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Seismic interpretation and generation of depth surfaces for late Palaeozoic strata in the Irish Sea Region

Energy and Marine Geoscience Programme

Commissioned Report CR/16/041

BRITISH GEOLOGICAL SURVEY

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Seismic interpretation and generation of depth surfaces for late Palaeozoic strata in the Irish Sea Region

T C Pharaoh, K Kirk, M Quinn, M Sankey & A A Monaghan

Keywords

Palaeozoic; Irish Sea; Seismic interpretation; Structure.

Front cover

Saltom Bay, Cumberland. View looking north-west across the Solway Firth Basin toward the distant Southern Upland Massif. Rocks in the foreground comprise the Permian Cumbrian Coast Group (including Brockram) unconformable on the Whitehaven Sandstone (late Westphalian-?Stephanian). Photo: Tim Pharaoh

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Foreword and acknowledgements

This report is a published product of the 21st Century Exploration Roadmap (21CXRM) Palaeozoic project. This joint industry-Government-BGS project comprised a regional petroleum systems analysis of the offshore Devonian and Carboniferous in the North Sea and Irish Sea.

Project sponsors are thanked for data donations and their involvement at Technical Steering Committee meetings, both of which have contributed to this synthesis. Centrica are thanked for donation of 3D seismic data. Seismic companies (CGG, IHS Global Limited, WesternGeco-Schlumberger) are thanked for allowing reproduction of selected regional seismic lines and for agreeing to the release of a set of 5 km resolution grids. Richard Milton-Worssell of OGA is thanked for requesting seismic data. Seismic interpretations for some post-Permian interpretations in the East Irish Sea were provided by agreement from the CO_2Stored Project, for which the assistance of Michelle Bentham is gratefully acknowledged. The assistance of John Williams in loading and quality controlling well data in the workstation environment is gratefully acknowledged. DETI are thanked for allowing re-use of seismic interpretations in the North Channel area (Quinn, 2008).

Colin Tiltman (Centrica) and Christian Matthieu (OGA) are thanked for technical review of this report.

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Summary

This report describes the methodology and results of a regional seismic interpretation of the basins of the Irish Sea. It does not review the basins of the Celtic Sea. The aim of the interpretation was to map the distribution of Palaeozoic basins and highs, interpreting the key Devonian-Carboniferous surfaces and main structural elements of the area. About 40,000 km of 2D seismic reflection data have been interpreted and tied to key released wells in the project area. The seismic and well data were augmented by donated reports from sponsor companies.

A set of 8 depth structure maps of key horizons have been produced for the pre-Permian succession. These maps provide a key dataset to aid assessment of the petroleum systems of the Palaeozoic strata within the study area. The surfaces, supplied digitally at a grid spacing of 5000 m, give a regional view of the topography of the horizons, and comprise:

- ‘UVAR’ (Variscan Unconformity) beneath Permian and Triassic strata
- Base Warwickshire Group (late Westphalian - ?Stephanian)
- Top Namurian (Base Pennine Coal Measures Group)
- Top Intra-Namurian (Top Bowland Shale in south, Base Millstone Grit elsewhere)
- Top Visean (Lower Carboniferous)
- Intra-Visean (amalgamated with Top Middle Border Group in north)
- Base Carboniferous (amalgamated with Base Clyde Plateau lavas in the North Channel to South-West Arran Sub-Basin)
- ‘UCAL’ Acadian (Caledonian) Unconformity)

It is important to note that the variable data quality and sparsity of deep wells leads to a seismic interpretation which is strongly driven by regional geological models, themselves heavily dependent on inference from the onshore area. This is particularly the case with the deeper Carboniferous horizons which are not penetrated by any well and which may be only weakly reflective. In such cases, picks from better quality data may be interpolated through areas with poor quality data, as a modelled surface, to ensure a continuous surface for gridding.

The well dataset has been re-interpreted (Wakefield et al., 2016) before integration with the seismic interpretation.

The following general observations are made:

The present study has confirmed the Permian-Mesozoic structural framework for the region established by Jackson and Mulholland (1993) and Jackson et al. (1995, 1996, 1997).

- The basin recognised in Quadrant 109 by Jackson and co-workers (op. cit.) is reinterpreted as a major Carboniferous half-graben structure controlled by a syndepositional fault on its NW side. It continues beneath thin Permo-Triassic cover into the Eubonia Basin and Ogham Platform, preserving a thick Westphalian succession, including inferred Warwickshire Group strata. It is inferred to have continued eastward into the Lagman Basin prior to its tectonic dissection by a combination of Variscan inversion and Permo-Mesozoic graben development along the Keys Fault.
- A belt of Variscan fold/thrust inversion structures on the Godred Croven Platform is correlated with structures on the Formby Platform and Ribblesdale Foldbelt onshore.

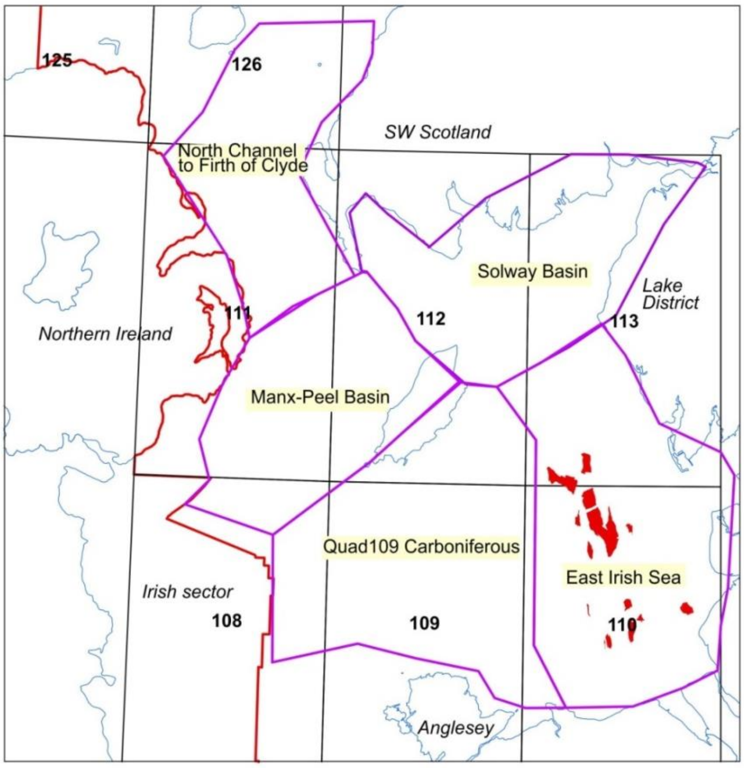
- The area of Carboniferous (undivided) subcrop depicted on mapping by BGS (1994) to north and west of the Isle of Man has been reclassified into Visean and Namurian elements.
- The presence of significant thicknesses of Carboniferous strata in the southern part of the North Channel is regarded as doubtful, but farther north, in the Larne, Rathlin and South-West Arran Sub-basins, greater thicknesses may be present.

A detailed description of tectono-stratigraphic development based on the seismic interpretation is given in Pharaoh et al. (2016b), integrated with the petroleum system analysis.

1 Introduction

1.1 BACKGROUND

The 21CXRM Palaeozoic Project aims to stimulate exploration of the Devonian and Carboniferous plays of the Central North Sea - Mid North Sea High, Moray Firth - East Orkney Basin and in the Irish Sea area. The objectives of the project include regional analysis of the plays and building of consistent digital datasets, working collaboratively with the OGA, Oil and Gas UK and industry. The project results are delivered as a series of reports and as digital datasets for each area. The East Irish Sea is a key hydrocarbon province providing a significant proportion of the UK’s gas production. Fields are Carboniferous-sourced, with a Triassic reservoir and cap rock. This report describes a regional seismic interpretation covering the Irish Sea study area (Figure 1). It does not include the Celtic Sea.



Focus of tasks
A. Regional structure, tectonics, stratigraphy with petroleum system focus including onshore links
B. Reservoir quality in Carboniferous (and Permian)
C. Source rock distribution, quality e.g. extent of Bowland Shale etc

Figure 1 Focus of tasks in the Irish Sea Study Area

The main focus of study across the Irish Sea area (Figure 1) was to undertake regional mapping of basin structure and stratigraphy, particularly of Carboniferous sequences (see also Pharaoh et al. 2016b).

1.2 RESOURCES AVAILABLE FOR THE INTERPRETATION TASK

A large amount of 2D and 3D seismic reflection data, released well information and reports, information provided by industry and published papers were used during the project (Section 2). Only a regional, reconnaissance mapping exercise was possible within the timescale of the project, using a fraction of the above seismic dataset. This, together with an agreement with the seismic data providers that a product with a grid resolution of 5000 m would be released, precluded evaluation of the Palaeozoic succession at the scale of the individual prospect. The aim of the seismic interpretation, combined with tasks examining the stratigraphy (Wakefield et al., 2016), petrophysics (Hannis, 2016), organic geochemistry (Vane, 2016) and thermal basin modelling (Gent, 2016), was to assess the regional scale petroleum systems of the Palaeozoic sequence (Pharaoh et al., 2016b). The seismic interpretation was undertaken by K. Kirk (responsible for interpretation of the HY832D dataset (ConocoPhillips) and parts of the TerraCube$^{\mathbf{REGRID}}$ 3D dataset focussed on the Morecambe fields; and T.C. Pharaoh (all remaining datasets) during the course of 200 working days in the period May to December, 2015.

The depth surfaces, described in the following sections, are key components of this assessment.

1.3 PREVIOUS BGS INTERPRETATIONS INCORPORATED

In the North Channel area, picks for the top of the Sherwood Sandstone Group, base of the Permian and base of the Carboniferous, created by M. Quinn in a previous project (Quinn, 2008), were imported into the workstation project. Picks for the Top Sherwood Sandstone, Top Permian and Base Permian, and more locally, Top Carboniferous Limestone and Intra-Namurian surfaces were imported from the DECC database, for the remainder of the region. Picks from the BGS interpretation for the NIREX repository studies, were imported with the assistance of A.G. Hulbert.

The region was the focus of a major offshore mapping programme using analog seismic data in the 1980’s and early 1990’s. The results of this work (BGS, 1994; Jackson et al., 1995) were used extensively in the present study. In the early 1990’s seismic interpretations, again using analog data, were produced on the ‘district’ and ‘regional’scales as part of the NIREX waste repository investigations, offshore Sellafield. Seismic interpretation work carried out for the ‘Isle of Man Memoir’, provided extensive information on the geology of the offshore area (Chadwick et al., 2001). An interpretation of the Larne and Portpatrick sub-basins was the subject of an unpublished report by Quinn (2008).

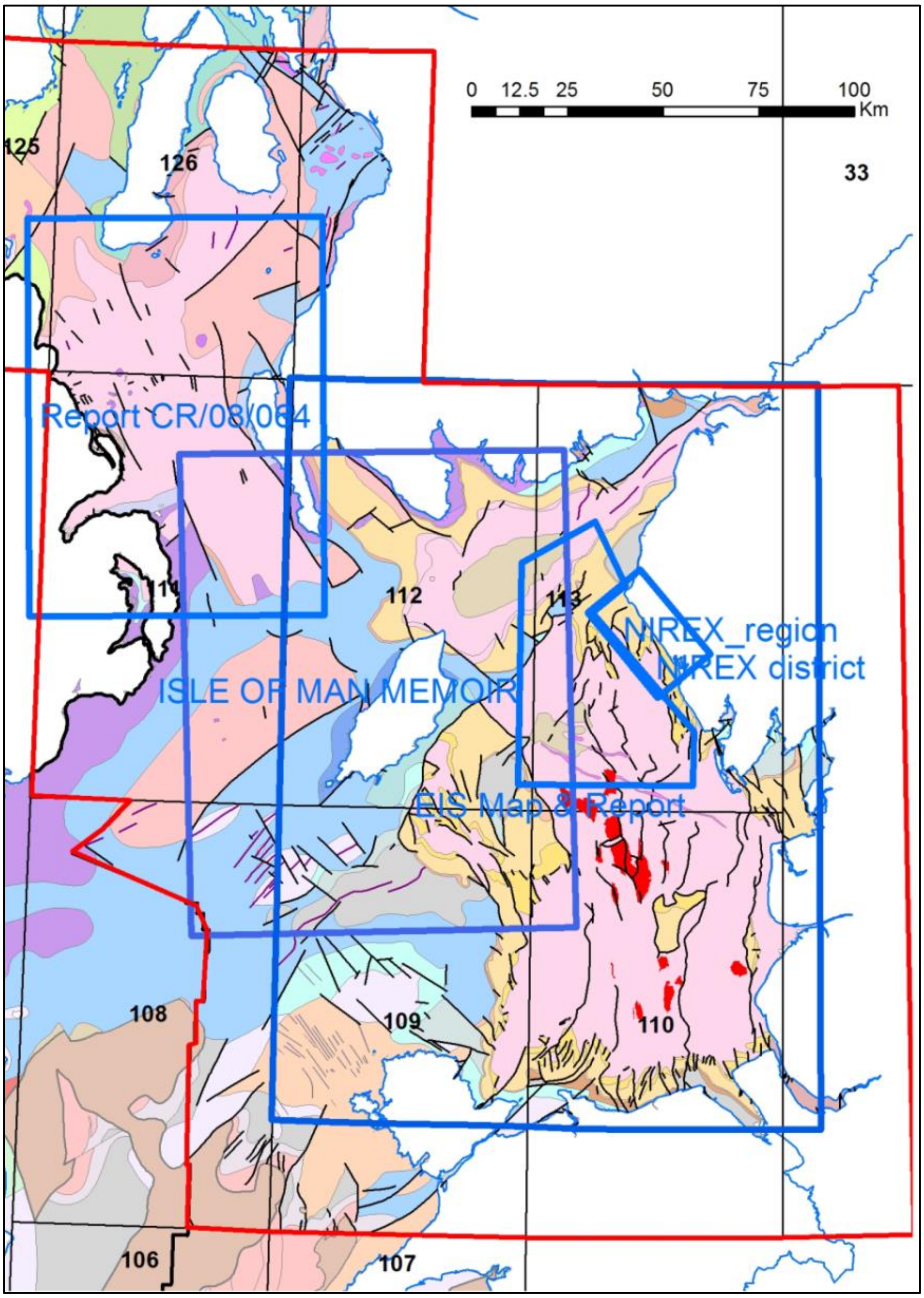


Figure 2 Geographical coverage of previous work incorporated into this report. Background bedrock geology from BGS 1:250,000 offshore DigMap BGS©NERC (Jurassic-Triassic in pink-browns, Carboniferous in grey and blue).

1.3 STRATIGRAPHICAL AND STRUCTURAL TERMINOLOGY

Previous stratigraphical terminology is summarised in Table 1, with the detail of the regional stratigraphy described in Wakefield et al., (2016). Structural terminology, after Jackson and Mulholland (1997), is summarised in Figure 3.

<table>
<tr><th>Chronostratigraphy</th><th colspan="2">Current lithostratigraphic name</th><th>Former lithostratigraphic name[1]</th></tr>
<tr><td>Upper Permian</td><td colspan="2">Cumbrian Coast Group</td><td>Cumbrian Coast Group (includes St Bees Shales & Manchester Marls)</td></tr>
<tr><td>Middle Permian</td><td colspan="2">Appleby Group</td><td>Appleby Group (includes Collyhurst Sandstone & Manchester Marls)</td></tr>
<tr><td>Stephanian</td><td colspan="2" rowspan="2">Warwickshire Group</td><td rowspan="3">Kidston Group</td></tr>
<tr><td rowspan="2">Westphalian</td></tr>
<tr><td colspan="2">Pennine Coal Measures Group</td></tr>
<tr><td rowspan="2">Namurian</td><td colspan="2">Millstone Grit Group</td><td rowspan="2">Bisat Group</td></tr>
<tr><td rowspan="2">Yoredale Group</td><td rowspan="2">Craven Group</td></tr>
<tr><td rowspan="2">Visean</td><td rowspan="3">Garwood Group</td></tr>
<tr><td>Border Group</td><td rowspan="2">Carboniferous Limestone Supergroup</td></tr>
<tr><td>Tournaisian</td><td>Inverclyde/Raven-stonedale groups</td></tr>
</table>

Table 1 Lithostratigraphical terminology used in this study compared with former nomenclature; [1] See: Jackson and Johnson (1996).

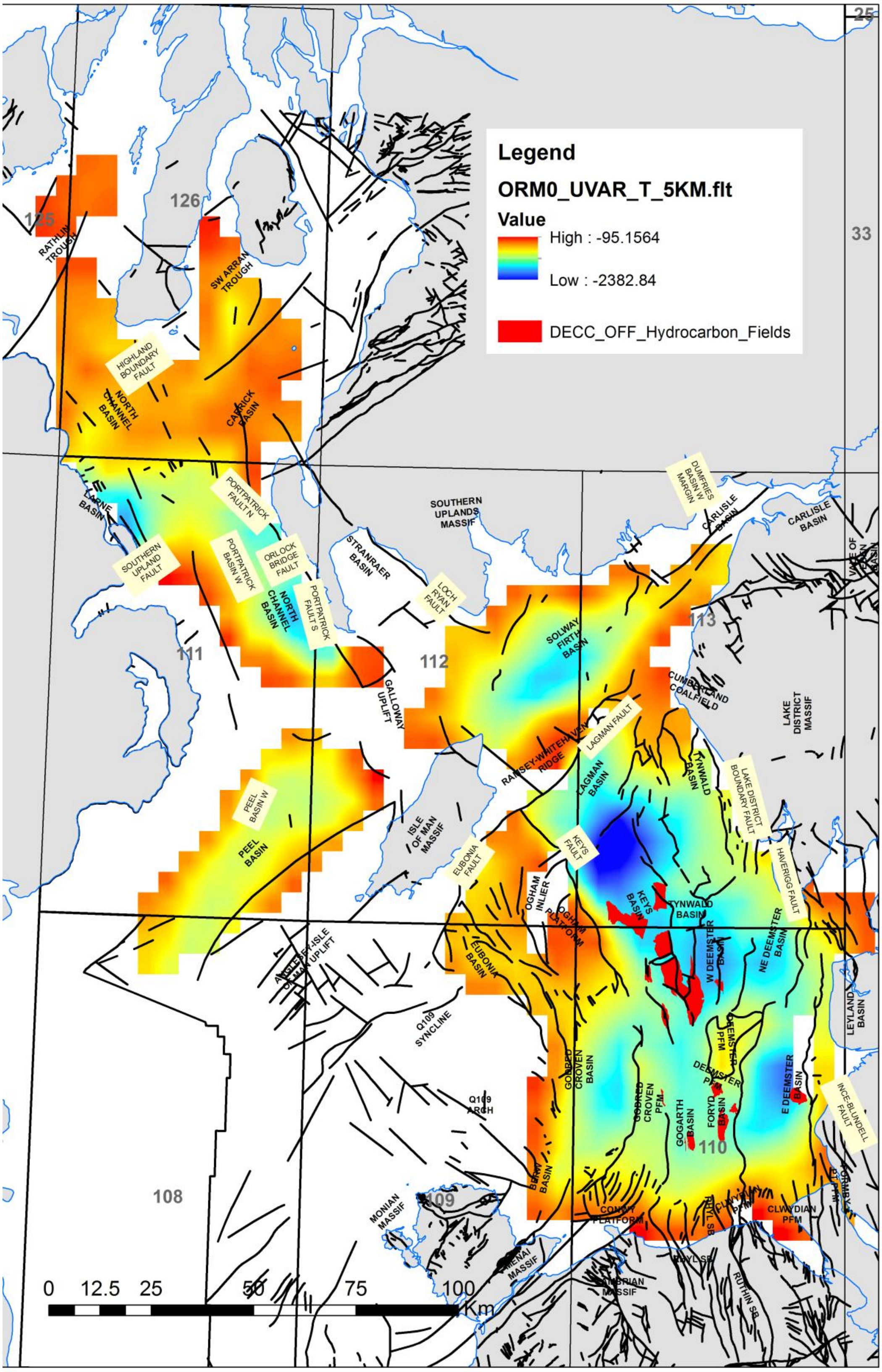


Figure 3 Structural terminology used in this report, following Jackson and Mullholland (1997). Structure map is the base Permian Unconformity TWTT in ms. DECC offshore hydrocarbon fields are in red.

2 Seismic Dataset

2.1 SELECTION OF SEISMIC SURVEYS (2D AND 3D)

The seismic dataset used in this study comprised 2D and 3D reflection seismic datasets provided to BGS under contract to DECC/OGA, covering Quadrants 108, 109, 110, 111, 112, 113, 125 and 126. Figures 4, 5 and 6 provide an indication of seismic data coverage within the region. Figure 4 shows the regional speculative 2D seismic reflection data acquired by geophysical contractors within the region, exceeding 40,000 km in total. Some of these data were provided from the DECC data store at BGS in Edinburgh; the rest were supplied following requests to the seismic contractors mediated through the good auspices of Richard Milton-Worssell at OGA. Use of these regional lines is by agreement with the geophysical contractors, specifically CGG, IHS and WesternGeco (Schlumberger), with release of interpretations agreed as 5 km resolution grids. Attention was focussed on regional lines with best resolution of the Carboniferous sequence, and approaching 30,000 km line length were examined by T. Pharaoh and K. Kirk. Figure 5 shows the proprietary 2D seismic reflection data acquired by exploration companies on their individual prospects, totalling a further 23,000 km. A limited number of these datasets were studied, totalling a further 8,000 km, mostly supplied by CDA. Finally, inshore data in the estuary areas (Figure 6) was provided by UKOGL, totalling a further 1500 km. Some 40 surveys were interpreted in the project. A full list of the seismic surveys used (in whole, or part) is presented in Table 2. Note that the regional data for Caernarfon Bay and the Celtic Sea, west and south of Anglesey, were not studied.

Since the 1990's, 3D data have also become available as key players in the basin have focussed on the production characteristics of their producing assets. 13 3D surveys obtained from CDA by the CO_2STORED project of BGS were incorporated with permission at the outset of the project. Subsequently, TerraCube REGRID data were provided by CGG GeoSpec, considerably enhancing the utility of the 3D dataset; and several processings of 3D data in the area of the Morecambe fields, by Centrica. The 3D data were used to resolve local structure. The assistance of all the companies and opganisations named above in providing data and permission for its use in the project is gratefully acknowledged.

