 m (measured depth in well IR 42/17-01A) to 2969 m (measured depth in well UK 103/02-01). The base of the Carboniferous is not proven in any wells so the true thickness is not substantiated. The thickness of proven Carboniferous strata ranges from 203 – 1321 m (measured thickness).

Some Carboniferous sandstone layers may be sealed by intraformational mudstones or claystones, however, there is no proven thick intraformational seal and the silty nature of the Carboniferous strata suggests that if CO₂ were injected into the Carboniferous strata, it would migrate into overlying Sherwood Sandstone Group.

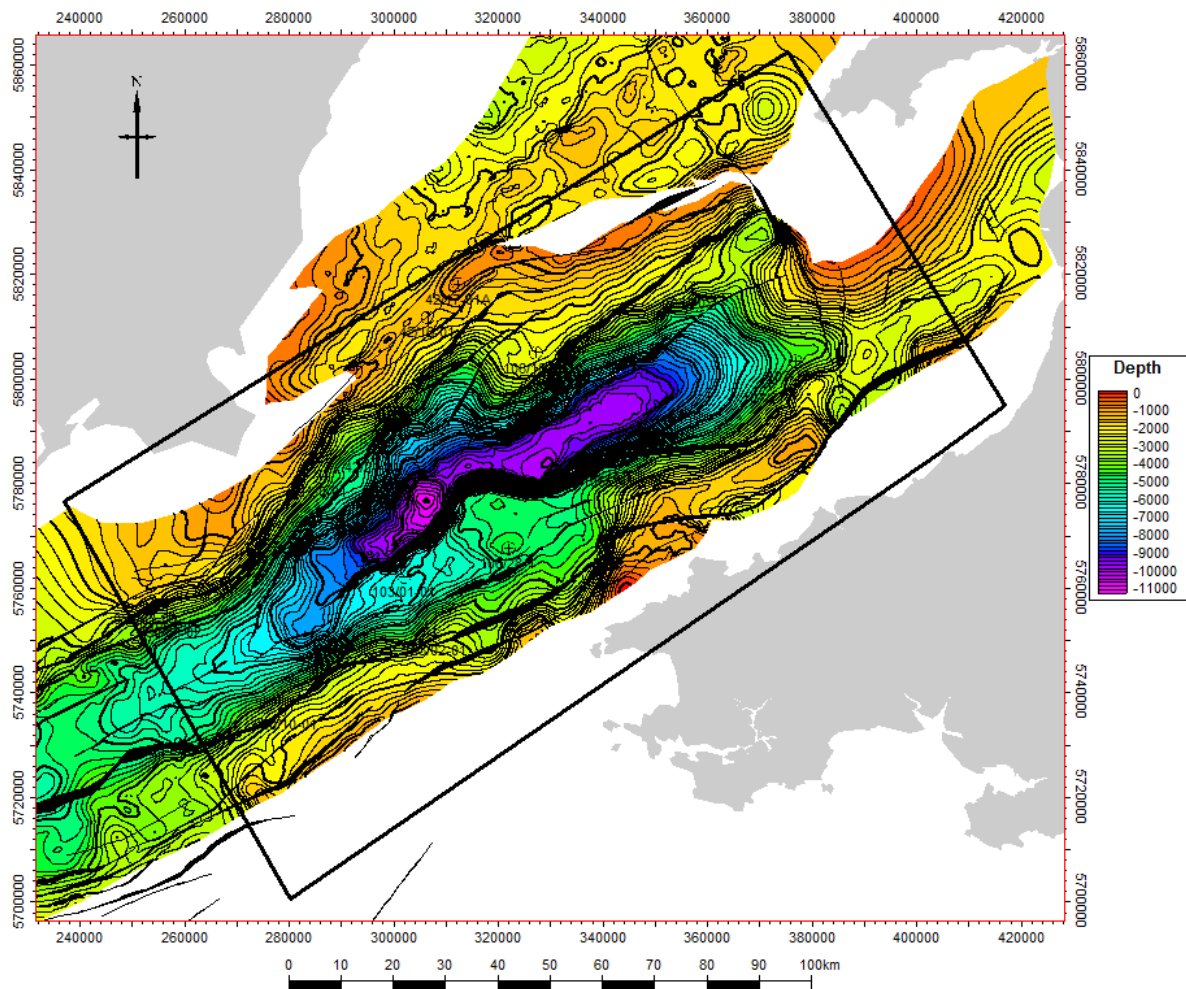


Figure 10: Model surface of depth to top Carboniferous strata (m)

6.2 SHERWOOD SANDSTONE GROUP RESERVOIR SEQUENCE

The Sherwood Sandstone Group was deposited unconformably on Carboniferous sediments. It comprises sandstones, siltstones and mudstones. Offshore deposits are generally finer grained than their onshore counterparts. The Sherwood Sandstone Group is proven in several wells around the edges of the basins.

The upper part of the sandstone is dominated by fluvial bar deposits which are separated by a distal floodplain mudstone from a lower sandstone unit dominated by arid alluvial wadi and fluvial bar deposits (Shannon, 1995).

The model Sherwood Sandstone Group reaches depths of approximately 9900 m in the centre of the basin (Figure 11). It reaches the seabed in discrete elongate pockets on the northern limb of the North Celtic Sea Basin. The top of the Sherwood Sandstone Group is not always proven in wells and sometimes some or all the sequence is absent (e.g. IR 42/17-01A, UK 106/20-01). The depth to top of the Sherwood Sandstone Group proven in wells varies from 1008 – 2720 m (measured depth in wells IR 42/16-01 and UK 103/02-01 respectively).

Based on the seismic interpretation, the Sherwood Sandstone Group reaches a thickness of over 1300 m in the basin depocentre (Figure 12) but has been removed by erosion over the basin margins. Proven thickness in wells varies from 5 – 564 m (measured depth in wells IR 50/03-03 and IR 42/16-01) which is considerably less than the model maximum thickness, however, there are no wells penetrating the Sherwood Sandstone Group in the depocentres so the maximum thickness is not substantiated by borehole data.

In the St George's Channel Basin, the Sherwood Sandstone Group is recorded in four wells where it comprises mainly sandstone (106/18-01), claystone and silty claystone with some interbedded fine to medium grained sandstone (UK 106/28-01) claystone and siltstone (UK 103/02-01). The greatest thickness of 441 m (measured thickness) is recorded in well UK 103/02-01 however unfortunately this lies below the optimal depth for CO₂ storage as outlined in Table 1. Around 123 m (measured thickness in well) of Sherwood Sandstone Group equivalent is penetrated by well UK 106/18-01.

In the North Celtic Sea Basin, the Sherwood Sandstone Group equivalent is only 5 m thick in well IR 50/03-03 where it is described as very fine to fine grained, strongly cemented by silica with no visible porosity. A thin (43 m in well) conglomerate/sandstone is penetrated by IR 50/10-01 underlain by undifferentiated Triassic strata which comprise mainly claystone and siltstone. Further north, a greater thickness (117 m measured thickness in well) of Sherwood Sandstone Group is proved in well IR 42/16-01, where it comprises an upper silty section and a lower sandy section. Around 326 m of Triassic sediments are penetrated by well IR 42/17-01A which contains sandstone layers towards the base. However, this sequence lies above the optimum depth (as defined in Table 1) for storage.

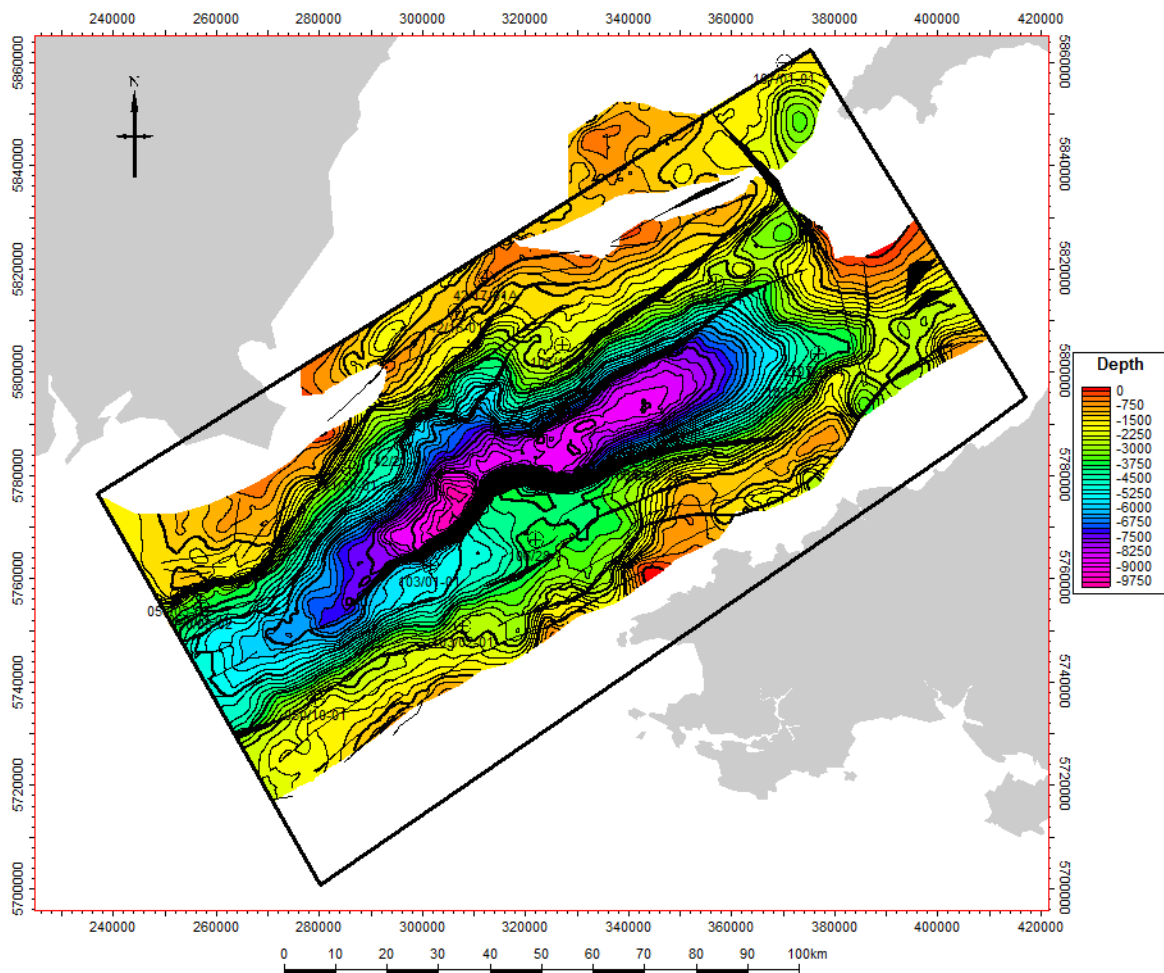


Figure 11: Model surface of depth to top Sherwood Sandstone Group surface (m)

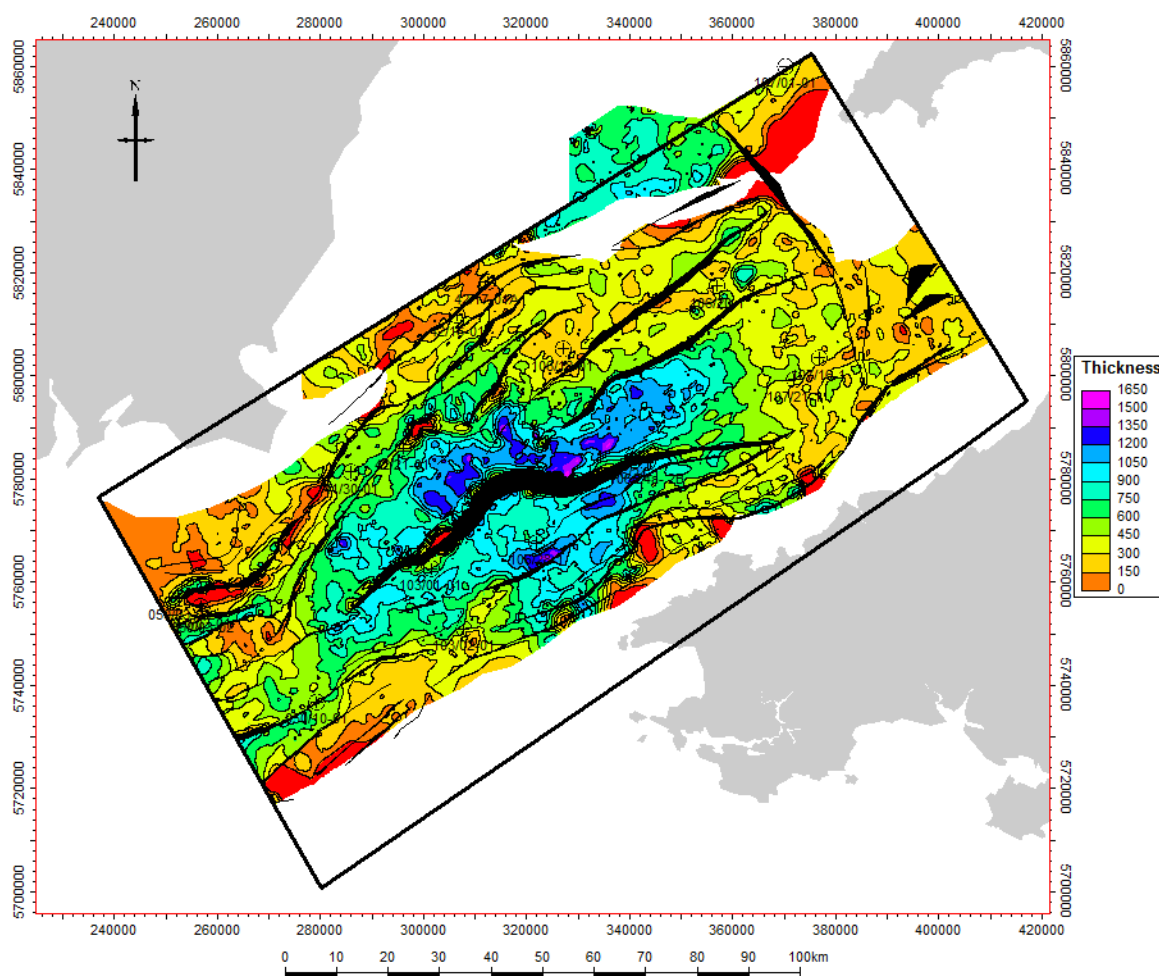


Figure 12: Model thickness map of the Sherwood Sandstone Group (m)

6.3 MERCIA MUDSTONE GROUP SEALING STRATA

The seal for the Sherwood Sandstone Group is the shales and evaporites of the Mercia Mudstone Group. The Mercia Mudstone Group provides an excellent seal for hydrocarbon reservoirs in the East Irish Sea Basin (Seedhouse and Racey, 1997). The Mercia Mudstone Group lies conformably on top of the Sherwood Sandstone Group. It is composed of mudstones, siltstones, halites, claystones, dolomites and subordinate sandstones (Tappin et al., 1994). This group of mudstones reaches thicknesses of over 1300 m in some parts of the study area according to well data.

The Mercia Mudstone Group in this area represents a wide range of depositional environments; the finer-grained sediments are related to a basinal environment some distance from the source and the halites may be related to a lacustrine environment with marine influences (Tappin et al., 1994).

The top of the Mercia Mudstone Group reaches depths of up to 7165 m (from the interpreted data, Figure 13) and it crops out at the basin margins (Tappin et al., 1994). Note that the seismic interpretation did not extend to the far north-east of the detailed study region due to overlap with the 3D interpretation carried out for the CISB thus this region was interpolated from a few well values only for this model. The depth to the top of the Mercia Mudstone Group proven in wells varies from 71 – 2368 m (measured depth in wells IR 50/03-03 and UK 106/24a-2B respectively).

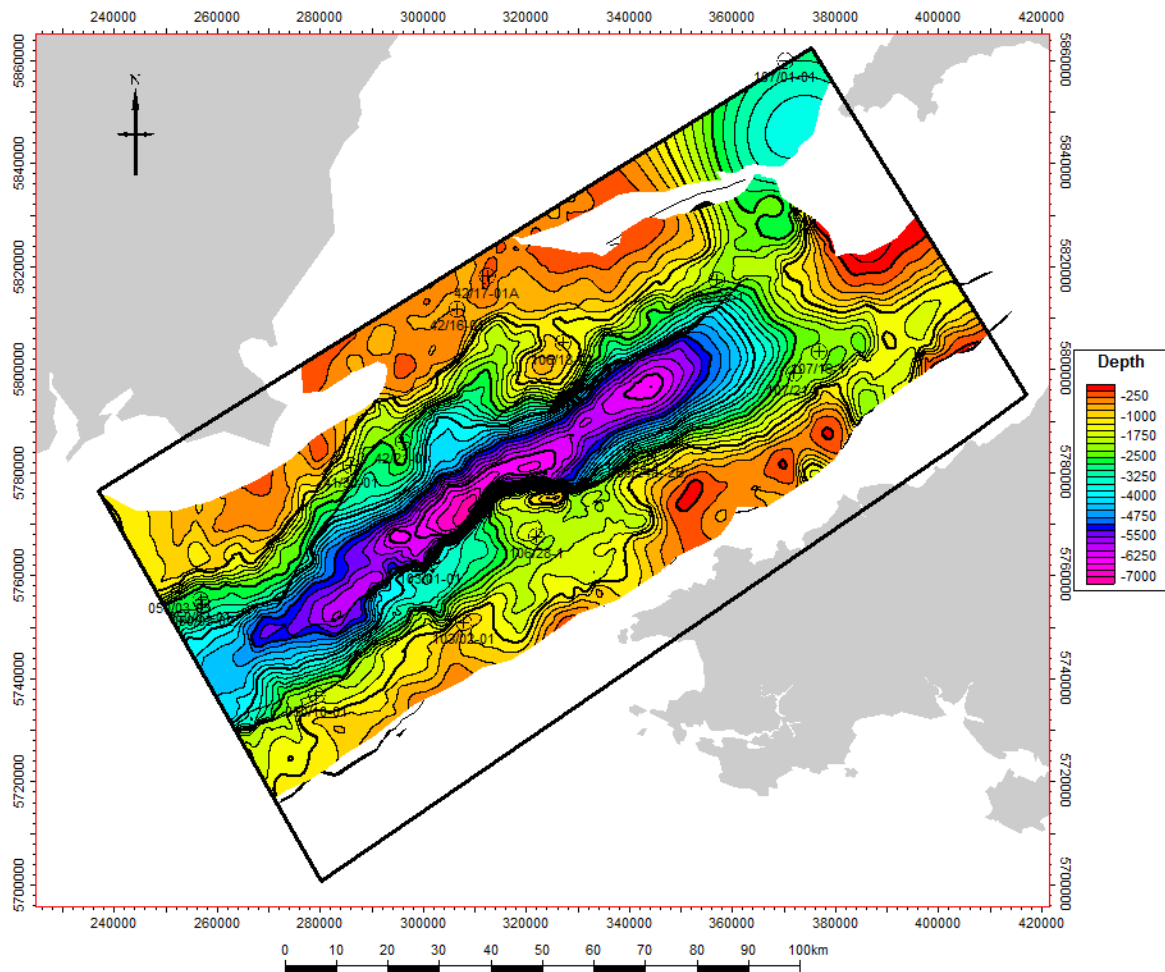


Figure 13: Model surface of depth to the top Mercia Mudstone Group (m)

The modelled thickness of the Mercia Mudstone Group is generally greater than the required 100 m recommended minimum thickness for sealing formations (Table 1, Figure 14), having a thickness of up to 4200 m in the basin depocentres. The proven thickness of the Mercia Mudstone Group varies from 71 - 1347 m (measured thickness in wells IR 50/03-03 and UK 106/28-01 respectively). In other parts of the detailed study region the wells terminate in the Mercia Mudstone Group (e.g. UK 106/24a-2B) and the full thickness of the sequence is not penetrated. The full thickness in the basin depocentres is not proven in wells.

In the St George's Channel Basin, the Mercia Mudstone Group has a recorded thickness of 500 – 1776 m (measured) thickness and comprises mudstone or claystone with evaporite beds and some minor siltstones, sandstones and carbonates (wells UK 103/02-01, UK 103/01-01, UK 106/20-01 and UK 106/18-01). In some wells the Mercia Mudstone Group is described as having calcareous cement or as being calcareous (e.g. IR 50/10-01 and UK 106/18-01) to the extent that in some wells marls are noted on the composite logs (e.g. UK 103/02-01). There is research currently being undertaken into the sealing ability of calcareous argillaceous rocks but this has not yet been completed and so the sealing ability of calcareous mudstones and claystones is not guaranteed. However, the great thickness of the Mercia Mudstone is encouraging in terms of its ability to contain buoyant CO₂ and evaporites could offer the additional benefit that salt under pressure can 'flow' which could potentially seal fractures.

In the North Celtic Sea Basin, the Mercia Mudstone Group has a recorded thickness of 71 – 498 m (measured) thickness (wells IR 50/03-03 and IR 41/30-01 respectively) and comprises claystone and siltstone with minor sandstone, evaporites and carbonates in some wells (wells IR 50/03-03, IR 50/10-1 and IR 41/30-01).

On the fringes of the Central Irish Sea Basin, silty Triassic sediments are noted in well IR 42/17-01A where the top of the undifferentiated Triassic section (173 m measured thickness) mainly comprises claystone. In well IR 42/16-01, the Mercia Mudstone Group comprises claystone and siltstone with minor sandstone, evaporites and carbonates. In borehole UK 107/01-01, over 1 km of Mercia Mudstone Group is proven capped by Quaternary sediments.

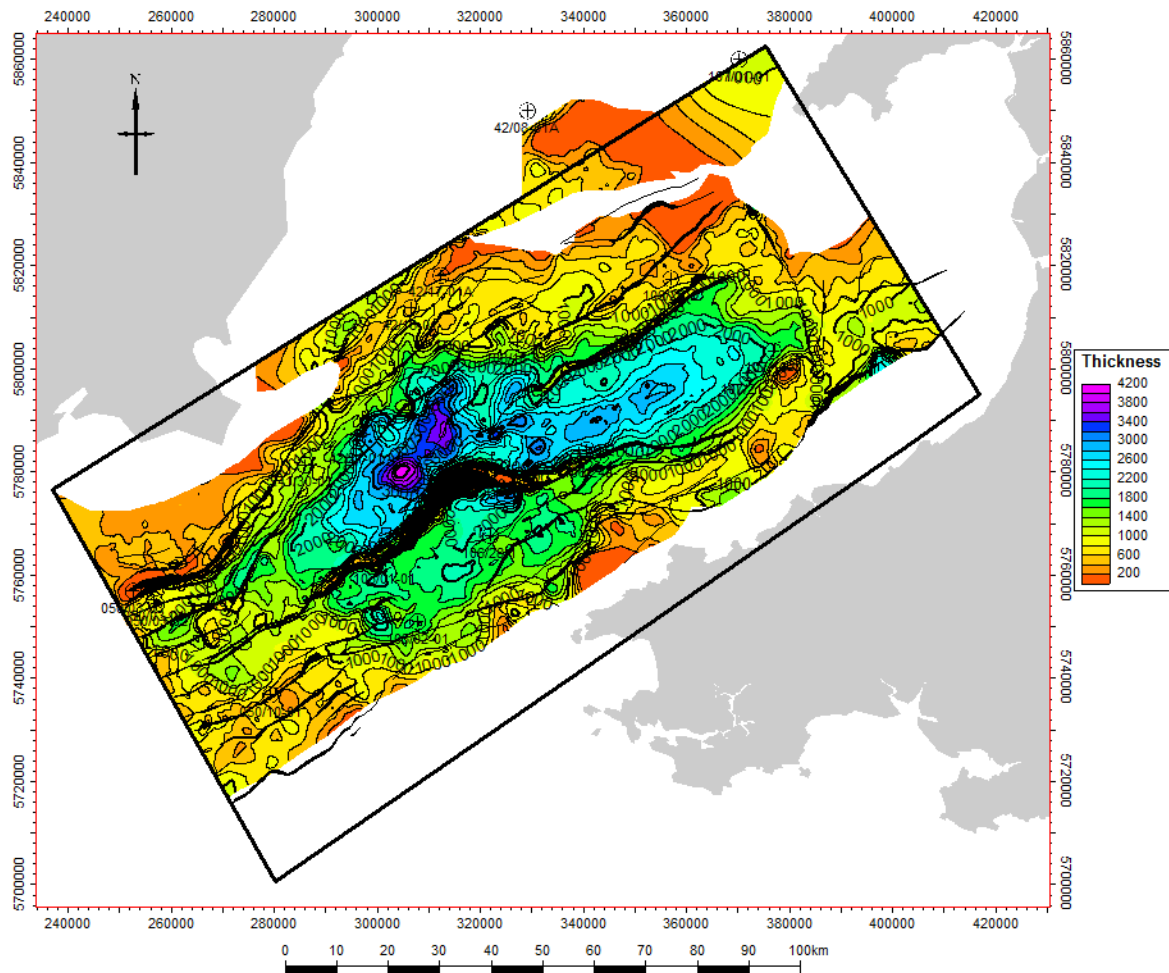


Figure 14: Model thickness map of the Mercia Mudstone Group (m). Note that in the north-east corner the model has been constructed from interpolation of well points only and not from interpretation on seismic data.

6.4 SINEMURIAN RESERVOIR SEQUENCE

The Lower Jurassic Sinemurian sandstones are part of a series of stacked sequences related to episodes where basin subsidence provided additional space to host sediment deposition. Sandstones are recorded as clean sandstones which coarsen/clean upwards (Kessler and Sachs, 1995). Deposition of Sinemurian sandstones occurred in a shallow marine shore-face shelf setting (Kessler and Sachs, 1995).

Sandstones are not noted in all wells where Sinemurian strata are recorded, in particular in the UK sector, most Sinemurian strata are argillaceous. In the St George's Channel Basin, Sinemurian strata mainly comprise claystones, mudstones or marls.

The modelled surface of the top Sinemurian strata lies at a maximum depth of up to 6170 m in the centre of the basin (Figure 15). It was picked as the top of the Sinemurian sequence as sandstones of Sinemurian age were not identified in all wells. The greatest depth to top of

Sinemurian strata is noted in well UK 103/01-01 at 3313 m (measured depth) where it is labelled as the Liassic Sandstone Formation (although here it mainly comprises claystone with minor siltstone). The smallest depth to top Sinemurian strata recorded in the detailed study area is 221 m (measured depth in IR 50/03-03, though this deposit is given as late Pliensbachian to Sinemurian on the composite log so this is not the true top of the Sinemurian strata). The depth to the modelled surface of the top Sinemurian sequence is greater in the basin depocentre where the depth to top is not proven in wells thus this interpretation is based on the surfaces produced from the seismic interpretation which have been depth converted to give a modelled surface in the depth domain.

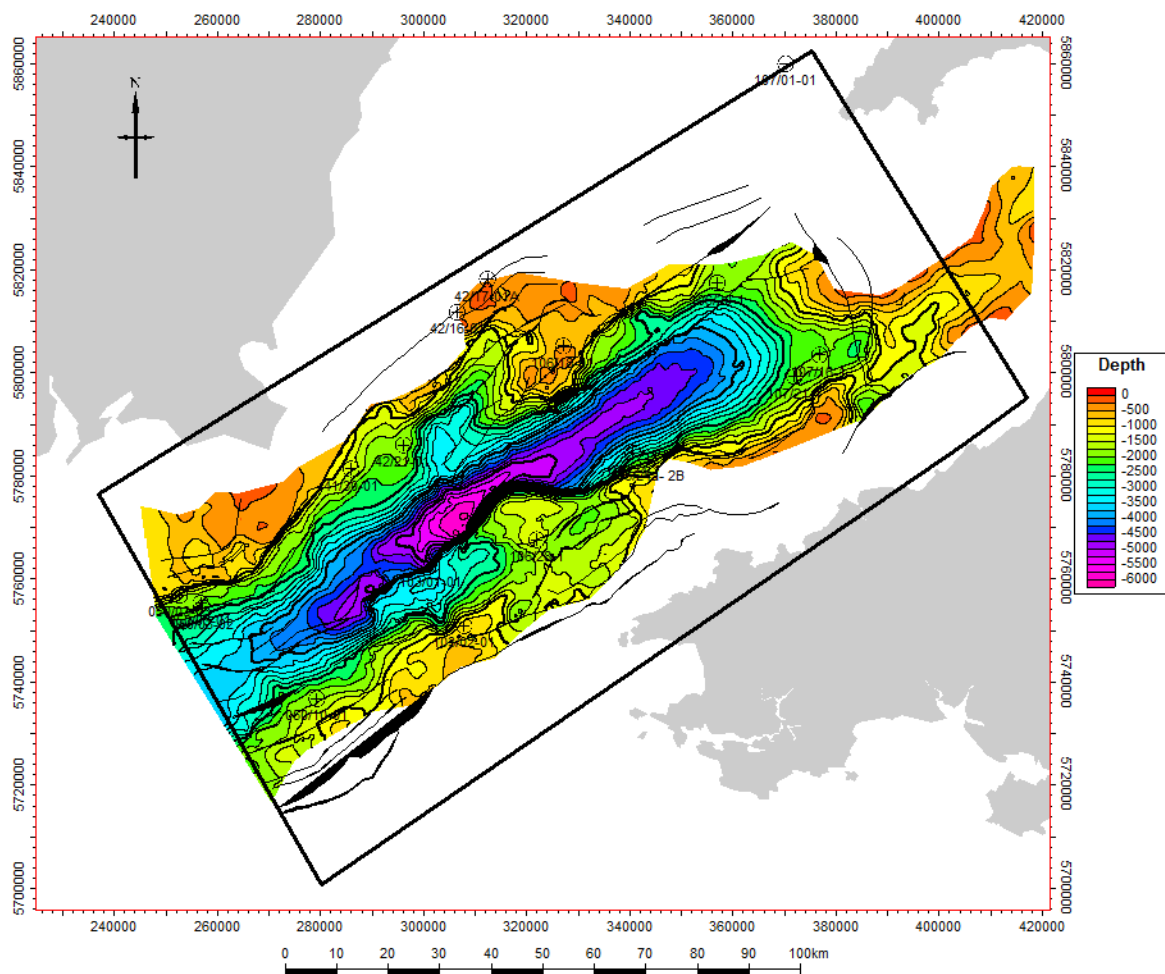


Figure 15: Model surface of the depth to top Sinemurian strata (m)

The thickness of the Sinemurian strata proven in wells varies from 67 – 790 m (measured thickness in wells IR 42/17-01A and IR 50/03-01 respectively, though in the latter case this includes some Pliensbachian strata).

In the St George's Channel Basin, the Sinemurian strata comprise argillaceous claystones and marls or mudstones with very minor limestone, siltstone and sandstone (wells UK 103/02-01, UK 106/28-01, UK 106/18-01, and UK 106/20-01). The Sinemurian strata comprise siltstones and claystones in well UK 103/01-01. The Sinemurian strata are frequently carbonaceous. Sinemurian strata are absent from well UK 106/24a-2B due to erosion or non-deposition.

In the North Celtic Sea Basin, the Sinemurian strata comprise varying proportions of sandstones, siltstones, claystones and limestones. A Sinemurian sandstone is recorded as a 71 m thick, fine to very fine grained sandstone body, with weak calcite cement and visible porosity in well IR 50/03-03. The remainder of the Sinemurian strata comprise mainly siltstone in this well. In well IR 41/30-01 Sinemurian strata comprise sandstones and siltstones with occasional claystones and

traces of limestone, these sandstones are described as very fine to fine grained, weakly cemented with very poor visible porosity (in this well, the Sinemurian sandstone interval is bounded at top and bottom by faults). In well IR 42/17-01A, the Sinemurian strata comprise siltstone. A Pliensbachian to Sinemurian sandstone layer is also present in IR 50/03-01 but the majority of this sequence comprises claystone. In well IR 42/21-01 a 43 m thick Pliensbachian sandstone is penetrated which is described as fine to very fine grained. This was not considered as a potential reservoir horizon in the original assessment but could be considered by future studies if it proved to be laterally continuous.

On the fringes of the Central Irish Sea Basin in well IR 42/17-01A, a thin sequence (64 m measured thickness) of Jurassic strata of Sinemurian – Liassic age which comprises claystone and siltstone is noted.

6.5 LOWER – MIDDLE JURASSIC SEALING STRATA

The potential seal for the Sinemurian sandstones comprises argillaceous strata of Lower – Middle Jurassic (Pliensbachian to Aalenian) age. However, in many wells a thick sequence of mudstone/claystone is absent or strata of this age contain significant quantities of siltstone which would not be guaranteed to act as an effective seal. Additionally, the claystones/mudstones are described as calcareous in many places. These Lower – Middle Jurassic strata may not offer an effective seal thus containment must be confirmed on a site by site basis.

In some areas, the argillaceous Lower - Middle Jurassic strata has thicknesses greater than the recommended minimum (Table 1). Thickness of these strata ranges from 0 m (e.g. well IR 50/03-03 where Cretaceous strata rests directly on strata of Pliensbachian age) to 942 m (IR 50/03-01). If the seal above the Sinemurian strata is insufficiently impermeable, either due to lithology or thinness, then CO₂ will migrate through into the overlying Bathonian strata – Inferior Oolite Group, thus the sealing ability of the uppermost seals remains critical in many cases even if Sinemurian strata are chosen as a storage reservoir.