The criteria for choice of data to interpret were principally the distance from wells with good velocity control, and seismic grid spacing and distribution, to ensure good regional coverage. Regional lines were chosen as the primary network, moving progressively to less well calibrated data at the margins of the basins. The seismic coverage in Quadrants 108, western part of 109 and 112 is sparse, and results in a reduced confidence of interpretation. It is hoped that these underexplored areas can be addressed by future government-sponsored seismic surveys.

Survey_Name	Current_Owner	Original_Owner	Year	Release_Rule
AUK90AD, 20-34	MAERSK	AMOCO	1990	PROPRIETARY
BG942-	BRITISH GAS	BRITISH GAS	1994	PROPRIETARY
CLY 87-M	MAERSK	CLYDE PETROLEUM	1987	PROPRIETARY
CLY87-	MAERSK	CLYDE PETROLEUM	1987	PROPRIETARY
DX94-	NHDA_CDA	?	1994	PROPRIETARY
E86G-	OGA_UKOGL	ENTERPRISE	1986	PROPRIETARY
E89H-	SHELL	SHELL	2005	PROPRIETARY
E92UK-	NHDA_CDA	ELF CALEDONIA LIMITED	1992	PROPRIETARY
EUK11193	NHDA_CDA	ELF CALEDONIA LIMITED	1993	PROPRIETARY
EUK11294-	NHDA_CDA	ELF CALEDONIA LIMITED	1994	PROPRIETARY
EUK95-	NHDA_CDA	ELF CALEDONIA LIMITED	1995	PROPRIETARY
GMB92-	SCHLUMBERGER	WESTERN GEOPHYSICAL	1992	SPEC
HEX-83- LINES	CGG DATA MANAGEMENT	HORIZON GEOPHYSICAL	1983	SPEC
HEX-85-	CGG DATA MANAGEMENT	HORIZON GEOPHYSICAL	1985	SPEC
HY832D-	CONOCOPHILIPS	HYDROCARBONS GREAT BRITAIN	1983	PROPRIETARY
IOM 0112/ 1994	TOTAL	ELF EXPLORATION UK PLC	1994	PROPRIETARY
JS110-86-	IHS	JEBCO	1986	SPEC
JS110-87-	IHS	JEBCO	1987	SPEC
JS-CELT90-	IHS	JEBCO	1990	SPEC
JSM-91-	IHS	JEBCO	1991	SPEC
JSM-92-	IHS	JEBCO	1992	SPEC
JS-MANX-	IHS	JEBCO	1988	SPEC
LNX85-	OGA_UKOGL	LENNOX	1985	PROPRIETARY
M90-110-	APACHE	MOBIL	1990	PROPRIETARY
M91-NC	APACHE	MOBIL	1991	PROPRIETARY
MB- (PHASE 1)	SCHLUMBERGER	WESTERN GEOPHYSICAL	?	SPEC
MB- (PHASE 2)	SCHLUMBERGER	WESTERN GEOPHYSICAL	?	SPEC
MP85WB-	SCHLUMBERGER	WESTERN GEOPHYSICAL	1985	SPEC
NC92-	IHS	JEBCO	1992	SPEC
P89/110-	PREMIER	PREMIER OIL PLC	1989	PROPRIETARY
SC87-	OGA_UKOGL	SHELL	1987	PROPRIETARY
SSL M- LINES	SCHLUMBERGER	SEISMOGRAPH SERVICE	1983	SPEC
SSL/84M- PREFIXED	SCHLUMBERGER	SEISMOGRAPH SERVICE	1984	SPEC
SW81-	OGA_UKOGL	SHELL	1981	PROPRIETARY
SW85-	OGA_UKOGL	SHELL	1985	PROPRIETARY
TW85MB-	CENTRICA	PERENCO	1985	PROPRIETARY
U038-87-	OGA_UKOGL	ULTRAMAR	1987	PROPRIETARY
WEST BRITAIN	SCHLUMBERGER	SEISMIC PROFILERS A.S.	1985	SPEC
WEST OF BRITAIN 1993	SCHLUMBERGER	WESTERN GEOPHYSICAL	1993	SPEC

Table 2 2D Seismic reflection surveys used in the project.

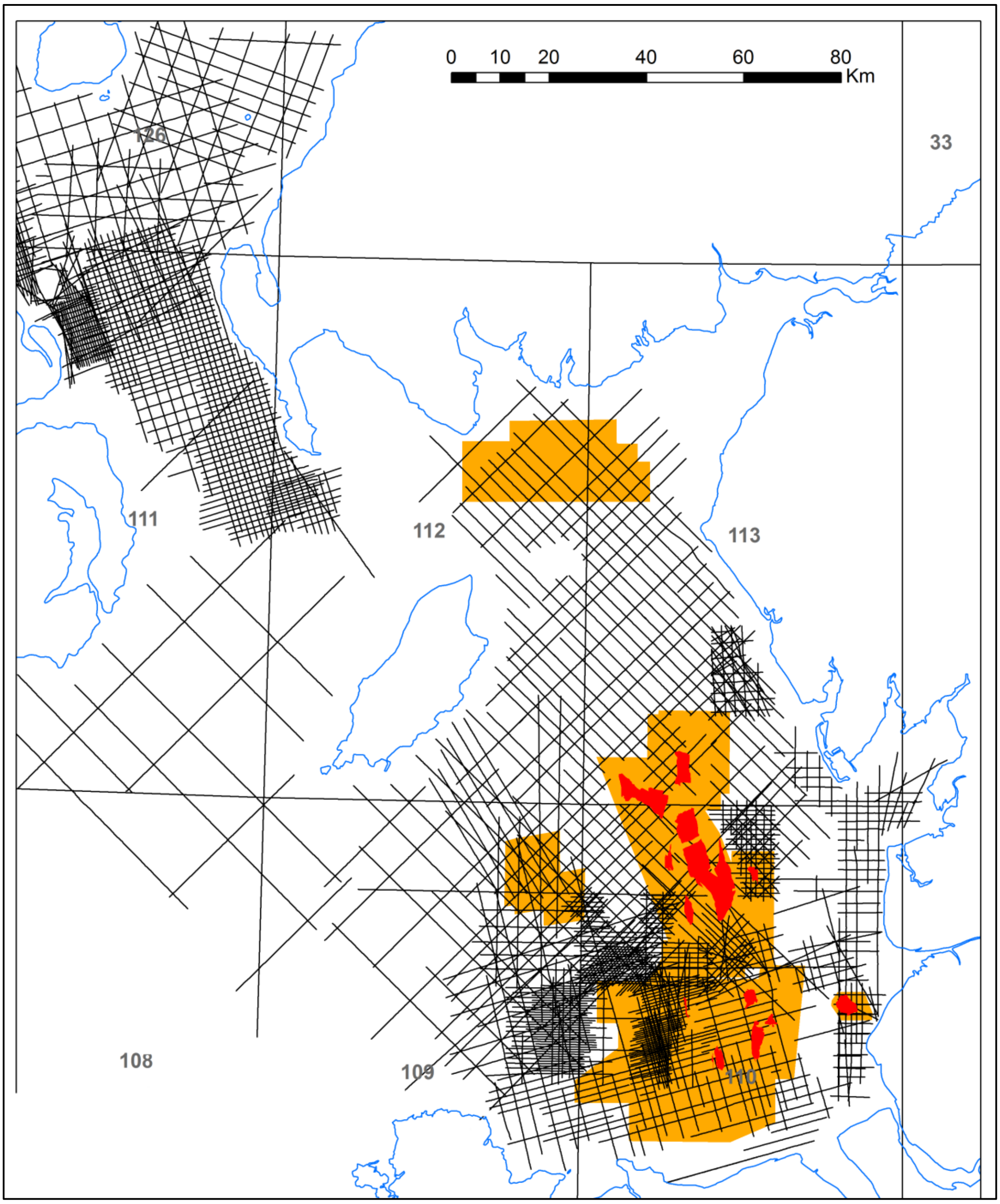


Figure 4 Regional speculative seismic data coverage from geophysical companies in the region. Black, 2D reflection seismic lines; Orange, outline of CGG GeoSpec TerraCube^{REGRID} 3D coverage; Red, DECC offshore fields

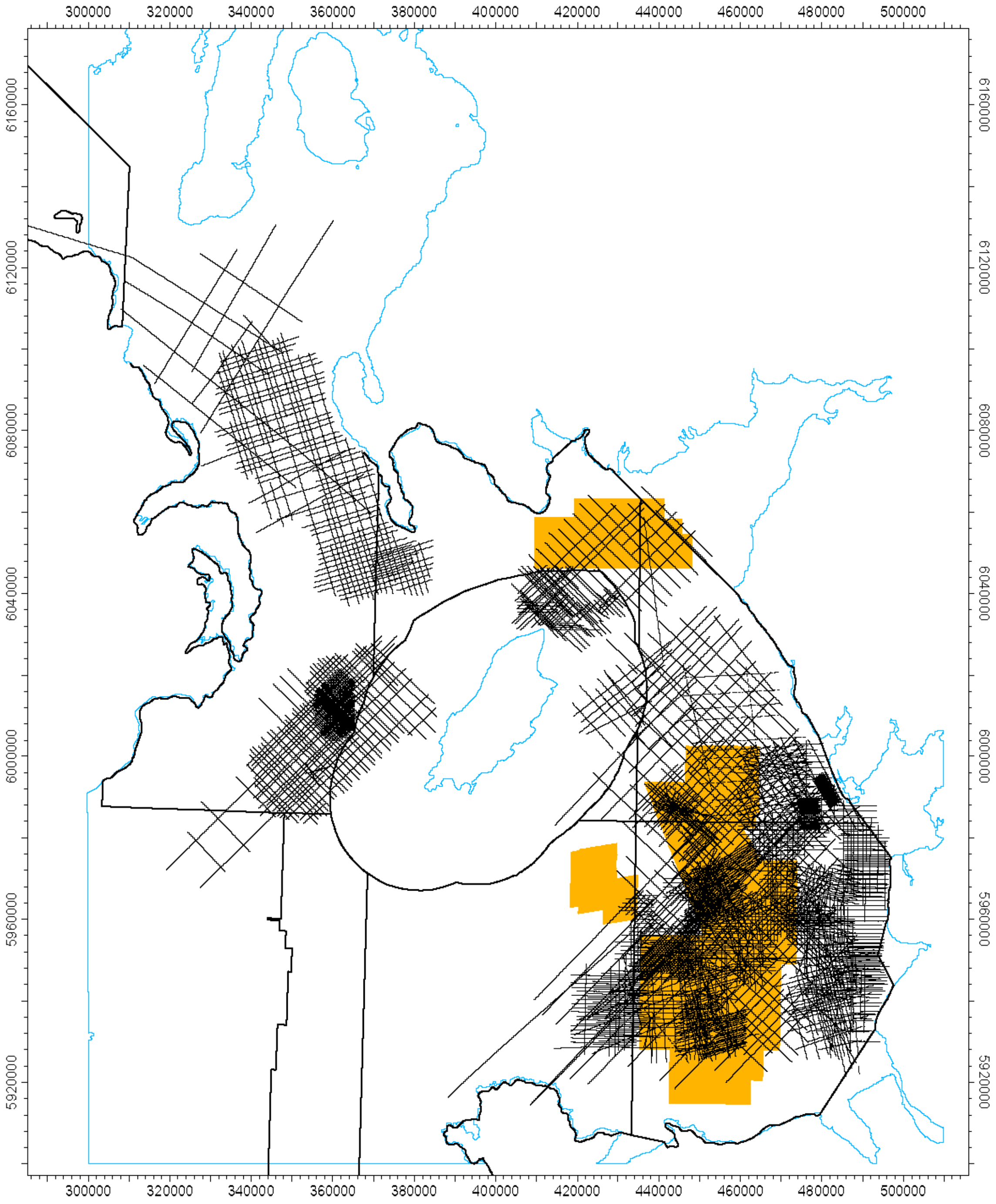


Figure 5 2D and 3D seismic coverage by exploration companies in the region, and available from CDA. Black, 2D reflection seismic lines; Orange, outline of CGG GeoSpec TerraCube^{REGRID} 3D coverage.

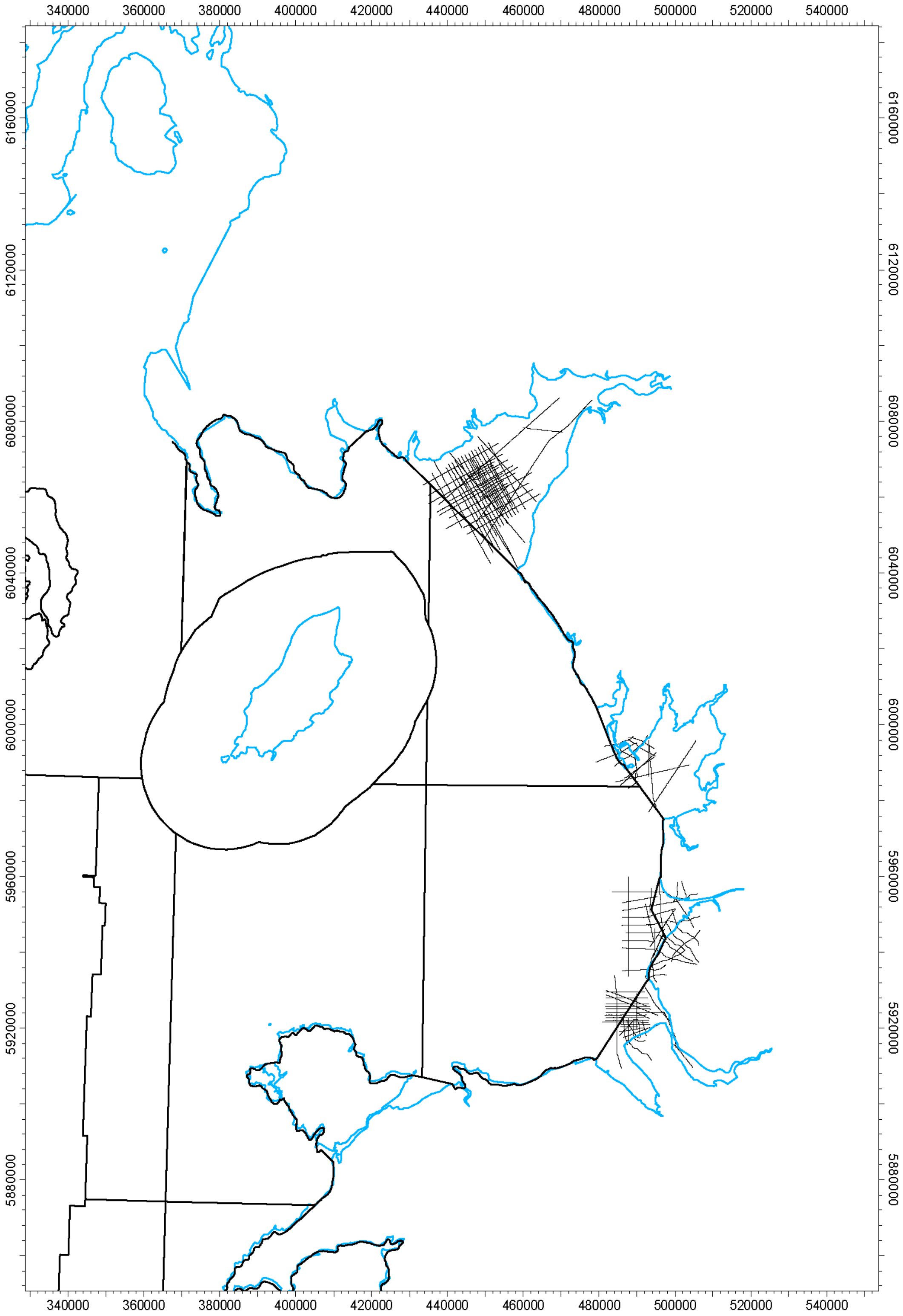


Figure 6 2D reflection seismic lines for the nearshore/estuary areas supplied to the project by UKOGL

3 Seismic Interpretation

3.1 SELECTED SEISMIC EVENTS

Choice of interpreted seismic events was based on the following key factors:

- High reflectivity and acoustic impedence events were mapped in preference, in order to obtain the most confident mapping over large areas. These were in fact relatively few in number, principally the Intra-Visean high amplitude event.
- Seismo-stratigraphic sequence boundaries inferred from regional knowledge of geophysical properties, e.g. the sharp contact of the moderately reflective Millstone Grit upon the poorly reflective Bowland Shale Group (Intra-Namurian pick) and the more transitional boundary of the Millstone Grit to the high amplitude/high frequency reflectivity associated with the Pennine Coal Measures.
- Structural discordance, e.g. at the Variscan (sub-Permo/Triassic) Unconformity and locally, at the base of the Warwickshire Group.
- The importance of events as part of the functioning petroleum system, e.g. seals in the Cumbrian Coast Group.

The following TWTT events were interpreted and gridded in the Petrel® (Registered Mark of Schlumberger) workstation environment:

1. RM80 UCAL (Caledonian-Acadian Unconformity)
2. RM70 Base Carboniferous
3. RM50 Top Middle Border Group (Intra-Visean)
4. RM48 Intra-Visean (Top Carboniferous Limestone)
5. RM40 Top Visean (Top Brigantian)
6. RM20 Top Intra-Namurian
7. RM15 Top Namurian
8. RM10 Base Warwickshire Group
9. RM0 UVAR (Variscan Unconformity)
10. Key overlying surfaces, identified in Figure 7.

Very limited picks for the seismic events listed at 4, 6, 9 and 10, were compiled from the following existing interpretations within BGS:

- BGS-DECC-OGA OGMRP contract
- Quinn (2008) on the North Channel Basin
- Projects for the NIREX (Sellafield) District and Region

It is important to note that the variable data quality and sparsity of deep wells leads to a seismic interpretation which is strongly driven by regional geological models, themselves heavily dependent on inference from the onshore area. This is particularly the case with the deeper Carboniferous horizons which are not penetrated by any well and which may be only weakly reflective. In such cases, picks from better quality data may be interpolated through areas with poor quality data, as a modelled surface, to ensure a continuous surface for gridding. In the diagrams which follow, the known extent of the surface beyond the area of seismic coverage is indicated by grey shading.

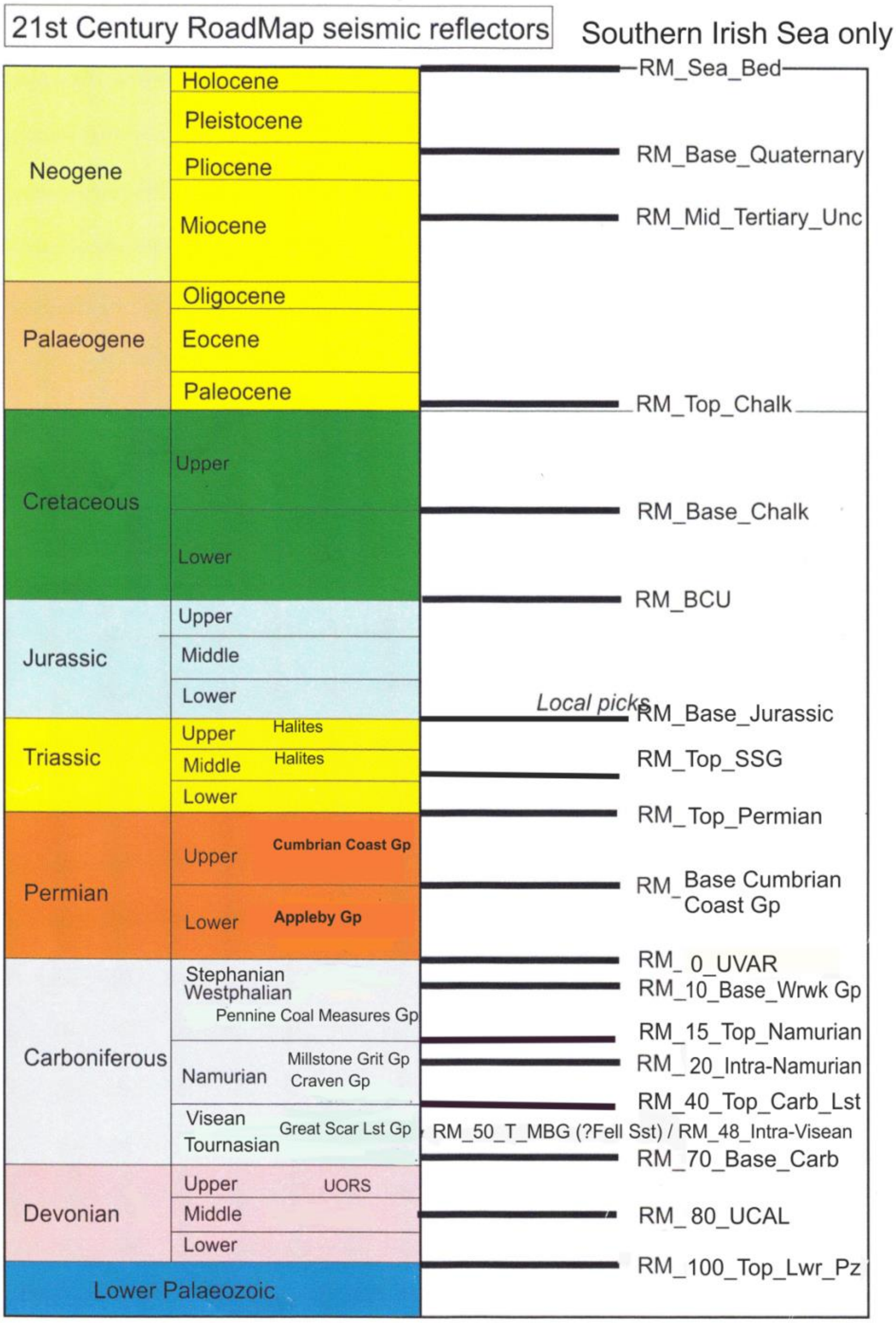


Figure 7 Seismic picks interpreted during the project. Key horizons are shown with bold black lines.