As the Sinemurian strata are unlikely to offer a good reservoir rock in the St George's Channel Basin, the lithology of the overlying strata in this basin is given here only for completeness. The Sinemurian strata are overlain by the upper part of the Lias Group which comprises calcareous claystones with thin limestones or mudstones (wells UK 106/28-01, UK 107/21-01, UK 106/18-01, UK 106/20-01). Siltstones and claystones with occasional limestones are noted in well UK 103/01-01 where Bajocian strata rest directly on strata of Sinemurian – Pliensbachian age.

In the North Celtic Sea Basin, the Sinemurian strata are overlain by Pliensbachian to Aalenian strata. These comprise siltstones (IR 41/30-01, IR 42/21-01) or calcareous claystones (IR 50/03-01) or calcareous claystones with thin limestones or mudstones (IR 50/10-01). In well IR 50/03-03, the Sinemurian strata are unconformably overlain by Cretaceous strata (though there are no cuttings returned so this interpretation is unconfirmed). In well IR 50/03-01, the Lower Jurassic sequence overlying the Sinemurian strata is 942 m thick (measured in well) and mainly comprises claystone.

6.6 INFERIOR OOLITE GROUP RESERVOIR SEQUENCE

During Middle Jurassic times, the North Celtic Sea Basin was dominated by a low-energy marine environment below storm wave base with high energy localised storm events supplying coarser grained sediments (Ewins & Shannon, 1995).

During early Aalenian times, sands accumulated in the St George's Channel Basin. Due to a marine regression, marine mudrocks in the North Celtic Sea basin grade into sandstones in the St George's Channel Basin during late Aalenian times (Bradshaw et al., 1992).

A widespread marine transgression occurred in early Bajocian times. Bajocian strata in the Celtic Sea basins comprises fully marine clays and muds (Bradshaw et al., 1992). In the centre of the St

George's Channel Basin there are marine shales, but sandy oolitic calcarenites occur along the basin margin (Bradshaw et al., 1992).

During late Bajocian times, fully marine sedimentation continued along the axes of the North and South Celtic Sea basins. Shelly mudstones and thin sandstones were deposited in the St George's Channel Basin (Bradshaw et al., 1992).

Sandstones of Aalenian – Bajocian age in the Inferior Oolite Group were identified as the main target having sandstones and limestones which could offer potential targets for storage. This layer is described as the Inferior Oolite Group reservoir sequence for this report. The top Bajocian strata were taken as the top of this sequence as this is frequently identified in wells. Generally sandstones or limestones are present in the Bajocian strata which could be considered for storage where they lie at optimal depth in the basin depocentres and where suitable caprocks are present. Where present, arenaceous Aalenian strata included in the Inferior Oolite Group reservoir sequence of this project comprise sandstones, siltstones and limestones. The base of this sequence was variable due to non-deposition of arenaceous material and erosion; the base of the Inferior Oolite Group sandstones generally coincided with the top of the Lower Jurassic sequence (Lias Group), where this was not indicated in wells, the base of the sandstone/limestone sequence of Bajocian/Aalenian age was used as the base of the Inferior Oolite Group reservoir sequence for this report.

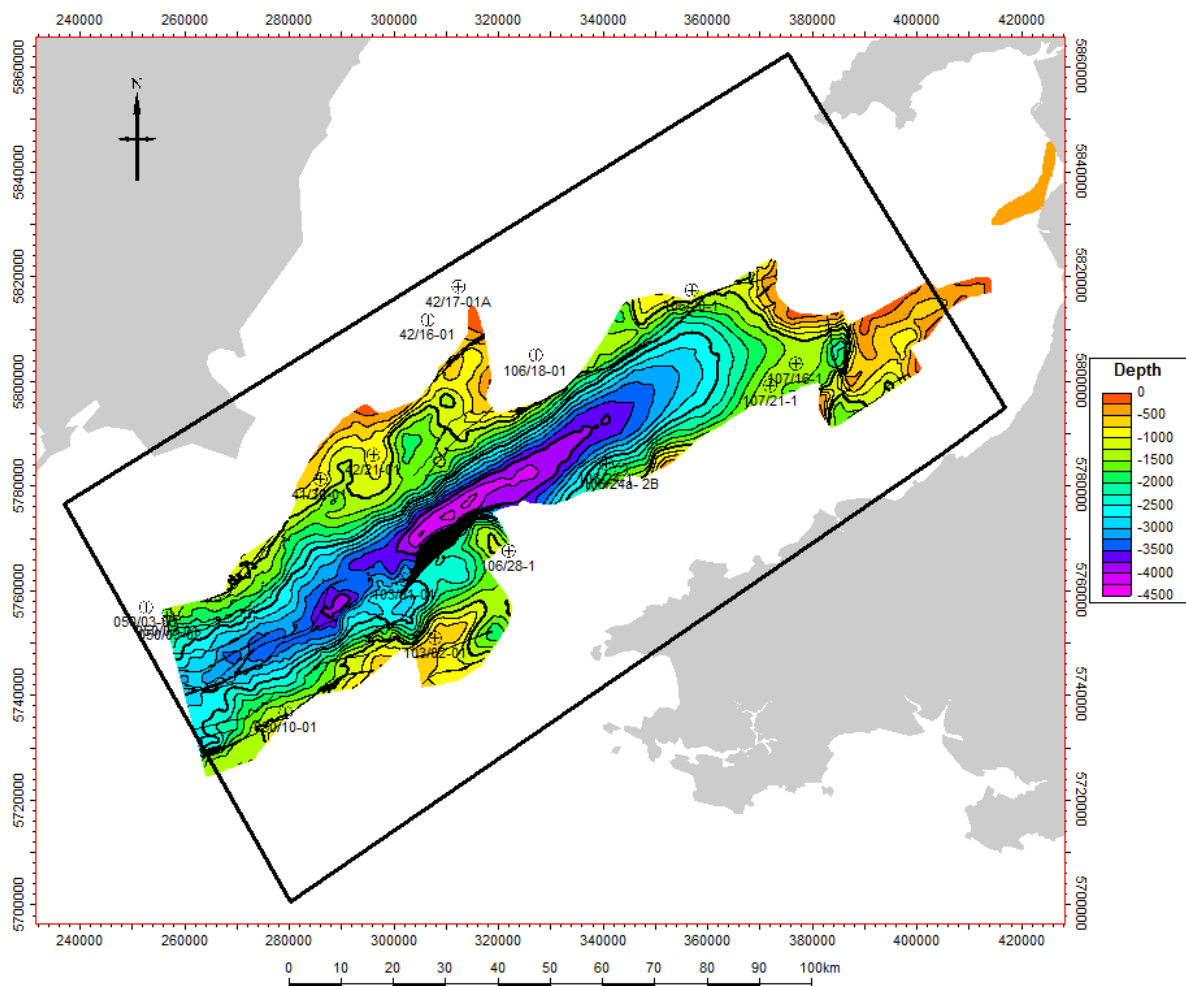


Figure 16: Model surface of depth to top Inferior Oolite Group reservoir sequence (m)

The top of the Inferior Oolite Group reservoir sequence model layer reaches a depth of almost 4300 m in the centre of the basin (Figure 16). Depth to top Inferior Oolite Group reservoir sequence ranges from 547 m (measured depth well UK 103/02-01, though this is noted as

‘possibly Bajocian’) to 3043 m (measured depth well UK 103/01-01). The depth to top Inferior Oolite Group reservoir sequence is not proven in the basin depocentres by wells so the maximum depth of the model surface is based on the depth-converted seismic interpretation.

Maximum depth to base of the modelled surface of the base of the Inferior Oolite Group reservoir sequence is nearly 4800 m in the basin depocentres (Figure 17). The depth to the base of the Mid Jurassic strata recorded in wells varies from 552 m (measured depth well UK 103/02-01 where it comprises an erosional surface) to 3067 m (measured depth in well UK 103/01-01).

The modelled thickness of the Inferior Oolite Group reservoir sequence reaches thicknesses of over 1100 m in small regions of the basin depocentre (Figure 18).

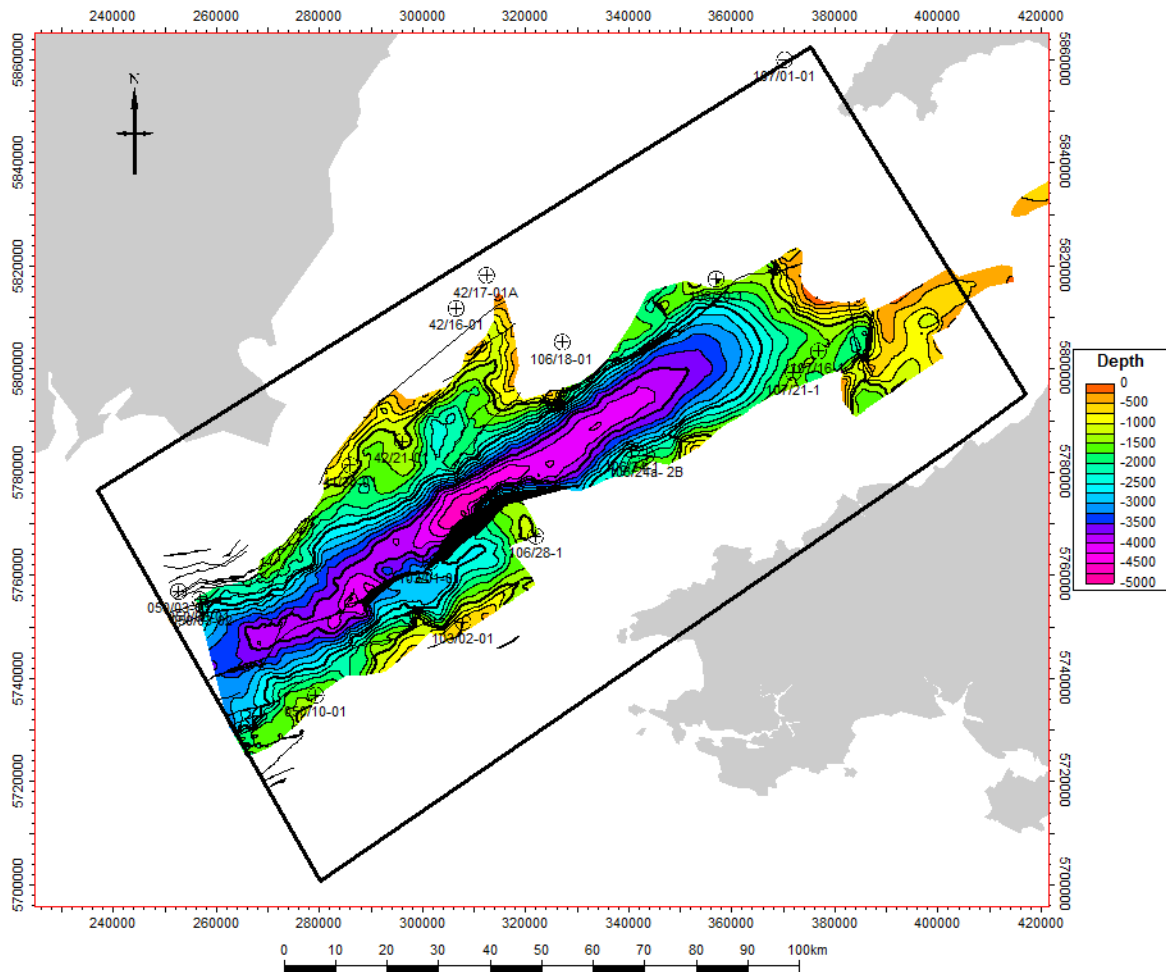


Figure 17: Model surface of base of Inferior Oolite Group reservoir sequence (m)

The sandstones within the Inferior Oolite Group are pale grey and fine grained (grading to siltstone in places), with calcareous cement, interbedded with mudstones, siltstones or limestones (Tappin et al., 1994) in the St George's Channel Basin. Reservoir strata comprise limestones with a varying proportion of sandstone (wells UK 103/02-01, UK 106/20-01, UK 107/16-01, UK 103/01-01). Aalenian strata of the Inferior Oolite Group reservoir sequence comprise sandstones and siltstones in well UK 107/16-01. In well UK 107/21-01, the base of the reservoir sequence is taken at the base of an Bajocian – Aalenian sandstone indicated on the log as underneath this the Aalenian strata comprises claystone. In well UK 106/24a-2B, UK 103/02-10 and UK 103/01-01, Aalenian strata are grouped with the Lower Jurassic strata as they comprise mainly claystone, so this was taken as the base of the Inferior Oolite Group reservoir sequence. The Inferior Oolite Group reservoir sequence, where proven, generally lies at optimal depth for storage. However, it is worth noting that in many places there is no obvious seal between this sequence and the overlying Bathonian strata and therefore these strata should in most cases be considered as

contiguous in terms of storage. In the St George's Channel Basin, the Inferior Oolite Group reservoir sequence have a (measured) thickness of around 25 – 582 m (measured thickness wells UK 103/01-01 and UK 107/16-01 respectively). There is no suitable caprock above the Bathonian/Bajocian strata in well UK 106/20-01. Bajocian sediments are not recorded in UK 106/28-01 due to erosion/non-deposition.

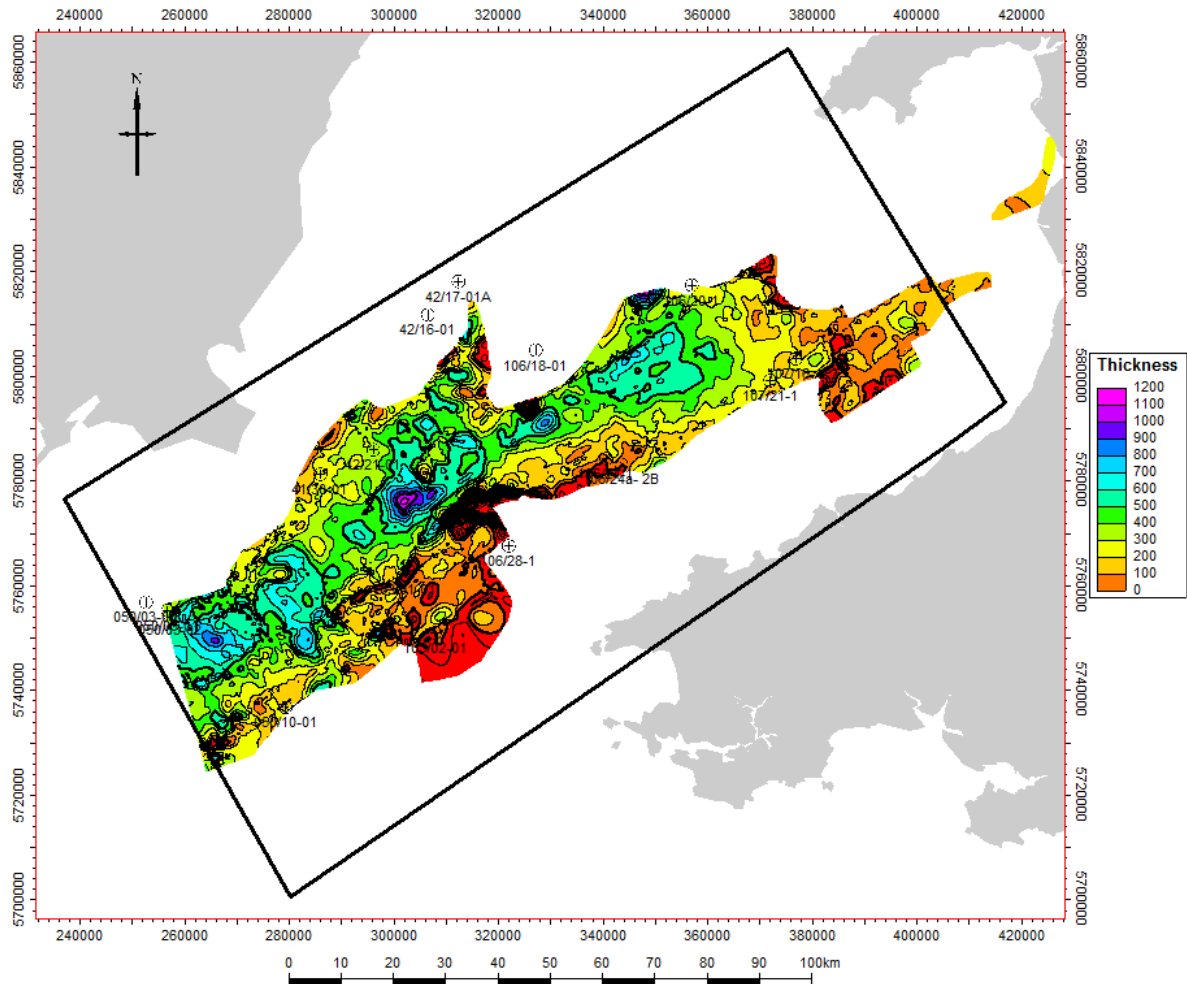


Figure 18: Model thickness of the Inferior Oolite Group reservoir sequence (m)

In the North Celtic Sea Basin, the Inferior Oolite Group reservoir sequence have a measured thickness of 92 – 636 m (wells IR 50/03-01 and IR 42/21-01 respectively). Reservoir layers comprise sandstones and limestones (wells IR 41/30-01), or sandstones and sandy siltstones (IR 50/03-01), or fine to very fine grained sandstones (IR 42/21-01) or fine to fine grained with calcareous cement and no visible porosity (IR 50/10-01). Inferior Oolite Group strata rich in sandstone/limestone are proven to lie at optimal depth for storage (c.f. Table 1) in wells IR 42/21-01 and IR 41/30-01 near the North Celtic Sea Basin centre and in borehole IR 50/10-01 on the basin margin. Inferior Oolite Group strata also lie at suitable depth for storage in well IR 50/03-01 on the margin of the North Celtic Sea basin but only a small amount of sandstone is proven in this well. Aalenian strata comprise siltstone in well IR 41/30-01, this was not included in the Inferior Oolite Group reservoir sequence as the log properties indicate a low proportion of sandstone. In well IR 42/21-01, base of the Inferior Oolite Group reservoir sequence is taken at the base of the Aalenian sandstone. In well 50/10-01, the base of the Inferior Oolite Group reservoir sequence was taken at base of Bajocian strata as the underlying Middle – Lower Jurassic strata comprise silty claystone.

6.7 BATHONIAN RESERVIOR SEQUENCE

Fully Marine clay and muds were deposited in the centres of the Celtic Sea Basins during the Bathonian Stage but there is evidence of a major late Bathonian regression in the Irish Sea Sector (Bradshaw et al., 1992). Bathonian strata generally rest conformably on Bajocian strata and there is no obvious regional seal separating potential reservoir strata. The Bathonian sequence often comprises beds of sandstone and limestone which could be considered together for storage where they have suitable reservoir properties. Bathonian strata are not present in all wells, having been removed by erosion or not deposited around the edges of the basins (e.g. in well IR 50/03-01). Sandstones are noted in most wells where Bathonian strata are present including UK 103/01-01, UK 103/02-01, UK 107/16-01, UK 107/21-01, UK 106/24-01, IR 50/10-01, IR 50/03-02 and IR 41/30-01.

The modelled surface of the top Bathonian strata reaches depths of almost 3800 metres in the centre of the basin (Figure 19). The depth to the top of the Bathonian strata are not proven in the basin depocentre nor is the maximum thickness proven as no wells are present in this region.

In the St George's Channel Basin Bathonian strata comprise mudstones becoming silty grading into minor sandstones interbedded with limestone (Bradshaw et al., 1992). In the St George's Channel Basin, the Bathonian strata penetrated by wells mainly comprise limestones and sandstones. The proven depth to the top of the Bathonian strata varies from 238 – 2514 m (measured depth in wells UK 103/02-01 and UK 103/01-01 respectively). Measured thickness varies from varies from 3.5 m (measured thickness in well UK 106/20-01 where most the Bathonian strata have been removed by erosion) to 219 m in well UK 103/02-01, though the Bathonian strata lie above optimum depth for storage in well UK 103/02-01. Further north, the Bathonian is more argillaceous and described as a 4 – 480 m thick sequence (measured thickness) of shale, siltstone and sandstone with some oolitic limestone (UK 106/24-01), mudstone (UK 106/20-01) or siltstone and claystone with some sandstone (UK 107/16-01 on the basin margin). Some Bathonian sandstone layers have good porosity (<32.7 %), but most are described as tight. An undifferentiated Bajocian/Bathonian siltstone with some sandstone is recorded in well UK 107/21-01. Bathonian sediments are not recorded in well UK 106/28-01 on the basin margin where Cenozoic deposits rest directly on Toarcian strata.

In the North Celtic Sea Basin, depth to top of Bathonian strata ranges from 329 – 1741 m (measured depth in wells IR 42/21-01 and IR 50/03-02 respectively though in the latter this is indicated as being Late Callovian – Bathonian in age so this is not true top Bathonian strata). A Bathonian sandstone is recorded as a 48 m interval of fine to medium grained sandstone with calcareous cement and no visible porosity in well IR 50/10-01. This is then overlain by 51 m (measured thickness) of Bathonian limestone. Around 130 – 198 m measured thickness of Bathonian strata are annotated in wells IR 41/30-01 and IR 42/21-01 which comprise limestones and sandstones. The sandstones are described as very fine to fine grained with poor to moderate porosity in both wells and are noted as being calcareous in well IR 42/21-01. In these latter two wells, the Bathonian strata lie above suitable depth for storage (c.f. Table 1). Recorded thicknesses of Bathonian strata reach a maximum of 512 m (measured thickness in well IR 42/21-01) though here the Bathonian strata lies above optimum depth for storage (c.f. Table 1).

The St George's Channel fault lies along the southern basin slope with other minor faulting with a NE-SW trend occurring mainly along the basin margins/flanks as well as along the basin axis in the west.

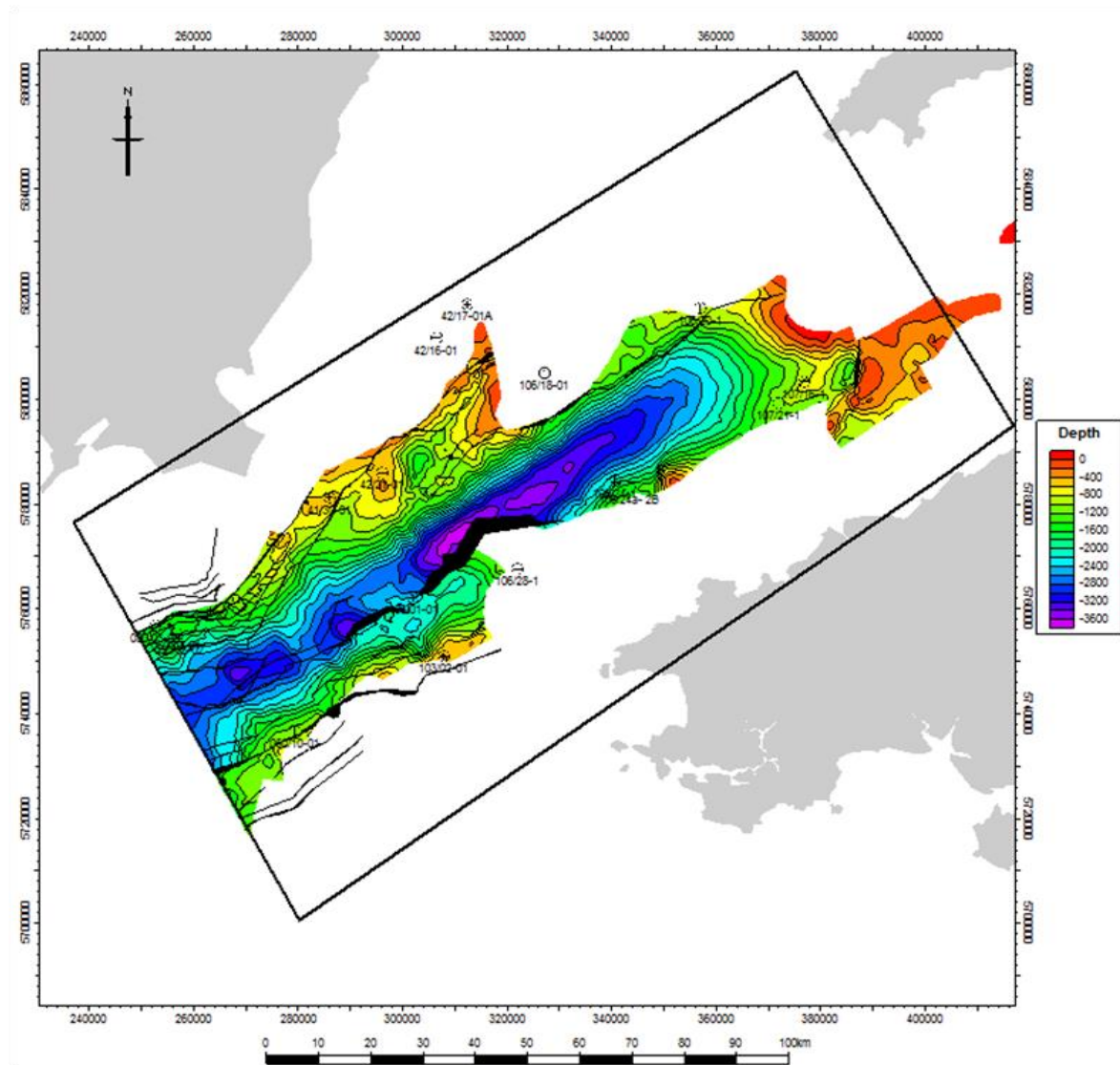


Figure 19: Model surface of depth to top Bathonian strata (m)

6.8 MIDDLE AND UPPER JURASSIC AND YOUNGER SEALING STRATA

The Middle – Upper Jurassic and younger strata overlying the Bathonian strata are of variable lithology and thickness providing local seals but not a substantial regional seal. Potential sealing horizons for the Bathonian and Inferior Oolite Group reservoir horizons could be found in the interbedded mudstones and siltstones of the Middle – Upper Jurassic sequence and younger strata. Potential sealing formations include the Oxfordian claystones, Kimmeridgian sequence and Tithonian (prev. Portlandian) claystones. The seals and lithologies overlying the Bathonian strata – Inferior Oolite Group reservoir sequence vary rapidly over short distances, for example, in well IR 50/03-03, the majority of the Lower – Upper Jurassic sealing formations have been removed, however, in nearby well IR 50/03-02 and IR 50/03-01, relatively thick sequences (up to 1290 m) of Callovian – Tithonian age strata (mudstones/claystones with interbedded sandstones and limestones) are present. The seals above the Bathonian – Inferior Oolite Group are critical to security of storage and thus the seal efficiency must be verified before a potential storage site could be seriously considered.

In the St George's Channel Basin, where it lies at optimal depth for storage, the Bathonian strata is overlain by 546 – 1700 m of Middle and Upper Jurassic siltstones, claystones, carbonates and minor sandstones (wells UK 103/01-01, UK 106/24-01, UK 107/21-01, UK 107/16-01). However, in the east part of the St George's Channel Basin, there are some regions with poor seals: In well UK 103/02-01 Bathonian strata lie directly underneath Quaternary sediments

which comprise unconsolidated sands and this could allow CO₂ to escape if it were injected near this area as it could migrate updip from the deeper portions of the Bathonian (or even older) formations into these Quaternary sediments and ultimately reach the seabed. In addition, Cenozoic sands rest directly on Aalenian/Toarcian strata in well UK 106/28-01, Bathonian sediments are not recorded, this could also offer a potential leakage pathway for CO₂ to migrate out of deeper formations.

In the North Celtic Sea Basin, Bathonian strata lie above optimum depth for storage. In wells IR 42/21-01 and IR 41/30-01, a 145 – 546 m (measured thickness) sequence of Upper Jurassic limestones, siltstones, claystones and sandstones rest unconformably on the Bathonian strata. As the proportion of sandstones and limestones (which are not likely to be good sealing lithologies) is quite high in this sequence, these deposits could offer a potential leakage pathway for CO₂ if it were injected close to this area into deeper parts of the Bathonian strata or older formations and was not trapped in a closure. Further south, on the basin margins, in wells IR 50/10-01 and IR 50/03-02 the Bathonian strata are overlain by 1180 – 1741 (measured thickness) of claystones, carbonates and minor sandstones of Upper Jurassic to Cretaceous (note there is no recovery of cuttings above 635 and 427 m measured depth respectively in these wells so lithology is unproven for the uppermost strata).

7 Reservoir Well Interpretation

Correlation of the wells across the study area indicated great variation in lithology, reservoir and caprock quality. Generalised well lithologies and well logs are shown in Figure 20, Figure 21, Figure 22 and Figure 23.

Average reservoir properties obtained from well composite logs, geological well reports and publications are given in Table 6.

Table 6: Average reservoir properties from well data analysis

Reservoir	Porosity (%)	Permeability (mD)	NTG
Bathonian strata	8 (core, 2 wells), 13 (log analysis, 4 wells)	0.54 (core, 1 well)	0.40 (log analysis, 7 wells)
Inferior Oolite Group reservoir sequence	13 (log analysis, 9 wells)	No data	0.60 (log analysis, 8 wells)
Sinemurian strata	10 (2 wells) 8 (log analysis, 3 wells, note data is sparse and not well distributed)	25.5 (RFT, 1 well, includes Hettangian at base)	0.28 (log analysis, 10 wells)
Sherwood Sandstone Group	9 (core, 2 wells) 8 (log analysis, 2 wells)	0.65 (1 well)	0.54 (log analysis, 7 wells)
Carboniferous strata	5 (core, 3 wells) 8 (log analysis, 5 wells)	0.03 (3 wells, core). Note core from UK 106/20-01 showed permeability mainly 0.01 and lower)	0.25 (log analysis, 5 wells)

Where core data are available, porosity is low in Carboniferous strata (average 5%) and permeability is generally very low (average 0.03 mD), even in sand-rich layers. The porosity and permeability of the Sherwood Sandstone Group is greater than for the underlying Carboniferous sediments but still quite low (average core porosity 9%, derived porosity 8% and permeability 0.65 mD). Average porosity of the Sinemurian strata is still low (average derived porosity and 8% and core porosity 10%, average permeability 25.5 mD from RFT data). Porosity values for the Bathonian and Inferior Oolite Group reservoir sequence are reasonable (both have an average derived porosity of 13%). More detail on the reservoir well log assessment is given in this section.