The character of the seismic reflectors picked within the Devono-Carboniferous sequence is as follows:

3.1.1 RM80 UCAL (Caledonian-Acadian Unconformity)

This is the most widespread horizon in the region (Figure 8). The mapping is subject to the caveats concerning uncertainty stated in Section 3.1, notably for this horizon, the lack of offshore well penetrations. The Acadian Unconformity truncates the structures of the Caledonian basement across the entire region, overstepping a number of Caledonian terranes from Anglesey in the south to the Highland Boundary Fault in the north (Figure 3). As a consequence, this seismic horizon is rather variable in amplitude and frequency. Usually it is not possible to see a structural discordance with the underlying metamorphic substrate. Neither is a high amplitude event usually present, for high velocity Carboniferous Limestone strata frequently overlie the metamorphic ‘basement’, with small contrasts in acoustic impedence. The typical circumstance is a gradual decrease in reflectivity of the sedimentary section, and the UCAL surface is picked at the bottom of this.

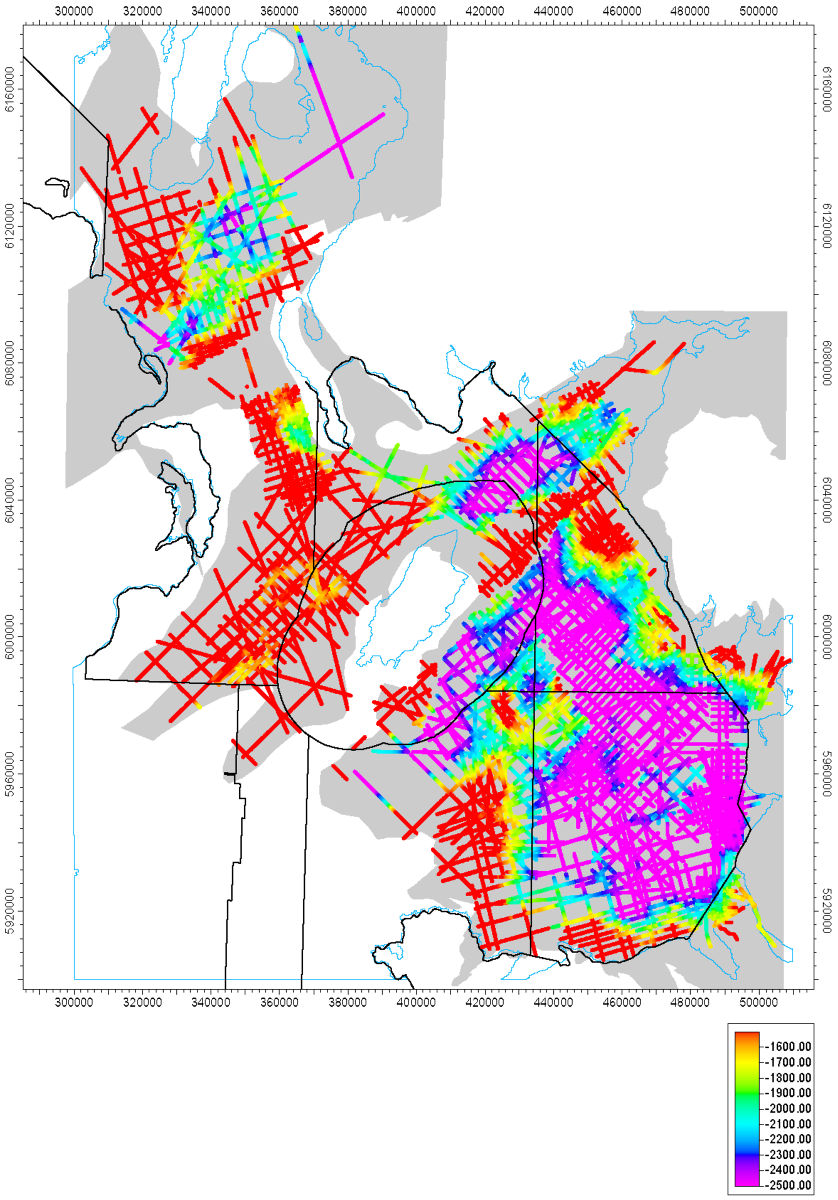


Figure 8 Extent of RM80_UCAL Acadian (Caledonian) Unconformity pick in TWTT (ms)

3.1.2 RM70 Base Carboniferous

The inferred Base of the Carboniferous is highly variable in character throughout the region and is unconstrained by wells offshore. In the south, massive Visean carbonates are inferred to overlie a more reflective sequence, which may either be possible anhydrite-bearing strata of Tournaisian age, or late Devonian strata. The latter may include the Peel Sandstone of the Isle of Man. There is no definitive borehole evidence in support of either hypothesis. In the southern part of the North Channel Basin, strata of this seismostratigraphic package are thin, and most likely of Devonian age. Farther north, the surface is marked by the base of the Clyde Plateau lavas, a highly reflective sequence, at a variable distance (0-1000 m) above the base of the Visean. Here the presence of a thick (1-2 km) package of Devonian strata is likely, thickening towards the Highland Boundary Fault.

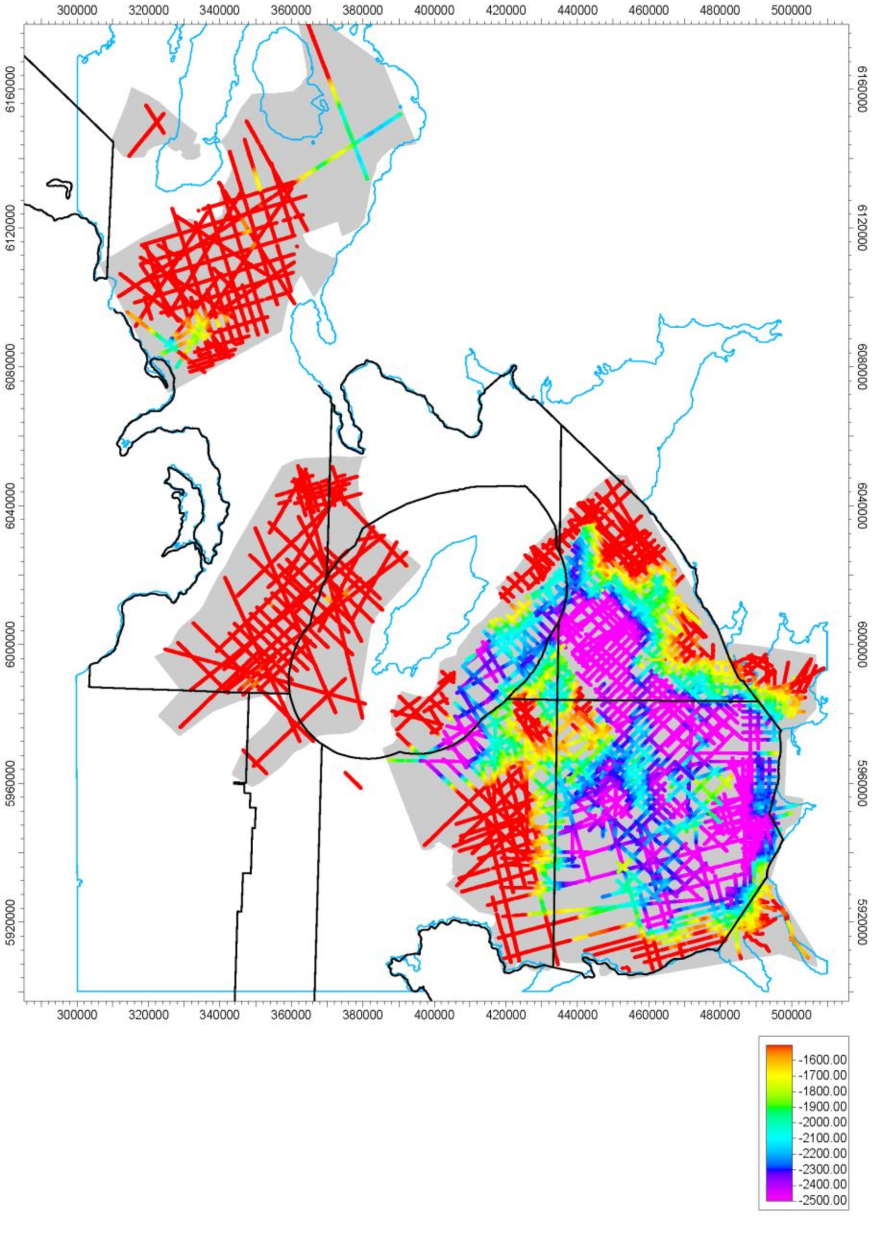


Figure 9 Extent of RM70_B_CARB Base of Carboniferous pick in TWTT (ms)

3.1.3 RM50 Top Middle Border Group

In the Solway Firth Basin (Figure 3), the most prominent pick is the top of the reflective sequence inferred to be the top of the Middle Border Group (mid Visean), although this is not confirmed by data from the limited well penetrations, which end in Yoredale facies. Possible causes of this reflectivity are the top of the Fell Sandstone, or anhydrite-rich strata of the Middle Border Group.

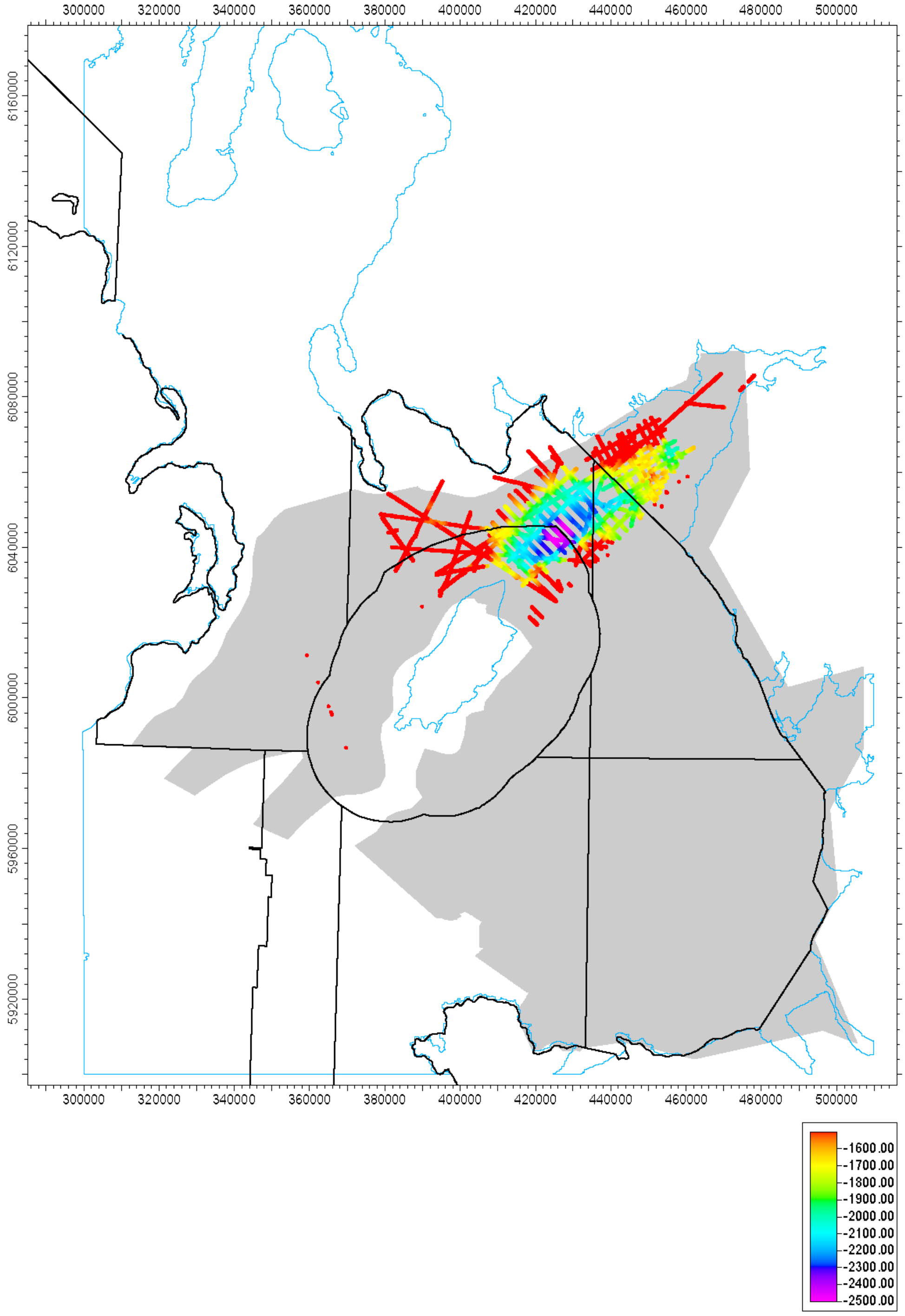


Figure 10 Extent of RM50_T_MBG Top Middle Border Group (?top Fell Sandstone) pick TWTT (ms).

3.1.4 RM48 Intra-Visean

In the East Irish Sea Basin, onset of strong reflectivity at a depth slightly greater than the Top Visean pick is inferred to correspond to the top of the massive platformal carbonates of the Carboniferous Limestone Supergroup. Throughout the southern part of the East Irish Sea Basin, the poorly reflective upper part of the Visean sequence is soon underlain by a strongly reflective, high-amplitude package (as shown in Figure 12) inferred to represent the top of the massive carbonate platform associated with the Carboniferous Limestone Supergroup. Four offshore wells constrain this pick.

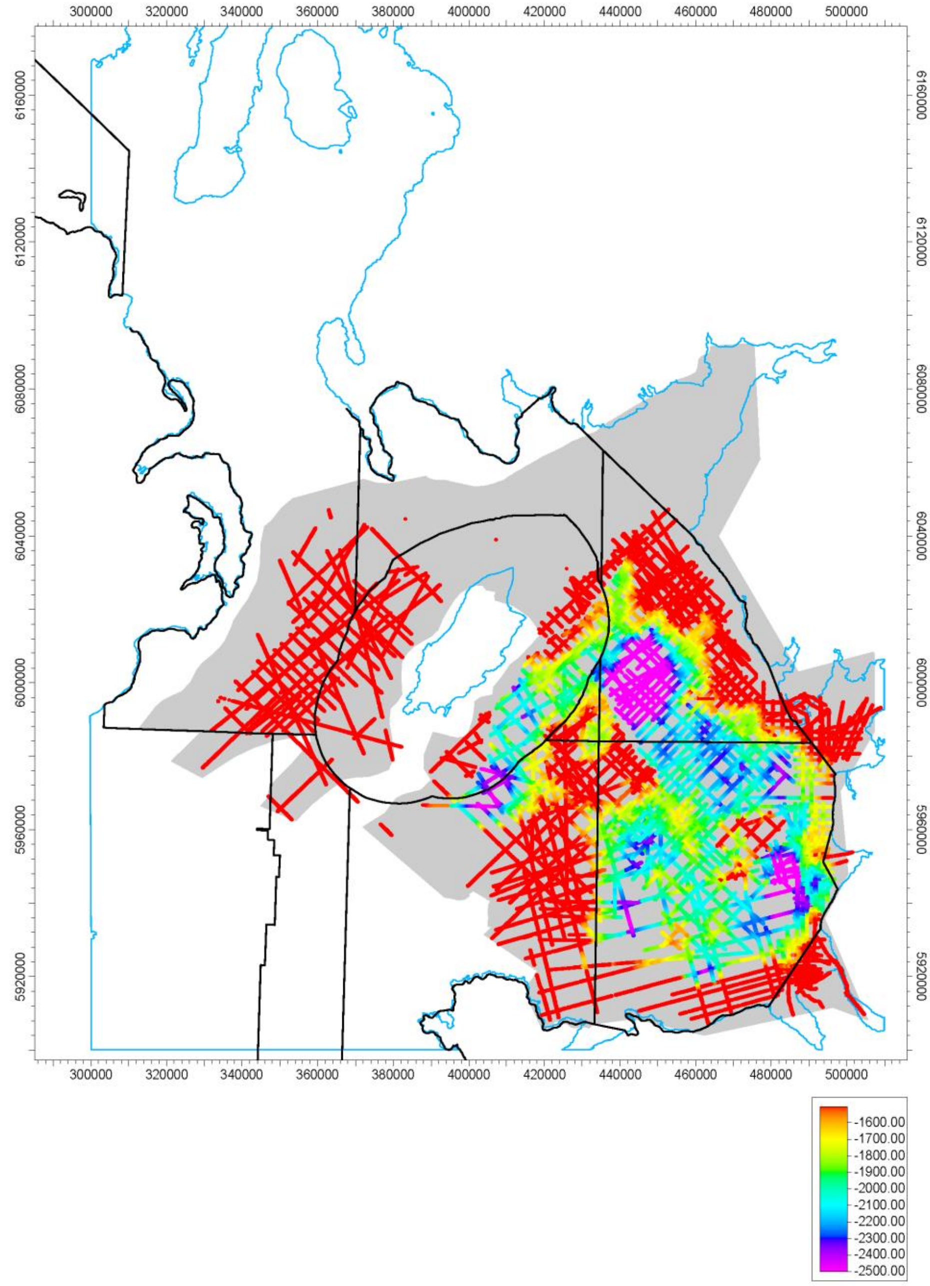


Figure 11 Extent of RM48_T_INTRA-VISEAN Top Intra-Visean pick TWTT (ms)

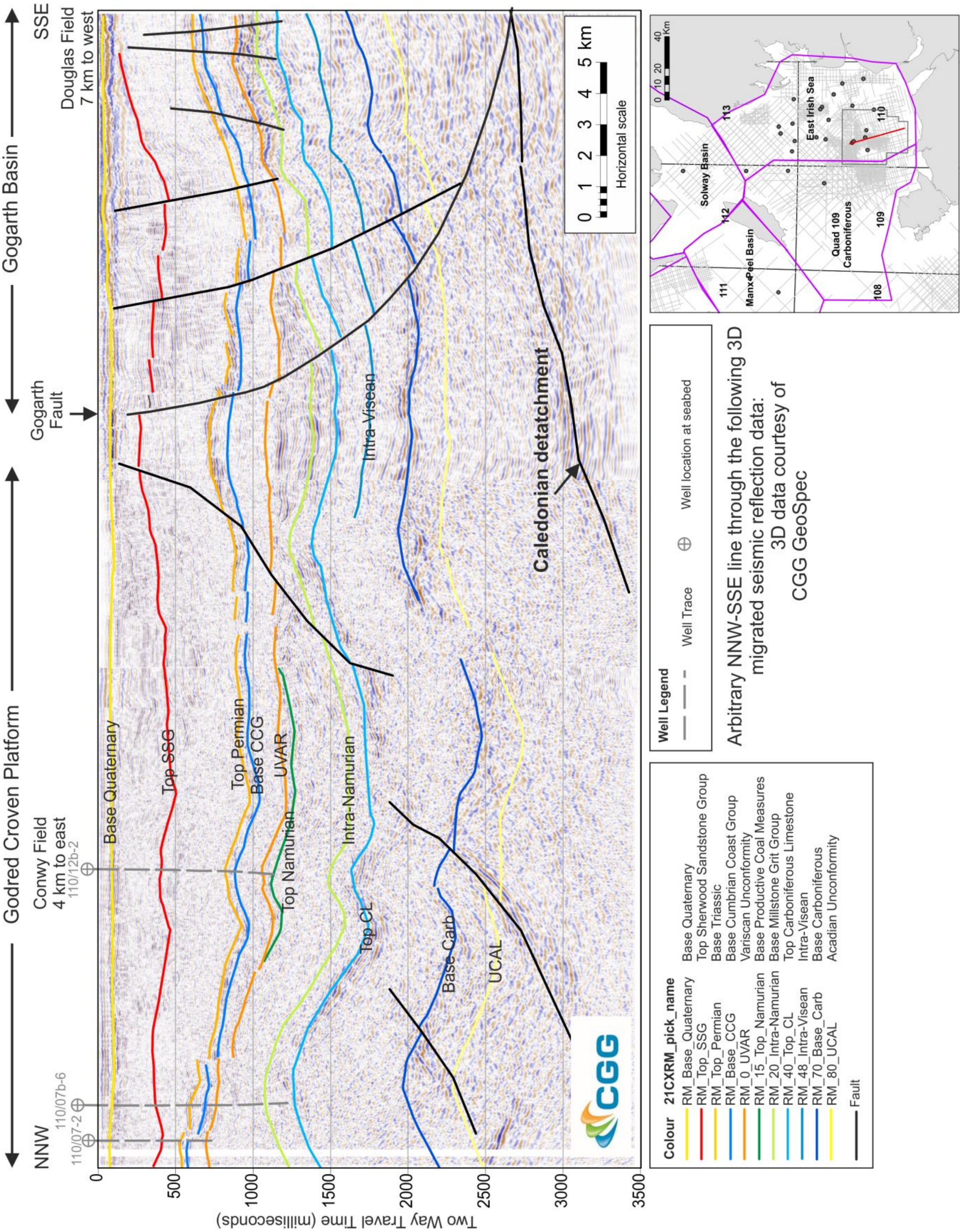


Figure 12 Arbitrary NNW-SSE line through the following 3D migrated seismic reflection data: TerraCube^{REGRID} 3D data courtesy of CGG GeoSpec. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

3.1.5 RM40 Top Visean

The quality and nature of this pick is highly variable throughout the region. In areas with thick basinal sequences of Bowland Shale Group strata, the accuracy of the Top Visean pick is unreliable except where constrained by the very limited well information (2 wells in the East Irish Sea Basin). Elsewhere, on the margins of the East Irish Sea Basin, a strong reflection from the inferred top of the Carboniferous Limestone Supergroup, lies very close to the Top Visean pick, reflecting the presence of thin or absent shales of Brigantian age.

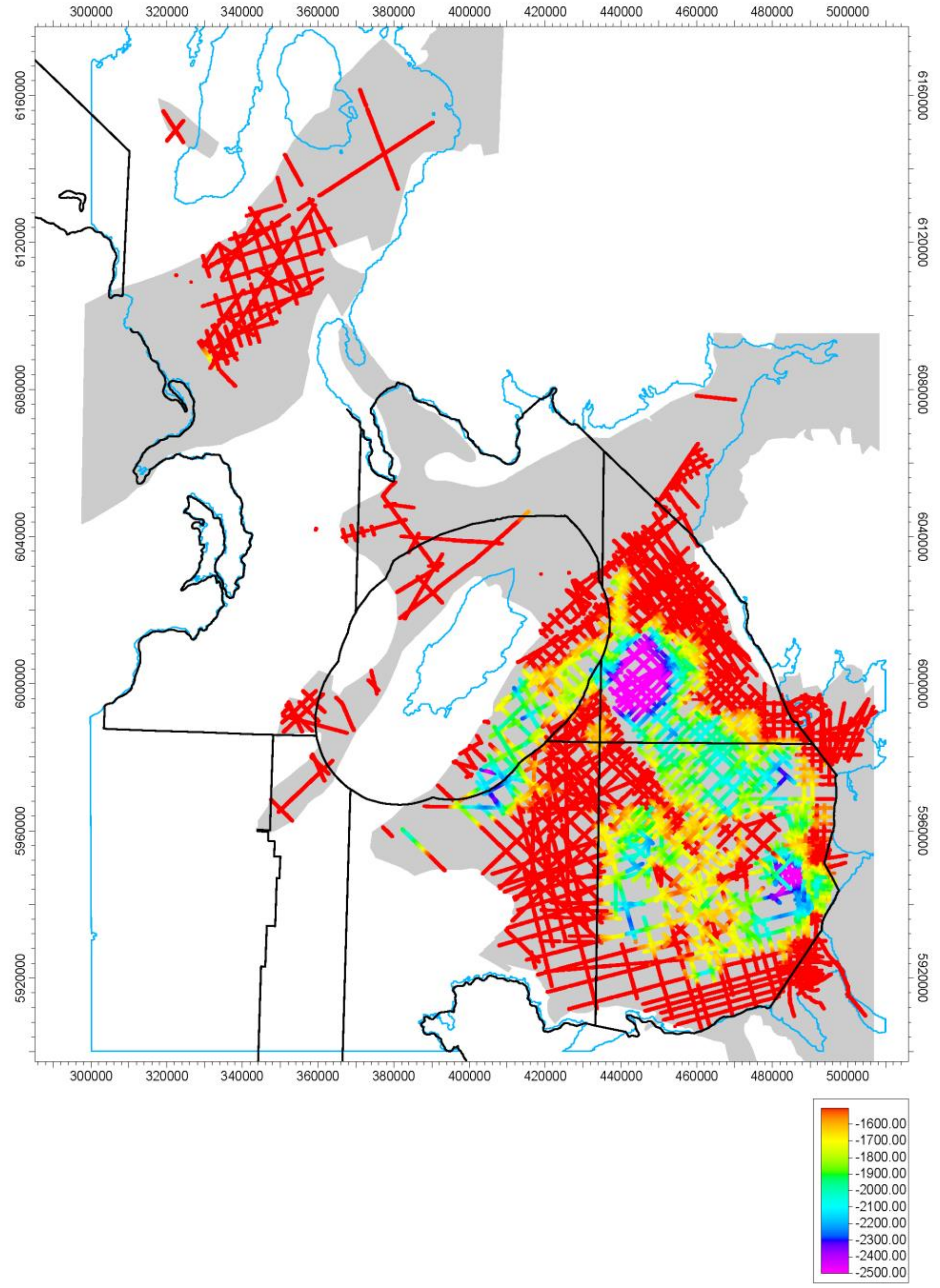


Figure 13 Extent of RM40_T_VISEAN Top Visean pick TWTT (ms)

3.1.6 RM20 Top Intra-Namurian

The contrast between the reflective Millstone Grit Group strata and the relatively transparent underlying shale-dominated sequence of the Bowland Shale Group (as shown by Figure 16) leads to a more confident pick for the Top Intra-Namurian than the Top Namurian pick (below) and Top Visean (above).

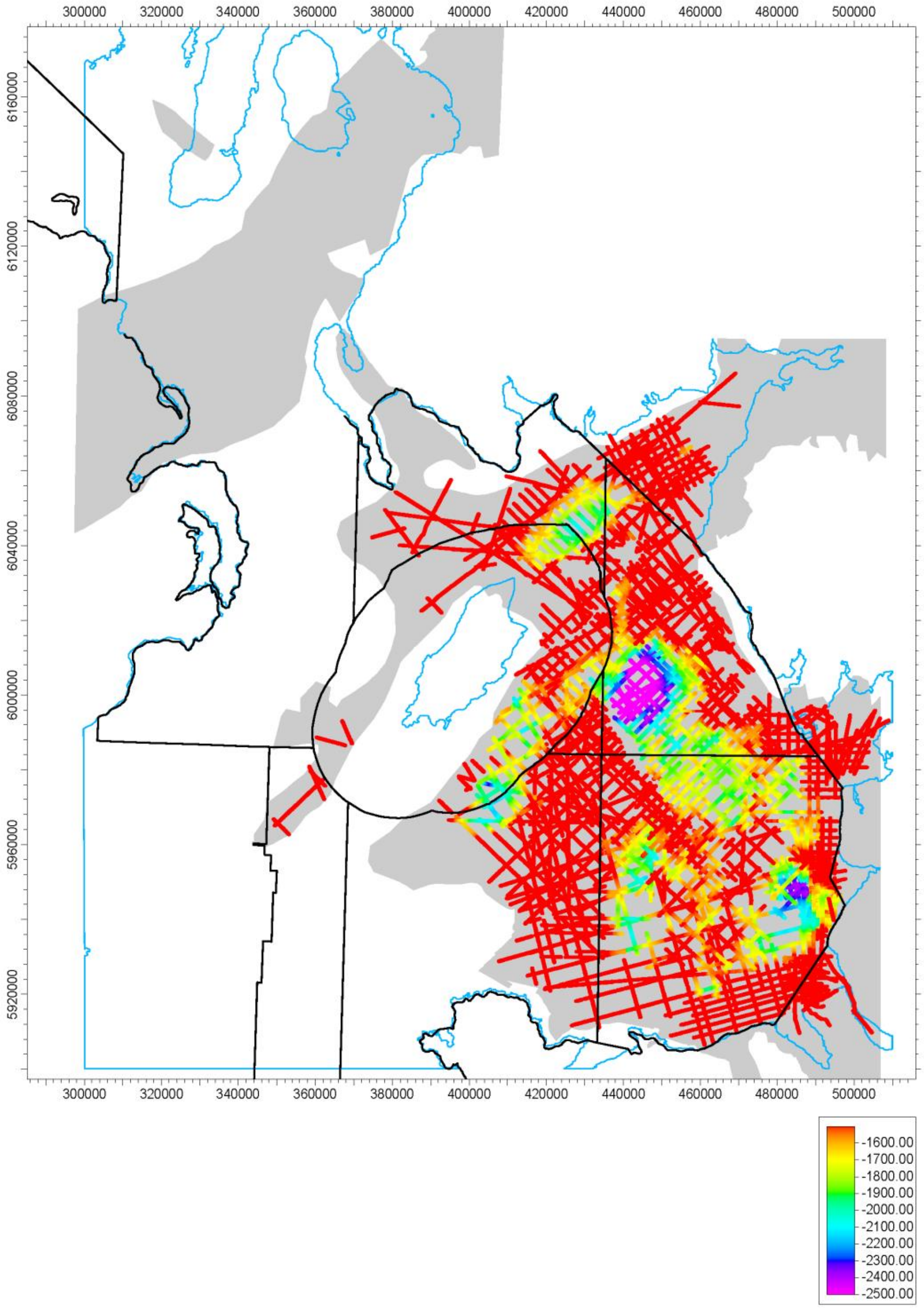


Figure 14 Extent of RM20_T_INTRA-NAM Top Intra-Namurian pick TWTT (ms)

3.1.7 RM15 Top Namurian

The boundary between Millstone Grit Group (Namurian) strata, and the overlying Pennine Coal Measures (Westphalian) is transitional in nature, marked by the incoming of thicker coals, sparse in the Namurian sequence. Both sequences are reflective, but the Westphalian strata exhibit higher frequency reflectivity due to the presence of coals (e.g, Figure 16). The appearance of this boundary is however highly variable between different vintages and processings of data, and from area to area, leading to local inconsistency of the picking unless borehole control with good biostratigraphical data is available. Twenty well ties from the East Irish Sea constrain this pick.

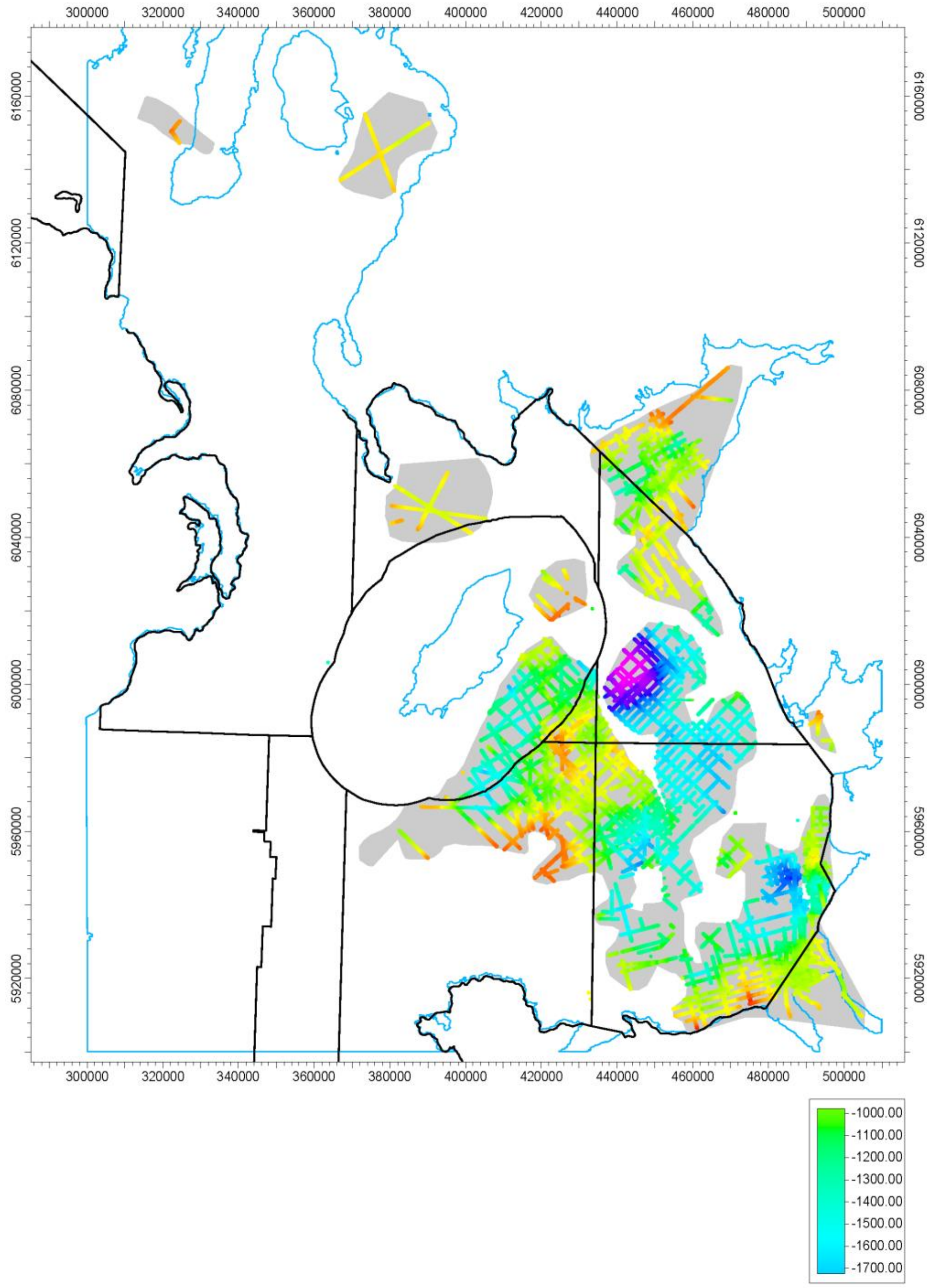


Figure 15 Extent of RM15_T_NAM Top Namurian pick TWTT (ms).

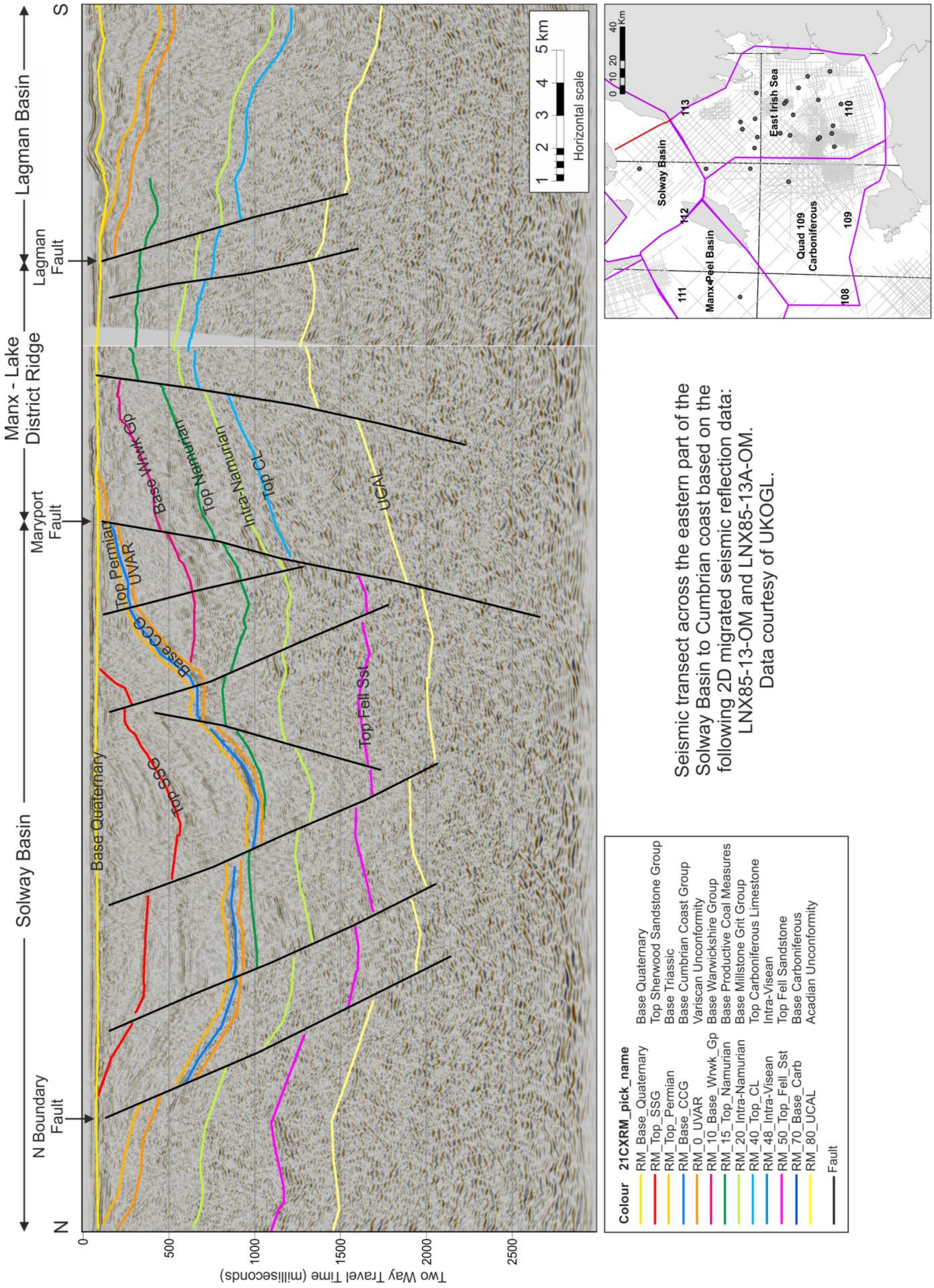


Figure 16 Seismic transect across the eastern part of the Solway Basin to Cumbrian coast based on the following 2D migrated seismic reflection data: LNX85-13-OM and LNX85-13A-OM. Data courtesy of UKOGL. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

3.1.8 RM10 Base Warwickshire Group

The 'Barren Measures' of the Warwickshire Group (late Westphalian to ?Stephanian) are fluvial-dominated clastic sequences lacking coals, are poorly reflective and generally have a more transparent aspect on seismic sections than the immediately underlying coal-rich Pennine Coal Measures (e.g. Figure 16). There may be difficulties locally distinguishing the boundary with the overlying Appleby Group (Collyhurst Sandstone), particularly where the latter is thick, although this is rarely the case outside the Main Graben of the East Irish Sea Basin. The Warwickshire Group is present in the Point of Ayr 4 well close to the North Wales coast but is not interpreted in any other offshore wells.

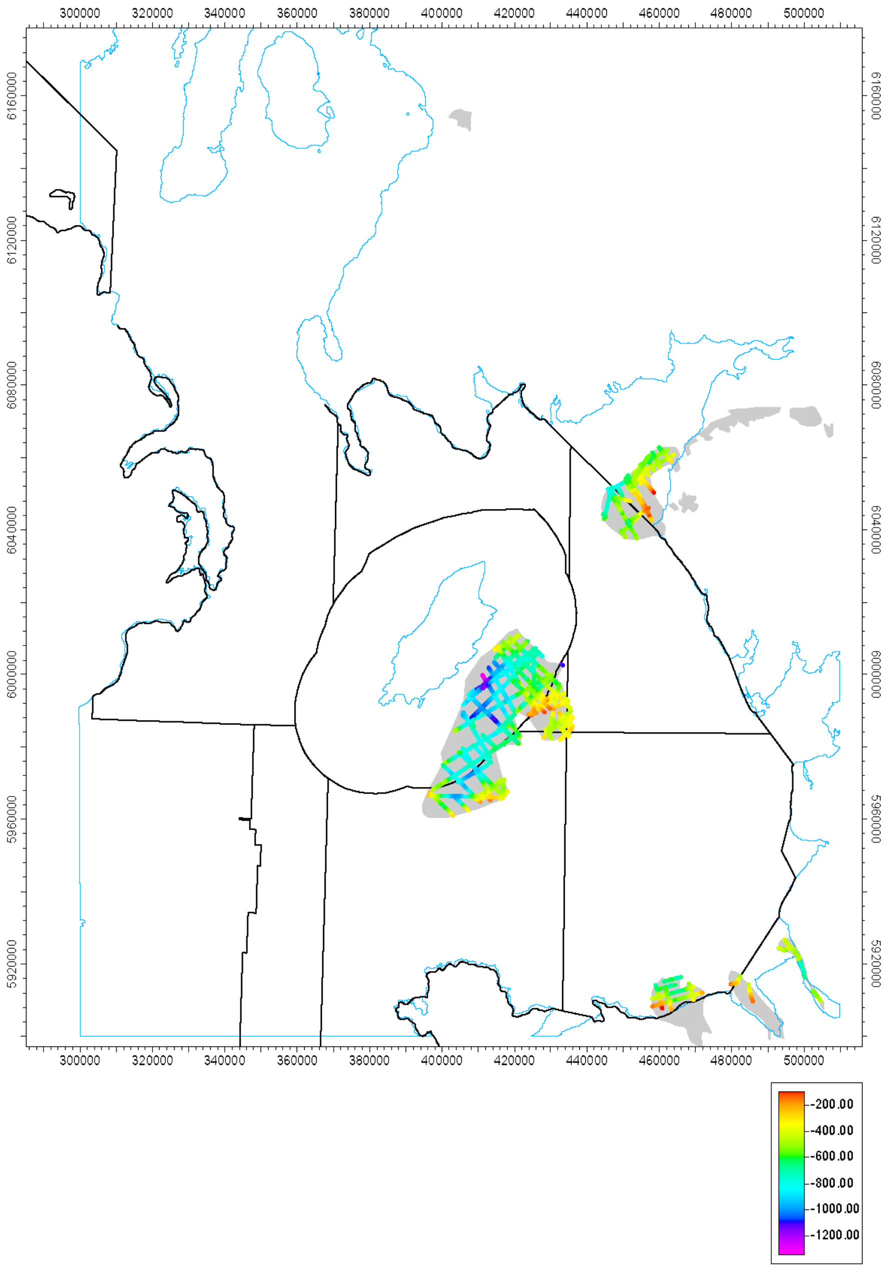


Figure 17 Extent of RM10_B_WG Base of Warwickshire Group pick TWTT (ms)

3.1.9 RM0 UVAR (Variscan Unconformity)

The unconformity at the base of Permian (locally Triassic) strata, developed upon a substrate of folded Carboniferous strata, is variably reflective, depending on the acoustic impedence contrast across the contact. Where Variscan inversion has been severe, truncation of steeper dips in the Carboniferous strata can be observed (Figure 16).