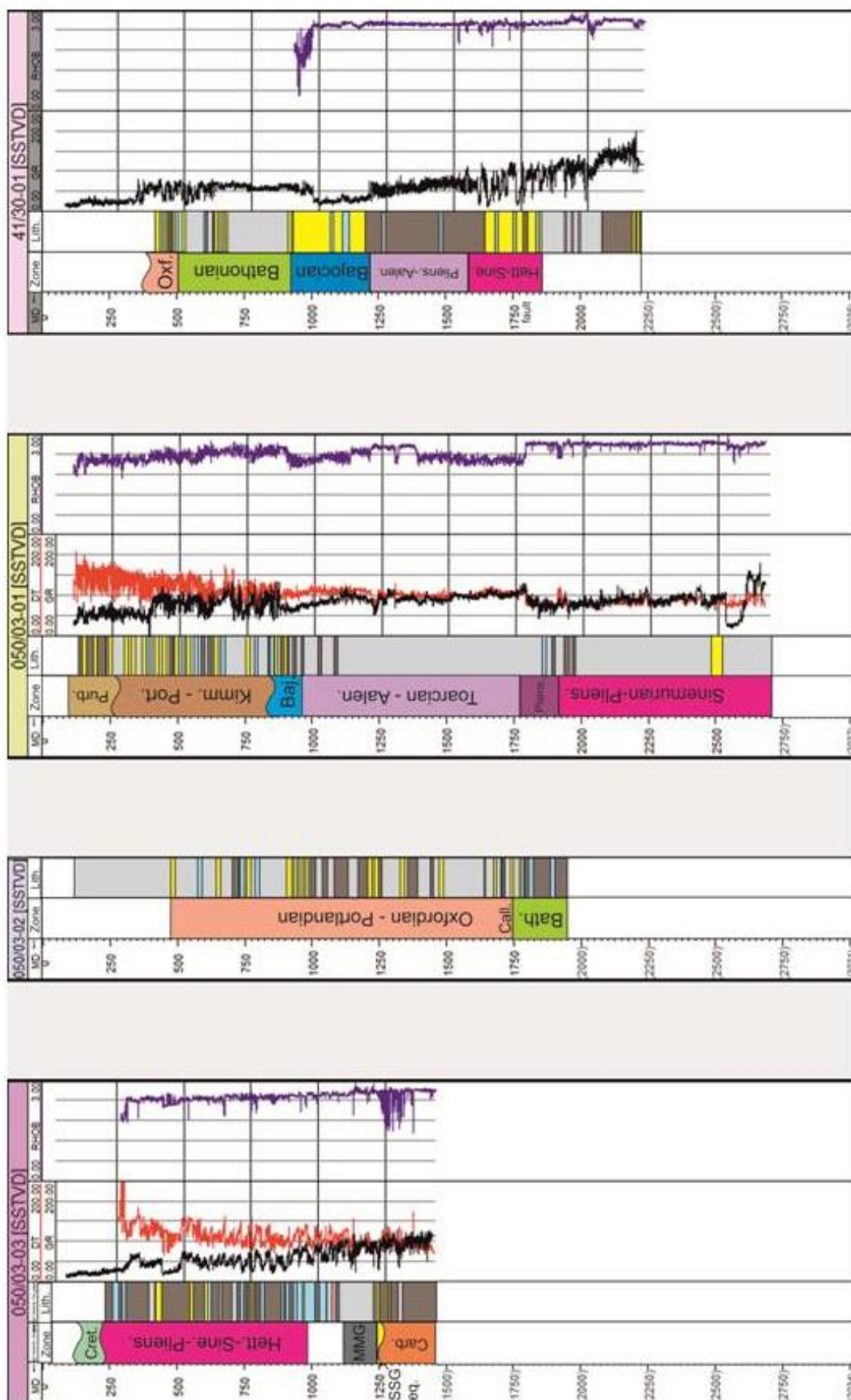


Figure 20: Well section 1, North Celtic Basin (Lith column shows representation of main lithologies from composite logs. Brown = siltstone, grey = clay/mudstone, yellow = sandstone, blue = limestone, pink = evaporites)

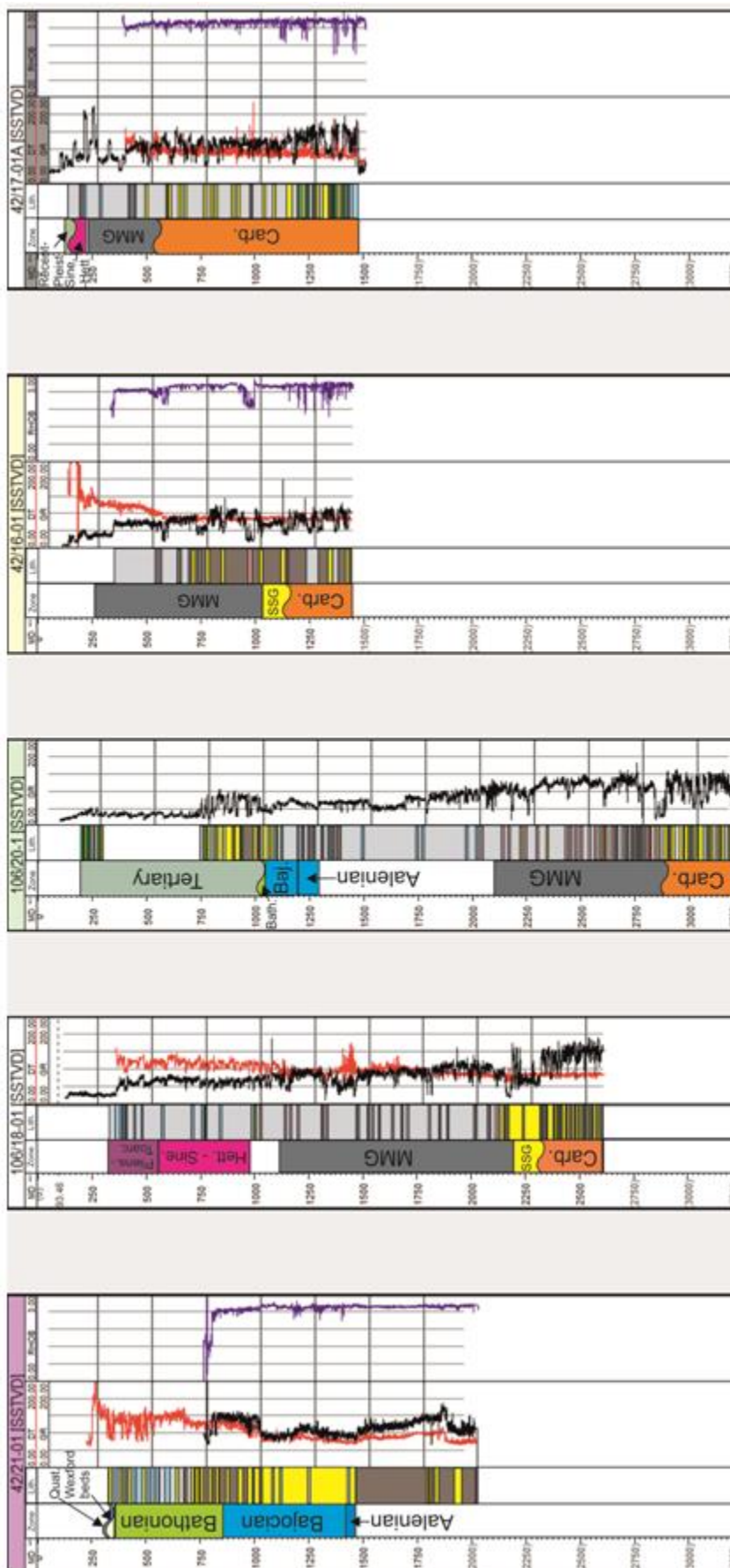


Figure 21: Well section 2, North Celtic Basin into the Central Irish Sea Basin. (Lith column shows representation of main lithologies from composite logs. Brown = siltstone, grey = clay/mudstone, yellow = sandstone, blue = carbonates, pink = evaporites, green = coal, purple = conglomerate)

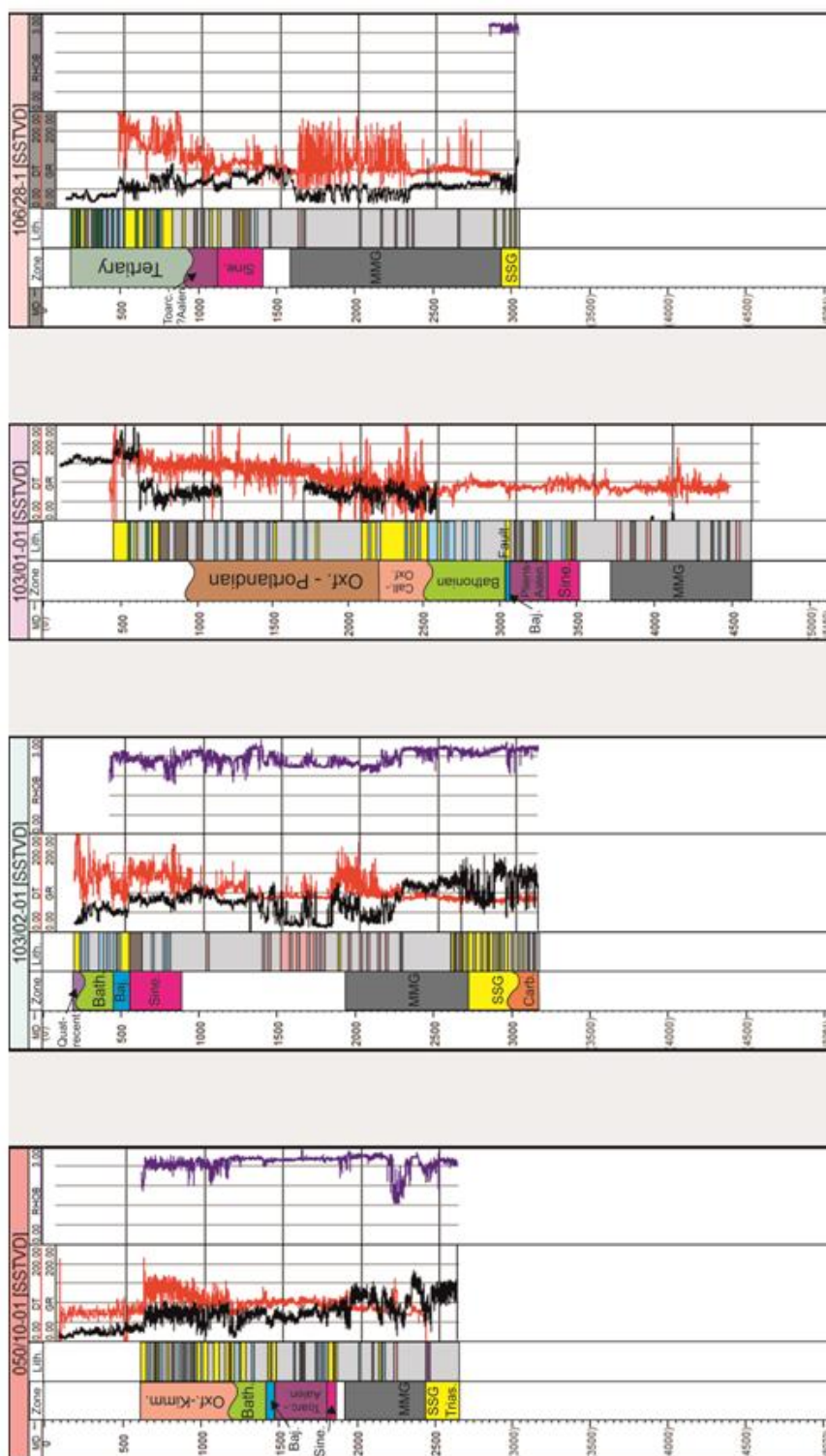


Figure 22: Well section 3, North Celtic Sea Basin across to St George's Channel Basin. (Lith column shows representation of main lithologies from composite logs. Brown = siltstone, grey = clay/mudstone, yellow = sandstone, blue = carbonates, pink = evaporites, green = coal. Note there is no composite log for UK 103/01-01 and the lith. column was constructed based on the geological well report)

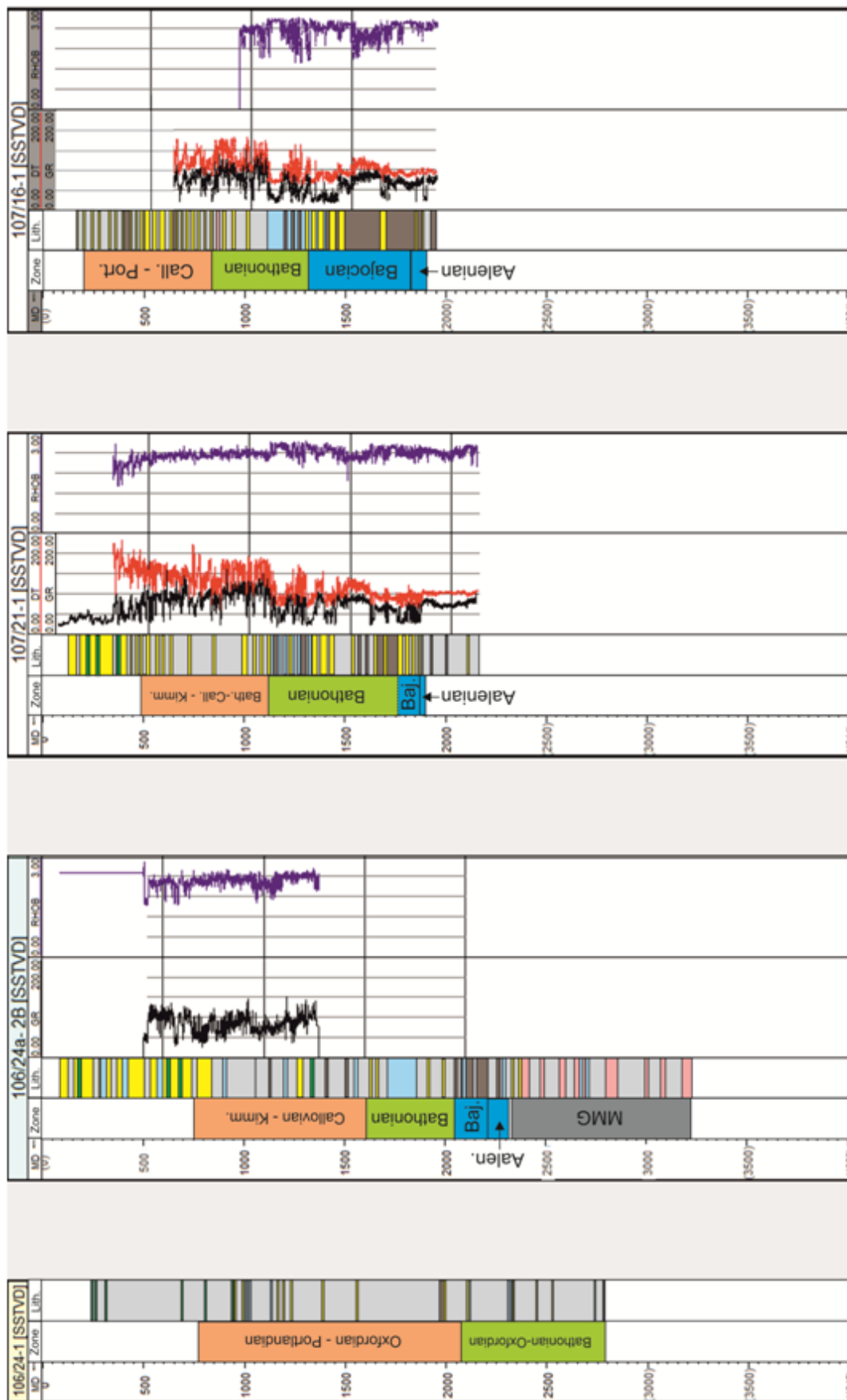


Figure 23: Well section 4, St George's Channel Basin (Lith column shows representation of main lithologies from composite logs. Brown = siltstone, grey = clay/mudstone, yellow = sandstone, blue = carbonates, pink = evaporites, green = coal. Note there are no composite logs for UK 106/24-01 or UK 106/24a-2B and the lith. column for these wells was constructed based on the geological well reports)

7.1 RESERVOIR PROPERTIES FROM WELL DATA

The reservoir quality of the selected horizons of interest (Carboniferous strata, Sherwood Sandstone Group, Sinemurian, Inferior Oolite Group and Bathonian strata) were assessed using geophysical well logs and core data from the well composite logs and geological well reports. The assessment was carried out across the Carboniferous, Sherwood Sandstone Group, Sinemurian, Inferior Oolite Group and Bathonian strata to assess any reservoir horizons. More detail is given in Appendix A on core data.

Net to gross (NTG) of the horizons of interest were calculated using gamma ray logs where available. The gamma ray log response to the main reservoir formations was examined and used to assess an appropriate cut-off between shaley lithologies (high GR response) and sandy lithologies (low GR response). Where pure sand and shale formations were not present in the horizon to be assessed, values from lithologies just above or below were used to ensure that an appropriate cut-off value was selected. The calculated NTG was then compared with the composite log interpretation and core lithologies to assess if the calculated value seemed reasonable. The estimated NTG ratios were generally low to fair (<59%) for the horizons of interest. The Carboniferous strata was included in this exercise because the lithology noted on the logs contained sandstone in many instances and it has been assessed as a potential hydrocarbon reservoir by energy companies.

The porosity of formations was assessed using core data and derivation of theoretical porosity values using the sonic (DT) and density (RHOB) logs.

The response of the sonic log (DT) depends on both lithology and porosity and the pore fluids present in the formation. For the horizons of interest, the sonic log was assessed over the whole formation thickness to generate a sonic derived porosity log (SPHI). The values used in this simple calculation were taken from the Schlumberger log interpretation charts (Schlumberger, 2009) as appropriate for sandstone or limestone, depending on the main reservoir rock within the formation. The accuracy of the sonic derived porosity log can be reduced by enlarged wells (where the tool loses contact with the sides), presence of gas (causes anomalously high readings as travel-time in gas is higher than in water), fine mudstone laminations (where the tool averages over the laminations incorrectly) or in uncompact sediments. Incorrect assumptions about the rock lithology and pore fluids can impact accuracy of assessment.

The bulk density log (RHOB) uses gamma rays to assess the density of the formation. A density derived porosity log (DPHI) was generated using a simple calculation making assumptions about the matrix density and pore fluid density. Values for the density of the matrix as appropriate for sandstone or limestone, depending on the main reservoir rock, were assumed using Schlumberger log interpretation charts (Schlumberger, 2009) and standard assumptions for fluid density were applied. As most holes were dry, it was assumed that the pore fluid did not contain gas. The accuracy of the porosity derived porosity log can be affected by enlarged wells or rough wellbores (where the tool loses contact with the sides), presence of hydrocarbons (presence of light gas in the pores), infiltration of drilling muds or mudcake on the wellbore walls. Incorrect assumptions about the rock lithology and pore fluids can impact accuracy of assessment.

The derived density porosity values were assessed for the horizons of interest across the whole horizon thickness. The reservoir layers were then selected using the net to gross cut-off (derived from the GR log) to calculate the derived porosity DPHI and SPHI over the reservoir layers only.

7.1.1 Calculated Net to Gross values for the potential reservoir sequences

The NTG values were calculated through interpretation of the gamma ray well logs. Calculated NTG ratios ranged from 25 – 59% for the horizons of interest.

7.1.1.1 CARBONIFEROUS STRATA

The NTG values for the Carboniferous were calculated using a small sample of wells (Table 7) the results show the mean NTG is 25%, showing on average only a quarter of this interval consists of potential reservoir formations. As there are so few wells which penetrate the Carboniferous strata (Figure 24) and the timescale over which the Carboniferous strata were laid down (and thus the lithology is so variable), the model should be used with caution.

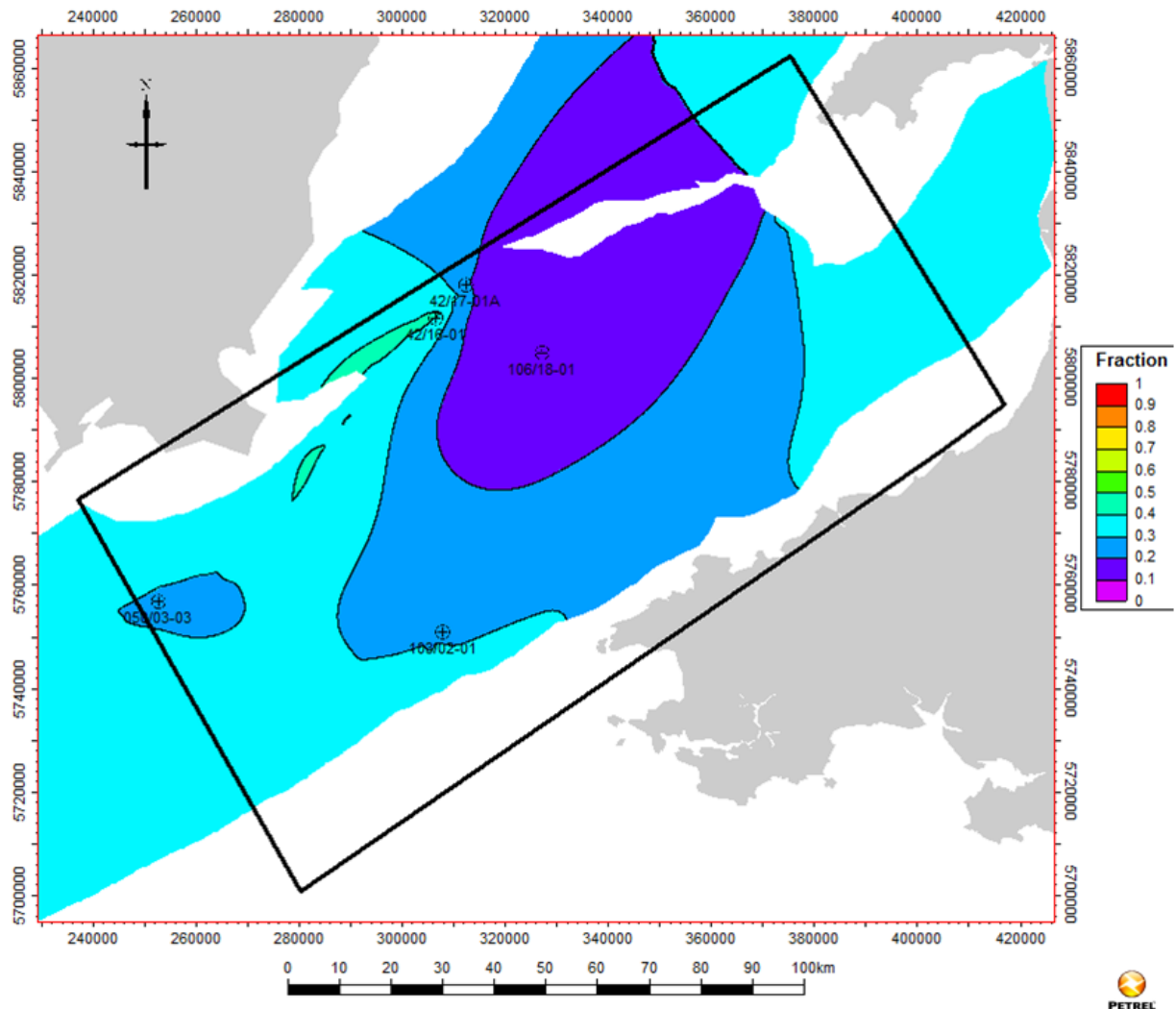


Figure 24: Model NTG of Carboniferous strata. Wells shown indicate data points

Table 7 Calculated Net to Gross values using a Vsh cut off of 0.5. Where GR is Gamma ray and NTG is net to gross for the Carboniferous sediments.

Well	GR _{min}	GR _{max}	GR _{off} log cut	NTG	Comments
UK 103/01- 1	-	-	-	-	Carboniferous not penetrated.
UK 103/02- 1 & 1B	44	143	93.5	0.25	0.1 from well report. Westphalian D.
UK 106/18- 1	50	120	85	0.11	Upper Coal measures shown as siltstone and claystone.
UK 106/20- 1	-	-	-	-	No logs.
UK 106/24- 1	-	-	-	-	Carboniferous not penetrated.
UK 106/24a- 2, 2A and 2B	-	-	-	-	Carboniferous not penetrated.
UK 106/28- 1	-	-	-	-	Carboniferous not penetrated.
UK 107/01 - 1	-	-	-	-	Carboniferous not penetrated.
UK 107/16- 1	-	-	-	-	Carboniferous not penetrated.
UK 107/21- 1	-	-	-	-	Carboniferous not penetrated.
IR 41/30-1	-	-	-	-	Carboniferous not penetrated.
IR 42/16-01	34	93	64	0.41	Westphalian to Stephanian sediments recorded, siltstone, sandstone and carbonates.
IR 42/17-01A	42	115	79	0.22	-
IR 42/21-1	-	-	-	-	Carboniferous not penetrated.
IR 50/10-1	-	-	-	-	Carboniferous not penetrated.
IR 50/3-1	-	-	-	-	Carboniferous not penetrated.
IR 50/3-2	-	-	-	-	No logs.
IR 50/3-3	50	96	73	0.28	-
			Mean	0.25	

7.1.1.2 SHERWOOD SANDSTONE GROUP

The NTG values for the Sherwood Sandstone Group are promising, with a mean value of 54% (Table 8). The NTG increases towards the Central Irish Sea Basin (Figure 25). The faults were included in the model surface as it is expected that due to the syndepositional nature of deposition here that the faults will affect the sedimentation patterns.

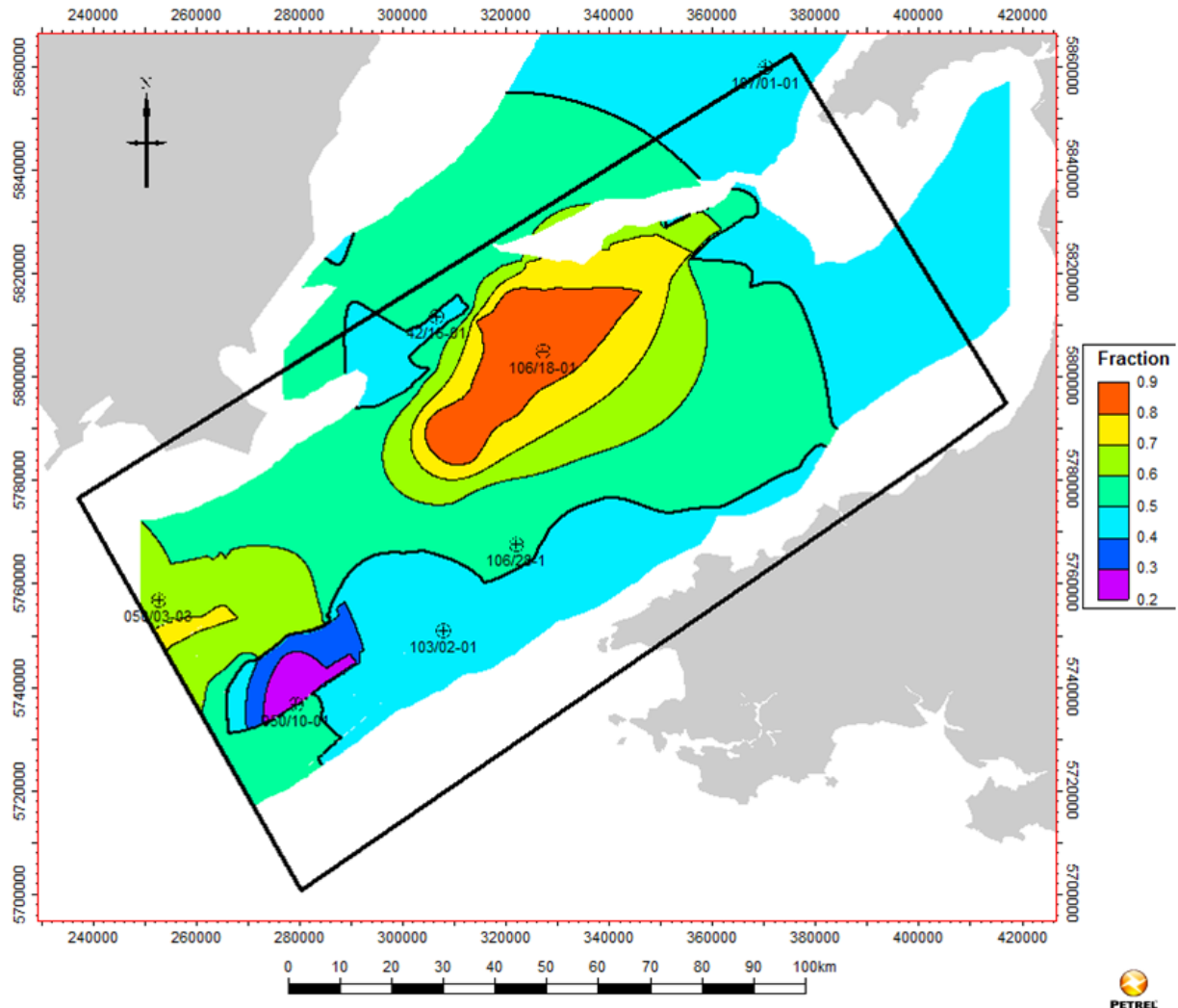


Figure 25: Model NTG for Sherwood Sandstone Group. Wells shown indicate data points

Table 8 Calculated Net to Gross values using a Vsh cut off of 0.5. Where GR is Gamma ray and NTG is net to gross for the Sherwood Sandstone Group.

Well	GR _{min}	GR _{max}	GR _{off} log cut	NTG	Comments
UK 103/01- 1	-	-	-	-	Sherwood Sandstone Group not penetrated.
UK 103/02- 1 & 1B	52	108	80	0.43	Main sand interval has NTG of 0.72 from well report.
UK 106/18- 1	39	100	70	0.86	-
UK 106/20- 1	-	-	-	-	Sherwood Sandstone Group removed by erosion/not deposited.
UK 106/24- 1	-	-	-	-	No logs.
UK 106/24a- 2, 2A and 2B	-	-	-	-	Sherwood Sandstone Group not penetrated.
UK 106/28- 1	30	73	52	0.53	Base of Sherwood Sandstone Group not penetrated.
UK 107/01 - 1	13	67	40	0.49	Base of Sherwood Sandstone Group not penetrated. GR log quite poor quality and has gaps. Geological log records NTG 0.42 in Permian and NTG 0.3 for the interval in the Triassic from 1211.6-1352.1 m mBRT.
UK 107/16- 1	-	-	-	-	Sherwood Sandstone Group not penetrated.
UK 107/21- 1	-	-	-	-	Sherwood Sandstone Group not penetrated.
IR 41/30-1	-	-	-	-	Sherwood Sandstone Group not penetrated.
IR 42/16-01	28	80	54	0.48	Interval shown as silty on composite log with sandstone layers at base.
IR 42/17-01A	-	-	-	-	Not clear if Sherwood Sandstone Group penetrated, there are a few sandstone bodies noted towards the base of the 'undifferentiated Triassic'.
IR 42/21-1	-	-	-	-	Sherwood Sandstone Group not penetrated.
IR 50/10-1	20	127	74	0.20	Sherwood Sandstone conglomerate unit NTG 0.11 for 2477.1 - 2433.8 m MD from composite log. Conglomerate is located at top of Sherwood Sandstone Group interval.
IR 50/3-1	-	-	-	-	Sherwood Sandstone Group not penetrated.
IR 50/3-2	-	-	-	-	No logs.
IR 50/3-3	25	79	52	0.69	Only 5 m measured thickness of Sherwood Sandstone Group.
			Mean	0.54	

7.1.1.3 SINEMURIAN STRATA

The NTG values are low for the Sinemurian strata, with a mean value of 28% (Figure 26). Based on the wells where Sinemurian strata are penetrated, in the St George's Channel basin wells, NTG is expected to be lower than indicated by the model surface since the wells all indicate the main lithology is clay/mudstone, therefore the high NTG values in the north-east may well be spurious in terms of usable reservoir (Figure 26). NTG is higher in the main depocentre and towards the Central Irish Sea Basin presumably reflecting the presence of more arenaceous material in the depocentre as fault movement created more accommodation space for sediments.

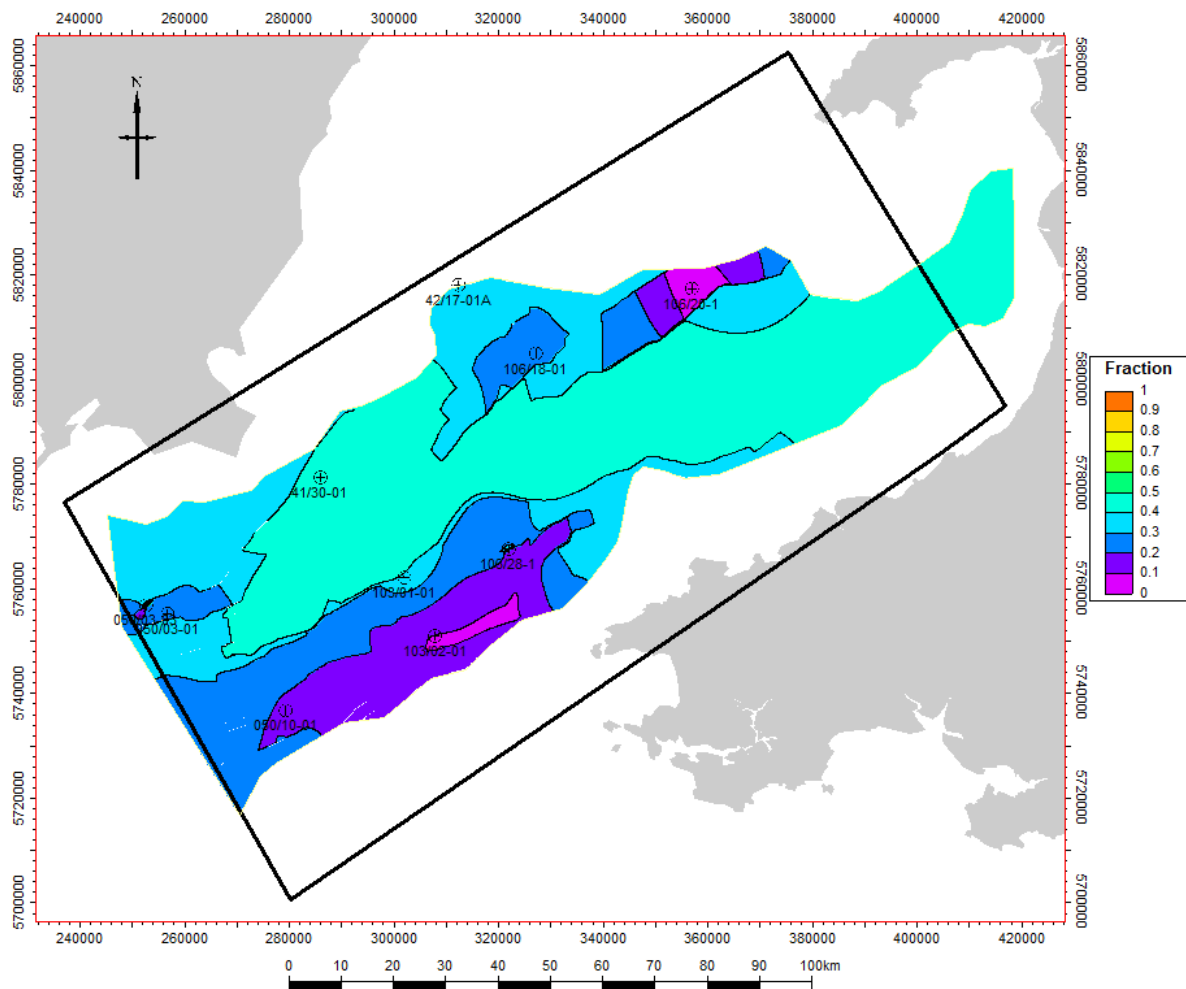


Figure 26: Model NTG for Sinemurian strata. Wells shown indicate data points

Table 9 Calculated Net to Gross values using a Vsh cut off of 0.5 for the Sinemurian strata.