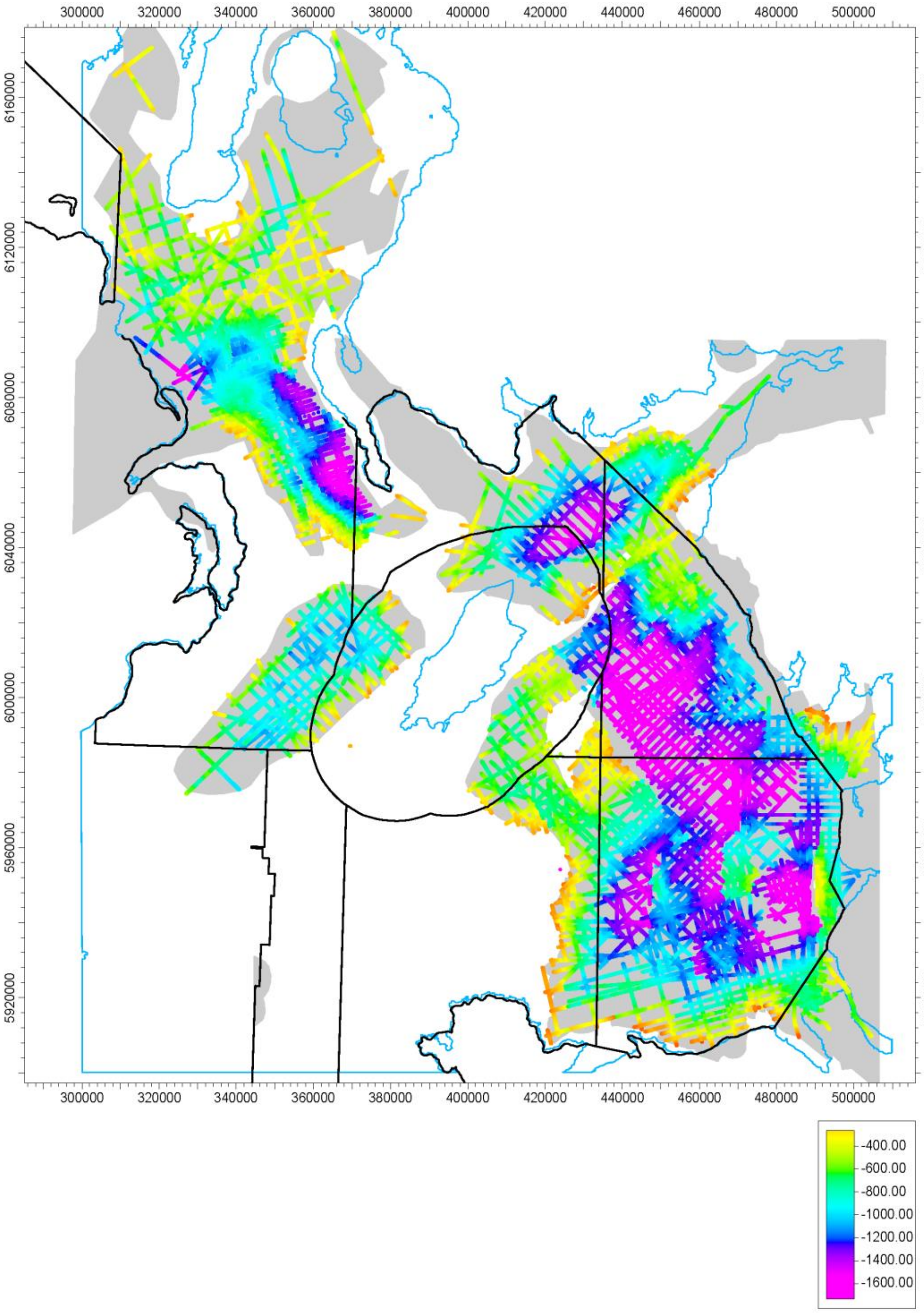


Figure 18 Extent of RM0_UVAR Variscan Unconformity pick TWTT (ms)

3.2 WELL INFORMATION

About 300 wells have been drilled in the region, but only 30 penetrate the Variscan Unconformity and enter Carboniferous or older strata (Figure 19). The well tops identified in the original well composite logs have been reviewed by Wakefield et al. (2016) and modified in the light of the seismic and stratigraphic investigations (Wakefield et al., 2016 and spreadsheet).

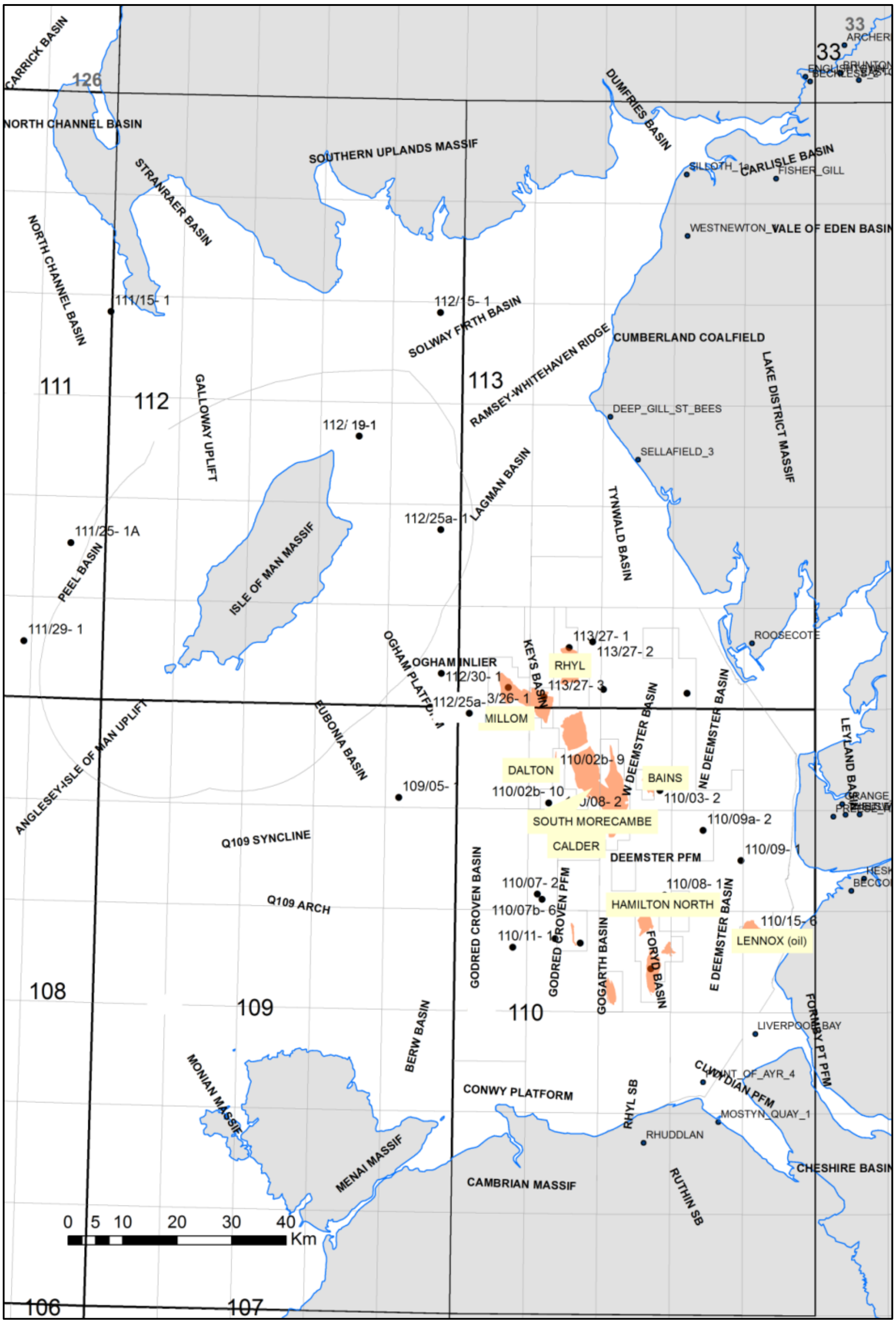


Figure 19 Key Carboniferous well penetrations (plus 111/15- 1) and DECC offshore hydrocarbon fields shown in orange.

Well	Carb_proving
109/05- 1	WN
110/02b- 10	WN
110/02b- 9	WN
110/03- 2	N
110/03b- 4	N
110/07- 2	N
110/07b- 6	N
110/08- 1	N
110/08- 2	N
110/09- 1	N
110/09a- 2	W
110/11- 1	N
110/12a- 1	N
110/12b- 2	N
110/13- 1	N
110/15- 6	ND
111/15- 1	EPz
111/25- 1A	D
111/29- 1	D
112/15- 1	ND
112/19-1	ND
112/25a- 1	ND
112/30- 1	WN
113/26- 1	WN
113/27- 1	WN
113/27- 2	ND
113/27- 3	N
113/28- 1	N
113/29- 2	N

Table 3 Wells penetrating the Variscan Unconformity and entering Carboniferous strata in the region. Key to penetrations: EPz, Early Palaeozoic; D, Visean; N, Namurian; W, Westphalian.

Further details of the Carboniferous strata penetrated can be found in Wakefield et al. (2016). Available well core porosity and permeability data have been summarised and integrated with a petrophysical analysis (Hannis, 2016).

3.3 SEISMIC CALIBRATION

Well ties have been achieved using available time-depth pairs, usually obtained from well velocity surveys, and comparison of wireline geophysical log curves with the seismic.

3.4 CHALLENGES DURING THE INTERPRETATION

Several challenges became apparent during the course of the project:

1. Limited penetration of the Palaeozoic sequence. The principal play for these basins focusses on the Ormskirk Sandstone Formation (uppermost Sherwood Sandstone Group) at comparatively shallow depths. Only 6 wells exceed 3 km in depth, and only one (110/11- 1) 4 km in depth, which is unusual for a basin with this degree of exploration maturity. It is the view of Pharaoh et al. (2016b) that the Palaeozoic sequences of the Irish Sea are significantly under-drilled and under-explored.
2. Poor seismic coverage in Quadrants 108, 109 and 112 (Figures 4 and 5).
3. Poor velocity information for strata below 2.5 km depth as a consequence of 1), impacts on reliable depth conversion.
4. Limited time to pick all horizons with the same degree of accuracy. This is particularly the case for the Top Namurian surface, which, as described above, is a very difficult pick to carry over long distances away from well control, even where the latter is of good quality.
5. Increasingly poor reflectivity with depth, and complete absence of well control, means that interpretations of deeper horizons, from Top Visean down, incorporate a greater component of modelling, and hence uncertainty, than the shallower horizons.

3.5 SEISMIC INTERPRETATION

3.5.1 Seismic interpretation of the East Irish Sea Basin

Data constraints on the seismic interpretation are described in section 3.

RM80 UCAL

The Acadian Unconformity (UCAL) underlies the entire region (Figure 8). It reflects the erosion of the various Caledonide terranes since their final juxtaposition by early Devonian time. In some places, folding and cleavage of the Lower Old Red Sandstone strata (e.g. in the Midland Valley and in Anglesey) demonstrate that this final phase of Caledonian deformation is of Emsian (middle Devonian age). In a number of places, thickening of the crust during deformation resulted in melting of the metasedimentary pile, and granites were generated, frequently penetrating to upper crustal levels. While no known examples of Devonian granites are found within the offshore basins, they are common in (and buoyantly underpin) the Caledonian massifs surrounding the basins. Examples include the Eskdale and Ennerdale plutons (Cumbrian Massif); the Criffell-Dalbeattie, Cairnsmore of Fleet and Loch Doon intrusions (Southern Uplands).

RM70 Base Carboniferous

This is a diachronous surface and of variable significance throughout the region. As it is nowhere proved by deep boreholes, and only known from limited outcrop at the margins of the East Irish Sea Basin, its nature is somewhat speculative. Throughout the East Irish Sea Basin, the poorly reflective zone beneath the Top Intra-Visean pick, here attributed to the massive Carboniferous Limestone Supergroup, is replaced by a zone of enhanced reflectivity which continues to the RM80 UCAL surface. It is possible that in some places, particularly in the north of the region (and as in Scotland) that this zone comprises Upper Old Red Sandstone strata of late Devonian age. It is also possible that anhydrite-bearing strata of Tournaisian age could be present, as in the East Midlands (Fraser et al., 1990; Pharaoh et al., 2011). The complete lack of well control means that no definitive conclusion can be reached. It is probably safest to regard the RM70 Base Carboniferous as a minimum depth surface for the Carboniferous; in places it may extend deeper, to the RM80 UCAL pick.

RM48-50 Intra-Visean

The RM48 pick (Top Carboniferous Limestone Supergroup) in the East Irish Sea Basin and Peel Basin, and the RM50 pick (Top Middle Border Group – Fell Sandstone) in the Solway Basin have been amalgamated for the depth conversion. There may be significant diachroneity associated with this pseudo-surface, as it combines the (?late Asbian) top of the inferred carbonate platform facies of the Carboniferous Limestone in the south and west with the (?mid Asbian) top of the Middle Border Group in the Solway Basin. Despite these known correlation problems, the pseudo surface nevertheless provides a useful indication of the approximate depth of the Asbian surface throughout the region.

RM40 Top Visean

The distribution of the mapped Top Visean surface is comparable to that of the overlying RM20 Top Intra-Namurian surface, from which it is separated by at most a few hundred metres, and often tens of metres or less (on highs such as the Conwy and Clwydian platforms). The surface is calibrated against the two wells entering Brigantian strata in the East Irish Sea Basin, and the well-mapped subcrop and outcrop at the periphery of the basin.

RM20 Top Intra-Namurian

Figure 14 shows that the strata of the Millstone Grit Group (and northern time-equivalents) subcrop across the entire area of the East Irish Sea Basin. The strongly diachronous nature of this surface is well-known from the onshore sequences (e.g. Wakefield et al., 2011). The map shows the distribution of the Bowland Shale Group source rock in the principal kitchen areas within the Keys, West and North-East Deemster basins, inferred to have sourced the Morecambe gas fields; kitchens within the East Deemster and Godred Croven basins are the inferred sources of oil and gas in the Hamilton, Douglas and Lennox fields in the south. In the Quadrant 109 Syncline and Eubonia Basin, kitchen areas comparable in size to the latter areas are interpreted to be preserved beneath thick late Carboniferous sequences little affected by Variscan and Cenozoic inversion.

RM15 Top Namurian

Pennine Coal Measures are patchily preserved within the Main Graben of the East Irish Sea Basin (e.g. Figure 21), a consequence of strong, multi-phase inversion during the Variscan Orogeny (Pharaoh et al., 2016b). Preservation is best in the west (Quadrant 109 Syncline, Eubonia Basin, Ogham Platform) and south (Clwydian Platform).

RM10 Base Warwickshire Group

The Warwickshire Group is restricted to the NW (Eubonia Basin), NE (Cumberland Coalfield) and southern (Rhyl Basin, Lancashire Coalfield) margins of the East Irish Sea Basin where it has survived the multiple inversion phases of Variscan and Cenozoic age which led to their erosion elsewhere.

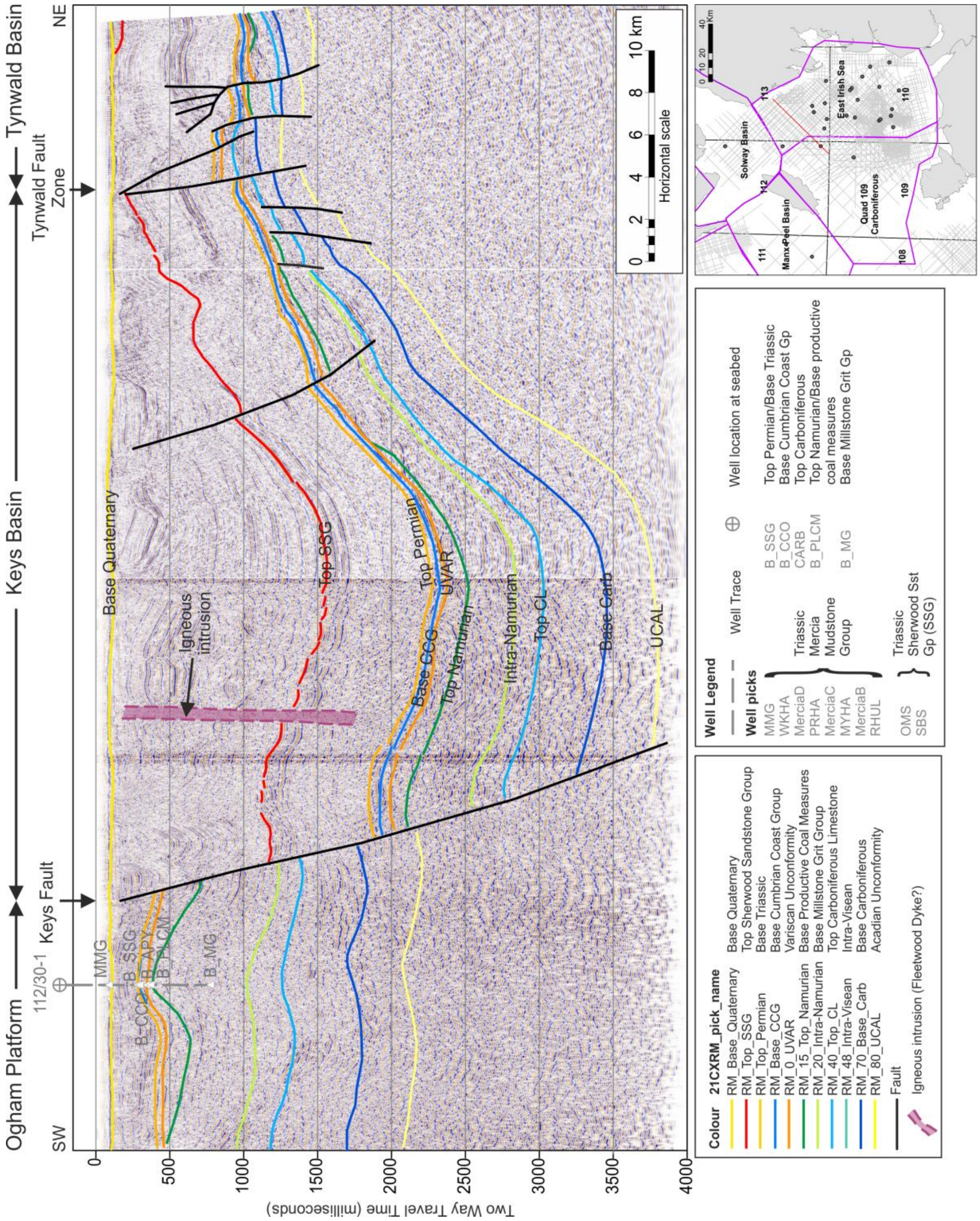


Figure 20 Migrated seismic reflection line across the Keys and Tynwald Basins: HY832-44. Data courtesy of ConocoPhillips. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

RM0 UVAR

The structure map in TWTT for UVAR (Figure 3) clearly shows the compartmentalisation of the East Irish Sea Basin into the Main Graben, with its Lagman, Keys, Tynwald, W and NE Deemster basins (northern complex) and Godred Croven, Gogarth and East Deemster basins (southern complex); and the platforms at the margins, namely the Ogham Basin and Platform, the Conwy and Clwydian platforms, the Formby Point Platform and Leyland Basin, and the Manx-Lake District (Ramsey-Whitehaven) Ridge.

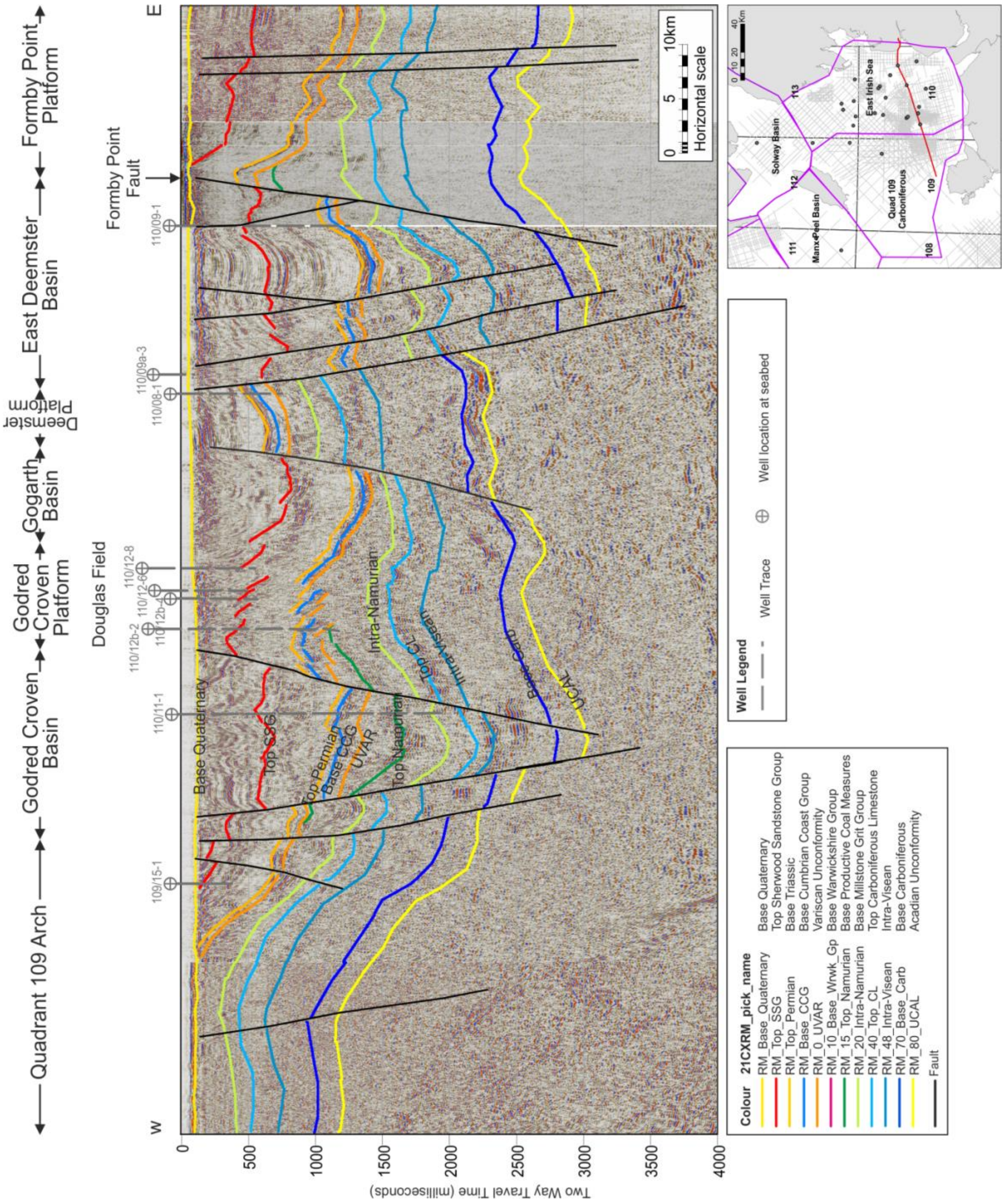


Figure 21 Seismic transect across Godred Croven Basin to the Fylde (onshore) based on the following 2D migrated seismic reflection data: JSM/91-311, GMB92-115, CLYM14-2, CLYM14-03-OM. Includes content supplied by WesternGeco (Schlumberger), UKOGL and IHS Global Limited; Copyright © IHS Global Limited, [2016]. All rights reserved. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

3.5.2 Seismic interpretation of the Solway Firth Basin

Data constraints on the seismic interpretation are described in section 3.

RM80 UCAL

As a consequence of the thick fill of Carboniferous strata in the Solway Firth Basin, and despite Variscan and Cenozoic inversion, the UCAL surface lies almost as deep as in the East Irish Sea Basin farther south.

RM50 Intra-Visean

As noted above, the RM50 pick (Top Middle Border Group – Fell Sandstone) in the Solway Basin has been amalgamated with the slightly younger RM48 pick (Top Carboniferous Limestone Supergroup) in the East Irish Sea Basin and Peel Basin, to produce an intra-Visean pseudo-surface. It corresponds to the (?mid Asbian) top of the Middle Border Group, although the actual source of the reflectivity mapped is uncertain. No equivalent of the RM70 Base Carboniferous pick of the East Irish Sea Basin was found in the Solway-Firth Basin. Rather, the strata of the Lower Border Group remain reflective until the inferred Acadian Unconformity (UCAL).