Well	GR _{min}	GR _{max}	GR _{off} ^{log cut}	NTG	Comments
UK 103/01- 1	39	89	64	0.35	Interval marked as Liassic sandstone but mainly comprises claystone in composite log.
UK 103/02- 1 & 1B	17	97	57	0.10	Mudstone dominated in composite log.
UK 106/18- 1	35	64	49	0.28	Includes latest Hettangian at base.
UK 106/20- 1	13	97	56	0.06	Comprises mudstone on composite log
UK 106/24- 1	-	-	-	-	No logs.
UK 106/24a- 2, 2A and 2B	-	-	-	-	Sinemurian removed by erosion/not deposited.
UK 106/28- 1	39	68	54	0.32	-
UK 107/01 - 1	-	-	-	-	Sinemurian removed by erosion/not deposited.
UK 107/16- 1	-	-	-	-	Sinemurian not penetrated.
UK 107/21- 1	-	-	-	-	Sinemurian not penetrated.
IR 41/30-1	9	97	53	0.47	Includes latest Hettangian at base.
IR 42/16-01	-	-	-	-	Sinemurian removed by erosion/not deposited.
IR 42/17-01A	32	92	62	0.39	Sinemurian – Hettangian log analysis interval. Noted on log as mainly siltstone and claystone.
IR 42/21-1	-	-	-	-	Only reaches Pliensbachian sandstone.
IR 50/10-1	32	83	57	0.19	Sinemurian shale is lower part of formation.
IR 50/03-1	20	101	61	0.25	Includes Pliensbachian in upper part of formation.
IR 50/3-2	-	-	-	-	No logs.
IR 50/03-3	21	94	57	0.93	Log only recorded for lower part of formation. Upper part includes Pliensbachian.
			Mean	0.28	

7.1.1.4 INFERIOR OOLITE GROUP

NTG values are generally quite promising for the Inferior Oolite Group reservoir sequence, averaging 60% (Table 10). This value includes sandstone and limestone reservoir layers. There is a general trend of NTG increasing towards the south (Figure 27).

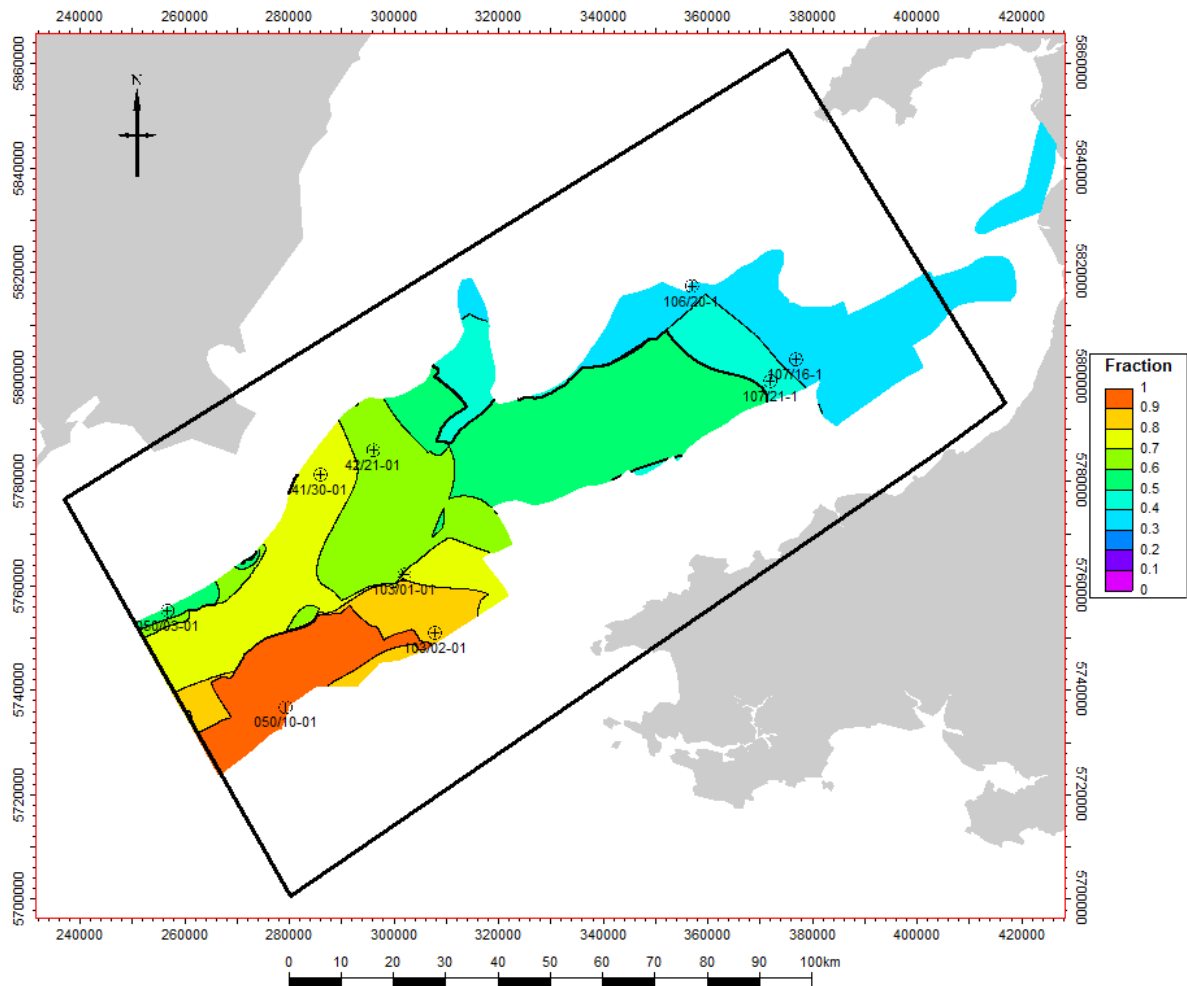


Figure 27: Model NTG for Inferior Oolite Group reservoir sequence. Wells shown indicate data points

Table 10 Calculated Net to Gross values using a Vsh cut off of 0.5. Where GR is Gamma ray and NTG is net to gross for the Inferior Oolite Group reservoir strata.

Well	GR _{min}	GR _{max}	GR _{log cut off}	NTG	Comments
UK 103/01- 1	12	73	43	0.43	-
UK 103/02- 1 & 1B	30	61	46	0.88	Note Bajocian is marked as possibly Bajocian. Interval contains limestone.
UK 106/18- 1	-	-	-	-	Inferior Oolite Group removed by erosion/not deposited.
UK 106/20- 1	29	63	46	0.42	-
UK 106/24- 1	-	-	-	-	No logs.
UK 106/24a- 2, 2A and 2B	-	-	-	-	No logs.
UK 106/28- 1	-	-	-	-	Inferior Oolite Group removed by erosion/not deposited.
UK 107/01 - 1	-	-	-	-	Inferior Oolite Group removed by erosion/not deposited.
UK 107/16- 1	15	81	48	0.30	-
UK 107/21- 1	18	81	50	0.48	Bajocian to Aalenian sandstone NTG 0.75 from well report on log analysis (but only considers thin sandstone interval not whole sequence).
IR 41/30-1	14	54	34	0.75	Inferior Oolite Group comprises sandstones and limestones.
IR 42/16-01	-	-	-	-	Triassic/Jurassic strata not differentiated at top of well.
IR 42/17-01A	-	-	-	-	Inferior Oolite Group removed by erosion/not deposited.
IR 42/21-1	67	120	94	0.69	Upper Inferior Oolite Group reservoir sequence shown as mainly sandstone on composite log with shale interval at the top.
IR 50/10-1	29	72	51	0.95	Inferior Oolite Group (Bajocian) shown as mainly sandstone on composite log with thin limestone interbeds. Middle Jurassic (Bathonian-Bajocian) NTG 0.02 in geological report.
IR 50/3-1	43	65	54	0.52	Limited sandstone in Inferior Oolite Group.
IR 50/3-2	-	-	-	-	No logs.
IR 50/3-3	-	-	-	-	Inferior Oolite Group removed by erosion/not deposited.
			Mean	0.60	

7.1.1.5 BATHONIAN STRATA

NTG values for the Bathonian strata are low, averaging 40%. Log interpretation indicates a broad range of values (0.08 – 0.7; Table 11) reflecting the wide variation in the presence of potential reservoir sandstones or limestones. NTG appears to be generally lower in the south (Figure 28).

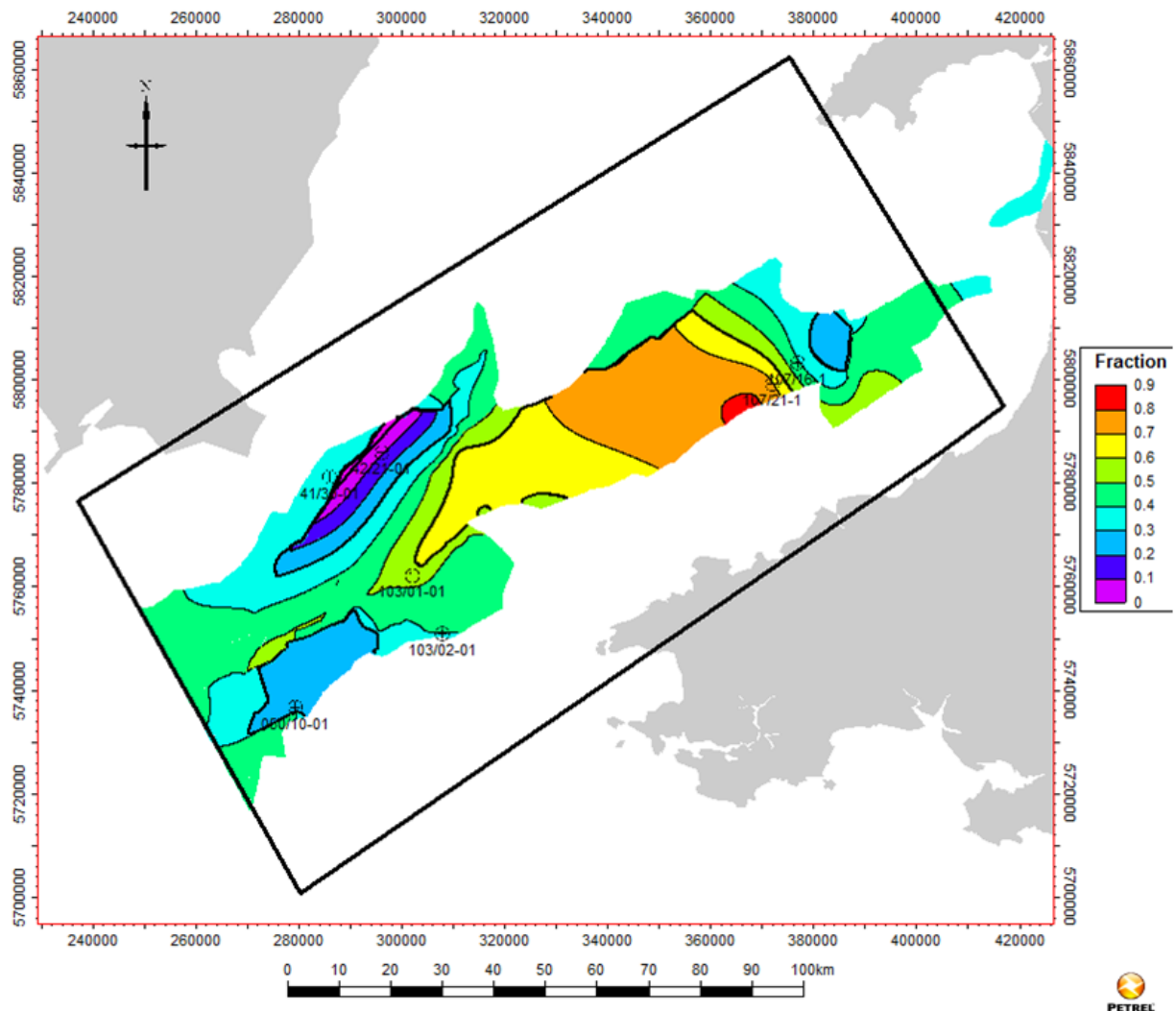


Figure 28: Model NTG map for Bathonian strata. Wells shown indicate data points

Table 11 Calculated Net to Gross values using a Vsh cut off of 0.5. Where GR is Gamma ray and NTG is net to gross for the Bathonian strata.

Well	GR _{min}	GR _{max}	GR _{off} log cut	NTG	Comments
UK 103/01- 1	20	79	50	0.56	Bathonian contains limestones.
UK 103/02- 1 & 1B	20	64	42	0.40	Bathonian contains limestones.
UK 106/18- 1	-	-	-	-	Bathonian removed by erosion/not deposited.
UK 106/20- 1	-	-	-	-	Only 3 m of Bathonian – cannot undertake analysis.
UK 106/24- 1	-	-	-	-	No logs.
UK 106/24a- 2, 2A and 2B	-	-	-	-	No Logs in Bathonian.
UK 106/28- 1	-	-	-	-	Bathonian removed by erosion/not deposited.
UK 107/01 - 1	-	-	-	-	Bathonian removed by erosion/not deposited.
UK 107/16- 1	17	102	59	0.41	Bathonian contains limestones.
UK 107/21- 1	19	100	60	0.70	Bathonian contains limestones.
IR 41/30-1	15	56	36	0.38	Bathonian contains limestones. GR values very low.
IR 42/16-01	-	-	-	-	Jurassic/Triassic not differentiated at top of well.
IR 42/17-01A	-	-	-	-	Bathonian removed by erosion/not deposited.
IR 42/21-1	58	123	91	0.08	Only lower part has a log, this is the very start of the GR log. Bathonian contains limestones. GR values very high
IR 50/10-1	10	63	37	0.24	GR values very low. Middle Jurassic (Bathonian-Bajocian) NTG 0.02 in geological report.
IR 50/3-1	-	-	-	-	Bathonian removed by erosion/not deposited.
IR 50/3-2	-	-	-	-	No logs. Late Bathonian sediments (Forest marble equiv.) described as having NTG 0.2.
IR 50/3-3	-	-	-	-	Bathonian removed by erosion/not deposited.
			Mean	0.40	

7.1.2 Calculated porosities for the potential reservoir sequences

The sonic (DT) and bulk density (RHOB) logs were used to calculate derived porosity curves for wells in the detailed study area. SPHI is derived from the sonic log and DPHI is derived from the bulk density log. Both these derived porosity curves are sensitive to the assumptions made about the lithology and native pore fluids. The NTG curves were then used to define potential reservoir layers within the Carboniferous strata, Sherwood Sandstone Group, Sinemurian and Bathonian strata and the Inferior Oolite Group reservoir sequence. The porosity of these potential reservoir layers was calculated for use in volumetric calculations for assessment of storage capacity as described later in this report.

7.1.2.1 CARBONIFEROUS STRATA

Porosity values for the Carboniferous reservoir horizons are generally low (Table 12, Table 13) with an average of 7% and little variation across the study area (Figure 29), though this could be partly due to the limited number of data points available. Two porosity-permeability (poro-perm) cross plots were prepared, one using data from well IR 42/16-01 (Figure 30) where the Carboniferous strata are of Stephanian age and the other using data from wells UK 106/20-01 and UK 106/18-01 where the Carboniferous Westphalian Coal Measures are penetrated. Most the data from the latter two wells had permeability <0.01 mD (Figure 31) and so it was not possible to plot a reliable trendline.

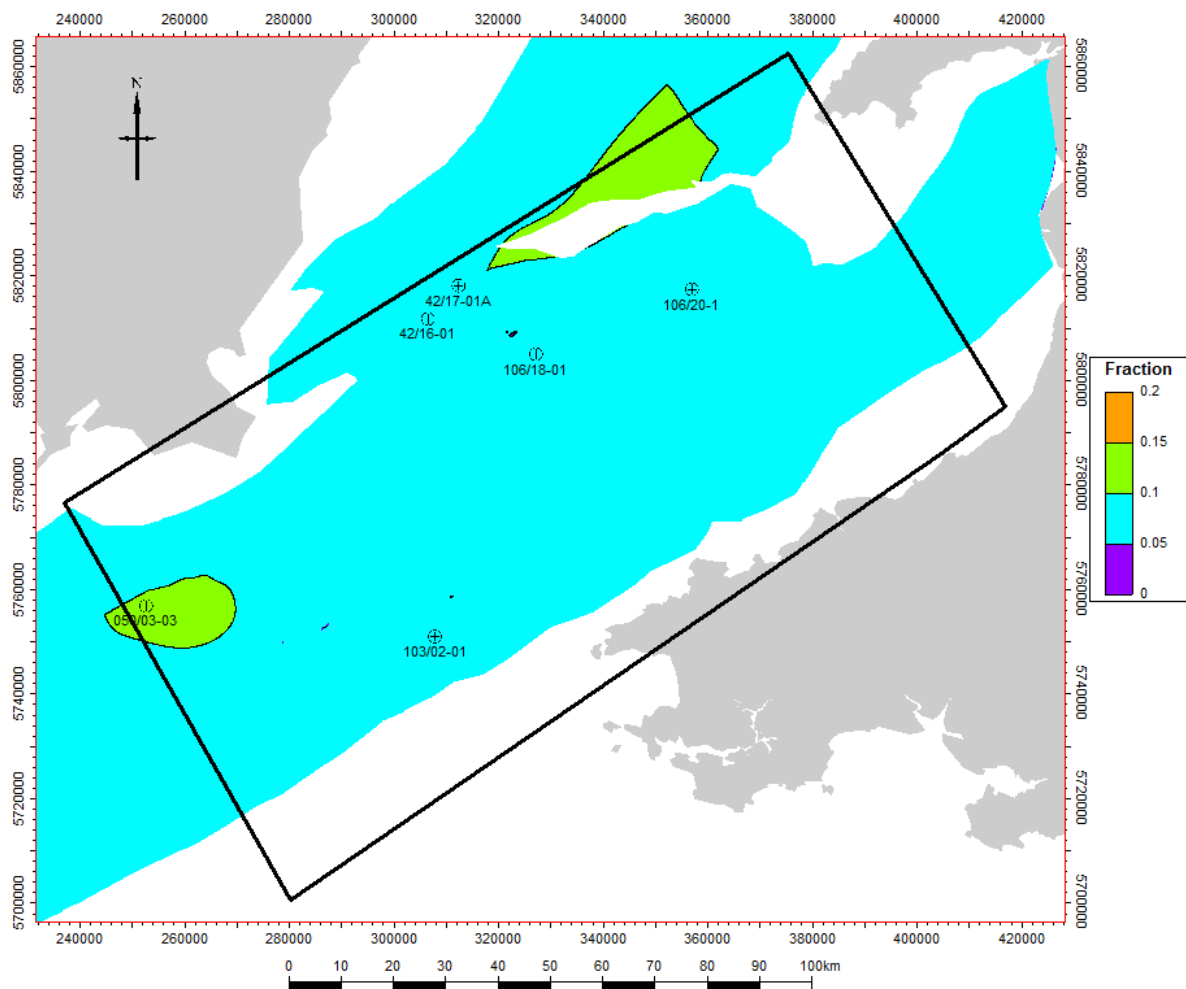


Figure 29: Model porosity of the Carboniferous reservoir horizons (note scale). Wells shown indicate data points from core data (UK 106/20-01 only) and log analyses

Table 12 Derived porosities of the Carboniferous reservoir horizons in the detailed study area.

Well	av SPHI	av DPHI	Comments
UK 103/01- 1	-	-	Carboniferous not penetrated.
UK 103/02- 1 & 1B	0.07	0.03	Carboniferous, including Westphalian D. Mainly comprises mudstone from geological summary. Dominated by mudstone so DPHI may be too high.
UK 106/18- 1	0.05	-	Upper Coal measures comprise siltstone and claystone on composite log. Porosity 1.6 – 6.1% and permeability <0.03 mD from sidewall cores shown on comp. log.
UK 106/20- 1	-	-	No logs. Core data permeability <0.01 – 0.02 mD, helium porosity 0.5 – 8.9%. Average vertical permeability Kl 0.01 mD, average helium porosity 5.7%.
UK 106/24- 1	-	-	Carboniferous not penetrated.
UK 106/24a- 2, 2A and 2B	-	-	Carboniferous not penetrated.
UK 106/28- 1	-	-	Carboniferous not penetrated.
UK 107/01 - 1	-	-	Carboniferous not penetrated.
UK 107/16- 1	-	-	Carboniferous not penetrated.
UK 107/21- 1	-	-	Carboniferous not penetrated.
IR 41/30-1	-	-	Carboniferous not penetrated.
IR 42/16- 01	0.08	0.02	Westphalian - Stephanian sediments recorded siltstone, sandstone and carbonates. RHOB log very noisy. Core has permeability 0.03 – 0.045 mD and porosity 0.17 – 7.2%. Average vertical permeability Kl 0.07 mD, average helium porosity 4.6%
IR 42/17- 01A	0.11	0.07	Westphalian D and Upper Carboniferous sediments. Sequence dominated by mudstone on composite log. Sandstones with porosities of up to 16% noted in geological log between 548.6 – 1132.3 m MD. Gas saturation noted in two sand bands between 1175.9 – 1192.4 m MD and 1388.1 – 1403.3 m MD which have porosities of 7 – 11% and 6 – 9% respectively. The Visean limestones have porosities of 3 – 5%. It is not clear if these porosities are from log interpretation or core analysis.
IR 42/21-1	-	-	Carboniferous not penetrated.
IR 50/10-1	-	-	Carboniferous not penetrated.
IR 50/3-1	-	-	Carboniferous not penetrated.
IR 50/3-2	-	-	No logs.
IR 50/3-3	0.13	0.11	Gas shows in Namurian – Westphalian sediments related to coal beds. Lithology is sandstone and siltstone dominated.

Table 13 Porosity of the Carboniferous reservoir horizons based on 5 wells within the study area

Data from sonic logs			Data from Bulk density logs		
av SPHI	SPI min	SPI max	av DPHI	DPHI min	DPHI max
0.08	0.02	0.14	0.06	0.01	0.27

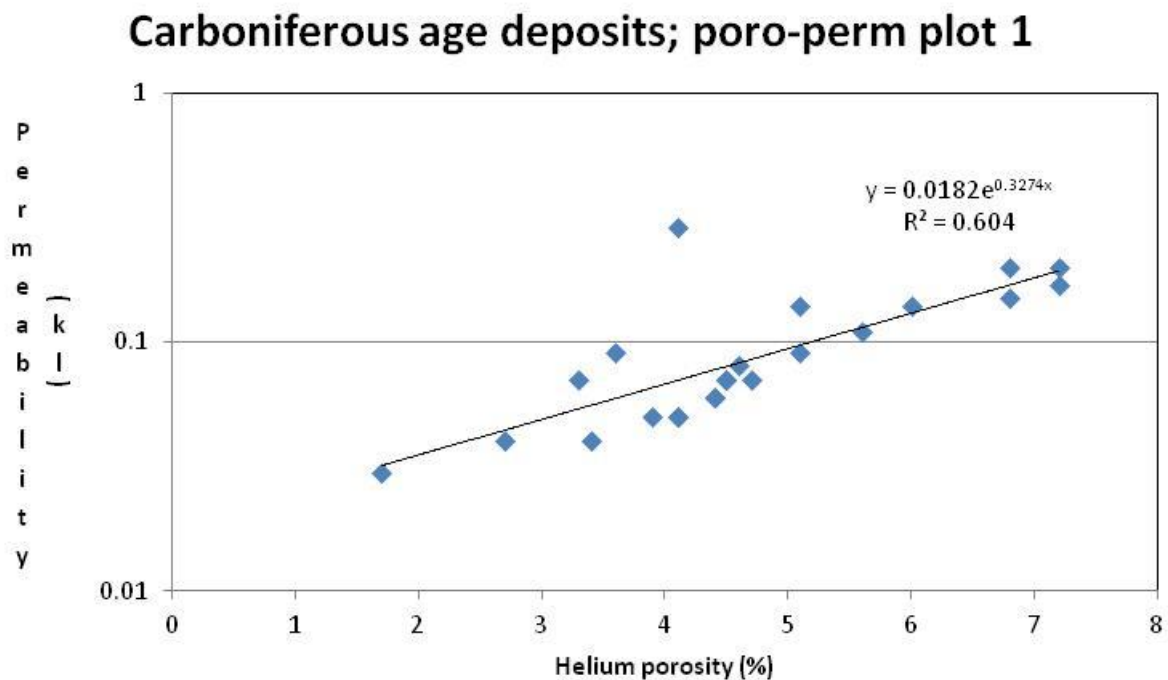


Figure 30: Helium porosity-vertical permeability plot for well IR 42/16-01

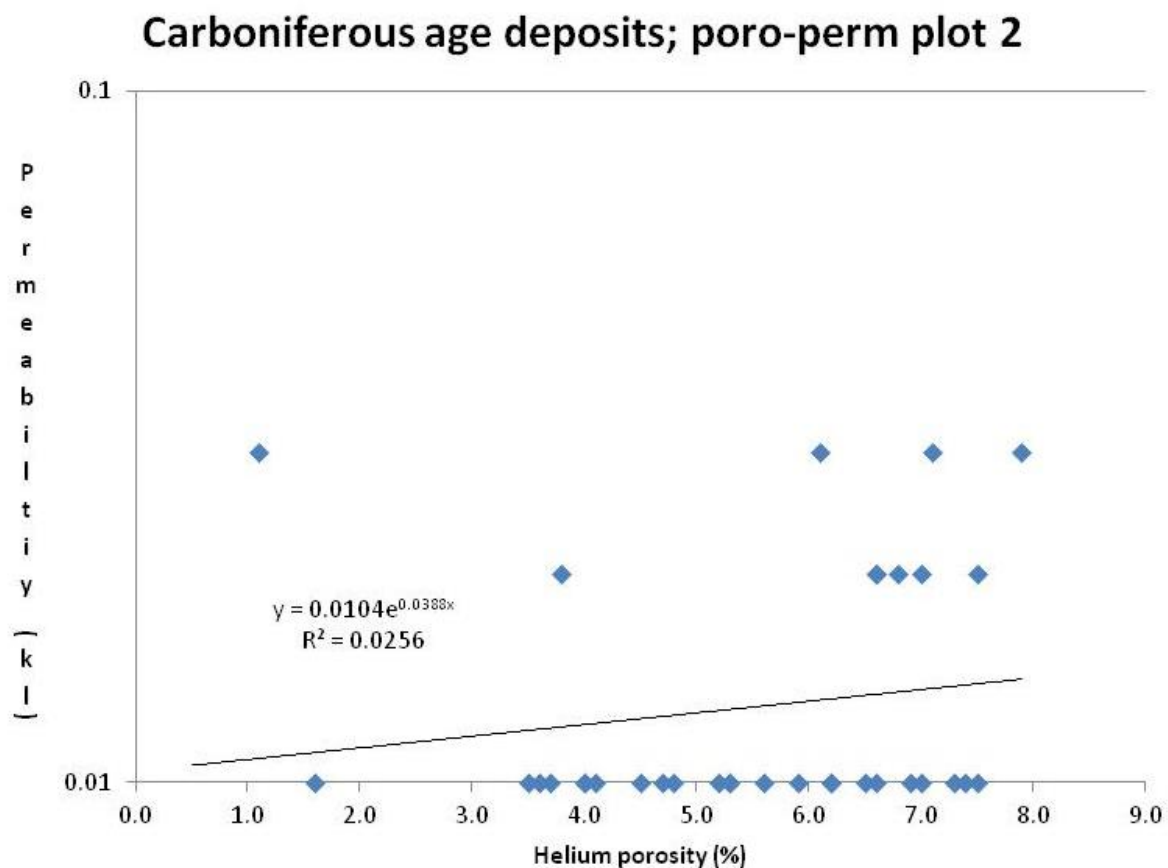


Figure 31: Helium porosity vs. permeability plot for wells UK 106/20-01 and UK 106/18-01, a reasonable trendline cannot be plotted using these data as most porosities are <0.01. (Note vertical permeability was used for UK 106/20-01, but for well UK 106/18-01, permeability data is provided with no orientation in the geological well report).

7.1.2.2 SHERWOOD SANDSTONE GROUP

The porosity of the Sherwood Sandstone Group reservoir horizons is disappointingly low (average 8% from Table 14 and Table 15) given the consistency of the lithology compared to the other reservoir formations considered. This value is less than the recommended minimum for storage (Table 1). This low porosity could be a result of poor sorting since in many wells the Sherwood Sandstone Group is described as having interbedded siltstone or as having layers of silty sandstone. Cementation, which reduces porosity, is also noted, for example, on the composite logs for IR 50/10-01 (calcareous and silica) and in the core analysis for UK 106/18-01. A porosity–permeability cross plot was prepared using data from UK 106/18-01 and IR 42/16-01 (Figure 33).

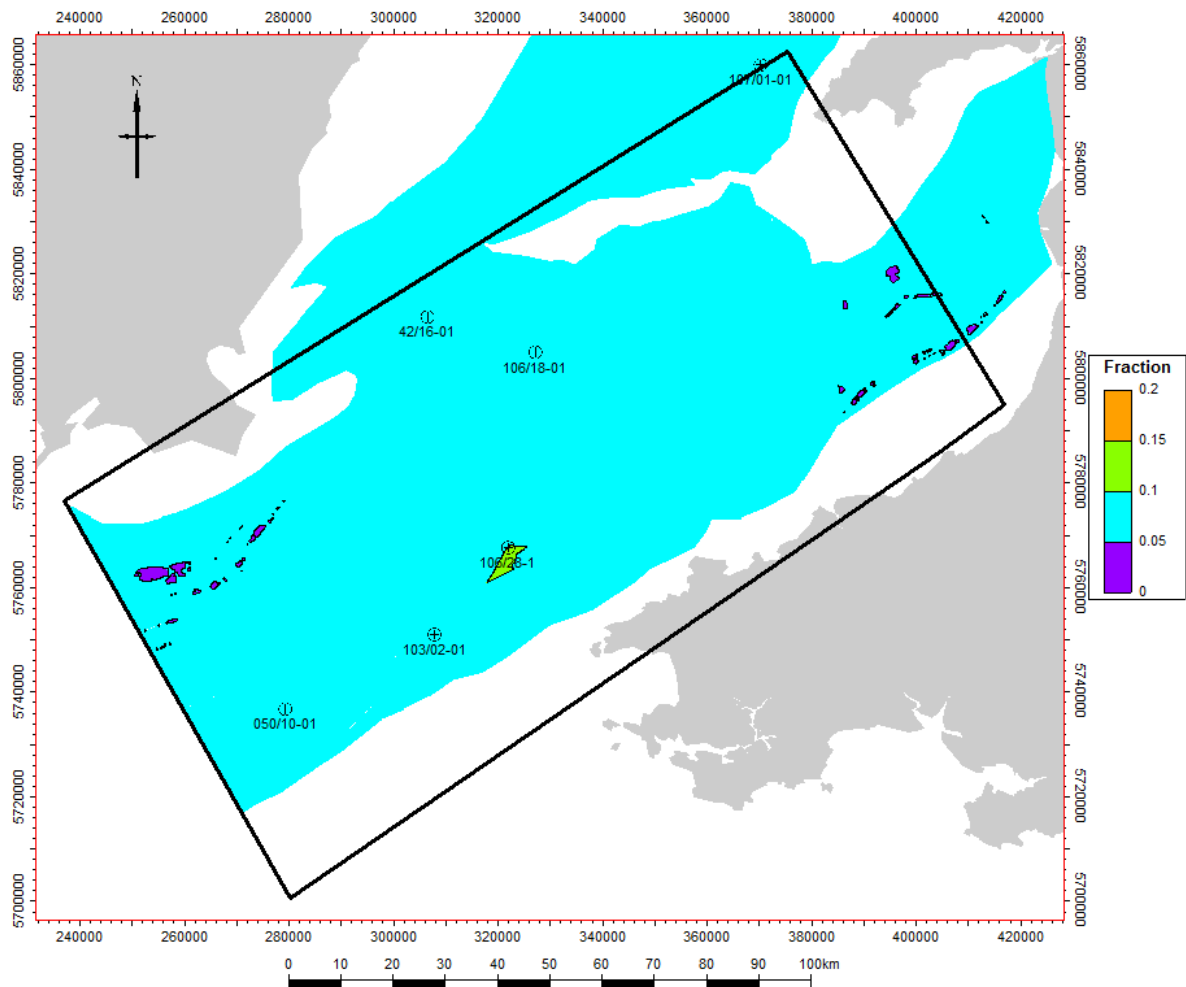


Figure 32: Model porosity of the Sherwood Sandstone Group (note scale). Wells shown indicate data points from log analysis

Table 14 Derived porosities of the Sherwood Sandstone Group reservoir horizons in the detailed study area.

Well	av SPHI	av DPHI	Comments
UK 103/01- 1	-	-	Sherwood Sandstone Group not penetrated.
UK 103/02- 1 & 1B	0.08	0.09	Sherwood Sandstone quite argillaceous.
UK 106/18- 1	0.08	-	Gas shows noted at top of Sherwood Sandstone Group on comp. log. Sidewall cores indicate sandstone porosity of 2.7 – 11% and permeability <0.01 – 7.6 mD (though most values are <0.02 mD).
UK 106/20- 1	-	-	Sherwood Sandstone Group removed by erosion/not deposited.
UK 106/24- 1	-	-	No logs.
UK 106/24a- 2, 2A and 2B	-	-	Sherwood Sandstone Group not penetrated.
UK 106/28- 1	-	0.10	Base of Sherwood Sandstone Group not penetrated. DT does not reach Sherwood Sandstone Group.
UK 107/01 - 1	0.05	-	Base of Sherwood Sandstone Group not penetrated.
UK 107/16- 1	-	-	Sherwood Sandstone Group not penetrated.
UK 107/21- 1	-	-	Sherwood Sandstone Group not penetrated.
IR 41/30-1	-	-	Sherwood Sandstone Group not penetrated.
IR 42/16-01	0.10	0.04	Interval shown as silty on composite log with sandstone layers at base. Core has permeability 0.02 – 40.9 mD and helium porosity 1.8 – 16.7%.
IR 42/17-01A	-	-	Not clear if Sherwood Sandstone Group penetrated, there are a few sandstone bodies noted towards the base of the ‘undifferentiated Triassic’. Log interpretation on the Comp. log indicated porosity of 8% in the thickest sandstone body which is around 13 m thick in well.
IR 42/21-1	-	-	Sherwood Sandstone Group not penetrated.
IR 50/10-1	0.09	-	Conglomerate is located at top of Sherwood Sandstone Group interval. Poor quality reservoir sands noted in geological well report with porosity <12% porosity with 4.6 m net thickness. No RHOB log in Sherwood Sandstone Group.
IR 50/03-1	-	-	Sherwood Sandstone Group not penetrated.
IR 50/03-2	-	-	No logs.
IR 50/03-3	-	-	Only 5 m MD of Sherwood Sandstone Group. Log interpretation in geological report has porosity <5%. Gas shows in Sherwood Sandstone Group on composite log.