RM20 Top Intra-Namurian

Figure 35 appears to give the impression that the early Namurian source rock is absent beneath the Solway-Firth Basin. This is not necessarily the case, as this map reflects the absence of a mappable interface of early Namurian age within an inferred sequence of Northumberland Trough type. There may well be slightly older sources (Scremerston Coal equivalent) present within this basin, as well as early Namurian sequences with a seismostratigraphic character atypical of the rest of the Irish Sea basins. Two wells in this basin terminated in Yoredale Group. Farther west, the presence of early Namurian strata cross the Galloway Uplift is regarded as highly likely.

RM15 Top Namurian

Pennine Coal Measures are well preserved in the eastern part of the Solway Basin, where they were formerly mined in the Cumberland Coalfield, and patchily, along the Manx-Lake District Ridge. They thin westward and appear to be absent beneath the western part of the basin as a consequence of Variscan inversion. Their presence is also inferred on the southern edge of the Stranraer Basin.

RM0 UVAR

The structure map for UVAR (Figure 3) emphasises the rather symmetrical, sag-like nature of the Permo-Triassic Solway and Peel basins.

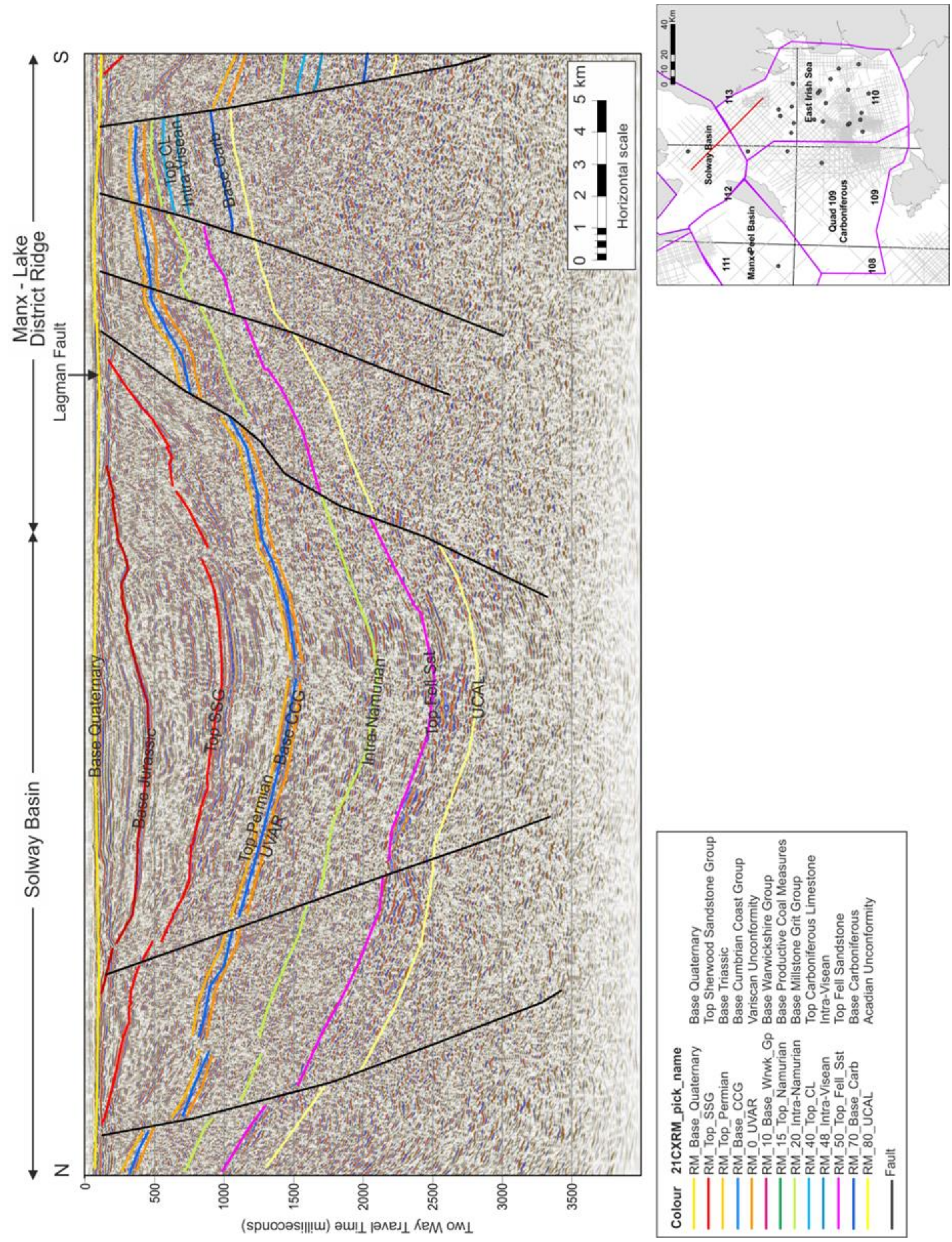


Figure 22 Seismic transect across the central part of the Solway Basin based on the following 2D migrated seismic reflection data: JSMANX-106A1. Includes content supplied by IHS Global Limited; Copyright © IHS Global Limited, [2016]. All rights reserved. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

3.5.3 Seismic interpretation of the Peel Basin

Data constraints on the seismic interpretation are described in section 3.

RM80 UCAL

In contrast to the Solway Firth Basin, the UCAL surface is at comparatively shallow level in the Peel Basin, reflecting the thin preserved Visean sequence there, and the effect of Variscan inversion.

RM70 Base Carboniferous

As in the East Irish Sea Basin, the more reflective sequence underlying the massive, poorly-reflective Carboniferous Limestone Supergroup in the Peel Basin and overlying the Acadian Unconformity is attributed to the basal Carboniferous and/or late Devonian sequence beneath the RM70 surface. The Peel Sandstone, exposed in a small N-S trending graben on the north coast of the Isle of Man, may be a component of this sequence.

RM48-50 Intra-Visean

In the Peel Basin, the RM48 pick (Top Carboniferous Limestone Supergroup) is calibrated by the two boreholes which penetrated Asbian strata beneath Brigantian. Although the interpreted carbonate platform extending from Quadrant 109 around the western coast of the Isle of Man is interpreted to continue to the Peel Basin, it is considerably reduced in thickness there, both due to low original syndepositional subsidence and significant Variscan inversion, which resulted in the erosion of almost all of the late Carboniferous strata.

RM20 Top Intra-Namurian

The presence of patches of thin early Namurian sequence is inferred to west of the Isle of Man, but these are poorly depicted by the 5 km grid presented.

3.5.4 Seismic interpretation of the North Channel Basin

Data constraints on the seismic interpretation are described in section 3, note particularly the lack of any offshore well control and the more limited number of seismic lines interpreted than in the adjacent areas.

RM80 UCAL

The UCAL surface is shown extending through the North Channel towards the Clyde basins. The only well in this area, 111/15-1, passed through the Portpatrick Fault into early Palaeozoic strata, missing any Devonian or Carboniferous strata (if any) that are present. Interpretation of the seismic indicates that characteristic Carboniferous reflectivity signatures are absent, and that if any strata are present, they are possibly thin sequences of Devonian age. In the Midland Valley, north of the Southern Upland Fault, a relatively thick (1-2 km) sequence of inferred Devonian strata overlies the unconformity, thickening towards the Highland Boundary Fault.

RM70 Base Carboniferous

In the Midland Valley segment of the North Channel Basin, north of the Southern Upland Fault, the base of the Clyde Plateau lavas can be inferred as the strongly reflective unit, close to the base of the Carboniferous, that provides a convenient seismic marker. A small area of this surface has also been mapped in the Machrahanish Sub-basin (Figure 23), part of the Rathlin Trough, to north of the Highland Boundary Fault.

RM20 Top Intra-Namurian

Early Namurian sequences are inferred to occupy significant areas of the SW Arran Trough and Carrick Basin, in continuity with the onshore succession of the Midland Valley, and extending westward into the Larne Basin.

RM15 Top Namurian

The presence of Coal Measures Group is inferred in the Carrick Basin, but as they are identified on only two seismic lines they cannot be mapped, and are therefore not shown on Figure 36.

RM0 UVAR

The structure map for UVAR (Figure 3) highlights the compound nature of the North Channel Basin, from an assymetric half-graben controlled by the Portpatrick Fault on the eastern side in the south, reversing polarity northward across the Southern Upland Fault to shift the depocentre westward into the Larne Trough. Farther north, the base Permian surface to the SW Arran Trough and Carrick Basin is interpreted as shallow and gently undulating.

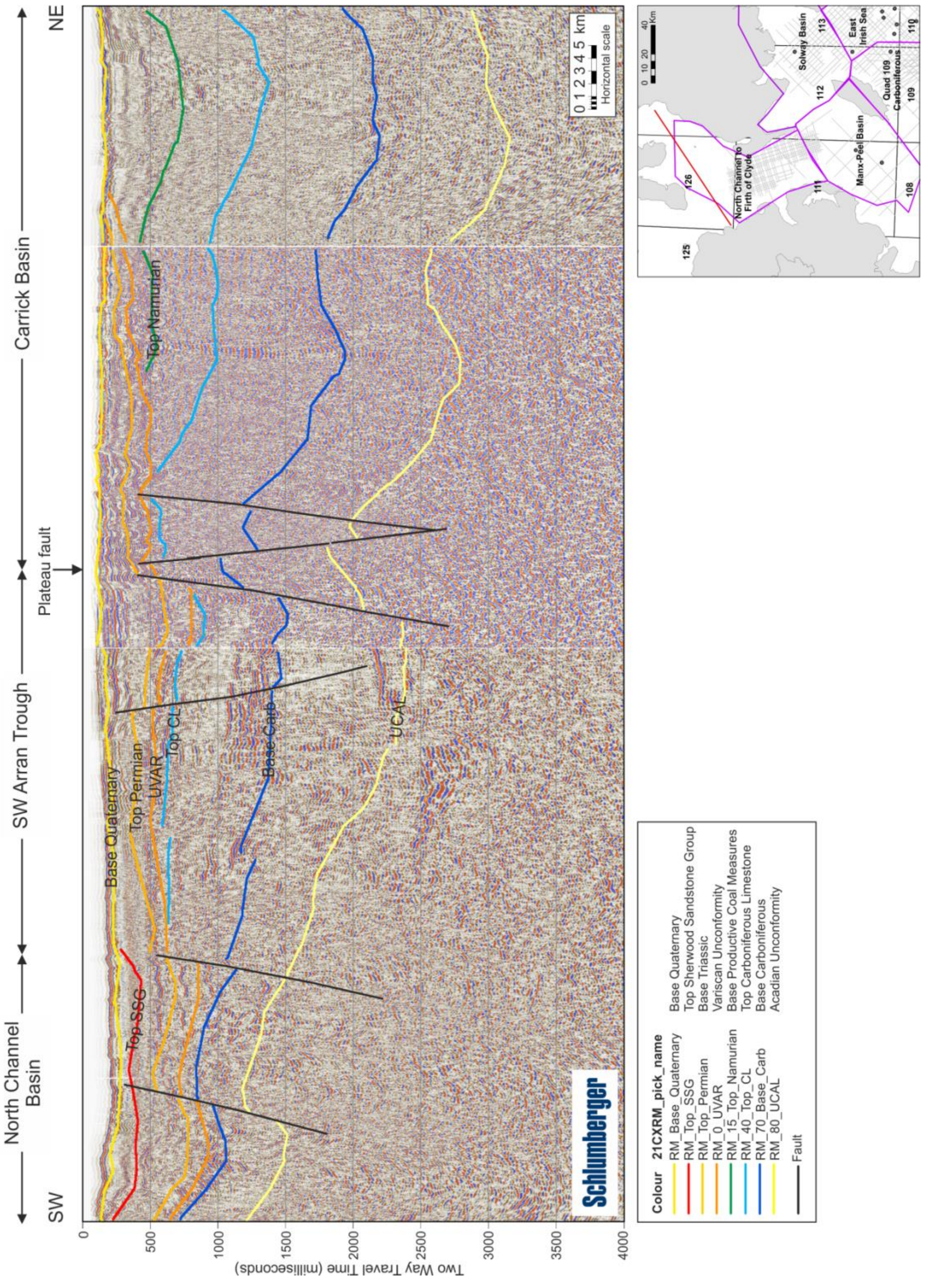


Figure 23 Seismic transect across the Firth of Clyde basins based on the following 2D migrated seismic reflection data: WB93-0101, WB93-0101B and WB93-0101A2. Data courtesy of WesternGeco (Schlumberger). Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

4 Depth conversion method and generation of depth structure maps

4.1 INTRODUCTION

Devonian and Carboniferous Time (TWTT) Surfaces were depth-converted to produce the depth structure maps presented in Section 5. The original grid spacing was 250 m and depth conversion was carried out at this resolution.

4.2 KNOWN DIFFICULTIES IN DEPTH CONVERSION

Significant problems in depth conversion are caused by:

- Local deep Quaternary erosion, both of glacial and post-glacial origin, resulting in local low-velocity anomalies.
- Local Cenozoic dyke intrusions (‘Fleetwood Dyke Complex’) (Figure 20) and their thermal effects, which result in localised high velocity anomalies. A particular case in point is the Rhyl Field which partially lies beneath the overhanging Fleetwood Dyke Complex (Centrica, pers. comm., 2015).
- Variation in content of salt and anhydrite in the overburden of Mercia Mudstone Group, causing significant velocity anomalies (Figure 24).
- Scarcity of constraining well data in all basins outside the East Irish Sea Basin, i.e. the Solway, Peel and North Channel basins, which are significantly underexplored.

4.3 METHODOLOGY

Various depth conversion procedures were tested to achieve the optimum result for a regional (as opposed to reservoir-scale) depth conversion. Assuming that the best method is one that produces the best match to wells without any further adjustment, the Average Velocity Method (Velocity Modelling, Petrel 2008) is both simple and effective. This was confirmed by comparing the UVAR TWTT surface depth converted using this method, to the depth of the well tops. Good agreement was achieved in most occurences, with the notable exception of 113/27-1 (Rhyl Field), which contains a 365 m section of basaltic dyke; and 110/15-6 (Lennox Field), where the Variscan Unconformity is faulted out by the Formby Point Fault. In the deepest part of the Keys Basin, the method gave a maximum depth for the base of the Permian as about 4800 m, which is perhaps slightly shallow (cf. Jackson et al., 1995). The accuracy of the Average Velocity Method is, furthermore, strongly dependent on the number of available well tops. As most wells in the East Irish Sea Basin are shallow, the rapidly declining number of well tops with depth (31 for the Variscan Unconformity, 19 for the Top Namurian, 4 for the Intra-Namurian and only 3 for the Top Visean) represents a significant challenge to application of the method.

Another approach is the stepwise, ‘layer-cake’ method adopted by Arsenikos et al. (2015) which works well in the Central North Sea, where a thick overburden of Cenozoic, Mesozoic and Zechstein evaporitic strata are present. However, a test in this region, for the Variscan Unconformity and deeper surfaces, produced a significantly less good agreement with the well-tops than the Average Velocity Method. The description and graphs relating to the 'layer-cake' method are shown below for completeness.

The 'layer-cake' method involves analysis of the velocity characteristics of individual formations, in particular the plot of TWTT versus Interval Velocity (Vint). Checkshot data for a subset of the wells was selected and analysed. The subset of 25 wells are those which penetrate Carboniferous strata beneath the Permo-Triassic section. A small number (<1%) of anomalous values were rejected. An initial bivariate plot of Vint v TWTT proved to be a useful filter. Bivariate plots of these parameters in the Mercia Mudstone Group (Figure 24) and the Permian (Figure 25) provided regressions with low significance. In both cases, the data have a wide spread, as a consequence of the variety of varied rock types (anhydrite, salt etc) besides shale, and the trend towards higher interval velocities with depth is actually clearer than the least-square regressions would appear to suggest if taken at face value. As a result, velocity data from these particular units are too variable to be used in the depth conversion process, and will not be considered further.

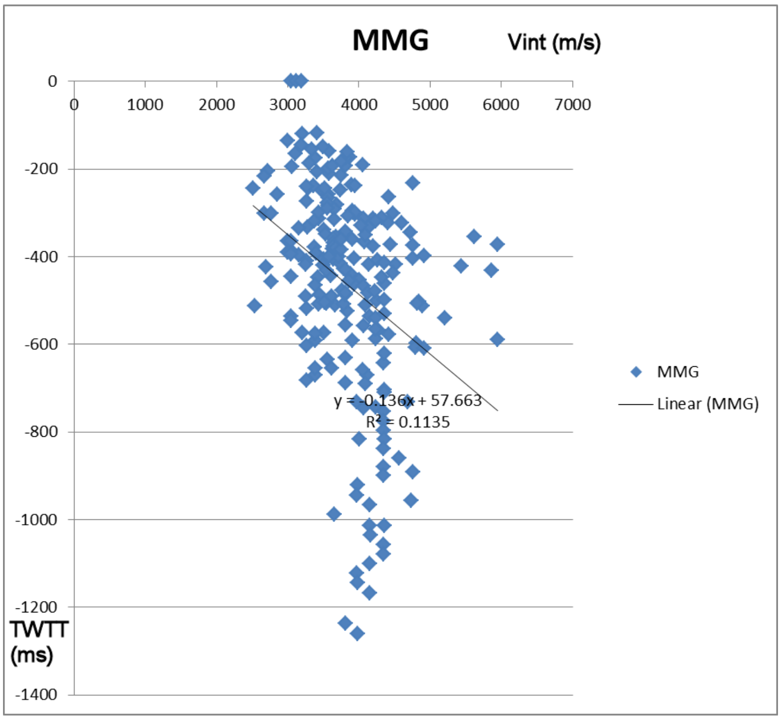


Figure 24 TWTT-Vint plot for the Mercia Mudstone Group for checkshot data in selected wells

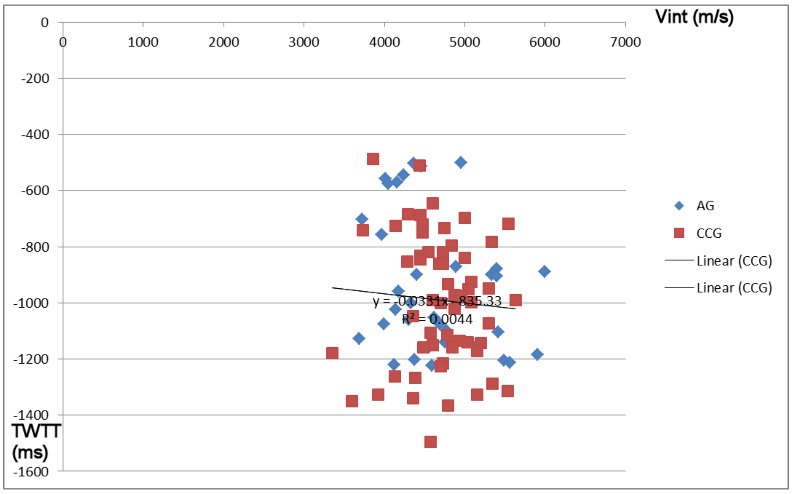


Figure 25 TWTT-Vint plot for checkshot data for the Permian strata in selected wells. Key: AG, Appleby Group; CCG, Cumbrian Coast Group.

By contrast, a plot of these parameters in the Sherwood Sandstone Group, yielded a regression with a high significance ($R^2 > 0.635$). It was also discovered that Namurian and Westphalian clastic sequences in the marginal areas of the East Irish Sea Basin, lay on the Sherwood Sandstone Group trend (Figure 26).

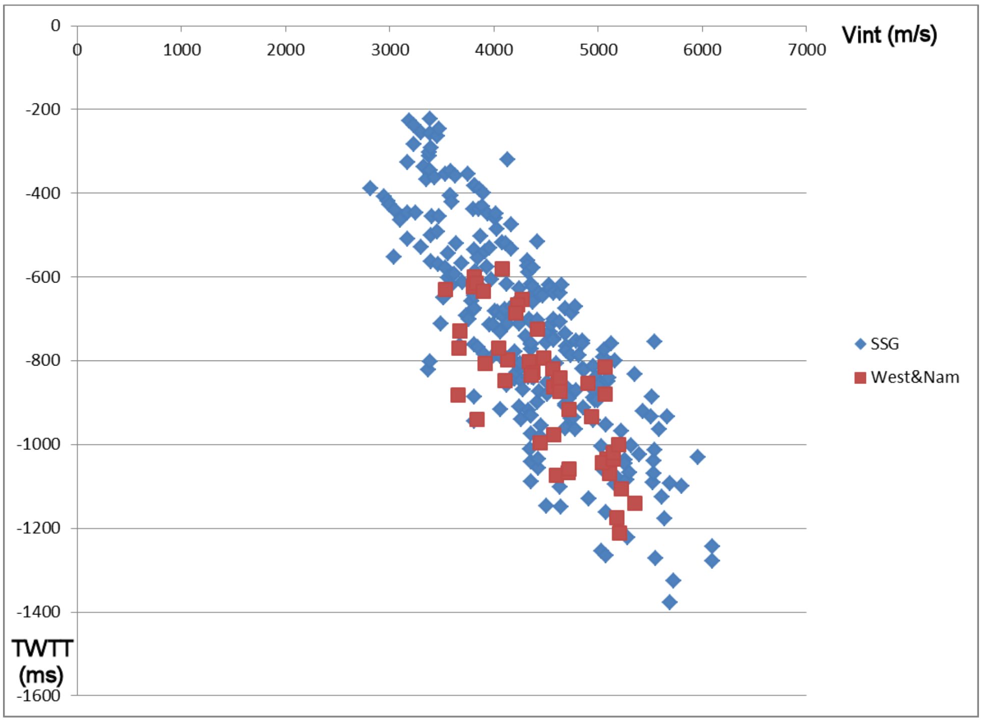


Figure 26 TWTT-Vint plot for checkshot data for 'marginal' late Carboniferous strata, and Sherwood Sandstone Group strata, in the selected wells.

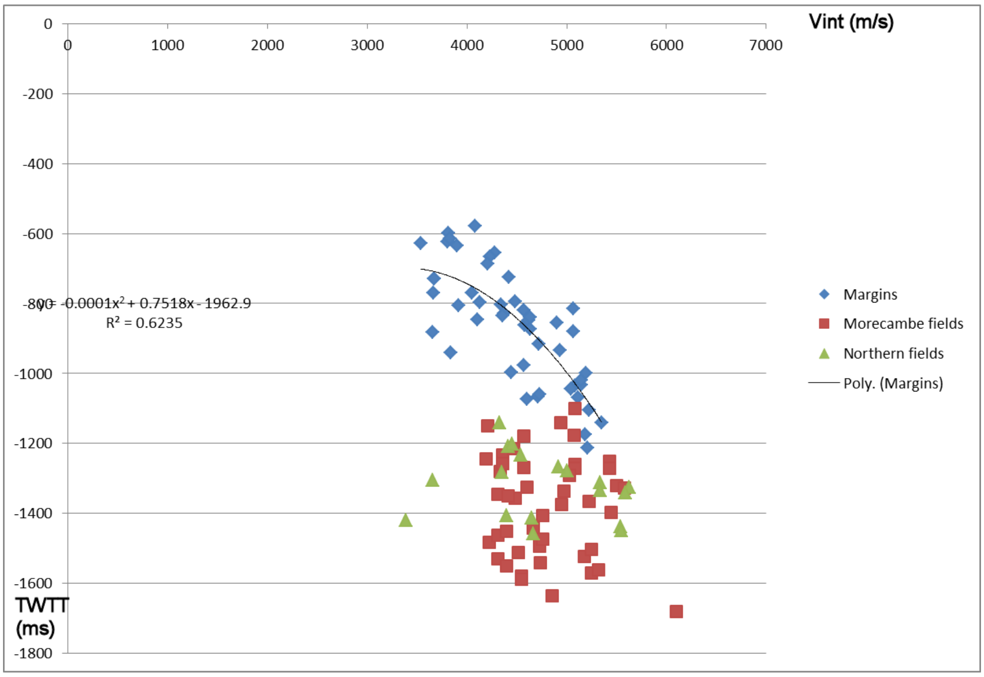


Figure 27 TWTT-Vint plot for checkshot data for late Carboniferous strata in selected wells.

By contrast, the data for the late Carboniferous strata underlying the Morecambe fields, are significantly offset from the Sherwood Sandstone Group trend (Figure 27). The contrasts between the Carboniferous beneath the gas fields, with those on the margins of the East Irish Sea Basin, are attributed to differing subsidence/uplift histories. The former have had the more complex history (Pharaoh et al., 2016b), and exhibit lower Vint values than 'Marginal' Carboniferous strata at the same depth (or TWTT, Figure 27).

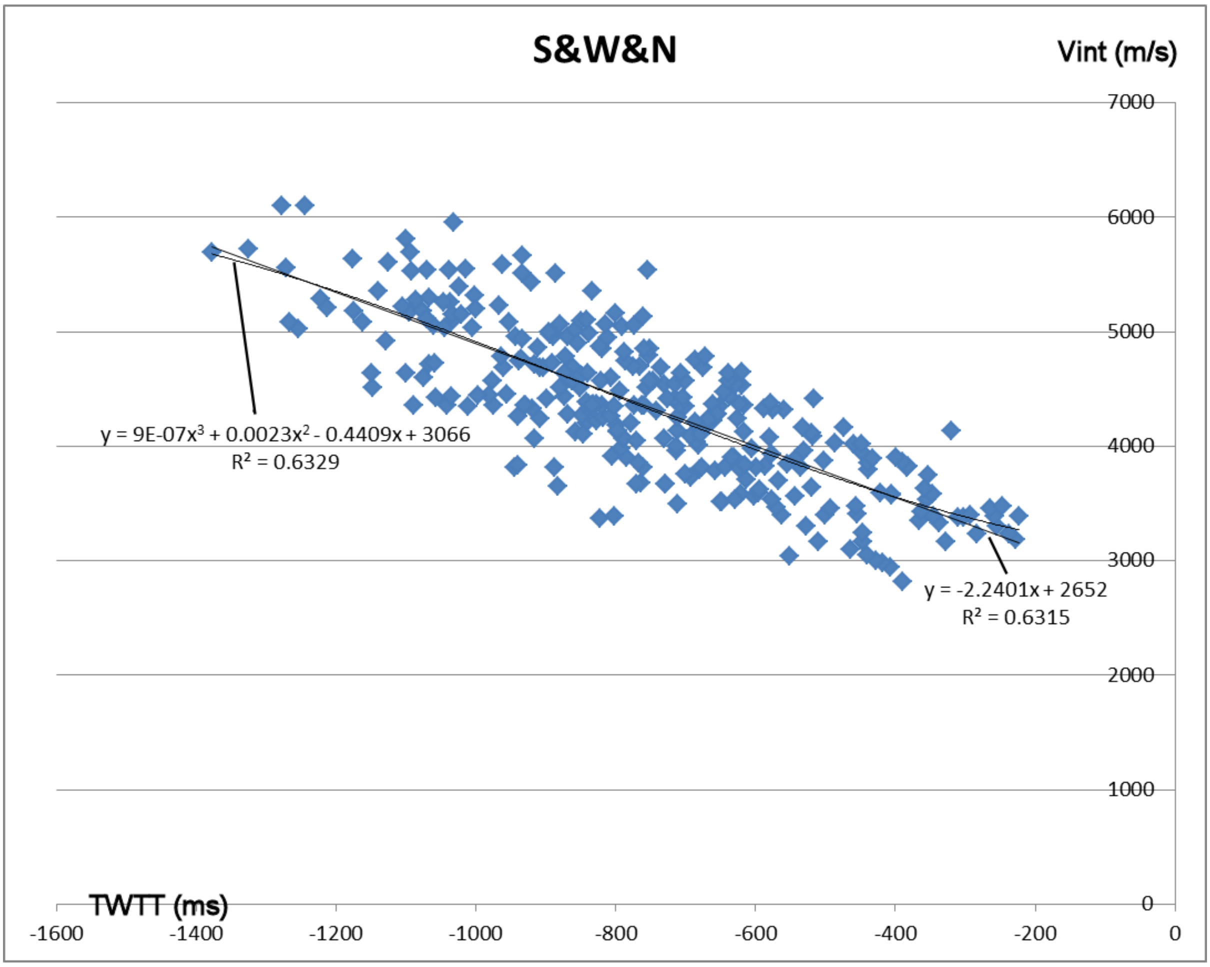


Figure 28 TWTT-Vint plot for checkshot data for 'marginal' late Carboniferous strata, and Sherwood Sandstone Group strata, in selected wells

The data for the Sherwood Sandstone Group and the 'Marginal' Carboniferous is plotted together in Figure 28, and yield both linear and non-linear (e.g. 3rd power polynomial) with significant regressions ($R^2 > 0.63$).

As the layer-cake and average velocity methods did not give optimal results for all horizons, a third method was used in the depth conversion of grids presented here. This 'time-depth' curve method (Petrel, 2008) is applicable to TWTT surfaces deeper than the well penetration, by extrapolation. It relies on the derivation of a time (TWTT) – depth (Z) function from quality well checkshot data. Initial experiment with the UVAR surface indicated that this would prove a relatively simple approach, but capable of handling surfaces below the depth of well penetration. In view of the problems identified above with the Average Velocity and Layer-Cake procedures, this was the method used to depth-convert all surfaces. The checkshot data for the Sherwood Sandstone Group, and the marginal Namurian and Westphalian depicted in Figure 28, were input into the Petrel *Function* facility and a regression obtained (Figure 29).

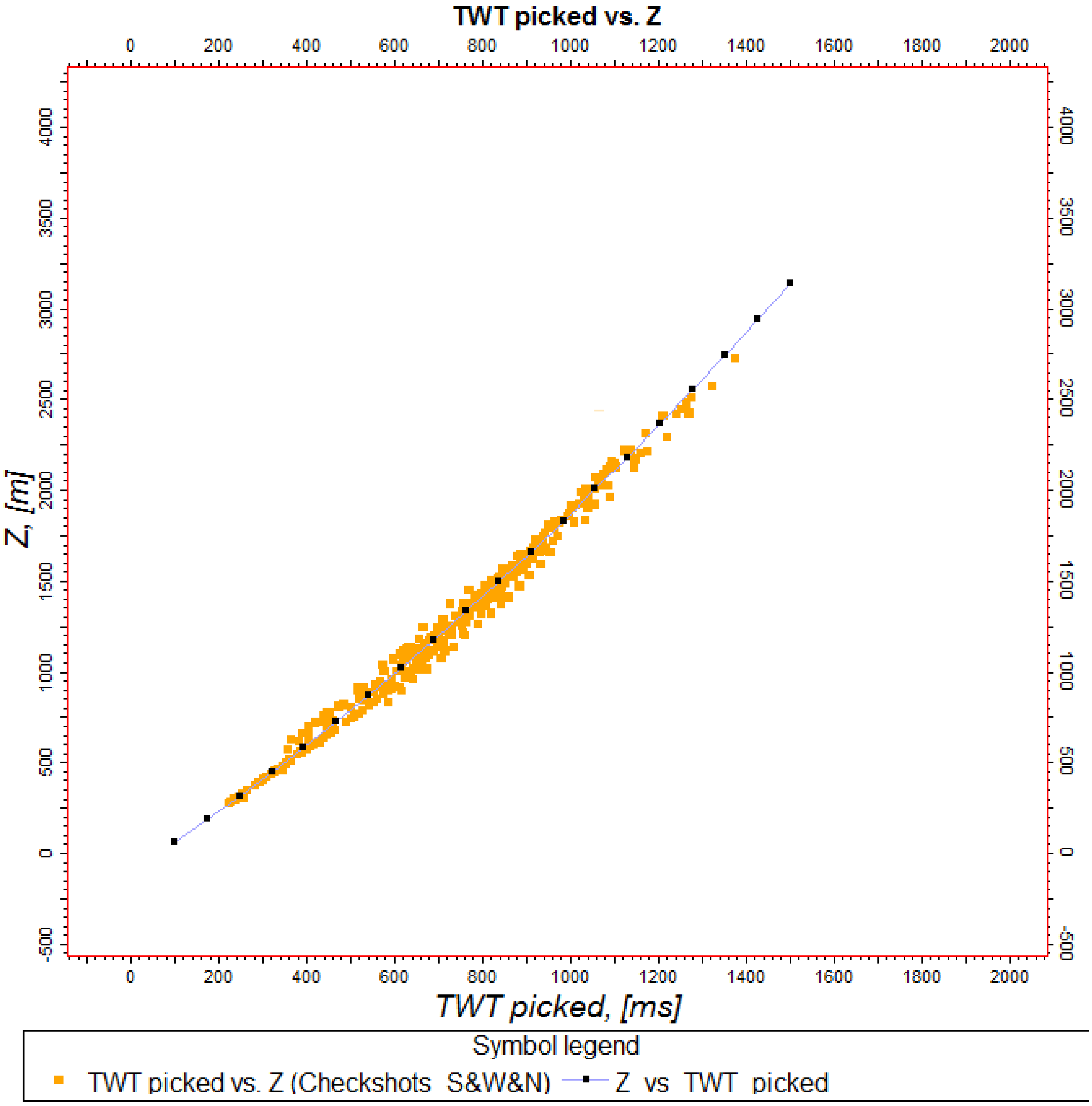
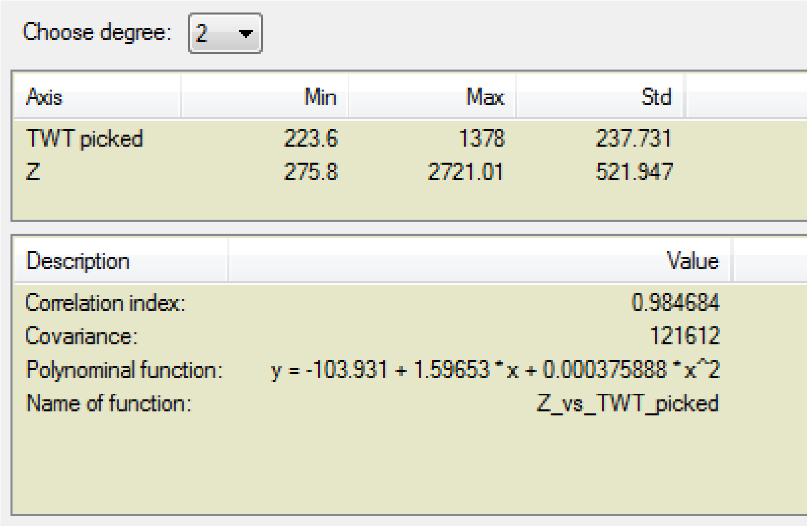


Figure 29 TWTT-Depth plot for checkshot data for 'marginal' late Carboniferous strata, and Sherwood Sandstone Group strata, in selected wells

The optimal fit is a 2nd order polynomial with the equation shown in Table 4. This regression curve is extrapolated beyond the 1400 ms TWTT (c. 2700 m depth) limit of the checkshot data depicted in Figure 29, to 4 s TWTT (Figure 30), and was used as the Z (TWTT) function for depth conversion of all the surfaces beneath the sub-Permian unconformity. In Petrel, Settings/Common Operations allows the value of the TWTT grid to be input into the equation, and directly converted to depth (Petrel Velocity Modelling, 2008).



Choose degree: 2

Axis	Min	Max	Std
TWT picked	223.6	1378	237.731
Z	275.8	2721.01	521.947

Description	Value
Correlation index:	0.984684
Covariance:	121612
Polynominal function:	y = -103.931 + 1.59653 * x + 0.000375888 * x^2
Name of function:	Z_vs_TWT_picked

Table 4 Regression equation for the checkshot data for 'marginal' late Carboniferous strata, and Sherwood Sandstone Group strata, shown in Figure 29.

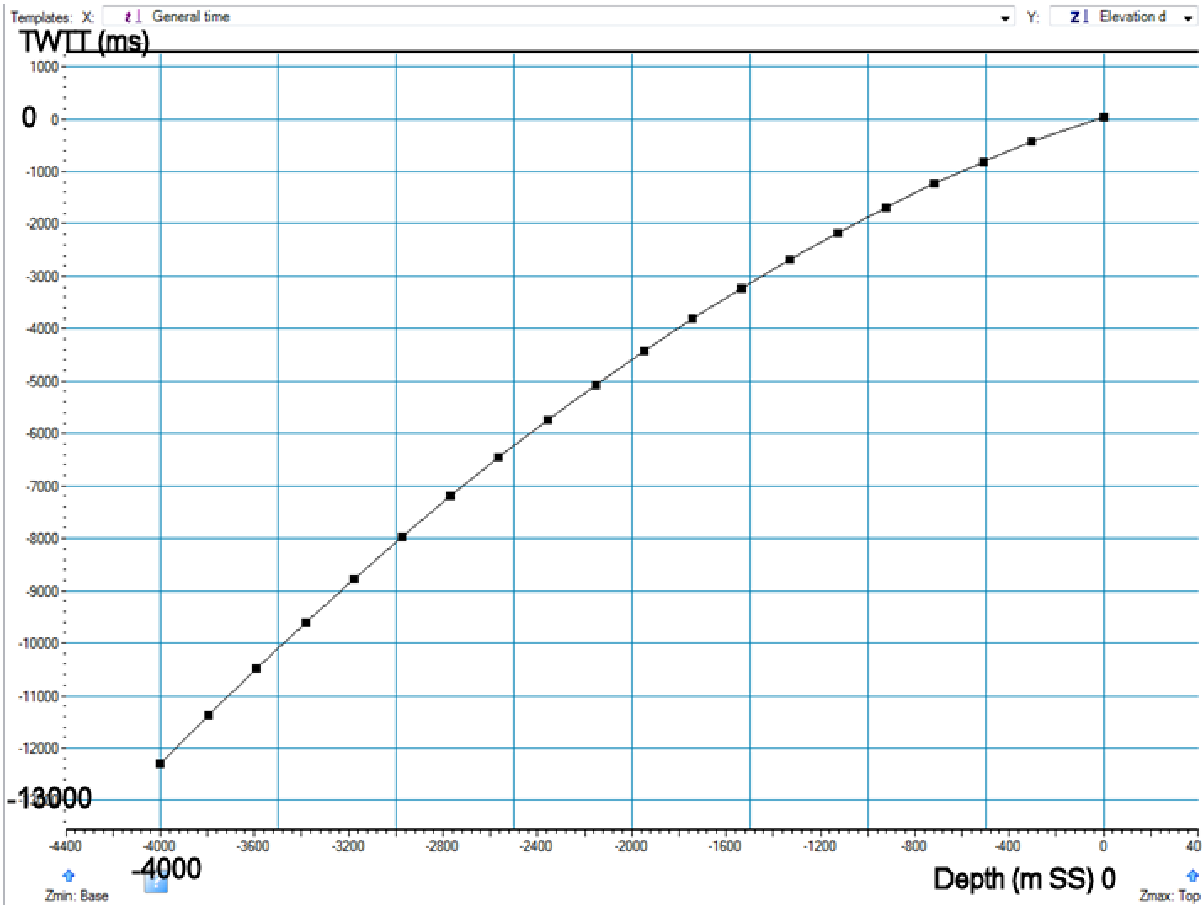


Figure 30 Time (TWTT ms)-Depth (m SS) curve in Figure 29, extrapolated to 4000 ms, and, used in the depth conversion calculations.

After much testing and comparison, the 'time-depth' curve method gave the best fit to well data throughout the succession and was used for depth conversion of the final grids presented here.

4.4 DEPTH CHECKING, RESIDUAL REDUCTION AND FINAL SURFACES

Following the depth conversion process described above, each provisional depth surface was inspected to check reasonable agreement with well tops, subject to the restriction noted in Section 4.3, due to the sparsity of deep wells. This was done in the *Surface creation* facility in Petrel, with the fit to well report generator enabled. In most cases, the level of the depth converted surface differed from the well top by less than 40 m (+/-). The provisional surfaces, for which a reasonable number of well tops were available (i.e. UVAR, Top Warwickshire Group, Top Namurian and Top Intra-Namurian) were then corrected to the well tops over an adjustment radius of 2500 m, to produce the final version of the surfaces.

Inspection of the surfaces generated, indicates that Permo-Triassic strata in the centre of the Keys Basin are 5800 m thick (Figure 38), which is compatible with the estimates of >5500 m stratigraphic thickness there of Jackson et al. (1995) and for >5000 m in the western part of the same basin (Chadwick et al., 2001). Figure 32 indicates a maximum depth of Carboniferous strata to 9930 m, possibly if 11000 m if underlying strata are of Carboniferous, rather than Devonian age. This is comparable to the 10 km estimated by Jackson et al. (1995). These comparisons suggest that the depth conversion process has produced reasonable results.

The TWTT and depth grids were checked for consistencies in a 3D Window view in Petrel. The grids were clipped using the extent polygons for each horizon and resampled from 250 m to 5 km.

The original grid spacing was 250 m and depth conversion was carried out at this resolution. Final grid resolution, as agreed with the seismic data companies, is 5000 m. Faults were interpreted at a 250 m resolution and upscaling the fault structure to 5000 m grid resolution results in an apparent mismatch due to scale difference. Faults are not included in the supplied depth grids due to these scaling difficulties

The re-sampling of grids to the much coarser resolution of the gridded product, and lacking the fault detail in this structurally complex area, has resulted in a poorer (somewhat generalised) fit of the final gridded surfaces to well ties.

5. Results

Images of the depth-converted surfaces delivered are presented here. TWTT surfaces are supplied digitally, but are not depicted here. The surfaces are:

RM80 UCAL (Caledonian-Acadian Unconformity)
RM70 Base Carboniferous
RM50 Top Middle Border Group (Intra-Visean)
RM48 Intra-Visean (Top Carboniferous Limestone)
RM40 Top Visean (Top Brigantian)
RM20 Top Intra-Namurian
RM15 Top Namurian
RM10 Base Warwickshire Group
RM0 UVAR (Variscan Unconformity)

5.1 PRODUCTS

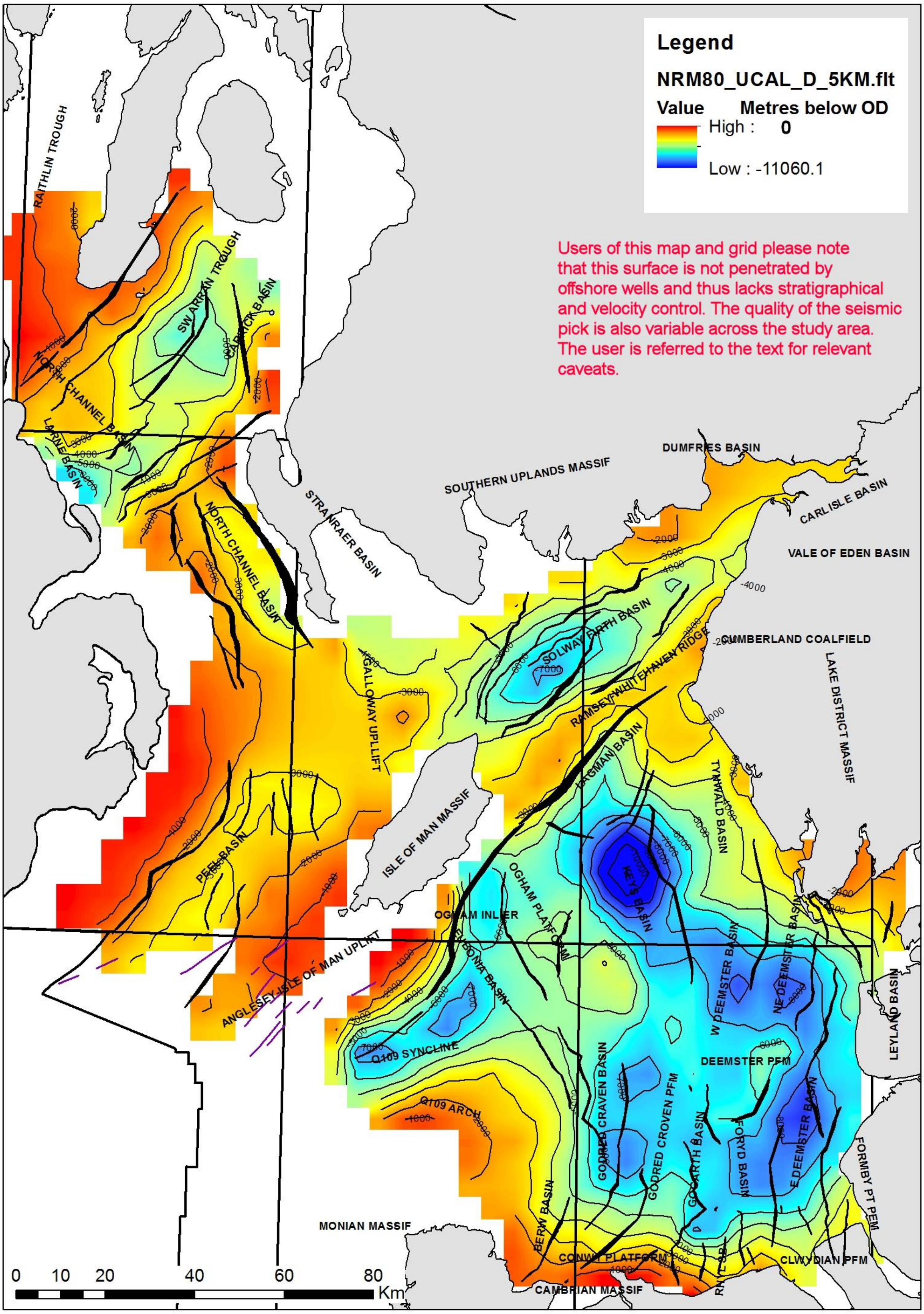
Gridded surfaces are supplied in a digital format suitable for import to:

- Petrel
- Zmap
- ArcGIS software packages

A smoothed fault shapefile applicable at the Variscan Unconformity level (UVAR) is also supplied. Users of the digital dataset should note the caveats described in section 4.4 on faults and fit to well ties, resulting from the resampling to 5 km resolution.