Table 15 Porosity of the Sherwood Sandstone Group reservoir horizons based on 6 wells within the study area

Data from sonic logs			Data from Bulk density logs		
av SPHI	SPHImin	SPHImax	av DPHI	DPHI min	DPHI max
0.08	0.03	0.15	0.08	0.00	0.15

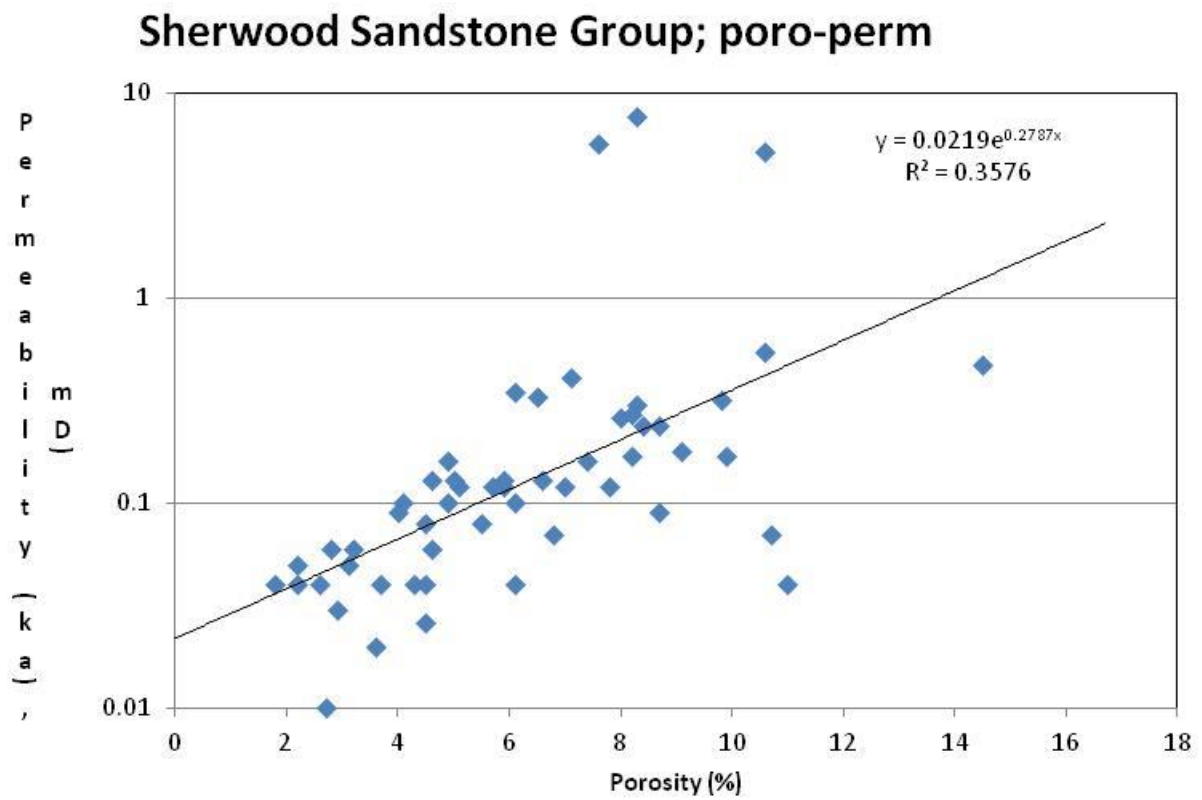


Figure 33: Helium porosity vs. vertical permeability for wells UK 106/18-01 and IR 42/16-01

7.1.2.3 SINEMURIAN STRATA

The porosity log analysis of the Sinemurian reservoir horizons was considered unreliable and some data-points have been removed as these were considered to be unrealistically high when compared with core data and the reported lithology of cuttings from the well geological reports thus only a few values were available to map the porosity across the study area (Figure 14). In the St George's Channel Basin, the lithologies noted on the composite logs and in the geological well reports mainly comprised mudstone and claystone with minor siltstone, limestone and sandstone. Overall the porosity is low in the Sinemurian reservoir layers, averaging 8% (Table 16 and Table 17) which is less than the recommended minimum value for porosity (Table 1).

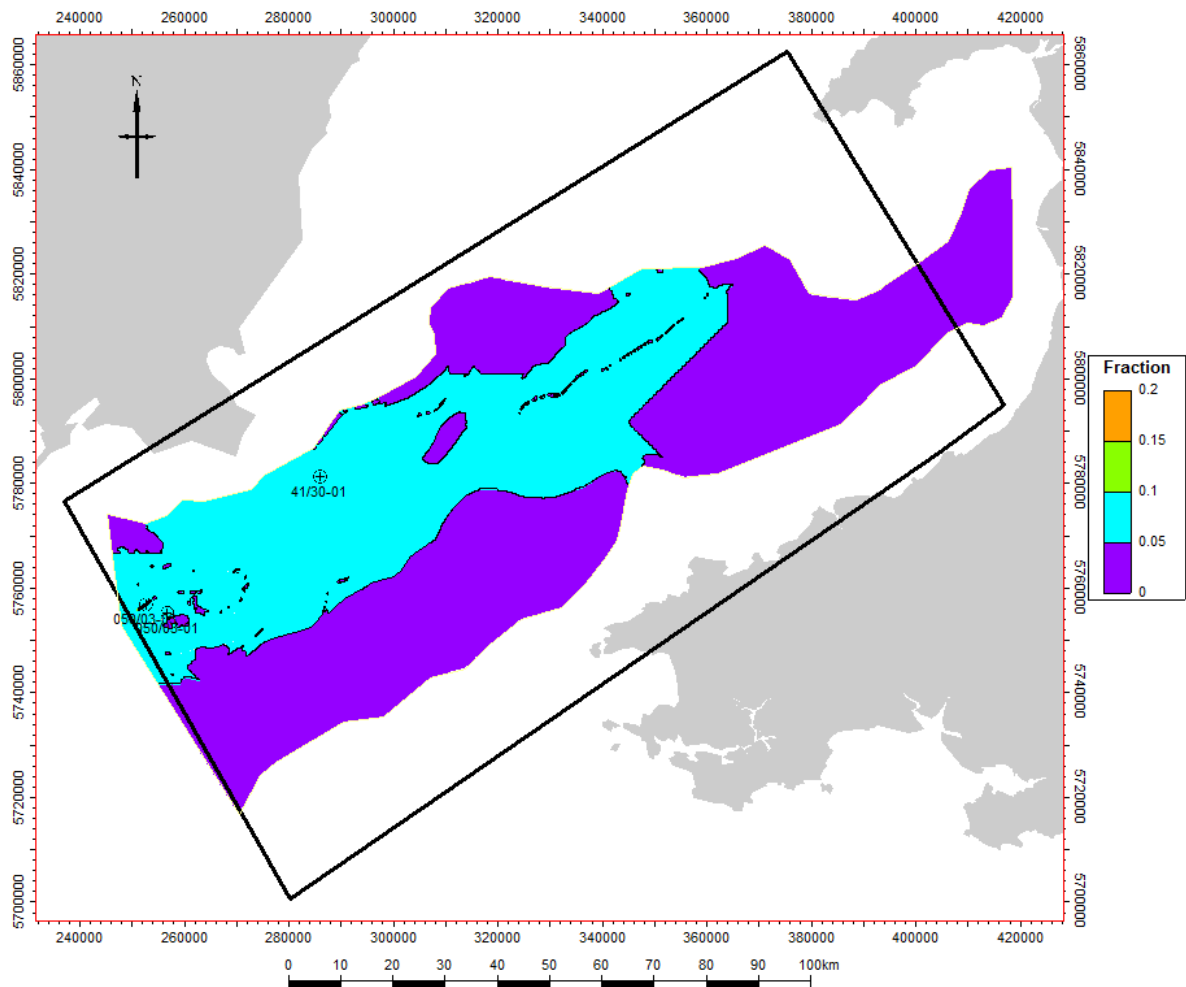


Figure 34: Model porosity of the Sinemurian reservoir layers (note scale). Wells shown indicate data points from log analysis (note sparsity of reliable data)

Table 16 Derived porosities of Sinemurian reservoir horizons within the detailed study area.

Well	av SPHI	av DPHI	Comments
UK 103/01- 1	-	-	Interval marked as Liassic sandstone but mainly comprises claystone in comp. log. sandstone signatures used for log analysis. Calculated porosity not realistic, most likely due to fine mud laminations in Sinemurian.
UK 103/02- 1 & 1B	-	-	Mudstone dominated in comp. log. Porosity analysis seems unreliable.
UK 106/18- 1	-	-	Includes latest Hettangian at base, Claystone dominates on comp. log. Limestone settings used for log analysis since this seems to be the main potential reservoir rock. Calculated porosity not realistic, most likely due to fine mud laminations in Sinemurian.
UK 106/20- 1	-	-	Used sandstone settings for more conservative estimate. DT log quite noisy.
UK 106/24- 1	-	-	No logs.
UK 106/24a- 2, 2A and 2B	-	-	Sinemurian removed by erosion/not deposited.
UK 106/28- 1	-	-	Mudstone dominated on strat. Log. Sandstone and limestone bands which could offer potential reservoir. Used sandstone settings for more conservative estimate. No RHOB log in Sinemurian. Calculated porosity not realistic, most likely due to fine mud laminations in Sinemurian.
UK 107/01 – 1	-	-	Sinemurian removed by erosion/not deposited.
UK 107/16- 1	-	-	Sinemurian not penetrated.
UK 107/21- 1	-	-	Sinemurian not penetrated.
IR 41/30-1	-	0.05	Includes latest Hettangian at base. Sandstone settings used for log analysis.
IR 42/16-01	-	-	Sinemurian removed by erosion/not deposited.
IR 42/17-01A	-	-	No logs in Sinemurian.
IR 42/21-1	-	-	Only reaches Pliensbachian sandstone. A few poor hydrocarbon shows noted in the Pliensbachian sandstone.
IR 50/10-1	-	-	Sinemurian shale is lower part of formation. Calculated porosity not realistic, most likely due to fine mud laminations in Sinemurian.
IR 50/3-1	0.05	-	Includes Pliensbachian in upper part of formation. Mudstone dominated on log. Pliensbachian-Sinemurian sediments have porosity around 0.05 from log interpretation on the Comp. log. Sandstone body near TD of Pliensbachian-Sinemurian age has porosity <0.10 from log interpretation on Comp. log. A few gas shows noted in Pliensbachian limestones above this interval.
IR 50/3-2	-	-	No logs.
IR 50/3-3	-	0.15	Log only recorded for lower part of formation. Upper part includes Pliensbachian, lower part in includes Hettangian strata. Comprises mixture of sandstone, limestone, claystone and siltstone. Sandstone settings used for log analysis. Sandstone bands in Sinemurian have porosities of 2 – 23% in geological well report but only around 12.2 m of net pay sand with over 15% porosity. Gas shows near top of Sinemurian in sandstone bed. Oil shows in Sinemurian-Hettangian sandstone bands. Calculated porosity not realistic, most likely due to fine mud laminations in Sinemurian. RFT permeability 0.36 – 198 mD (average 25.5 mD) including some Hettangian strata towards base of formation.

Table 17 Porosity of the Sinemurian reservoir horizons based on 3 wells within the study area

Data from sonic logs			Data from Bulk density logs		
av SPHI	SPHImin	SPHImax	av DPHI	DPHI min	DPHI max
0.05 (1 well)	0.00	0.23	0.10 (2 wells)	0.00	0.17

7.1.2.4 INFERIOR OOLITE GROUP

The porosity of the reservoir horizons within the Inferior Oolite Group reservoir sequence is generally reasonable (average 13%; Table 18 and Table 19) based on log analysis. The modelled surface suggests that deeper burial in the North Celtic Sea Basin has reduced porosity in the depocentre where the values range from 0 – 2% compared to the outer edges where the model porosity reaches up to 23% (Figure 35).

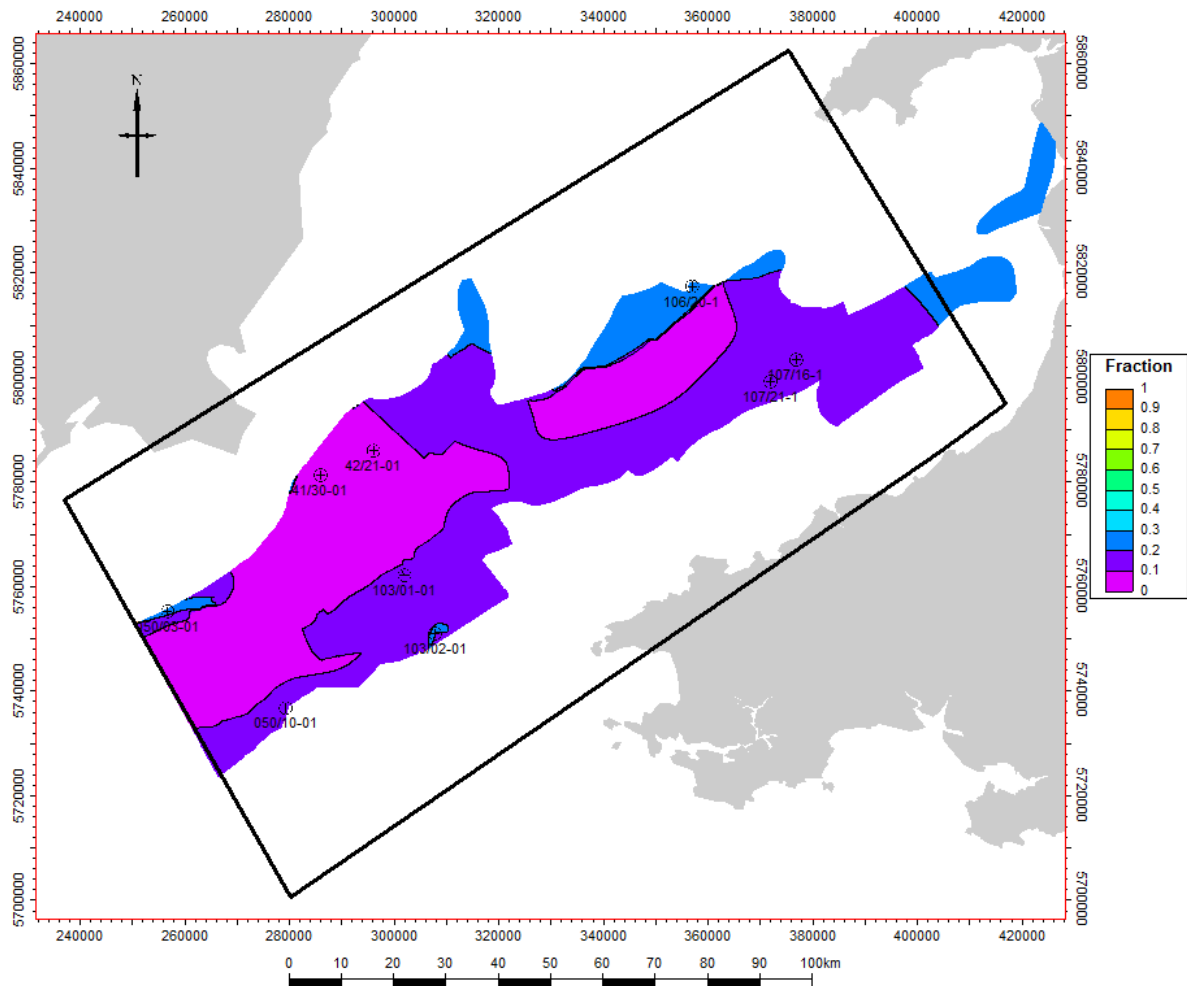


Figure 35: Model porosity of the reservoir horizons within the Inferior Oolite Group reservoir sequence. Wells shown indicate data points from log analysis

Table 18 Derived porosities of reservoir horizons within the Inferior Oolite Group reservoir sequence in the detailed study area.

Well	av SPHI	av DPHI	Comments
UK 103/01- 1	0.02	-	DT log quite noisy. Sandstone settings applied for log analysis. No RHOB log. Gas shows noted in Bajocian sandstone, probably related to fractures according to geological well report. Top Lower Jurassic used as base of layer since Aalenian – Toarcian comprises claystone and siltstone.
UK 103/02- 1 & 1B	0.23	0.17	Note Bajocian is marked as ‘possibly Bajocian’. Interval and contains sandstone and limestone. Used sandstone settings for log analysis to give more conservative estimate
UK 106/18- 1	-	-	Inferior Oolite Group removed by erosion/not deposited.
UK 106/20- 1	0.25	-	Inferior Oolite Group a mix of sandstone with minor limestone and mudstone. Used sandstone settings for log analysis as this is main reservoir. No RHOB log. DT has a lot of spikes and mudstone may mean this derived porosity is unrealistically high. No hydrocarbons noted on log. Base taken at marked base Inferior Oolite Group on composite log based on log.
UK 106/24- 1	-	-	No logs.
UK 106/24a- 2, 2A and 2B	-	-	No logs in Inferior Oolite Group.
UK 106/28- 1	-	-	Inferior Oolite Group removed by erosion/not deposited.
UK 107/01 - 1	-	-	Inferior Oolite Group removed by erosion/not deposited.
UK 107/16- 1	0.10	0.12	Inferior Oolite Group a mix of sandstone with minor limestone and mudstone. Used sandstone settings for log analysis for more conservative estimate. DT and RHOB logs noisy and value for derived porosity may be too high.
UK 107/21- 1	0.11	0.12	Inferior Oolite Group a mix of sandstone and siltstone. Used sandstone settings for log analysis.
IR 41/30-1	-	0.07	Inferior Oolite Group contains calcareous claystones and minor dolomites. Main reservoir rock is sandstone so this was used for log analysis. No DT log. Aalenian strata not included in Inferior Oolite Group log analysis as very silty.
IR 42/16-01	-	-	Triassic/Jurassic strata not differentiated at top of well.
IR 42/17-01A	-	-	Inferior Oolite Group removed by erosion/not deposited.
IR 42/21-1	0.15	0.05	Inferior Oolite Group shown as mainly sandstone on composite log with shale interval at the top. Base taken at base of Aalenian sandstone. Sandstone settings used for log analysis.
IR 50/10-1	0.17	0.05	Bajocian shown as mainly sandstone on composite log with thin limestone interbeds. Middle Jurassic (Bathonian-Bajocian average porosity 0.13) from geological well report. Base of Inferior Oolite Group taken at base Bajocian as underlying Aalenian comprises silty claystone.
IR 50/3-1	0.18	0.21	Bajocian has thin sandstone and limestone layers, mainly comprises claystone. Log analysis on composite log indicates porosity 13% in these thin sandstone layers. Aalenian strata not included in Inferior Oolite Group reservoir sequence as cores indicate they comprise claystone. Porosity analysis seems high considering lithology core cuttings, this may be an issue caused by thin claystones interbeds.
IR 50/3-2	-	-	No logs.
IR 50/3-3	-	-	Inferior Oolite Group removed by erosion/not deposited

Table 19 Porosity of the reservoir horizons within the Inferior Oolite Group reservoir sequence based on 9 wells in the detailed study area

Data from sonic logs			Data from Bulk density logs		
av SPHI	SPHImin	SPHImax	av DPHI	DPHI min	DPHI max
0.15	0.00	0.33	0.11	0.00	0.33

7.1.2.5 BATHONIAN STRATA

The porosity of the Bathonian reservoir horizons is reasonable (average 13%; Table 20 and Table 21) based on log analysis. The derived porosity values seem quite consistent across much of the study region but there are two values which seem to fall outside this. It should be noted that the model shown here is based on a limited number of well data (Figure 36).

A porosity-permeability plot was prepared using data from well UK 106/24-01. Permeabilities of over 1 mD were observed where porosity was over 10%, although this permeability is still low compared with the suggested suitable values from Chadwick et al. (2008), these core samples showed some of the highest permeabilities observed in the detailed study region.

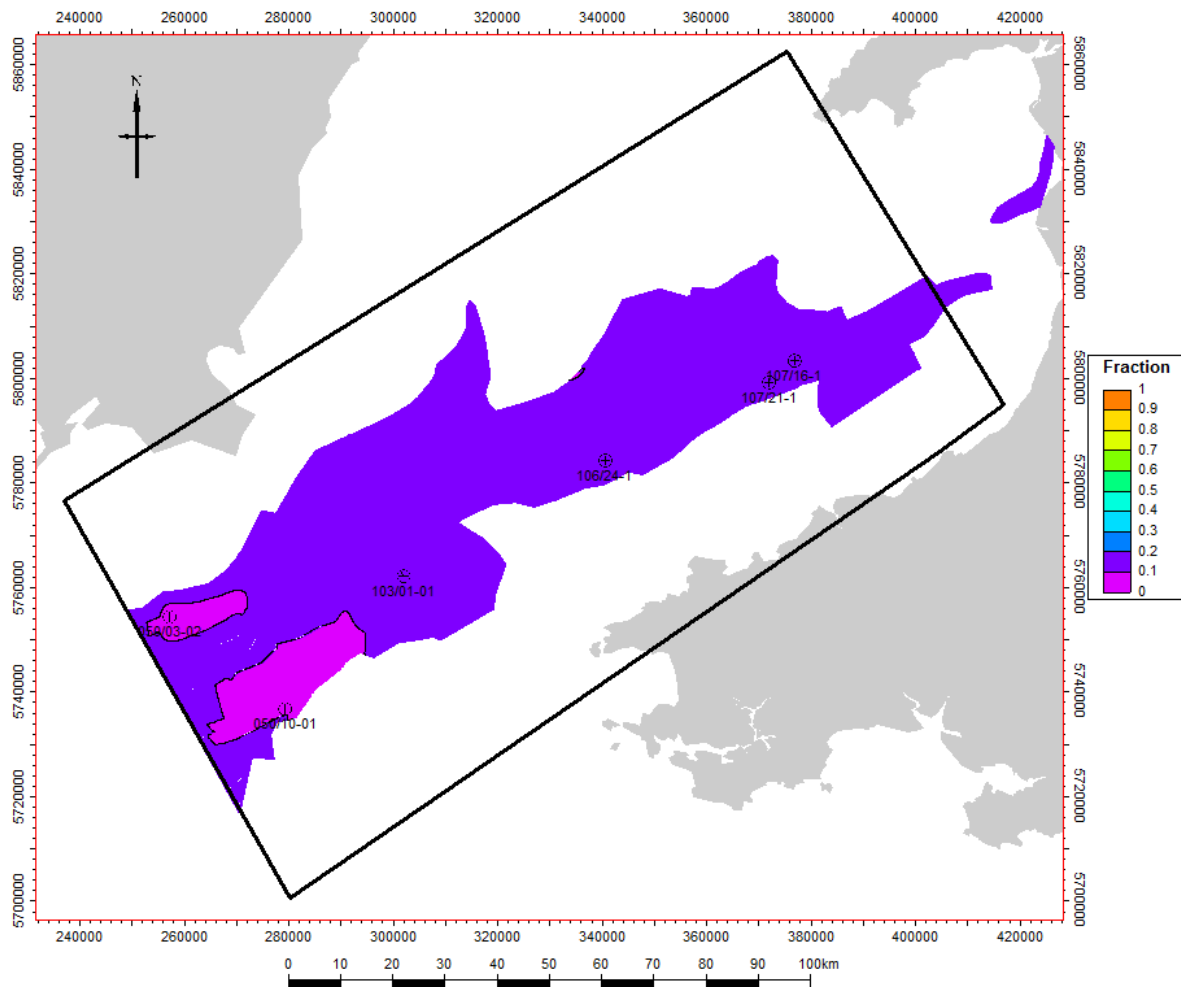


Figure 36: Model porosity of Bathonian strata. Wells shown indicate data points from core data (IR 50/03-02 and UK 106/24-01 only) and log analysis

Table 20 Derived porosities of the Bathonian reservoir horizons within the detailed study area

Well	av SPHI	av DPHI	Comments
UK 103/01- 1	0.15	-	Bathonian contains limestones. Used limestone values in log as limestone is main reservoir rock No RHOB log. Gas shows noted on comp. log in Bathonian limestones and sandstone probably related to fractures according to geological well report.
UK 103/02- 1 & 1B	-	-	Bathonian contains limestones. Used limestone value as this is main reservoir rock. RHOB log only present at very base of Bathonian, so figure not reliable. No hydrocarbons noted in log but DPHI porosity too high.
UK 106/18- 1	-	-	Bathonian removed by erosion/not deposited.
UK 106/20- 1	-	-	Only 3 m of Bathonian – unable to undertake analysis.
UK 106/24- 1	-	-	No logs. Core permeability 0.03 – 1.9 mD, helium porosity 7.4 – 16.3%. Average vertical permeability KI 0.34 mD, average helium porosity 11%.
UK 106/24a- 2, 2A and 2B	-	-	No Logs in Bathonian.
UK 106/28- 1	-	-	Bathonian removed by erosion/not deposited.
UK 107/01 - 1	-	-	Bathonian removed by erosion/not deposited.
UK 107/16- 1	0.17	0.20	Bathonian contains limestones. Logs very noisy and value for derived porosity may be too high.
UK 107/21- 1	0.16	0.09	Bathonian contains limestones.
IR 41/30-1	-	-	Bathonian contains limestones. No sonic log and RHOB log only at very base so not reliable.
IR 42/16-01	-	-	Jurassic/Triassic not differentiated at top of well.
IR 42/17-01A	-	-	Bathonian removed by erosion/not deposited.
IR 42/21-1	-	-	Bathonian contains limestones. RHOB log only at very base so not reliable. DT log very noisy at top of Bathonian.
IR 50/10-1	0.10	0.04	Bathonian contains limestones. Oil shows noted in Bathonian limestones in geological well report. Middle Jurassic (Bathonian-Bajocian average porosity 13%).
IR 50/3-1	-	-	Bathonian removed by erosion/not deposited.
IR 50/3-2	-	-	No logs. Oil and gas shows noted in Late Bathonian strata. Late Bathonian (Forest Marble equiv.) core 1758.1 – 1776.4 m MD noted as having average net sand porosity and permeability of 5.3% and 0.1 mD respectively in the geological report. Bathonian oolites noted as being thin and having porosity up to 7.6% in the geological well report (presumably from core taken from 1871.8 – 1873.9 m measured depth). Oil and gas shows noted within Bathonian strata in well report.
IR 50/3-3	-	-	Bathonian removed by erosion/not deposited.

Table 21 Porosity of the Bathonian reservoir horizons based on 4 wells within the detailed study area

Data from sonic logs			Data from Bulk density logs		
av SPHI	SPIHmin	SPIHmax	av DPHI	DPHI min	DPHI max
0.15	0.00	0.33	0.13	0.00	0.33

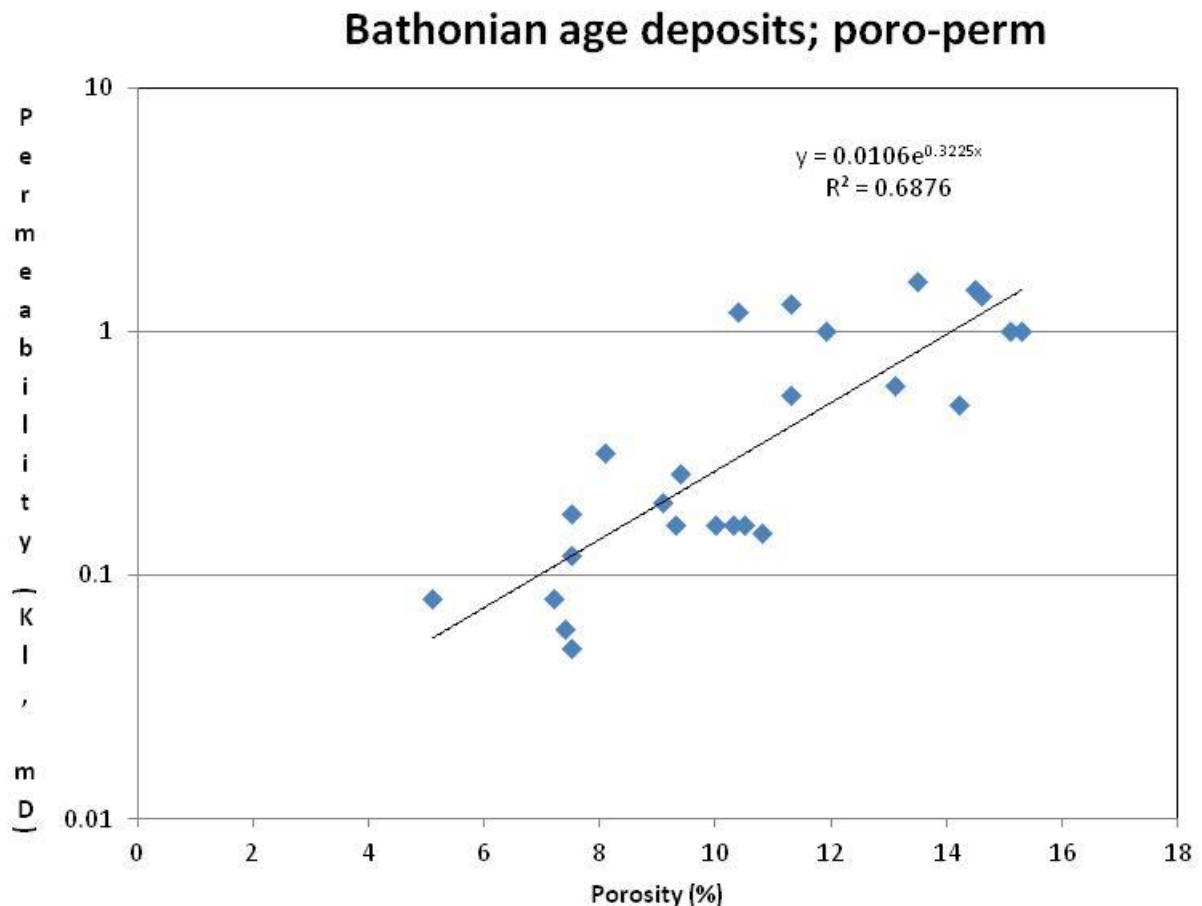


Figure 37: Helium porosity vs. vertical permeability for Bathonian strata using data from well UK 106/24-01

7.1.3 Summary of reservoir quality assessment using log analysis and core data

Overall, the log analyses produced satisfactory results for NTG and derived porosity for most horizons with only the Sinemurian strata presenting issues in terms of perceived reliability of log analyses when the calculated values were compared with data from cuttings and core data.

The NTG values were generally quite low for the Carboniferous strata (average 25%), the Sinemurian strata (average 28%) and the Bathonian strata (average 40%). The NTG values are more promising for the Sherwood Sandstone Group (average 54%) and Inferior Oolite Group reservoir sequence (average 60%).

For reference, the suggested optimum values for reservoir formations as set out in Chadwick et al. (2008) are given in Table 1. In comparison with these recommendation, the derived porosities were low for the Carboniferous reservoir horizons (average 8%), Sherwood Sandstone Group (average 8%) and Sinemurian reservoir horizons (average 8%). Derived porosity values are more promising for the reservoir horizons within the Inferior Oolite Group reservoir sequence (average 13%) and Bathonian reservoir horizons (average 13%) but still lower than the optimum values. Permeability for the Carboniferous reservoir horizons averaged 0.03 mD (3 wells), 0.56 mD for the Sherwood Sandstone Group (1 well), 25.5 mD for the Sinemurian reservoir horizons (1 well) and 0.54 mD for the Bathonian reservoir horizons (1 well). There are no permeability data for the Inferior Oolite Group strata.

The reservoir quality is generally quite poor for all formations when the NTG, porosity and permeability are considered together with only isolated bands within the reservoir horizons having porosity $\geq 10\%$ and no permeability data > 200 mD.

8 Assessment of CO₂ storage capacity in the reservoir horizons

Twenty three small closures have been identified using the modelled top horizon depth surfaces for the Carboniferous strata, Sherwood Sandstone Group, Sinemurian and Bathonian strata and Inferior Oolite reservoir sequence. These closures are based on seismic interpretation of mostly 2D data across the detailed study region. Comments in Table 22 summarise the potential storage opportunities in the study area in this section. Closures were identified in all potential reservoir horizons. The total storage volume in these closures is estimated to be between 4.04 – 24.06 MtCO₂ (million tonnes of CO₂), depending on the storage efficiency factor used (Table 27). Twelve of these closures lie at optimum depth for storage (Table 1). These closures would need more detailed study to improve confidence in security of storage as most of these closures have issues with the seal quality or faults. If only closures at optimum depths were considered (800 < 2500 m depth) then the storage capacity of the identified closures is 2.6 – 15.5 MtCO₂. If only closures where the porosity is expected to be $\leq 10\%$ (Table 1) are considered, then only the closures in the Sinemurian, Inferior Oolite Group reservoir sequence and Bathonian strata can be considered (the only core data where a few samples indicate porosity $> 10\%$ in the Sherwood Sandstone Group are noted in well UK 106/18-01 and IR 42/16-01 where there are no identified closures). Using these two criteria, only closure 107/16_BAJ3 is viable and then only if the upper Bathonian strata are sealing. However, closure 42/21_BAJ1 is only a little shallower than the optimum depth and calculated CO₂ density is high so this closure could also be considered depending on the in situ reservoir and pressure conditions. When considering the seal above these two closures, the seal above closure 107/16_BAJ3 would need further investigation as here the Bathonian strata comprise interbedded limestones and claystones and as there is no identified closure, CO₂ could migrate into the Bathonian strata and potentially reach the surface. For closure 42/21_BAJ1, the Bathonian strata is unlikely to form a good seal as it contains many limestone and siltstone layers.

As closure volume is so low, and there are so many uncertainties relating to reservoir quality, the potential for unconfined aquifer scenarios is also considered in the Sherwood Sandstone Group and in the Bathonian strata plus Inferior Oolite Group reservoir sequence. In order for these scenarios to be considered, more data would be needed on the sealing properties of faults, the completion of wells and the quality of the stratigraphical seal (particularly in the case of the Bathonian plus Inferior Oolite Group reservoir sequence option). Flow simulations would be required to assess the likelihood of CO₂ migrating through an unconfined aquifer to reach potential manmade/natural pathways noted in this report.

The regions which could be considered for an unconfined aquifer storage scenario are in the Sherwood Sandstone Group (on the basin margins around blocks UK 106/30, 107/20, 107/12), northeast of UK 107/16-01 and around wells IR 42/16-01 (though here there is a chance of CO₂ migrating above 800 m depth) or UK 106/18-01. The caprock quality would need confirming for the latter two areas as the Mercia Mudstone Group is silty in this region. Unconfined aquifer storage scenarios could also be investigated in the Bathonian strata and/or Inferior Oolite Group reservoir sequence around wells UK 106/24a-2B and UK 106/24-01 and UK 107/16-01 and UK 107/21-01 if the reservoir and seal quality proves sufficient. The main disadvantages of unconfined aquifer storage are the increased uncertainty of plume migration (in terms of location and speed) and the increased cost in meeting the requirements of the EU Storage

Directive/National Competent Authority when applying for a storage licence. The EU Storage Directive requires the Storage Site Operator to demonstrate financial resources to monitor the storage complex and for unconfined aquifer storage, as there is potentially a large region which will need to be monitored and modelled to confirm site performance, increased costs for the monitoring programme would be expected. In all scenarios, the Storage Site Operator has to demonstrate that contingency funding is available to correct any irregularities over the storage complex and any secondary formations that CO₂ could potentially migrate into which would also increase costs if a large unconfined aquifer region was selected for storage.

Overall, more primary data would be required before any of these storage options could be recommended including 3D seismic data over areas of interest, sampling cores to confirm reservoir and seal quality and in drilling new wells with the specific aim of confirming injectivity potential and seal quality.

Table 22: Summary of storage closures in the detailed study region

Closure name	Closure description	Closure storage volume (assuming 100% pore space can be used ¹)	Reservoir quality	Seal quality	Comments
42/21_BTH1	Dome closure	0.2	Limestones and sandstones beings considered. Average porosity good, NTG is poor.	Seal quality needs confirming as only a small sample is available.	Less than 800 m depth.
42/21_BAJ1	Dome closure	0.003	Inferior Oolite Group reservoir sequence has good NTG and mainly comprises sandstone. Porosity expected to be reasonable based on model.	CO ₂ expected to migrate into Bathonian. Bathonian has closure. Seal quality needs confirming.	Slightly less than 800 m depth.
42/22_BAJ2	Dome closure	0.01	Good porosity and NTG expected based on model but no well data.	CO ₂ expected to migrate into Bathonian. No closure in Bathonian.	Less than 800 m depth.
107/16_BAJ3	Dome closure with bounding fault on part of eastern tip	0.3	Inferior Oolite Group reservoir sequence comprises sandstone and siltstone. NTG quite low but average derived porosity looks quite good. No poro-perm samples.	CO ₂ expected to migrate into Bathonian. No closure in Bathonian. Upper Bajocian comprises mainly claystone which may seal.	Fault on boundary updip of formation.
041/28_SNE1	Dome closure	0.0028	Derived porosity and NTG low but no poro-perm samples. Composite log from nearby well implies good sandstone content.	Overlying sediments silty, lower Bathonian claystone. Seal needs confirming.	Less than 800 m depth.

¹ See later tables for calculated 'effective' storage volumes, this figure has been provided here for summary purposes only

041/29_SNE2	Dome closure with fault cutting the northern tip	0.002	Derived porosity and NTG low but no poro-perm samples. Composite log from nearby well implies good sandstone content.	Overlying sediments silty claystone. Seal needs confirming.	Less than 800 m depth. Fault with small offset penetrates closure.
050/09_SNE3	Dome closure with western fault boundary	0.01	Sinemurian thin but contains sandstones. Derived porosity and model NTG low.	Overlying sediments silty claystone. Seal needs confirming.	Sinemurian juxtaposed against Bathonian and Bajocian by faulting.
050/09_SNE4	Dome closure	0.06	Sinemurian thin but contains sandstones. Derived porosity and model NTG low.	Seal contains many sandstone layers. Seal needs confirming.	
107/16_SNE5	Dome closure	0.2	No log data, modelled NTG good but porosity expected to be low. In this region the lithology is expected to be argillaceous based on other wells.	Seal contains many sandstone layers. Seal needs confirming.	
042/08_SSG1	Dome closure. Cut by 2 faults on southern tip of closure	1.6	Derived porosity quite low but modelled NTG reasonable. No well data.	Thick Mercia Mudstone Group sequence comprising mainly claystone based on seismic interpretation.	Less than 800 m depth. Fault cuts through closure, no observed offset of Sherwood Sandstone Group
106/09_SSG2	Dome closure	0.1	Derived porosity quite low but modelled NTG reasonable. No well data.	Thick Mercia Mudstone Group sequence comprising mainly claystone.	
106/27_SSG3	Dome closure with fault boundary on north-west edge. Additional fault in north-west tip	2.8	Derived porosity quite low but modelled NTG reasonable. No well data.	Mercia Mudstone Group thick and likely to be good seal.	Deeper than 2500 m. Faults present including one which has large throw.
106/27_SSG4	Dome closure bounded by fault on southern edge	0.3	NTG expected to be reasonable, porosity expected to be quite low from log analysis. Base of Sherwood Sandstone Group not penetrated by well in this sector.	Mercia Mudstone Group thick and likely to be good seal.	Deeper than 2500 m. Fault along one boundary.
106/30_SSG5	Dome closure cut by 2 east-west trending faults	0.4	NTG expected to be reasonable, porosity expected to be quite low from log analysis.	Good thickness of Mercia Mudstone Group expected from model, likely to be good seal.	Less than 800 m depth. Faults with small offsets present.

107/21_SSG6	Dome closure cut by 1 fault on western margin	22.5	Derived porosity quite low but modelled NTG reasonable. No well data.	Good thickness of Mercia Mudstone Group expected from model, likely to be good seal.	Less than 800 m depth. Small fault present downdip from closure.
107/12_SSG7	Dome closure, boundary maybe in contact with fault on western most tip of closure	7.3	Derived porosity quite low but modelled NTG reasonable. No well data.	Seal properties not proven.	Fault present along south-western margin.
042/08_CAR1	Fault-bounded dome structure	34.3	NTG quite low and derived porosity quite low. No well data.	Migration into Sherwood Sandstone Group expected. Carboniferous closure areal extent greater than overlying closure in Sherwood Sandstone Group.	At least 8 faults cutting through this closure, but all have small offsets.
106/09_CAR2	Faulted dome closure	1.0	NTG quite low and derived porosity quite low. No well data.	Migration into Sherwood Sandstone Group expected. Carboniferous closure areal extent greater than overlying closure in Sherwood Sandstone Group.	At least 4 faults cutting through this closure with small to medium offsets.
106/27_CAR3	Fault-bounded dome closure to north, south and west	3.9	NTG quite low and derived porosity quite low. No well data.	Migration into Sherwood Sandstone Group expected. Carboniferous closure not completely overlapped by closure in Sherwood Sandstone Group.	Deeper than 2500 m. This closure has faults on three sides.
106/30_CAR4	Dome closure	0.03	NTG quite low and derived porosity quite low. No well data.	Migration into Sherwood Sandstone Group expected. No closure in overlying Sherwood Sandstone Group.	
107/21_CAR5	Dome closure	0.02	NTG quite low and derived porosity quite low. No well data.	Migration into Sherwood Sandstone Group expected. Closure in Carboniferous enclosed by closure in Sherwood Sandstone Group.	

107/21_CAR6	Dome closure with fault boundary on eastern edge, cut by second fault parallel to boundary fault	13.5	NTG quite low and derived porosity quite low. No well data.	Migration into Sherwood Sandstone Group expected. Closure in Carboniferous enclosed by closure in Sherwood Sandstone Group.	Boundary fault and faults through closure.
107/17_CAR7	Fault-bounded dome closure	5.1	NTG quite low and derived porosity quite low. No well data.	Migration into Sherwood Sandstone Group expected. Closure in Carboniferous almost completely enclosed by closure in Sherwood Sandstone Group.	Deeper than 2500 m

8.1 IDENTIFICATION OF POTENTIAL STORAGE SITES

Chadwick et al. (2008) defined the geological setting required for a first pass screening of a geological storage site for CO₂. Indicators for successful geological storage sites are described in Table 1.

Potential storage sites in the detailed study area have been identified on the basis of the following criteria:

- They lie at a depth below 800 m where CO₂ would be in its dense phase.
- Structural closures have been identified which have the potential to retain buoyant fluids.
- They have good reservoir properties.
- They are sealed by a caprock.

For the purposes of calculating potential volumes of CO₂ that might be stored in the Carboniferous, Sinemurian and Bathonian strata, Inferior Oolite Group reservoir sequence and the Sherwood Sandstone Group, it is assumed that injected CO₂ will migrate buoyantly from the injection point to accumulate in ‘closed’ structural highs where it would be permanently trapped. Structural maps of these strata were therefore analysed to identify such structures. Identified closures are shown in figures 33 to 37. It should be borne in mind that there is, in general, a relatively high risk of leakage associated with these storage prospects because of the large number of faults observed on the seismic data. This risk would need further assessment. The risk of leakage through faults is controlled by fault transmissibility and fault orientation relative to the local stress regime. If faults are orientated such that only a small amount of stress is required to produce failure, then the risk of these faults being reactivated is higher. No data were available on the current stress regime from the well data or the World Stress Map in the Celtic Sea Basin. Data from nearby in the UK (Sathar et al., 2012; Sellafield region) suggest that the stress regime is variable over short distances due to the complex tectonic history of this region.

8.1.1 Carboniferous storage options

The Carboniferous strata lie directly underneath the Sherwood Sandstone Group and as there is no regional seal any injected CO₂ would most likely migrate upwards into the Sherwood Sandstone Group. All the identified closures (Figure 38) lie underneath closures identified in the

Sherwood Sandstone Group so CO₂ could still potentially be trapped if injected into the Carboniferous strata. The closures within the Carboniferous strata lie distant from wells where the Carboniferous is penetrated, leading to increased uncertainty in reservoir quality. For example, closures 107/21_CAR5 and 107/17_CAR7 lie close to wells UK 107/16-01 and UK 107/21-01, but these wells terminate in Jurassic sediments.

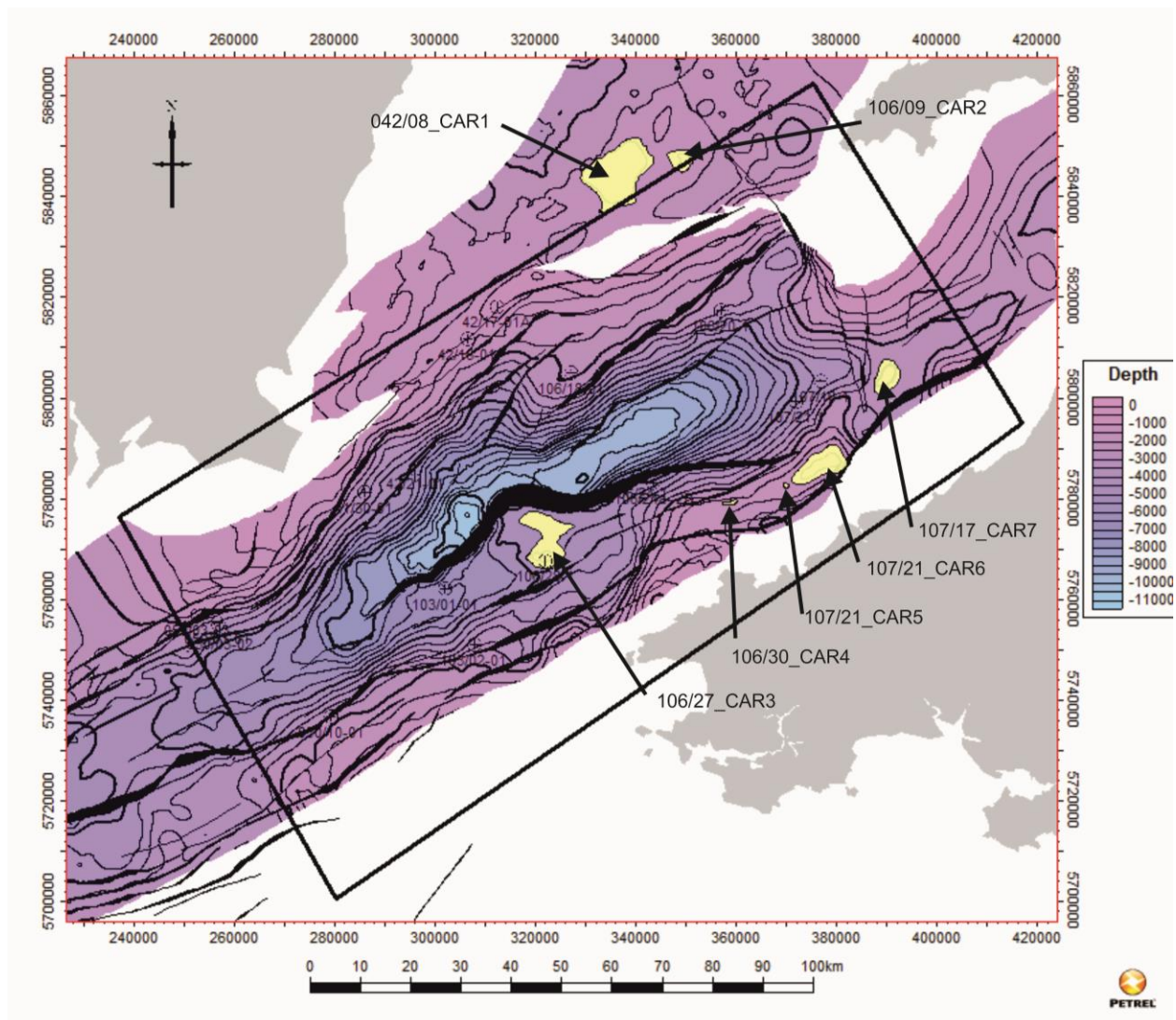


Figure 38: Model surface top of Carboniferous strata with seven identified closures. Two were noted on the border with the Central Irish Sea Basin, this region has been studied in more detail using 3D seismic data which clearly gives a more accurate storage assessment.

Carboniferous sandstones are identified in wells IR 50/03-03, UK 106/20-1, IR 42/17-01A, UK 106/18-01, UK 103/02-01 and IR 42/16-01, however, sandstone layer thickness is very variable. The Carboniferous reservoir horizons generally have low porosity and permeability and therefore are likely to have low storage potential. Core data has average values of 5% and 0.03 mD for porosity and permeability respectively. The highest values identified from core samples taken from sandstone layers are 16% (well IR 42/17-1A) and 0.045 mD (well IR 42/16-01) but most samples have permeability <0.03 mD. Derived values for porosity have very low values (average 8%). NTG for the Carboniferous strata was expected to be 25%.

As the Carboniferous reservoir quality is poor, it is likely that storage in Carboniferous reservoirs could only be considered in conjunction with the overlying Sherwood Sandstone Group though multiple well perforations. More detailed reservoir characterisation would be needed at potential sites to assess this option.

8.1.2 Sherwood Sandstone Group storage options

The Sherwood Sandstone Group has some storage potential but reservoir quality would need to be confirmed by additional core testing. Lithology is generally consistent across the detailed study region and the sandstone is almost always present in varying proportions. Close to the basin depocentres the Sherwood Sandstone Group is dominated by sandstone (well UK 106/18-01). The sandstone is not penetrated by wells in the depocentre of the basins so reservoir thickness and quality is not fully demonstrated by current data. On the basin margins and in the north of the St Georges Channel basin, the Sherwood Sandstone Group has been removed or thinned by erosion.

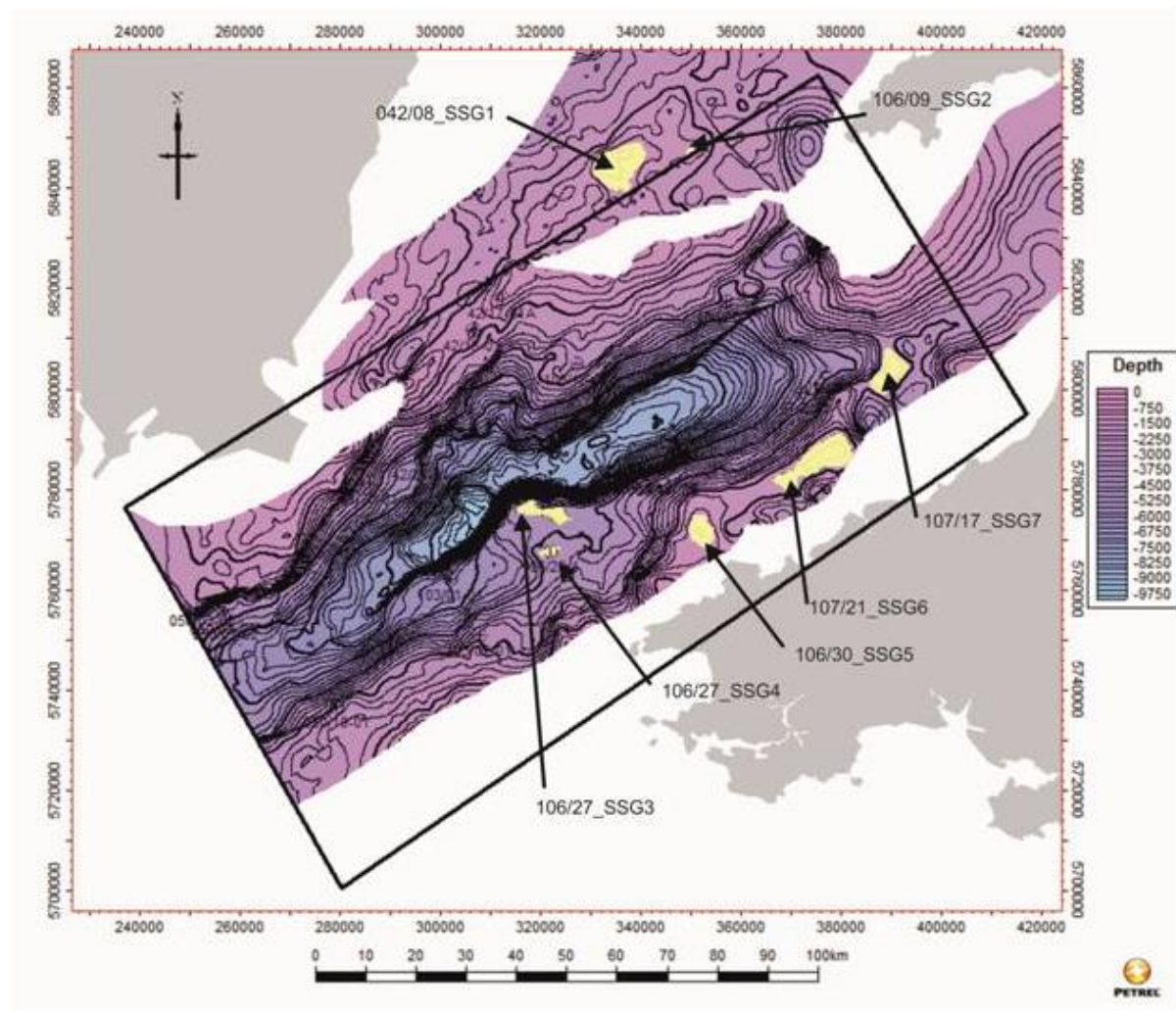


Figure 39: Model surface of top Sherwood Sandstone Group with seven identified closures. Two were noted on the border with the Central Irish Sea Basin, this region has been studied in more detail using 3D seismic data which offers a more accurate storage assessment.

The limited core data available indicates average porosity of 9% (core data) and permeability of 0.65 mD. Derived porosity for reservoir horizons was calculated to be 8%. NTG was calculated to be 54%. Reservoir quality is poor (compared to values in Table 1).

The closures identified in the Sherwood Sandstone Group (Figure 39) are often fault controlled so the sealing ability of the faults would be extremely important to security of storage. Many of the closures in the UK sector are not close to wells reducing the number of potential leakage pathways but also unfortunately reducing certainty in reservoir and seal quality. However, generally, the Mercia Mudstone Group is expected to offer a strong seal due to its great thickness. Note that closures 042/08_SSG1 and 106/09_SSG2 lie in the Central Irish Sea Basin

and the reader is referred to the more detailed 3D interpretation for this region. Closure 107/17_SSG7 appears to have reasonable size, but the reservoir and seal properties are not proven in wells, so have been interpolated using the model. Closure 107/21_SSG6 lies close to the edge of the Sherwood Sandstone Group and if the large faults along the eastern boundary of the detailed study area are not sealing, then this closure will not be secure. Closure 106/30_SSG5 lies updip of well UK 106/24A-2B where a good thickness (853 m measured depth to TD) of Mercia Mudstone Group is recorded mainly comprising mudstone with sandstone and evaporites. Based on seismic interpretation, the Mercia Mudstone Group is also expected to cover this closure with a reasonable thickness providing a strong potential seal. Closure 106/27_SSG3 and 106/27_SSG4 lie close to well UK 106/28-01 where a Triassic sandstone is penetrated (assumed to be Sherwood Sandstone Group) which normally would be considered as a potential reservoir rock but here the sequence contains a lot of interbedded mudstones. The overlying Mercia Mudstone Group comprises mainly claystone with some thin evaporite and sandstone beds (over 1520 m measured thickness) and so would be expected to form an effective seal.

Due to the great thickness of the Mercia Mudstone Group (<1300 m), the Sherwood Sandstone Group could also be considered for unconfined aquifer storage. Unconfined aquifer storage raises the important question of would the CO₂ become trapped through dissolution or shorter term trapping mechanisms before a natural or manmade leakage pathway was reached. There are numerous faults in the study region which cut through the Sherwood Sandstone Group, Mercia Mudstone Group and overlying layers, if these faults are not sealing, then CO₂ could migrate up the fault zone(s) to the seabed. Unfortunately, there are no data on the sealing ability of faults. The wells used for this study all indicated dry holes or uneconomic quantities of hydrocarbons, and no fields in this region show hydrocarbons trapped against faults. As an additional cautionary observation, the assessment carried out by Marathon Oil company and Summit Petroleum (1993) on the Dragon Field (Block UK 103/01) indicated that the faults were believed to have allowed hydrocarbons to migrate out of the Upper Jurassic Callovian – mid Oxfordian sandstones though there is no comment on fault seal for deeper horizons. For unconfined aquifer scenarios, there are too few seismic data in the far south-east of the detailed study area so this region was not considered for unconfined aquifer storage in this study. The region around the closures in the UK sector (106/30_SSG5, 107/21_SSG6, 107/17_SSG7) is more promising as a large quantity of seismic data are available but unfortunately reservoir quality is not confirmed as the Sherwood Sandstone Group is not penetrated by wells nearby. Closure 106/27_SSG3 and 106/27-01_SSG4 are very deep so compaction may have reduced reservoir quality plus nearby borehole 106/28-01 indicates that the Sherwood Sandstone Group contains a large proportion of claystone. The region around well UK 106/18-01 and IR 42/16-01 could also be considered, though seal quality would need to be confirmed as the Mercia Mudstone Group contains many silty layers and is calcareous in parts. The region around well IR 42/16-01 should be considered with caution as the Sherwood Sandstone Group is above 800 m depth in nearby well IR 42/17-1A. The thinnest recorded Mercia Mudstone Group interval is in well IR 50/03-03 (71 m measured thickness) so this region should also be avoided.

8.1.3 Sinemurian storage options

Only a few small closures were identified in the Sinemurian strata (Figure 40). The Sinemurian strata may have some minor storage potential in the North Celtic Sea Basin, but it is only penetrated by a couple of wells in the south of the study area. The overlying strata tend to be silty so there is a potential for CO₂ to migrate upwards into the Inferior Oolite Group and potentially higher in the stratigraphical sequence. In wells IR 50/10-01 and IR 41/30-01, which lie close to the four identified closures in the Irish Sector, the top part of the Liassic succession is silty and so may permit upward migration of the CO₂. The lower part of the Bathonian strata however are quite argillaceous so may actually form part of the seal (though the sequence also contains limestone and sandstone layers and is calcareous in part so sealing ability would need

rigorous testing). For all the closures in the Irish Sector, more data is required to fully assess security of storage and to assess the boundaries of the storage complex and if the CO₂ is expected to migrate through the silty layers immediately overlying the potential Sinemurian reservoir rocks.

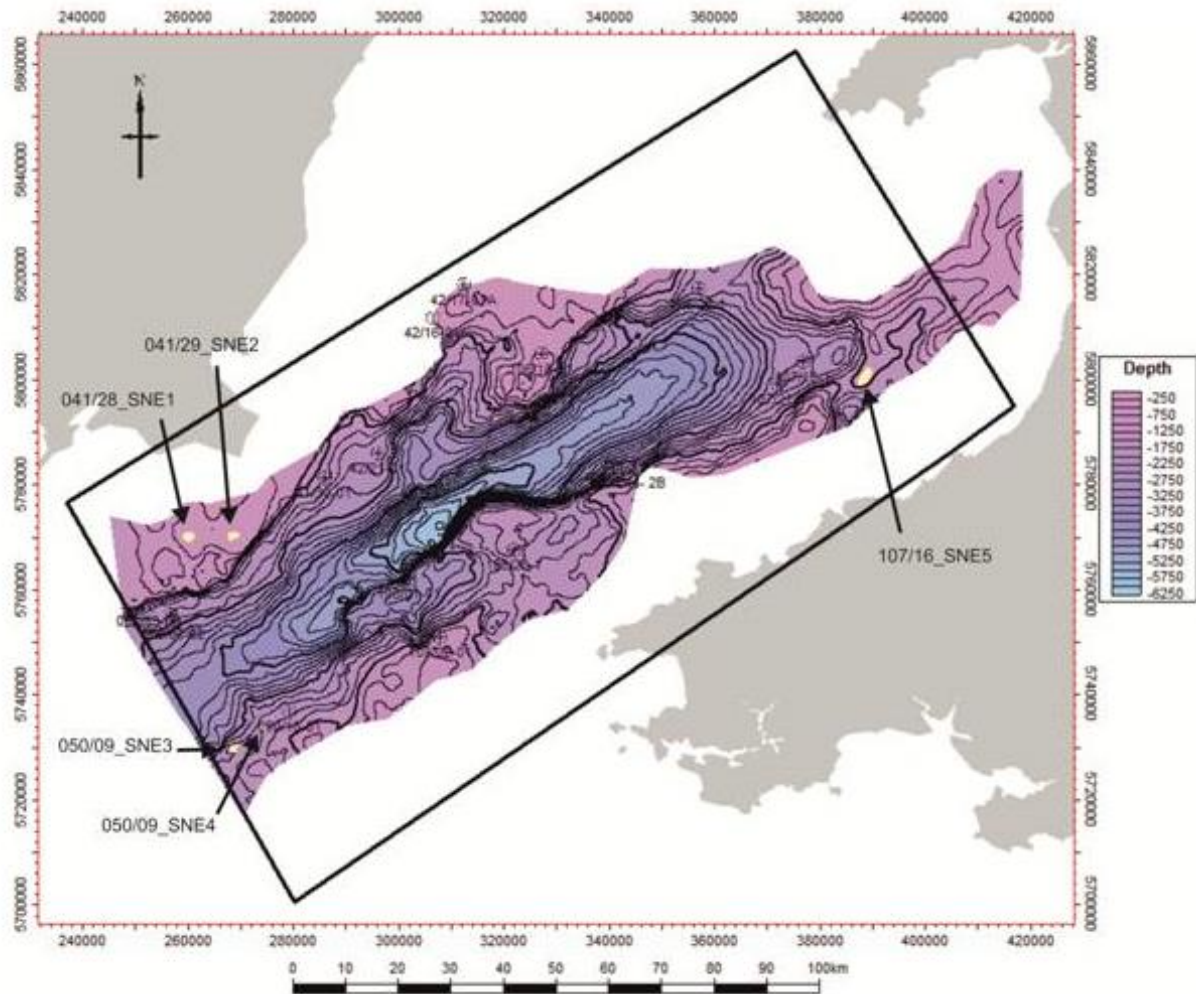


Figure 40: Model surface of top Sinemurian strata surface with five small identified closures

The Sinemurian strata have no apparent reservoir potential in the St George's Channel Basin as it comprises argillaceous claystones and siltstones where it is penetrated by wells in the south and is absent in the northwest of the basin due to erosion. It is not penetrated by any wells in the north east of the basin and so reservoir quality here cannot be assessed. Sinemurian closures in the UK sector occur where porosity is low and the main lithology is likely to be claystone/mudstone so storage capacity is expected to be very poor (closure 107/16_SNE5).

Reservoir quality in the Sinemurian strata is generally quite poor (average core porosity 10%, derived porosity of reservoir layers average 8% and permeability 25.5 mD from RFT log) compared to the recommendations made in Table 1. NTG was calculated to be 28%. Thus, considering this poor reservoir quality, the uncertainty in the overlying seals and the small size of the closures, the sandstones of Sinemurian age do not appear to offer good storage potential.

8.1.4 Inferior Oolite Group reservoir sequence storage options

The reservoir horizons within the Inferior Oolite Group reservoir sequence offer some limited storage potential, relatively thick (>50 m) sandstone layers are observed in a few wells (e.g. IR 50/03-01, IR 50/10-01 and IR 41/30-01).

The quality of the caprock would have to be confirmed in the North Celtic Sea Basin as the overlying strata have highly variable lithology. There is no obvious seal between the Inferior Oolite Group and the overlying Bathonian strata.

The option of using the reservoir horizons within the Bathonian strata (sandstones and limestones) and Inferior Oolite Group reservoir sequence to provide a stacked storage solution would need to be investigated in the St George's Channel Basin as there is no strong seal present between these strata.

Closure 42/21_BAJ1 (Figure 41) lies underneath a closure identified in the overlying Bathonian strata (though the top of this closure in the Bathonian strata lies above 800 m depth). In well IR 42/21-01, the lower part of the Bathonian strata (137 m measured thickness) comprises mainly claystone with some thin limestone beds, which could form a potential seal but would need investigation.

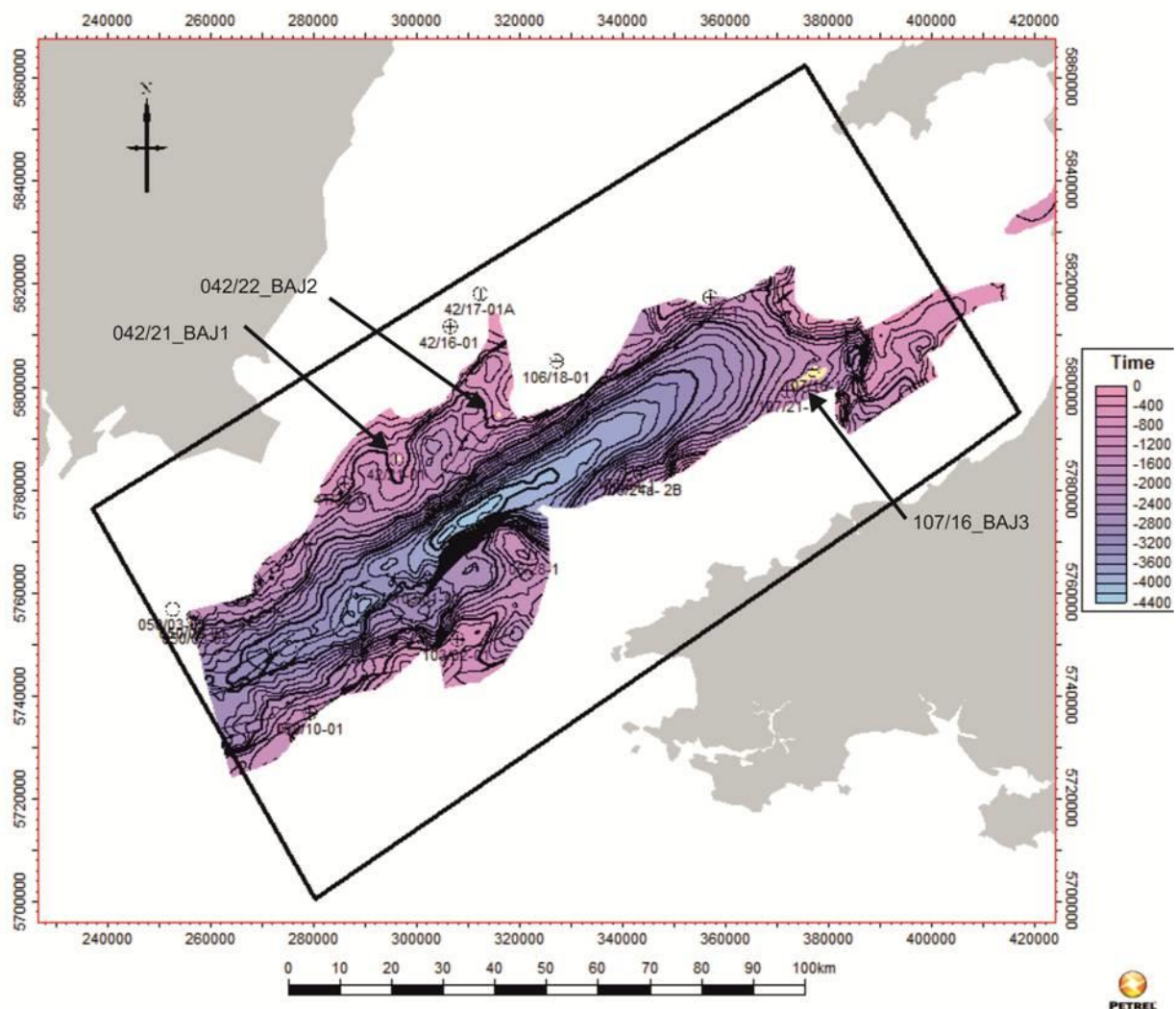


Figure 41: Model surface of Top Inferior Oolite Group reservoir sequence with three identified closures

There are no closures noted in the top Bathonian strata model surface above closures 42/22_BAJ2 and 107/16_BAJ3 (Figure 41) and thus if CO₂ migrated from the Inferior Oolite Group into the Bathonian strata, CO₂ could migrate outside the defined closure outlines. There is a possibility that the strata overlying 107/16_BAJ3 mainly comprises claystone if the lithology is similar to that found in well UK 107/16-01 where the Middle – Upper Jurassic (Callovian – Kimmeridgian) claystones are interbedded with sandstones. However, closure 107/16_BAJ3 is not too far from faults which could offer a potential migration route out of the storage complex. Closure 42/22_BAJ2 lies at a depth of less than 800 m and so the CO₂ is unlikely to be in its dense (liquid) form. In addition, this closure lies close to the edge of the geographical limits of the Inferior Oolite Group so migration out of the storage reservoir into younger strata could also be an issue.

Assessment of reservoir quality for the Inferior Oolite Group reservoir sequence was based only on log analysis as no detailed core data were available. The average derived porosity for reservoir layers within the Inferior Oolite Group reservoir sequence is 13%, which is within the accepted limits for storage sites (Table 1). NTG is calculated at 60%.

8.1.5 Bathonian storage options

The Bathonian strata generally offer poor storage potential, with a low proportion of sandstone. In most wells limestone is present, often alternating with sandstone beds which could be considered as a storage option but would need further study to verify injectivity. Removal of overlying beds by erosion means that in many cases the Bathonian strata also lack a seal.

Average core porosity is 8% and average permeability is 0.54 mD. Derived porosity is 13%. NTG is calculated at 40%. These figures indicate that reservoir quality is not promising for storage when compared against the recommendations in Table 1.

Only one closure is identified, 042/21_BTH1, and this lies at a depth of less than 800 m (Figure 42).

Unconfined aquifer storage could be considered in the combined Bathonian and Inferior Oolite Group strata. In the St George's Channel Basin there are a few possible options: In wells UK 107/16-01 and UK 107/21-01, the lowest part of the Bathonian comprises limestone with sandstone beds near the base and rests directly on Bajocian sandstones, siltstones and claystones so could potentially be considered jointly for storage. The area around UK 107/16-01 may have some potential if the Bathonian limestone and Bajocian siltstone have sufficient reservoir quality but at present this is not confirmed. The overlying seal would also need investigation. The region around well UK 107/21-01 could have some potential in the Inferior Oolite Group reservoir sequence and Bathonian strata and the overlying Middle – Upper Jurassic strata appear to contain a good proportion of claystone. The region around UK 103/01-01 could be considered in Bathonian limestones and Callovian – Oxfordian sandstones, however updip of this lies well UK 103/02-01 where the Bathonian is shallow and has no suitable caprock so this region is probably not suitable for storage as there is no obvious barrier to the CO₂ migrating up-dip (but this would have to be confirmed with more detailed and dynamic modeling). As an additional cautionary note, the Dragon Field in this sector is believed to contain an uneconomic quantity of hydrocarbons due to leakage along faults. Areas around wells UK 106/24a-2B and UK 106/24-01 contain a large proportion of claystone and are not ideal, however, a layer with measured thickness of 171 m comprising sandstone and limestone was noted in well UK 106/24-01 and a thick limestone sequence is noted in 106/24a-2B so this region may offer a combined limestone/sandstone option if the lithology is laterally continuous.

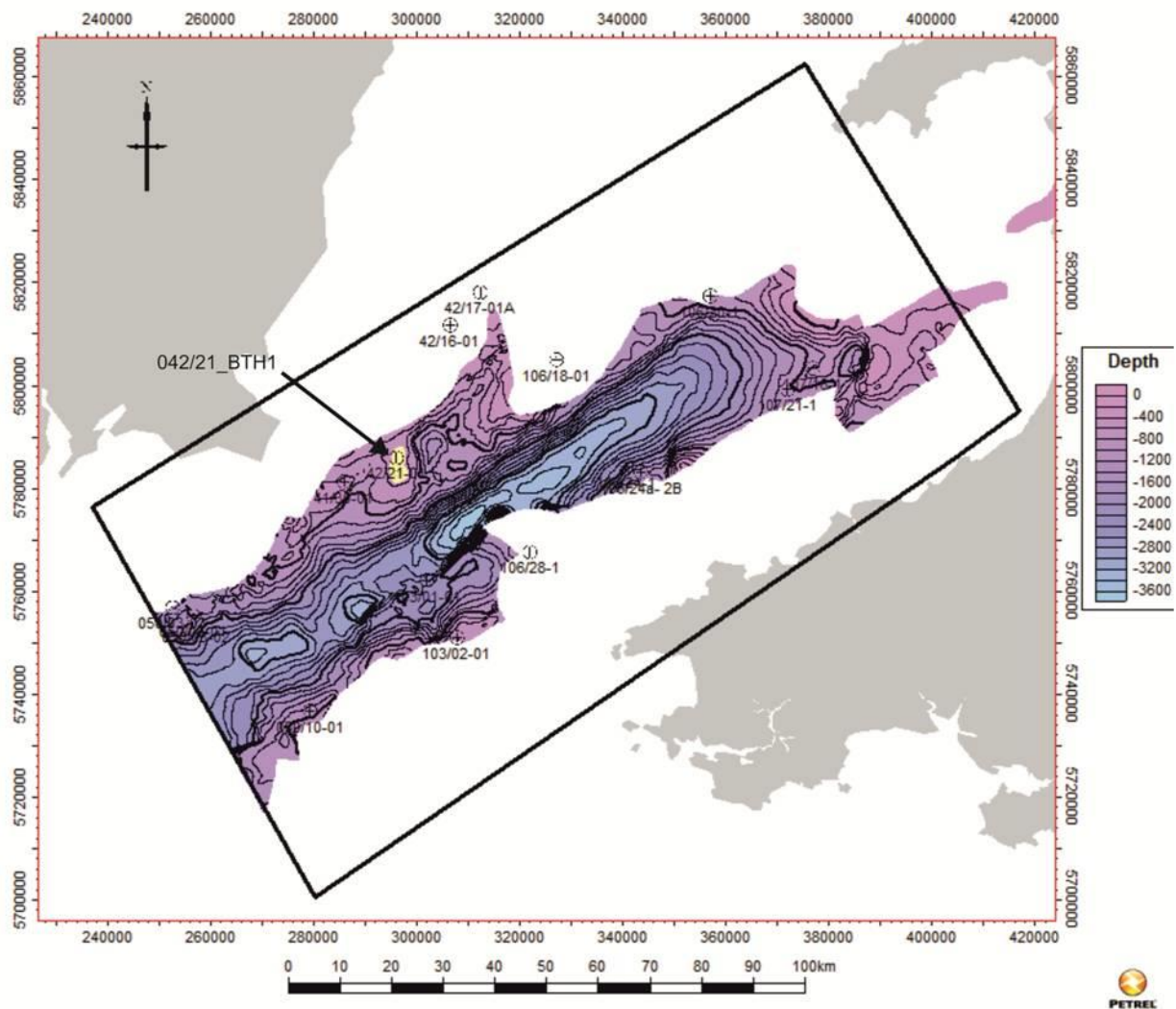


Figure 42: Model surface of top Bathonian strata with one identified closure

In the North Celtic Sea Basin, the Bathonian strata are frequently too shallow for storage. The only region where the strata lie at suitable depths are in the south of the detailed study region. They do lie at a suitable depth around well IR 50/03-02 but this is close to the edge of the Bathonian strata so there is a possibility that CO₂ could migrate into younger strata. Additionally, in nearby wells IR 50/03-01 and IR 50/03-03, Bathonian strata are absent due to erosion.

Bathonian strata are also at a suitable depth on the basin margin around IR 50/10-01, however the overlying sequence do not seem to contain a thick mudstone/claystone dominated sequence and in fact contain large quantities of sandstone so may not offer a suitable seal.

Storage in the combined Bathonian strata and Inferior Oolite Group reservoir sequence could be considered where it lies below 800 m in an unconfined aquifer scenario around wells UK 107/16-01 and UK 107/21-01. Storage in Bathonian reservoirs could be considered around wells UK 106/24a-2B and UK 106/24-01 (if the lithology proves laterally continuous). All the unconfined aquifer storage options would require assessment of the likelihood of CO₂ migrating into regions where there is no suitable caprock, regions where the pressure is too low for CO₂ to remain in its highly dense phase or where leakage may occur through faults on a site by site basis. The seal quality would also have to be studied in detail since the overlying formations and lithologies are quite variable.

8.2 STATIC CAPACITY CALCULATION AND ASSUMPTIONS

Simple estimates of static CO₂ storage capacity were calculated for each of the closures. The net pore volume of each closure was estimated. Then the mass of CO₂ which could occupy the net pore volume was calculated by applying the calculated CO₂ density at reservoir conditions to the net pore volume (the CO₂ density was derived from an estimated reservoir temperature, a hydrostatic pressure gradient and the Span and Wagner (1996) equation of state) and finally a storage efficiency factor was applied, representing the sweep efficiency and CO₂ saturation considered to be achievable in a putative storage project. This methodology gives a ‘first pass’ theoretical static storage capacity. However, it does not take potential pressure limitations into account. More sophisticated “dynamic” capacity estimates using a numerical reservoir simulator were not made due to the lack of appropriate data.

The method used can be summarised as:

‘Effective’ CO₂ storage capacity = net pore volume x density of CO₂ at reservoir conditions x Storage efficiency factor

8.2.1 Pore Volume

The volume of each structure was calculated by intersecting the top modelled surface of each horizon with a flat surface at the level of the lowest closing contour, and by calculating the intervening volume using simple surface calculations in Petrel (Table 23). Formation bulk porosities were derived from the well log analysis and used to estimate the net pore volume over the reservoir layers within the horizons of interest as a simplified volumetric calculation.

Table 23 Summary of volumes and reservoir properties for each of the closures identified in the Celtic Sea Basin

Closure	Bulk volume m ³	Pore volume m ³	Net pore volume m ³	NTG	Porosity	Depth to crest (m)	Comments
42/21_BTH1	100850446	15127567	2269135	0.15	0.15	349	Porosity from model
42/21_BAJ1	79700	6376	4208	0.66	0.08	791	Porosity from model. Assumed 10 m reservoir thickness ² .
42/22_BAJ2	210167	35728	17150	0.48	0.17	628	Porosity from model. Assumed 10 m reservoir thickness.
107/16_BAJ3	10519085	1157099	370272	0.32	0.11	1264	Porosity from model
041/28_SNE1	2468257	123413	37024	0.30	0.05	303	Porosity from model
41/29_SNE2	2928373	146419	45390	0.31	0.05	211	Porosity from model
50/09_SNE3	1218502	60925	12185	0.20	0.05	1719	Porosity from model
50/09_SNE4	6365263	318263	79566	0.25	0.05	1838	Porosity from model
107/16_SNE5	12496711	624836	256183	0.41	0.05	1066	Porosity from model
042/08_SSG1	671626669	33581333	19812987	0.59	0.05	312	Porosity from model
106/09_SSG2	3123763	156188	92151	0.59	0.05	907	Porosity from model
106/27_SSG3	76312004	6868080	3708763	0.54	0.09	3559	Porosity from model
106/27_SSG4	8259655	825966	437762	0.53	0.1	3490	Porosity from model
106/30_SSG5	138543738	6927187	3255778	0.47	0.05	437	Porosity from model
107/21_SSG6	1121552850	56077643	26917268	0.48	0.05	597	Porosity from model
107/17_SSG7	402515223	20125761	9459108	0.47	0.05	1993	Porosity from model
042/08_CAR1	2355491828	235549183	42398853	0.18	0.1	1088	Porosity from model
106/09_CAR2	81954906	8195491	1311278	0.16	0.1	1460	Porosity from model
106/27_CAR3	453785976	22689299	5218539	0.23	0.05	4408	Porosity from model
106/30_CAR4	3333429	166671	41668	0.25	0.05	1310	Porosity from model
107/21_CAR5	1143683	68621	19214	0.28	0.06	1210	Porosity from model
107/21_CAR6	897478350	53848701	16693097	0.31	0.06	872	Porosity from model
107/17_CAR7	285243708	19967060	6589130	0.33	0.07	2347	Porosity from model

8.2.2 Density of CO₂

Density of the CO₂ was calculated by applying the Span and Wagner (1996) equation of state for CO₂ to an estimate of pressure and temperature at reservoir conditions. Temperature data is sparse, only being available in 7 wells in the detailed study area (Table 24). Surface temperature was assumed to be 10 °C. Some measurements were taken at the bottom hole and were recorded a number of hours after drilling during which drilling fluid was circulated, potentially reducing the ambient temperature of the reservoir. As a result the temperatures recorded may be inaccurate and a little lower than the true reservoir temperature in some cases, but in the absence of better quality data these measurements were used to estimate the geothermal gradient in the study area. The estimated average temperature gradient for the area is 27 °C/km.

² Note A uniform reservoir thickness of 10 m had to be assumed for the Petrel calculation for several closures where they only encompassed 1 contour line. These are marked with 'Assumed 10 m reservoir thickness'.

Table 24 Temperature gradient in the study area.

Well Number	Depth of measurement (m)	Temperature (°C)	Temperature gradient (°C/m)	Temperature gradient (°C/Km)
IR 50/03-01	2677.36	77.78	0.025	25
IR 42/17-01A	1488.95	48.89	0.026	26
IR 42/16-01	1426.16	43.33	0.023	23
UK 107/01-01 (taken days after drilling)	2436.27	66.67	0.023	23
IR 50/03-03 (taken days after drilling)	1437.13	56.67	0.032	32
IR 50/10-01 (taken days after drilling)	1924.51	76.11	0.034	34
UK 107/21-01	2131.47	60.00	0.023	23
Average			0.027	27

The average reservoir pressure gradient was determined from four wells (see Table 25).

Data on pressure in the wells is only available for a few wells (IR 50/03-02, IR 42/16-01, UK 107/01-01, IR 50/03-03 and UK 106/20-01). Using an average lithostatic pressure of 0.140 psi/metre does not indicate that any of the formations are overpressured though outside the detailed study region some wells indicate overpressure in the Upper Jurassic formations (e.g. well IR 48/24-10z as described in Lansdowne 2012; well IR 49/19-01 as described in Fastnet Oil and Gas, 2013).

Table 25 Pressure data in the study area.

Well Number	Depth of measurement (m)	Hydrostatic pressure (psi)	Formation pressure (psi)	Hydrostatic pressure gradient (psi/m)	Formation Pressure gradient (psi/m)
IR 50/03-02	1784.91	3264.0	2694.0	1.84	1.51
IR 50/03-03	836.98	1616.4	1258.4	2.00	1.53
UK 106/20-01	1036.5		1544.6		1.49
UK 107/01-01	1454.51		2331.7		1.60
Average				1.85	1.53

The CO₂ density was calculated using pressure and temperature gradients of 1.53 psi/m and 27 °C/Km respectively derived from wells summarised in Table 24 and Table 25. CO₂ densities range from as little as 0.082 t/m³ in the shallower closures to 0.835 t/m³ in the deeper closures with an average of 0.67 t/m³ (Table 26).

Table 26 Data used for storage capacity calculations and storage capacity at 100 % storage efficiency.

Closure name	Total rock volume (Km ³)	Mean NTG	Mean porosity	Depth to crest (m)	Temp (°C)	Pressure (bars)	CO2 density (t/m ³)	Storage capacity (Mt)
42/21_BTH1	0.1	0.15	0.15	349	9.5	37.0	0.097	0.20
42/21_BAJ1	0.0001	0.66	0.08	787	21.2	83.0	0.824	0.003
42/22_BAJ2	0.0002	0.48	0.17	628	17.0	66.2	0.831	0.010
107/16_BAJ3	0.01	0.32	0.11	1264	34.1	133.3	0.798	0.30
041/28_SNE1	0.002	0.3	0.05	303	8.2	32.0	0.075	0.0028
041/29_SNE2	0.003	0.31	0.05	211	5.7	22.3	0.049	0.002
050/09_SNE3	0.001	0.2	0.05	1712	46.2	180.6	0.784	0.01
050/09_SNE4	0.006	0.25	0.05	1838	49.6	193.9	0.781	0.06
107/16_SNE5	0.012	0.41	0.05	1066	28.8	112.5	0.812	0.20
042/08_SSG1	0.7	0.59	0.05	312	8.4	32.9	0.082	1.60
106/09_SSG2	0.003	0.59	0.05	907	24.5	95.7	0.820	0.10
106/27_SSG3	0.08	0.54	0.09	3559	96.1	375.4	0.751	2.80
106/27_SSG4	0.008	0.53	0.1	3490	94.2	368.2	0.752	0.30
106/30_SSG5	0.14	0.47	0.05	437	11.8	46.1	0.136	0.40
107/21_SSG6	1.12	0.48	0.05	597	16.1	63.0	0.835	22.5
107/17_SSG7	0.4	0.47	0.05	1993	53.8	210.2	0.773	7.30
042/08_CAR1	2.4	0.18	0.1	1088	29.4	114.8	0.809	34.3
106/09_CAR2	0.08	0.16	0.1	1460	39.4	154.0	0.793	1.00
106/27_CAR3	0.45	0.23	0.05	4408	119.0	465.0	0.748	3.90
106/30_CAR4	0.003	0.25	0.05	1310	35.4	138.2	0.798	0.03
107/21_CAR5	0.001	0.28	0.06	1210	32.7	127.6	0.798	0.02
107/21_CAR6	0.9	0.31	0.06	872	23.5	92.0	0.811	13.5
107/17_CAR7	0.3	0.33	0.07	2347	63.4	247.6	0.769	5.10
Notes: Depth to crest in red text means the unit is shallower than recommended and in green text is deeper than recommended for CO ₂ storage.						Total Storage Capacity (Mt) if all available pore space utilised		93.77

8.2.3 Storage efficiency factors

Storage efficiency (E) is defined as the fraction (by volume) of the reservoir pore space that can be filled by CO₂ (free or dissolved). For a detailed discussion of storage efficiency, see IEA Greenhouse Gas R&D Programme (2009). Storage efficiency factors are site specific and are best estimated by numerical flow simulation.

Using the data available and without carrying out detailed dynamic flow simulations, storage efficiency factors for the identified formation closures are largely unknown. This study has therefore used a range of storage efficiency factors from published work, in order to take into account the uncertainty (Table 27).

Table 27 Storage capacity at a range of different storage efficiency factors

	Storage efficiencies						
	Closed structure (Williams et al., 2013)	Site specific scale clastics P50 (Goodman et al., 2011)	Site specific scale clastics P90 (Goodman et al., 2011)	Homogenous Quarter dome (IEAGHG, 2009)	Homogenous Half dome (IEAGHG, 2009)	Homogenous Three quarter dome (IEAGHG, 2009)	Homogenous Dome (IEAGHG, 2009)
	0.042	0.0679	0.1498	0.17	0.18	0.24	0.25
<i>Closure name</i>	<i>Mt</i>						
42/21_BTH1	0.009	0.015	0.033	0.037	0.039	0.053	0.055
42/21_BAJ1	0.0001	0.0002	0.0005	0.00059	0.00062	0.0008	0.0009
42/22_BAJ2	0.0006	0.0010	0.0021	0.0024	0.0026	0.0034	0.0036
107/16_BAJ3	0.01	0.02	0.04	0.05	0.053	0.071	0.074
041/28_SNE1	0.0001	0.0002	0.0004	0.00047	0.0005	0.00067	0.0007
41/29_SNE2	0.0001	0.0002	0.0004	0.00047	0.0005	0.00067	0.0007
50/09_SNE3	0.0004	0.0006	0.0014	0.0016	0.0017	0.0023	0.0024
50/09_SNE4	0.0026	0.0042	0.0093	0.0106	0.0112	0.0149	0.0155
107/16_SNE5	0.009	0.014	0.031	0.035	0.037	0.05	0.052
042/08_SSG1	0.07	0.11	0.24	0.28	0.29	0.39	0.41
106/09_SSG2	0.003	0.005	0.011	0.013	0.014	0.018	0.019
106/27_SSG3	0.12	0.19	0.42	0.47	0.5	0.67	0.7
106/27_SSG4	0.12	0.19	0.42	0.47	0.5	0.66	0.69
106/30_SSG5	0.02	0.03	0.07	0.075	0.08	0.106	0.11
107/21_SSG6	0.94	1.53	3.37	3.82	4.05	5.40	5.62
107/17_SSG7	0.31	0.50	1.10	1.24	1.32	1.75	1.83
042/08_CAR1	1.44	2.33	5.14	5.83	6.17	8.23	8.58
106/09_CAR2	0.04	0.07	0.16	0.18	0.19	0.25	0.26
106/27_CAR3	0.16	0.27	0.58	0.66	0.7	0.94	0.98
106/30_CAR4	0.001	0.002	0.005	0.0057	0.006	0.008	0.0083
107/21_CAR5	0.0006	0.001	0.0023	0.0026	0.0028	0.0037	0.0038
107/21_CAR6	0.57	0.92	2.03	2.30	2.44	3.25	3.38
107/17_CAR7	0.21	0.34	0.76	0.86	0.91	1.22	1.27
Total capacity (Mt)	4.04	6.53	14.41	16.36	17.32	23.09	24.06

These results can only be considered to be a rough guide to the potential storage capacity.

In the UK Storage Appraisal Project (Gammer et al., 2011), storage was considered uneconomic in storage units with an estimated static capacity of less than 50 Mt. If this cut-off is applied to the closures assessed in the study area none of the closures would be large enough for significant storage of CO₂. Even if proximally located individual structures were to be considered as a potential cluster, accessed from a single platform, they would not offer sufficient storage capacity of economic interest.

As mentioned above, the storage efficiencies of the closures could be better determined by site specific dynamic modelling of CO₂ injection into these closures, but this is beyond the scope of this study.

8.3 RISKS AND LIMITATIONS OF THE METHODOLOGY

The assessment of potential closures based on modelled surfaces, the density of available data and assumptions made during the depth conversion will impact the accuracy of closure identification. The depth of the Sherwood Sandstone Group and top Carboniferous surfaces is not proven by wells in the basin depocentres and is based on seismic interpretation alone. Faults will also potentially impact the ability of the closures to contain buoyant CO₂ and the sealing ability of the faults in the detailed study area is generally not known.

8.3.1 Data availability

The interpretation was based on available data and the limitations of data coverage and resolution should be considered. The surfaces were interpreted mainly using 2D data and thus resolution is not as accurate as if 3D data were utilised. The well data available gives good coverage across the area but as the lithology of the reservoir horizons is so variable, it is clear that any regions being considered for storage would need additional well data on a closer spacing to give a fuller picture of the proposed storage complex. In addition, the wells do not always penetrate the deeper formations and the depth to the top Sherwood Sandstone Group and top Carboniferous strata is not proven in the basin depocentres.

8.3.2 Faults

Due to the complexity of the faulting in the Celtic Basin and the spacing of the available 2D seismic data, it is difficult to produce a definitive seismic interpretation. This region has a very high density of faulting and only faults which clearly displaced horizons were picked. Based on the high fault density, and the quality of the seismic data, it is likely that faults that cannot be resolved on the seismic data present. Additionally, some faults may exist between the seismic grid spacing and therefore will have been missed.

As a result the structural maps represent the interpreter's best judgement given the data available and the structural complexity. They should not be considered definitive. For a more comprehensive fault interpretation, 3D seismic data would be required focused around the potential storage regions.

In the Sherwood Sandstone Group, many of the closures are related to faulting. One or two of the closures have a boundary which comprises a fault. Faults may act as conduits for fluid flow by:

- allowing the migration of fluids across the fault where the reservoir is juxtaposed with permeable formations (cross-fault migration), or;
- allowing vertical migration of fluids via the fault itself, to the surface or shallower formations.

Conversely faults can also act as barriers to fluid flow due to:

- the juxtaposition of the reservoir formation against impermeable sealing formations, or;
- the presence of low permeability fault rocks along the fault plane formed by movement of the fault.

The integrity of many of the closures relies on both the sealing capacity of the top seal and the sealing capacity of one or more faults. Seal quality is described in Section 6.

Few of the faults observed in this study near the closures have an offset greater than the thickness of the caprock. Closure 106/27_CAR3 being an exception to this; the Carboniferous

structure is juxtaposed next to the Sinemurian strata and the Mercia Mudstone Group (see Figure 43). If CO₂ were injected into closures and it migrated via the faults it is unlikely to reach the surface unless a permeable horizon (thief zone) is encountered in the cap rock or unless the fault itself is not sealing.

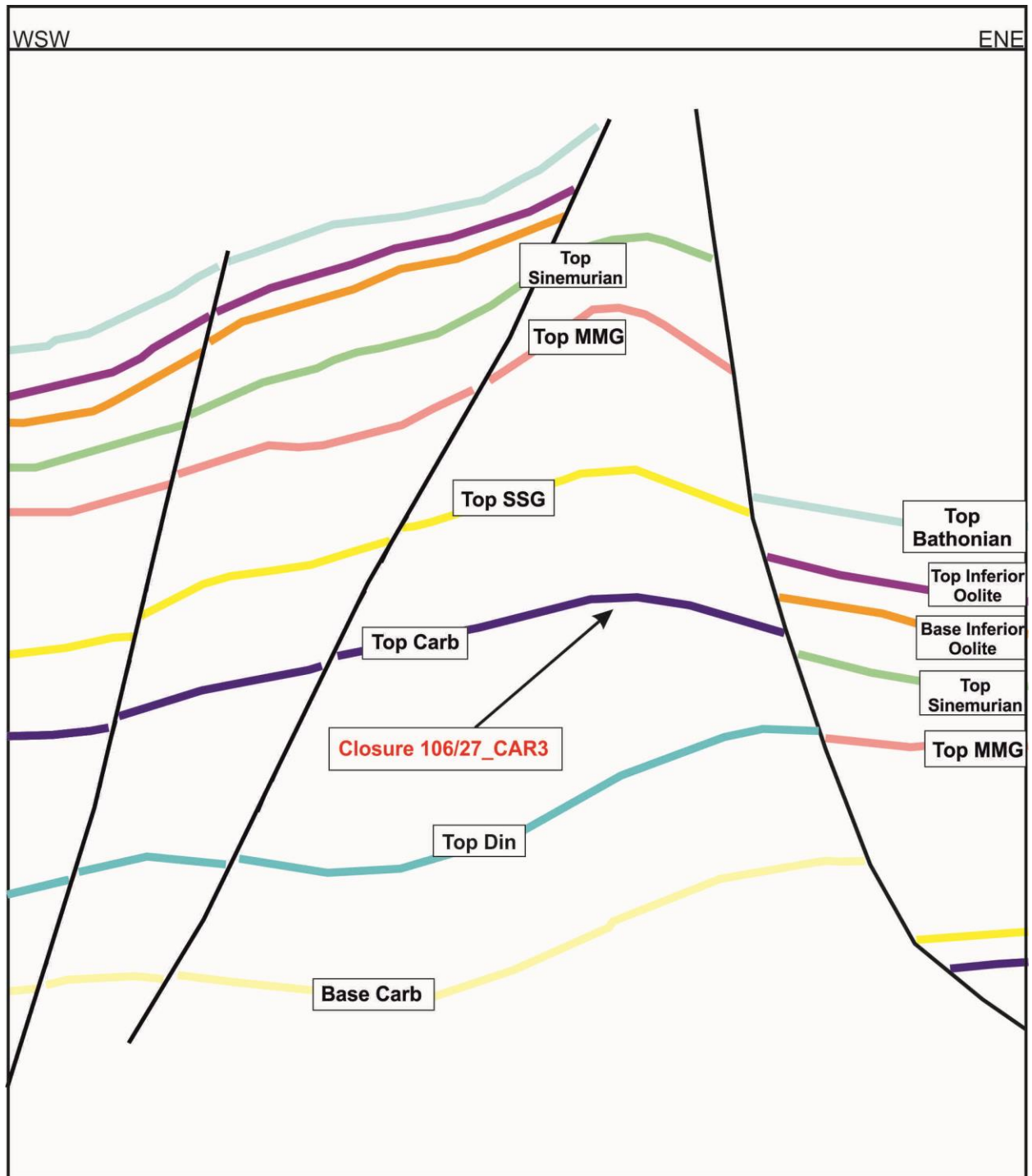


Figure 43 Closure 106/27_CAR3 sketched on WSW – ENE orientated seismic line

The juxtaposition of reservoir across faults associated with each closure was examined using seismic lines which transect the closures (where possible) this is summarised within Table 28.

There are few comments in the geological well reports stating nearby faults have leaked and are therefore not sealing. For example, for well IR 42/17-01A, the geological report notes that the well is dry and that the escape route offered by major faults in this area is believed to be the reason for this. The Dragon Prospect in Block UK 103/1 is believed to contain uneconomic

quantities of gas due to leakage along faults (Marathon Oil company and Summit Petroleum, 1993).

Table 28 Summary of closures with faults in the Celtic Sea Basin

Closure	Faults	Comments
107/16_BAJ3	NE1-1	Occurs on the boundary, is up-dip of the formation in this area.
041/29_SNE2	NCB31	Small offset but shallow structure (less than 800 m).
050/09_SNE3	Unnamed	Sinemurian strata is juxtaposed against the Bathonian and upper Bajocian strata.
042/08_SSG1	WA_14A2, WA_6C	Cutting through the closure near the southern boundary, no offset of the geology.
106/27_SSG3	SW2_6_SGF	Up-dip of main formation for this closure.
	SGC09_SGF	Large throw – Sinemurian strata is juxtaposed against Kimmeridge strata.
106/27_SSG4	SGC06	Boundary fault along southern margin.
106/30_SSG5	SGC02_BF, SGC04	Small offsets but shallow structure (less than 800 m).
107/21_SSG6	SGC03, Unnamed fault	Small offset, down-dip from main closure.
107/17_SSG7	SGC02_BF	Closure may be clipped by this fault on south-western margin. Uncertain juxtaposition on this fault.
042/08_CAR1	CIW11, SW_12A, SW1_12, CIW08, CIW07, CIW06	There are at least 8 faults running through this closure – the offset is generally small to none.
	CIW10	
	W4_14A2, CIW07, CIW06	
106/09_CAR2	CIW04, 3 unnamed faults	There are at least 4 faults running through this closure with small to medium offsets.
106/27_CAR3	SW2_7, SGC06, NE92_5, SGC09_SGF	SW2_7 is boundary fault eastern margin. SGC06 - South boundary fault no real offset. NE92_5 - Western margin boundary fault..
107/21_CAR6	SGC03, SGC02_BF	South-eastern boundary faults on edge of basin and juxtaposition unknown on SGC03, only small offset on SGC02_BF.

In summary therefore, it is not known whether the faults that define the potential closures that could be used for CO₂ storage in the Celtic Basin are likely to be sealing. Analogies between the EISB which suggest that faults in the Mercia Mudstone Group can seal significant gas columns, should be balanced against indications that the faults in Celtic Sea Basin may be allowing or may have allowed hydrocarbons to leak out of the reservoir horizons. Without further data and research, the sealing potential of the relevant faults is unknown and it must therefore be assumed that they present a significant risk to the storage integrity of the closures.

Finally, all of the closures were identified using mainly 2D seismic data with an irregular line spacing of 1 to greater than 20 km. Structural maps have been constructed by interpolation between these seismic lines and it is therefore inevitable that any geological features that happen

to lie between the seismic lines, such as additional faults and changes in the morphology of the formations will not appear on maps resulting from this study. It is therefore strongly recommended that if any of the closures are identified as having potential for CO₂ storage purposes, a 3D seismic survey should be acquired over the area of the mapped closure to improve the resolution of the data and to reduce geological uncertainty.

8.3.3 Depth conversion

Depth conversion is a key uncertainty in the depth surfaces produced during seismic interpretation. The TWTT (two-way travel time) surfaces were depth converted using a highly simplistic constant interval velocity for the overburden. The velocity of the caprock interval is highly sensitive to variations in lithology, and density contrasts caused by disparities between current and maximum burial depths. Laterally across the study area, both of these factors vary considerably.

Uncertainty in the top reservoir depth maps will impact the delineation of structural closures and thus their estimated storage capacity. It is therefore strongly recommended that if any of the closures are identified as having potential for CO₂ storage purposes, a 3D seismic survey should be acquired over the area of the mapped closure to improve the resolution of the data and to reduce the potential error in the interpretation of top reservoir.

9 Conclusions

Following the initial seismic interpretation across the whole of the Celtic Basin, a detailed study region covering the north region of the North Celtic Basin adjacent to the Central Irish Sea Basin and the St George's Channel Basin was selected for detailed study to avoid potential conflicts with ongoing oil and gas exploitation when identifying potential storage opportunities.

The main horizons of interest were the Sherwood Sandstone Group, Sinemurian strata, the Inferior Oolite Group reservoir sequence and Bathonian strata. The Carboniferous strata were also considered during the assessment as this is a potential hydrocarbon reservoir and contains sandstone layers. A summary of the storage assessment carried out for this report is given in Table 29.

Table 29 Summary of suitability of the study area for CO₂ storage.

Feature	Comment
Reservoir Quality	poor to fair.
Reservoir compartmentalisation	Faults present in reservoirs but compartmentalisation is unknown.
Depth of reservoir	Large portions below 800 m, however, many potential reservoir regions also deeper than optimum depth (2500 m).
Storage capacity	In defined closures generally tiny to 0 when considering reservoir depth, reservoir quality and seal quality.
Storage efficiency	Unknown.
Closure	Closure coarsely mapped on a 2D grid but precise architecture of the closures unknown.
Caprock	Present but sealing capacity unknown.
Caprock thickness	In wells ranges between 0 and 130 m.
Faulting	Closely spaced faults with unknown seal capacity across the whole region.
Tectonic activity	Not investigated in this study

Data from wells was used to assess reservoir quality; lithology, net to gross and porosity of the potential reservoir formations. Although the Carboniferous strata contain sandstones, the permeability of these layers was generally very low and therefore overall this formation has limited potential for storage. The Sherwood Sandstone Group generally has the most consistent lithology across the study region and generally contains sandstone layers. The Sherwood Sandstone Group porosity and permeability data from cores was disappointingly low (average 9% and 0.65 mD respectively) however it may be possible to target promising sandstone layers. The Sinemurian strata have very variable lithology, in the St George's Channel Basin they mainly comprise mudstone and claystone, however, in the rest of the study area, there are more porous and permeable sandstones noted, particularly around IR 41/30-01 in the North Celtic Basin. The Inferior Oolite Group reservoir sequence and Bathonian strata have potential reservoir layers in sandstones and/or limestones and porosity generally appears to be reasonable (core average porosity 8% and permeability 0.54 mD for Bathonian strata and derived porosities 13% for reservoir horizons in both strata). The lithology of these strata is variable and in many cases the two intervals would have to be considered together for storage where there are no apparent seals separating them. The main issue with the Inferior Oolite Group reservoir sequence and the Bathonian strata is the need to confirm the overlying seal is of sufficient quality.

A small number of closures (23) have been identified in the model top horizon surfaces for the Bathonian and Sinemurian strata, Inferior Oolite Group reservoir sequence, Sherwood Sandstone Group and Carboniferous strata. These closures have been identified based on seismic mapping of (mainly) 2D data across the detailed study region. Overall the closures identified have a low total estimated storage capacity of 4 – 24 MtCO₂ depending on the storage efficiency factor used. However, this storage volume includes closures above and below optimum depth for storage, faulted closures and closures where the reservoir quality is expected to be poor. If depth and closures where porosity is expected to be $\leq 10\%$ (based on the recommendations in Table 1) are considered, only closures in the Inferior Oolite Group reservoir sequence and Sinemurian strata are suitable for storage. The security of the identified closures would need to be investigated through collection of new data as the robustness of the seal is not confirmed by the current dataset and lithology is highly variable. Additionally, faults cut through/form one or more of the boundaries for some of these closures and the sealing ability of these faults is

unproven. There are examples where it seems faults have allowed hydrocarbon to migrate to the sea bed or where faults have formed an effective seal trapping hydrocarbons (in the Central Irish Sea Basin). Taking all these factors into consideration, none of the closures seem particularly suitable for storage. However, a small pilot scale test could be considered; in particular, a study considering the sealing ability of faults or silty/calcareous caprocks would be beneficial to understanding security of storage and would contribute to the body of knowledge on current topics of interest for CCS.

As potential storage volume offered by closures is so low, the potential for unconfined aquifer scenarios was also considered in the Sherwood Sandstone Group and in the Bathonian strata and/or inferior Oolite Group reservoir sequence. In order for these scenarios to be considered, more data would be needed on the sealing properties of faults, the completion of wells and, particularly in the case of the Bathonian plus Inferior Oolite Group option, in the quality of the stratigraphical seal. Flow simulations would be required to assess the likelihood of CO₂ migrating in an unconfined aquifer to reach the potential manmade/natural pathways described here. The regions which could be considered for an unconfined aquifer storage scenario, subject to confirmation of reservoir and seal quality, are in the Sherwood Sandstone Group (on the basin margins around blocks UK 106/30, UK 107/20, UK 107/12, northeast of UK 107/16-01 and around wells IR 42/16-01 or UK 106/18-01) and Bathonian and/or Inferior Oolite Group (around wells UK 106/24a-2B and UK 106/24-01 and UK 107/16-01 and UK 107/21-01). The main disadvantage of unconfined aquifer storage is the increased storage footprint which would increase the cost of any project, particularly considering the need to demonstrate financial security in order to meet the requirements of the EU Storage Directive.

The main uncertainties in this study arise from lack of data; most of the region is only covered by 2D seismic data, wells do not always penetrate the reservoir/seal horizons, porosity and permeability data are not always available. In addition, various assumptions were made during depth conversion and well log interpretation which also increase uncertainty. The lack of 3D seismic data and assumptions made during depth conversion will affect accuracy of closure delineation. Assumptions made during well log interpretation will impact assessment of reservoir quality and capacity assessment for the closures. In addition, no injection testing has been carried out in this region which increases general uncertainty of the injectivity of the potential reservoir horizons. Overall, more primary data would be required before any of the storage options outlined in this report could be recommended; ideally, 3D seismic data over areas of interest, sampling cores to confirm reservoir and seal quality and drilling of new wells with the specific aim of confirming injectivity potential and seal quality.

10 Recommendations for further work

Study of the seals in order to understand the lithology and distribution would help to understand the sealing characteristics of the caprock and will provide information for further fault analysis. The sealing ability of silty caprocks and calcareous claystone/mudstone strata are current topics of interest for CCS in general. A study of the sealing properties of faults in areas highlighted to have potential for storage (e.g. around well UK 103/01-01) such that confidence in security of storage can be increased or areas can be discarded if leakage risk along faults is deemed too high would also be necessary. The risk of leakage along faults and what makes a fault more likely to leak CO₂ are current topics of interest for CCS.

Static modelling and dynamic simulation of CO₂ injection into promising closures and in areas selected as having unconfined aquifer storage potential to provide a more realistic storage assessment.

Other specific studies which would increase confidence in the storage options discussed in this report are:

- Study of the sealing potential of the Bathonian above the Inferior Oolite Group reservoir sequence from well IR 41/30-01
- Study sealing potential of Bathonian Claystone in well IR 50/10-01
- Confirm if siltstones of the Dogger Claystone and Siltstone formations (Inferior Oolite Group and Bathonian strata) are sealing in well IR 41/21-01
- Confirm sealing properties of Mercia Mudstone Group in well IR 42/16-01, UK 106/18-01
- Confirm sealing properties of upper Bathonian strata in UK 107/16-01
- Confirm sealing properties of Callovian – Middle Oxfordian sediments in well UK 107/21-1
- Confirm sealing properties of Middle and Upper Jurassic layers above the Bathonian strata in well UK 103/01-01. Confirm sealing ability of formations above Sherwood Sandstone Group in IR 42/16-01
- Confirm sealing properties in regions where unconfined aquifer scenarios are suggested in the Sherwood Sandstone Group (blocks UK 106/30, 107/20, 107/12, northeast of UK 107/16-01 and around wells IR 42/16-01 or UK 106/18-01) and in the Bathonian strata and/or Inferior Oolite Group reservoir sequence (around wells UK 106/24a-2B and UK 106/24-01 and UK 107/16-01 and UK 107/21-01).
- Confirm reservoir properties through core testing for Inferior Oolite Group sandstones in wells IR 41/30-01, IR 50/10-01
- Confirm reservoir properties through testing Sherwood Sandstone Group samples in the UK sector near wells

However, after detailed investigation (as recommended by Lewis et al. 2009) this region offers significantly less storage potential than described by Lewis et al, 2009. Given the limited storage potential and considerable potential risks to storage containment, injectivity and security it is not recommended that further resources are allocated to investigation of storage potential in this region at this time. If any resources are available, they could be used to undertake a focused pilot with a research agenda which could decrease uncertainty in some of the current research questions for CO₂ storage.

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11 Appendix A: Well lithology assessment

The lithologies of potential reservoir and seal horizons were assessed for each well and observations were made on likely reservoir and seal quality.

11.1.1 Carboniferous

Well IR 50/03-03 penetrates what are believed to be Namurian C to Westphalian A strata from 1250.3 – 1463.3 m MD (Measured depth). These comprise sandstones, siltstones with minor claystones and coal. This is overlain by around 5 m of sandstone equivalent to Sherwood Sandstone Group.

Well IR 42/16-01 penetrates strata of Westphalian D to C and Stephanian D to A age from 1150.3 – 1639.8 m MD. These comprise siltstones and sandstones with bands of limestone and occasional coals. These are overlain by around 18 m of Sherwood Sandstone Group sandstones and siltstones.

Visean and Westphalian D and C age strata are penetrated by well IR 42/17-01A from 548.6 - 1488.9 m MD which comprises siltstones and sandstones with coal layers. The Visean strata are limestones. These are overlain by 'undifferentiated Triassic' (comprising siltstones and claystones) then a thin conglomerate which is described as the Sherwood Sandstone Group equivalent.

Well UK 106/18-01 penetrates Upper Carboniferous deposits from 2325.3 - 2613.4 m MD. These comprise sandstones and siltstones with occasional claystones. These are overlain by around 132 m of Sherwood Sandstone Group equivalent sandstones.

Westphalian strata are penetrated by well UK 106/20-1 from 2888 – 3220 m MD. These comprise sandstones and claystones in equal measure with minor siltstone and a few coal layers and are overlain by the MMG. The Carboniferous deposits are Coal Measures and comprise mudstone, siltstone and sandstone. Porosity was described as 'nil' and 'poor' in the conventional core taken between 3174 and 3192 m MD and testing indicated porosity of 0.5 – 7.9% and permeabilities <0.01 – 0.05 mD. No oil or gas shows were recorded.

Well UK 103/02-01 penetrates Westphalian D strata which comprise mudstones and sandstones with a couple of coal layers from 2969.4 - 3173.0 m MD. These are overlain by almost 250 m of Sherwood Sandstone Group which comprise sandstones and mud/claystones.

11.1.2 Top Sherwood Sandstone Group and Mercia Mudstone Group

Well IR 50/03-3 penetrates the Sherwood Sandstone Group equivalent (1245.1 – 1250.3 m MD) and records it as very being very fine to fine grained, strongly cemented by silica with no visible porosity. Five sidewall cores were attempted but only one showed a small recovery of material. This thin layer of sandstone is underlain by sandstones, siltstones and claystones with a few coal seams of Namurian C to Westphalian D age. The Sherwood Sandstone Group equivalent layer is overlain by the Mercia Mudstone Group (MMG) which is 71 m thick (MD in the well) and is in turn overlain by Triassic and Lower Jurassic limestones.

Well IR 50/10-1 penetrates a sandstone/conglomerate unit at 2433.8 – 2477.1 m MD which is considered to be the Sherwood Sandstone Group equivalent. This unit comprises well cemented, moderately sorted sandstone with red argillaceous matrix cement, interbedded sandstone, siltstone and claystone (weak to strong silica cements in the sandstone, calcite cements in the siltstone) and a fining upwards conglomerate. Core from 2440.8 – 2469.2 m MD was taken and analysis in the well geological report porosity is measured as 12% and NTG of 0.11. This layer is underlain by 'undifferentiated Triassic' sediments to TD which largely comprises claystone with

occasional siltstone and silty sandstone interbeds. The Mercia Mudstone Group in well IR 50/10-01 caps the Sherwood Sandstone Group equivalent layer. The MMG comprises over 500 m (MD in the well) of claystone with minor thin limestone beds and around 30 m of halite. This in turn is overlain by the Hettangian Shale and Sinemurian Shale units which combined comprise over a hundred metres of claystones in the well.

The Mercia Mudstone Group is penetrated in well IR 41/30-01 from 1950.7 m MD to TD and over 280 m (MD) thick. It comprises predominantly claystone with occasional anhydrite beds near the top and occasional conglomerates, sandstones and interbedded siltstones and sandstones near the TD of the well.

The Sherwood Sandstone Group equivalent is penetrated by well IR 42/16-01 from 1033.3 – 1150.4 m MD. The upper part comprises siltstone with minor limestone and the lower part comprises sandstone and basal conglomerate. Core from this sandstone has porosity 2.6 – 10.7% and horizontal permeability 0.04 – 0.41 mD. The Sherwood Sandstone Group equivalent is underlain by the Stephanian and Westphalian which comprise siltstones, carbonates and sandstones with some coal stringers. A core taken from a Westphalian sandstone had a porosity of 3.2 – 7.3% and a horizontal permeability of 0.05 to 0.34 mD. The Sherwood Sandstone Group equivalent is overlain by 776 m MD of the Mercia Mudstone Group (labelled as the Keuper Shale in the well log) which comprises mainly claystone and siltstone with minor sandstone. Layers of halite and anhydrite are present around 548.6 and 944.9 m MD.

Triassic sediments are penetrated by well IR 42/17-01A at 222.5 – 548.6 m MD. Although undifferentiated in the well log, the upper section mainly comprises siltstone with minor limestone and several sandstone layers are noted from 484.6 – 548.6 m MD where the contact with the underlying Stephanian sediments is faulted. The well geological report notes that the well is dry and that the escape route offered by major faults in this area is believed to be the reason for this. Cores were taken in the Carboniferous sediments.

The Sherwood Sandstone Group equivalent is penetrated by well UK 106/18-01 from 2201.9 – 2325.3 m MD. This layer mainly comprises sandstone and a large number of cores were collected with porosities ranging from 1.6 – 11.0% and permeabilities ranging from <0.01 – 0.54 mD. The Sherwood Sandstone Group equivalent is underlain by sediments of Carboniferous age which comprise claystones, massive sandstones and siltstones. The Sherwood Sandstone Group equivalent is overlain by the Mercia Mudstone Group equivalent from 1137.5 – 2201.9 m MD which mainly comprises claystone with minor siltstone and sandstone and some halite layers.

In well UK 106/20-01, Carboniferous sediments are directly overlain by 809 m MD of Mercia Mudstone Group at 2888 m MD, comprising mudstone with frequent siltstone layers towards the base and evaporite layers throughout the sequence. The Carboniferous comprise sandstones, siltstones and mudstones.

In well UK 106/24a-2B, the Sherwood Sandstone is not penetrated. The Mercia Mudstone comprises two layers; Keuper Mudstone comprising of interbedded sandstone and clay overlying the Keuper Salt which comprises salt with varying amounts of anhydrite. The well history report however indicates that no salt was seen in the cuttings while drilling this interval and instead small chips of shales similar to those of the overlying layer and anhydrite were retrieved. The Mercia Mudstone Group is penetrated from 2368.3 – 3221.1 (TD) measured depth.

The Sherwood Sandstone is penetrated by well UK 103/02-01 from 2528.6 – 2969.4 m MD (labelled as the Bunter Sandstone of Ladinian to late Scythian age) where it comprises sandstone, claystone, mudstone and siltstone, becoming increasingly silty towards the base. Testing of cores from the main sands from 2673.7 – 2808.4 m MD indicated an average porosity of 9.6 %. The well report gives a net thickness for sandstone of 97.5 m over this interval which gives a NTG of 0.72. The Sherwood Sandstone Group rests unconformably on Carboniferous strata (Westphalian D) consisting of sandstone, siltstone and mudstone with some coal seams. The well report notes 17.4 m net thickness of sand in this 181.7 m thick sequence, giving a NTG of 0.1. The Sherwood

Sandstone Group is overlain by 1775.8 m of Mercia Mudstone Group (labelled as Keuper Formation) which comprises mudstone, marl and claystone with anhydrite, halite and anhydrite beds.

The Mercia Mudstone Group is penetrated by well UK 103/01-01 from 3716.1 – 4968.2 m MD (TD) and comprises claystone with minor siltstones and dolomites and occasional sandstones. Thick halite layers and some thin anhydrite bands are present. This well does not reach the Sherwood Sandstone Group.

Triassic sandstone is penetrated by well UK 106/28-01 from 2932.2 – 3051.0 m MD which comprises claystone and silty claystone with some interbedded fine to medium grained sandstone. One core was taken at 2414.0 – 2418.0 m MD which comprises mudstone.

11.1.3 Top Sinemurian strata and Jurassic sealing strata

A Sinemurian sandstone is penetrated by well IR 50/03-3. This late Sinemurian sandstone from 445.6 to 516.6 m MD is described as a massive sandstone with very fine to fine grains which is well sorted with weak calcite cement. The massive sandstone becomes more argillaceous towards the base. Directly underneath this layer are sandstones interbedded with siltstones and claystones (516.6 - 983.9 m MD), the sandstones are described as being generally less than 12 m thick and tightly cemented with calcite. These sandstones are very fine grained and well sorted. Sidewall cores were taken at 862.6 and 855.9 m MD. The sandstones are water wet. In well 50/03-3, the Sinemurian sandstone is overlain by calcareous claystone and interbedded calcareous claystones and limestones of Sinemurian age. There are no returns above 315.5 m MD.

A Sinemurian sandstone is penetrated by well IR 50/10-01 at 1800.7 – 1813.0 m MD. This sandstone is described as being silty and very fine grained with no visible porosity. This is underlain by the 'Sinemurian shale' which comprises claystone. In this well, the Sinemurian sandstone is overlain by Liassic shales which in the well comprise 335 m of claystone with thin limestones (depth 1466.1 - 1800.8 m MD).

A Sinemurian sandstone (labelled Liassic sandstone) is penetrated in well IR 41/30-01 from 1582.8 – 1786.7 m MD. It comprises interbedded sandstones and siltstones with occasional claystones and traces of limestone. The sandstones are described as very fine to fine grained, weakly cemented with very poor visible porosity. The Sinemurian sandstone is underlain by claystones and siltstones of the Liassic marl formation. The Sinemurian sandstone is overlain by the Liassic shale equivalent which comprises an argillaceous siltstone grading locally to sandstone with occasional fine to very fine grained sandstones. The top and bottom of the Sinemurian sequence are bounded by faults.

Well IR 42/21-01 does not penetrate as deep as the Sinemurian sediments but a Pliensbachian sandstone is noted from 1923.3 – 1966.0 m MD which is described as fine to very fine grained, moderately well sorted. The rest of the Pliensbachian comprises siltstones.

Well IR 42/17-01A penetrates Sinemurian to Hettangian strata at 158.5 – 222.5 m MD. These comprise siltstone overlain by claystone.

In well UK 106/18-01, Sinemurian sediments are largely argillaceous and comprise claystones and marls with some siltstone and limestone layers and very minor sandstones. Sinemurian sediments are penetrated from 570.0 to around 896.1 m MD. The Liassic marl equivalent (same age as the Liassic sandstone) comprises calcareous claystone and claystone with minor muddy limestone. This is overlain by the Liassic shale equivalent which comprises calcareous claystone with sandstone.

Well UK 106/20-01 penetrates Sinemurian to Pliensbachian strata at 1803 – 1962 m MD which comprise highly calcareous mudstone with minor limestone and very minor sandstone. This is

overlain by Liassic calcareous mudstones and Aalenian mudstones with minor limestone and siltstone.

The Sinemurian to Pliensbachian strata are absent in well UK 106/24a-2B and Toarcian strata rests directly on Triassic strata.

In well UK 103/02-1 the Sinemurian sequence, penetrated from 552.0 – 883.92 mainly comprises mudstone which is silty in places with some small gas shows (the upper part of this sequence is Domerian to Sinemurian age). The Domerian to Sinemurian strata comprise siltstone and claystones with occasional limestones and sandstones.

Well UK 103/01-01 penetrates Sinemurian strata (Liassic sandstone formation) from 3313.2 – 3518.9 m MD which mainly comprise siltstone and claystone with minor limestone. This layer is underlain by the Liassic marl formation (Hettangian – earliest Sinemurian) comprising claystone which is calcareous in places and minor limestone and siltstone. The Sinemurian strata are overlain by 246.0 m MD of siltstones and claystones from the Pliensbachian – Aalenian stages, with limestones present in the Pliensbachian strata. The claystones are calcareous in part.

The sequence from Pliensbachian to Late Sinemurian mainly comprises mudstone and shale with thinly interbedded siltstones in well UK 106/28-01 from 1121.7 – 1374.6 m MD. Siltstone is recorded in this interval from 1211.6 – 1303.2 m MD. The early Sinemurian to Hettangian strata become increasingly limestone dominated as you move down the sequence below 1374.6 m MD. Early Sinemurian to Hettangian strata are underlain by Triassic age Rhaetic to Norian strata and the MMG sequence which is claystone dominated. The late Pliensbachian to late Sinemurian strata are overlain by an early Toarcian to Aalenian mudstone dominated sequence 191.4 m MD thick which is in turn unconformably overlain by Cenozoic sandstones, siltstones and interbedded sandstones and siltstones with minor lignite and limestone.

11.1.4 Inferior Oolite Group

A sandstone-poor Bajocian sequence is present in well IR 50/03-01 from 880.3 – 972.3 m MD. It comprises claystone with minor sandstone and siltstone. This is underlain by early Jurassic sandy siltstones, claystones and sandstones. The Bajocian strata is unconformably overlain by Kimmeridgian to Tithonian sediments which comprise sandstone, limestone and claystone beds over 245 m thick in the well, these are then unconformably overlain by Lower Purbeckian interbedded limestones, sandstones and claystones.

A Bajocian sandstone body is penetrated by well IR 50/10-01 (1414.3 – 1466.1 m MD). This is described as very fine to fine grained sandstone with calcareous cement and no visible porosity. This sandstone is overlain by Bathonian claystone (1279.6 – 1414.3 m MD).

Bajocian strata are penetrated by well IR 41/30-01 from 1007.4 – 1224.1 m MD and comprise sandstones and limestones. The sandstones are described as fine to medium grained, moderately sorted with poor to moderate porosity. The Bajocian strata is underlain by the Lower Jurassic sequence (siltstones, claystones, sandstones, interbedded sandstones and siltstones and a few minor limestone beds) which are in turn underlain by the Sinemurian strata. The Lower Jurassic section is divided into the Liassic shale unit (which comprises siltstone grading locally to sandstone and claystone), the Liassic sandstone (comprises interbedded sandstones and siltstones with calcite cement with poor visible porosity) and the Liassic marl (which comprises calcareous siltstones and claystones with minor limestones). Cores were taken in the Bathonian, Bajocian (excluding the Bajocian sandstone layers), Liassic shale, Liassic sandstone and Liassic marl. The thick Bajocian sandstone layer is overlain by around 79 m of Bajocian sandstones and claystones and over 340 m (MD in well) Bathonian claystones (carbonate and non-carbonate) with minor siltstones and carbonates.

A Bajocian sandstone is penetrated by well IR 42/21-01 from 1100.3 – 1417.3 m MD. This comprises mainly fine to very fine grained sandstone with poor visible porosity and minor siltstones and limestones. The Bajocian sandstone rests directly on Aalenian sandstones (which

are grouped with the Bajocian sandstone as the Middle Jurassic sandstone in the well log). The Aalenian sandstones are described as fine to medium grained with poor to moderate sorting. These are underlain by the Liassic shale unit which comprises siltstone with some sandstone layers towards the base of the interval. The Bajocian sandstone is overlain by the Dogger claystone and siltstone units which are over 500 m (MD) thick and comprises claystone, siltstone and sandstone with minor limestone.

Bajocian strata comprise sandstones and limestones (Inferior Oolite Formation; 1020 – 1024 m MD) underlain by mudstone with minor limestone and siltstone of Bajocian to Aalenian age in well UK 106/20-01. The Bajocian strata are overlain by 4 m of Bathonian mudstones followed by Cenozoic sandstones, mud/claystones and siltstones with coal seams.

In well UK 103/02-01 the Bajocian strata comprises mainly limestone with sandstone and are penetrated from 457.2 - 552.0 m MD. The lowest 31 m of this sequence comprises mainly sandstone in which core tests indicate an average porosity of 17%. The Bajocian sequence is directly overlain by the limestone and claystone dominated Bathonian deposits.

A thin Bajocian sandstone is penetrated by well UK 103/01-01 from 3042.5 – 3067.2 m MD. This comprises mainly limestone with minor sandstone. The sandstones are described as clean, fine grained and moderately consolidated. The Bajocian sandstone is overlain by siltstones, claystones and minor sandstones of Bathonian age and underlain by the Liassic shale unit which comprises siltstones and claystones with minor sandstones.

Bajocian strata are recorded from 2050.7 – 2208.0 m (MD) in well UK 106/24a-2B. These comprise siltstone with minor occurrences of clay, shale and traces of limestone. The Bajocian strata are overlain by 448.1 m (measured thickness) Bathonian strata which comprise shale and clay with minor sandstone and some limestone. The Bajocian strata are directly underlain by Aalenian strata which comprises clay with traces of siltstone and limestone.

Cenozoic sands rest directly on Aalenian/Toarcian sediments in well UK 106/28-01, Bajocian sediments are not recorded.

Well UK 107/21-01 penetrates early Bathonian to Bajocian strata from 1572.8 – 1758.7 m MD which comprises siltstone, limestone and claystone with some sandstone. The top of the early Bathonian strata comprises almost 53 m (measured thickness) of claystone. Underneath this, there are two dominantly sandy layers separated by a claystone layer. These upper sandstones were reported to be very tight with only 2 m (out of 9 m) having a porosity >10%. The lower sandstone has an average porosity of 20% reported in the well completion report. These are underlain by a Bajocian to Aalenian sandstone with some siltstone and claystone. These sandstones are described as fine to very fine grained with moderate sorting. The geological report indicated that they comprised approximately 92.4 m of the 123.4 m interval (i.e. NTG of 0.75). Log analysis indicates that approximately 37.2 m of the sandstone had porosities of 20 – 28% and 22.6 m had porosities of 15 – 20%. The Bajocian to Aalenian sandstones are underlain by calcareous claystones of Aalenian to Toarcian age. In well UK 107/16-01, the lower part of the Bathonian strata from 1113.7 m MD comprises mainly limestone with a sandstone layer around 20 m thick at the base which rests directly on Bajocian sandstones and limestones.

Early Bajocian strata is penetrated by well UK 107/16-01 from 1321.3 – 1824.5 m MD. The top part of this down to 1402.1 m MD mainly comprises sandstone and limestone, the middle part comprises siltstones and sandstones and the lower part from 1709.9 m to the base of the Bajocian sequence mainly comprising siltstone with minor sandstone. The Bajocian strata are underlain by the Aalenian strata which comprises dominantly siltstone with minor sandstone. A few sidewall cores were taken from the Early Bajocian to Toarcian sequence with most of the sandstone described as fine grained and some were noted as poorly cemented.

11.1.5 Top Bathonian strata, Oxford Clay and Kimmeridge Clay formations

A Bathonian sandstone is penetrated by well IR 50/10-01 at 1231.7 - 1279.6 m MD. It is described as fine to medium grained with calcareous cement and no visible porosity. Thin claystone and sandy limestone beds are present. The Bathonian sandstone is underlain by Bathonian claystone and overlain by Bathonian limestone (which comprises oolitic/peloidal limestone and contains claystone layers) from 1180 – 1231.7 m MD which is in turn unconformably overlain by the Oxford Clay Formation (which comprises over 80 m (MD) of sandstone, claystone with occasional dolomitic limestone overlain by around 60 m (MD) of claystone).

Bathonian strata are penetrated by well IR 41/30-01 from 531.9 – 661.4 m MD. Sandstone layers are present. They are described as very fine to fine grained sandstones with poor to moderate porosity. This sandstone layer is underlain by Bathonian claystones and unconformably overlain by Upper Jurassic limestones, siltstones and claystones which are in turn overlain by the Lower Cretaceous Wealden Group comprising sandstones and siltstones (though cuttings were only recovered from the basal layer of the Wealden Group).

Bathonian strata comprising limestones and sandstones are penetrated by well IR 42/21-01 from 329.2 – 527.3 m MD. The sandstones are described as very fine to fine grained, well sorted and calcareous. This layer is underlain by the Dogger Formation which comprises claystone, siltstone and sandstone with minor limestone. It is unconformably overlain by the Late Jurassic strata which comprise claystone and sandstone with some lignite stringers.

In well UK 106/20-01, the Bathonian (Great Oolite Formation) comprises mudstone at 310.9 m MD.

In well UK 103/02-01, Bathonian strata lies directly underneath Quaternary sediments. The Bathonian sequence is penetrated from 238.4 – 457.2 m MD and comprises limestone and claystone with minor siltstone.

Well UK 103/01-01 penetrated Bathonian strata from 2514.3 – 2722.8 m which comprise limestone and sandstone, becoming dominantly sandy towards the base. Below this, the early-mid Bathonian strata comprise claystones and siltstones with minor sandstones and a few limestone bands near the top (down to 3042.5 m MD). The Bathonian strata are underlain by thin Bajocian sandstones (24.7 m MD thick) followed by claystones and siltstones of the Liassic shale unit. The Bathonian Strata are overlain by Middle and Upper Jurassic siltstones, claystones and carbonates with minor sandstones. On the well log, many of these claystones are noted as being calcareous, particularly in the Kimmeridgian sequence.

Cenozoic sands rest directly on Aalenian/Toarcian sediments in well UK 106/28-01, the Bathonian sequence is not recorded.

Well UK 106/24-01 penetrates strata of Lower Oxfordian to Bathonian age from 2075.7 – 2243.6 m MD which comprise shale, siltstone and sandstone. The sandstones are described as having poor porosity. Bathonian strata are recorded from 2243.6 – 2784.7 m MD which comprise shale, siltstone and sandstone with some oolitic limestone and a few oil/gas shows. The layers which contain alternating limestone and sandstone beds are penetrated from 2243.6 – 2414.9 m MD. The sandstone in the Bathonian sediments is described as fine to very fine grained. A core taken from 2406.4 – 2413.7 m mainly comprised sandstone with porosity 10 – 22% and permeability 0.8 – 2.4 mD (though the lower part of the core sample became increasingly silty and the bottom layer was shale). A core was also taken from 2287.5 – 2288.7 m MD with a porosity of 5 – 9% and a permeability of 0.5 – 1.2 mD. Five sidewall cores were also taken over the interval 2403.0 – 2745.6 with porosities ranging from 3 – 32.7 % and permeabilities ranging from 23 – 680 mD. The Oxfordian deposits above 2075.7 m MD comprise over 371 m MD of shales with minor sandstones and siltstones.

Well UK 107/21-01 penetrates strata of Callovian to Bathonian age at 920.5 – 1121.7 m MD which comprise siltstone and claystone with some tight sandstones that reach a thickness of <12 m. This is underlain by late Bathonian strata from 1121.7 – 1572.58 m (measured depth) which comprises an upper section of claystone (to 1129.9 m measured depth) and underlain by a lower section of limestone with thick clay and siltstone interbeds becoming increasingly sandy and silty. Sandstone beds are noted on the composite log from 1335.0 – 1458.2 m MD. Below 1335.6 m MD, the Bathonian comprises sandstone and claystone and the sandstones are noted to be up to 42.7 m thick in the well report. A dominantly tight sandstone layer is present between 1394.5 – 1458.2 m MD. These Bathonian strata are underlain by early Bathonian to Bajocian siltstones with some sandstone. The Callovian to Middle Oxfordian strata which overlie the Callovian to Bathonian strata from 920.5 – 548.64 comprise claystone with minor sandstone. Minor oil shows were noted in the early Oxfordian to late Callovian strata. The Bathonian strata rest directly on Bajocian sandstones, siltstones and claystones so could be considered jointly for their storage potential.

In well UK 106/24a-2B, Bathonian strata are encountered from 1602.6 – 2050.7 m MD. These comprise shale and clay with minor sandstone and massive limestones from 1737.4 – 1865.4 m (MD). The sandstone is light grey to light brown, fine grained, calcareous in part and silty to very silty. The Bathonian strata are overlain by 68 m (measured) Callovian shale and 456.6 m (measured) Oxfordian shale and clay with traces of siltstone, sandstone, limestone, dolomite and lignite. The Bathonian strata are underlain by Bajocian siltstone with minor occurrences of clay, shale and traces of limestone. Sidewall cores were taken in the Callovian and younger Upper Jurassic sequence.

Bathonian strata is also penetrated by well UK 107/16-01 at 841.2 – 1321.3 m MD. The upper part comprises mainly claystone with siltstone and minor sandstone and anhydrite. The lowest part from 1113.7 m to 1321.3 m MD comprises limestone. The Bathonian strata are underlain by Bajocian limestones and sandstones and overlain by Jurassic siltstones, sandstones and claystones. In well UK 107/16-01, the lower part of the Bathonian strata from 1113.7 m MD comprises mainly limestone with a sandstone layer around 20 m thick at the base which rests directly on sandstones and limestones of Bajocian age.