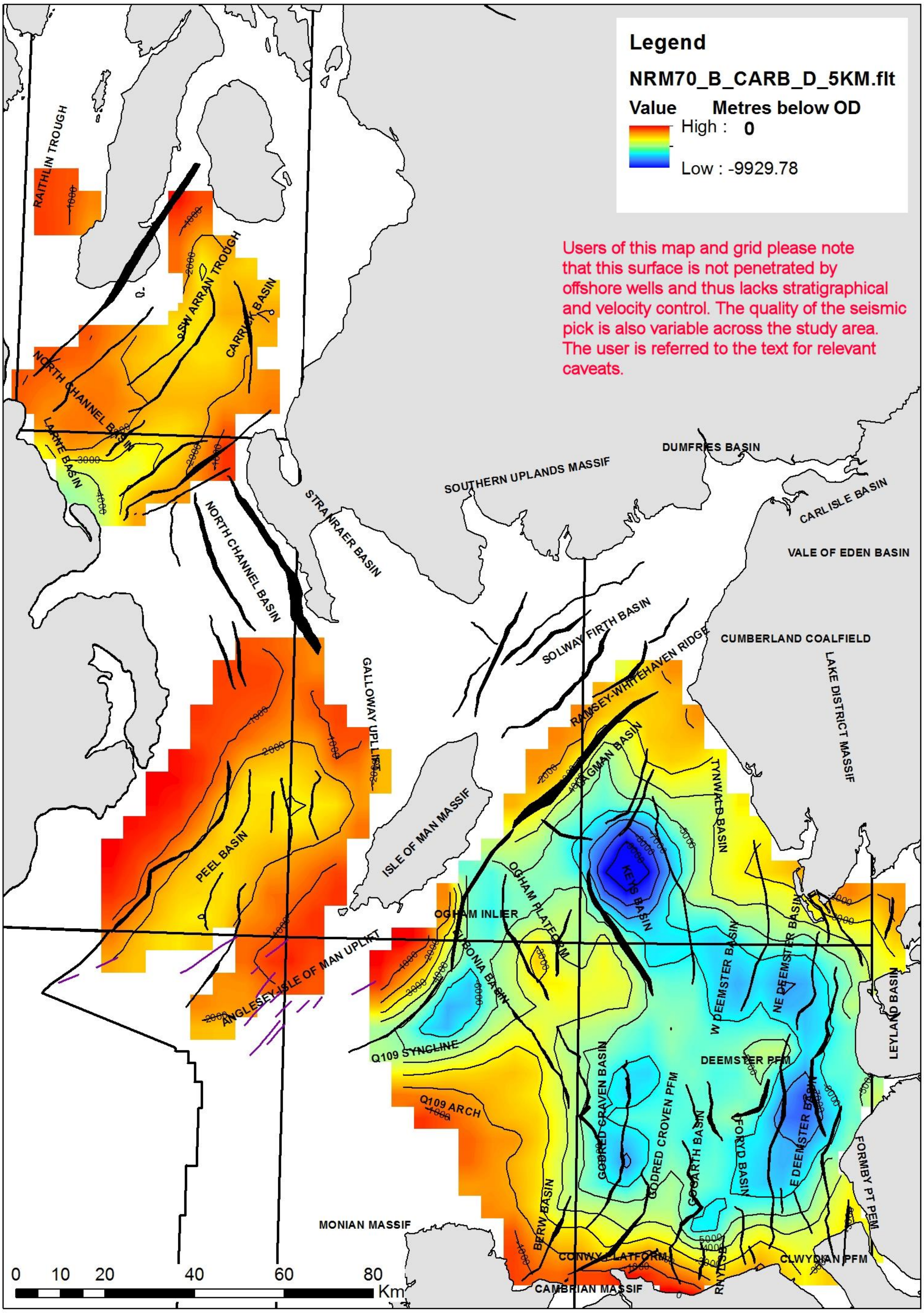
5.2 DEPTH STRUCTURE MAPS FOR KEY HORIZONS

A set of structure maps in depth (metres below sea level) derived from the depth converted maps is presented at a grid resolution of 5 km.



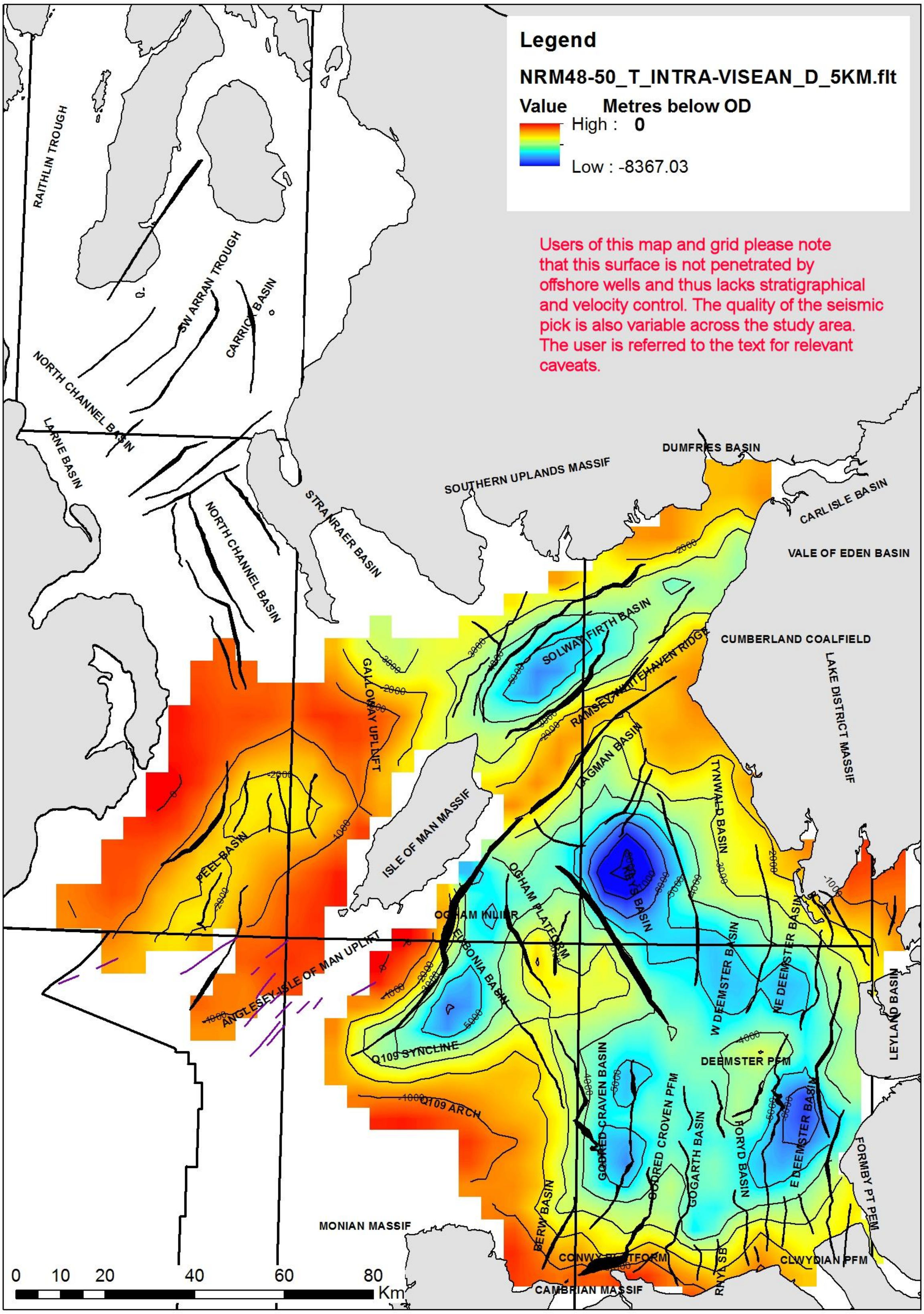
Users of this map and grid please note that this surface is not penetrated by offshore wells and thus lacks stratigraphical and velocity control. The quality of the seismic pick is also variable across the study area. The user is referred to the text for relevant caveats.

Figure 31 Structure map in depth (metres sub sea level) for the Acadian (Caledonian) Unconformity.



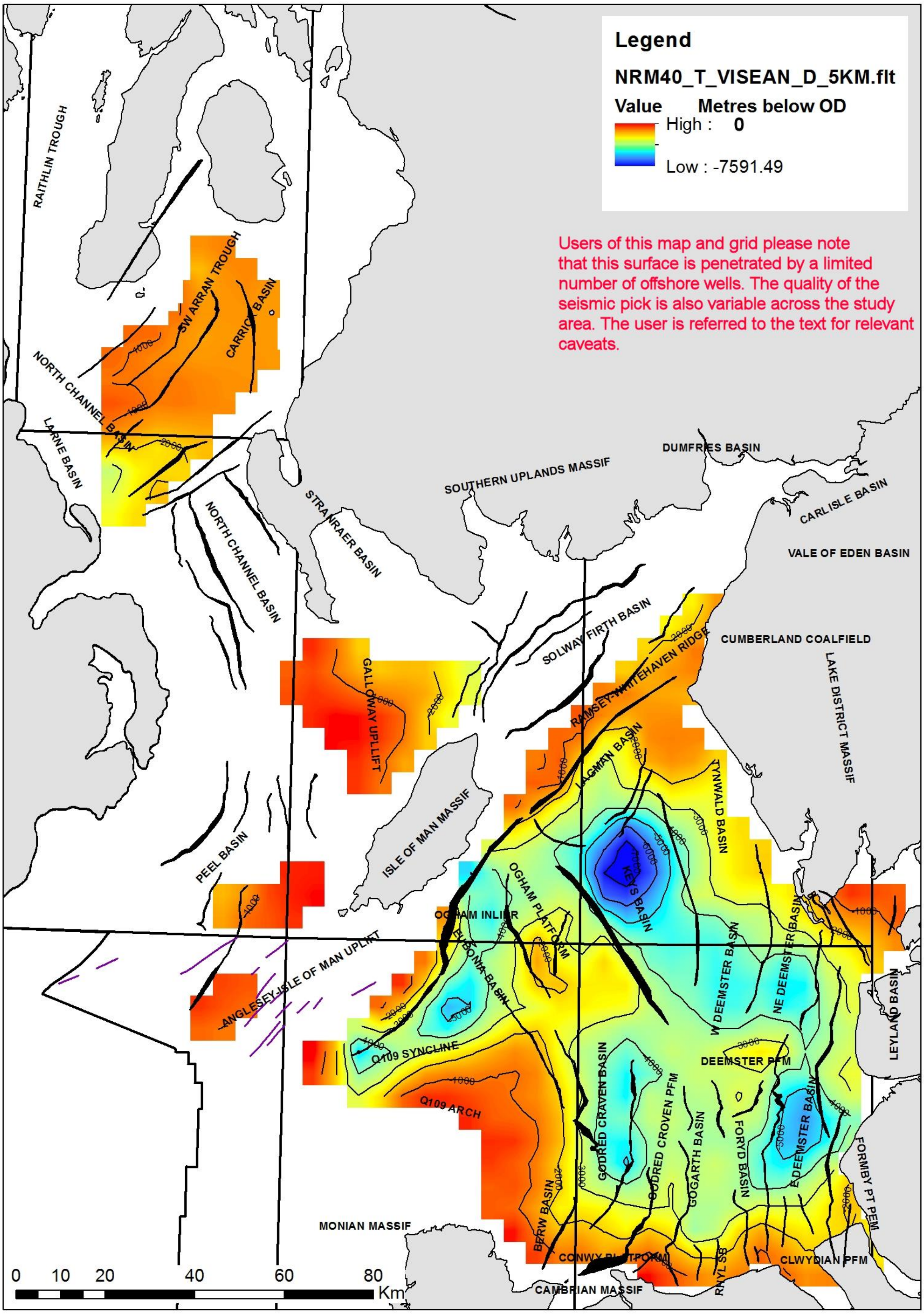
Users of this map and grid please note that this surface is not penetrated by offshore wells and thus lacks stratigraphical and velocity control. The quality of the seismic pick is also variable across the study area. The user is referred to the text for relevant caveats.

Figure 32 Structure map in depth (metres sub sea level) for the Basal Carboniferous pick.



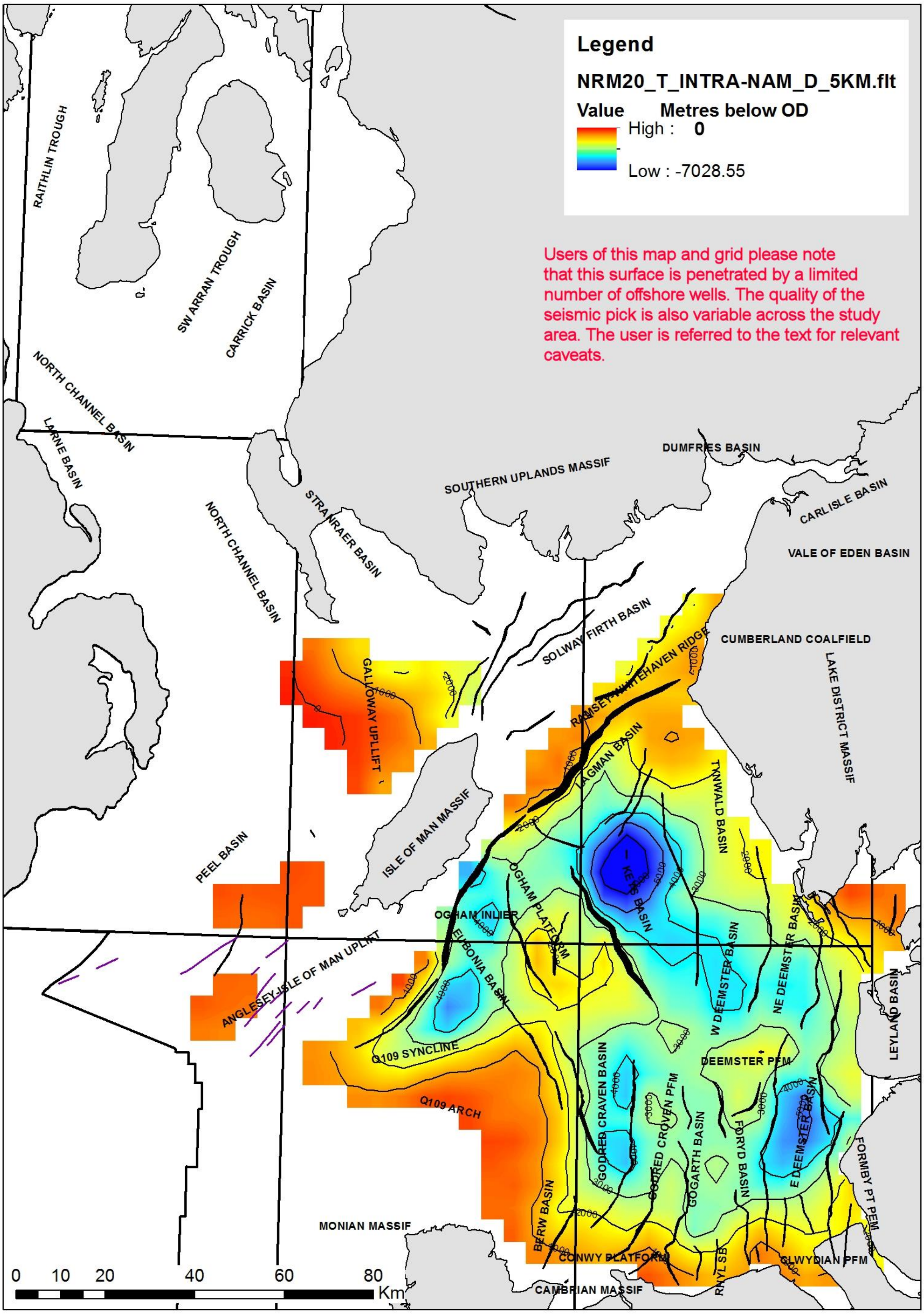
Users of this map and grid please note that this surface is not penetrated by offshore wells and thus lacks stratigraphical and velocity control. The quality of the seismic pick is also variable across the study area. The user is referred to the text for relevant caveats.

Figure 33 Structure map in depth (metres sub sea level) for the Intra-Visean pick.



Users of this map and grid please note that this surface is penetrated by a limited number of offshore wells. The quality of the seismic pick is also variable across the study area. The user is referred to the text for relevant caveats.

Figure 34 Structure map in depth (metres sub sea level) for the Top Visean (Carboniferous Limestone Supergroup).



Users of this map and grid please note that this surface is penetrated by a limited number of offshore wells. The quality of the seismic pick is also variable across the study area. The user is referred to the text for relevant caveats.

Figure 35 Structure map in depth (metres sub sea level) for the Intra-Namurian pick, equated with the base of the Millstone Grit Group

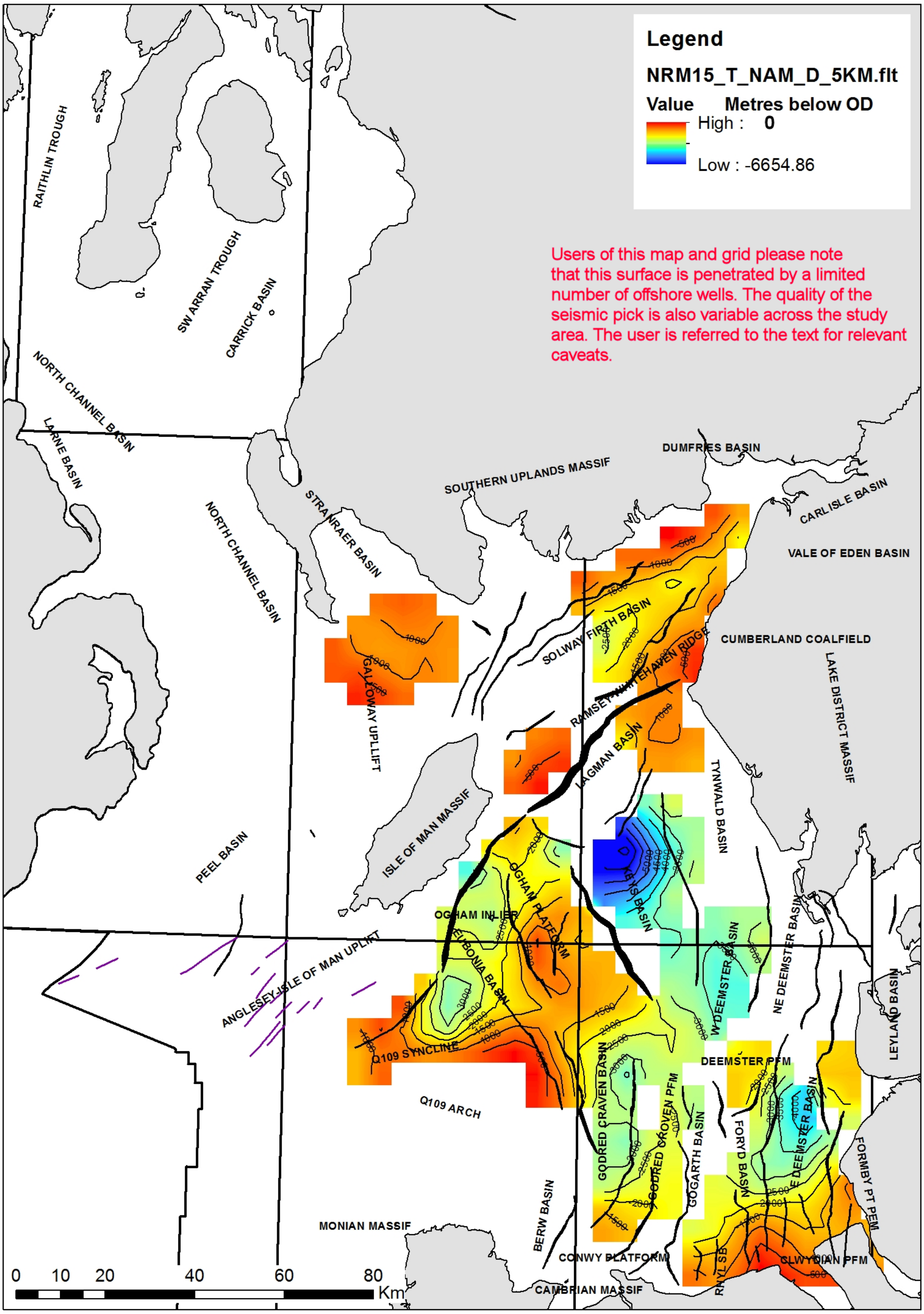
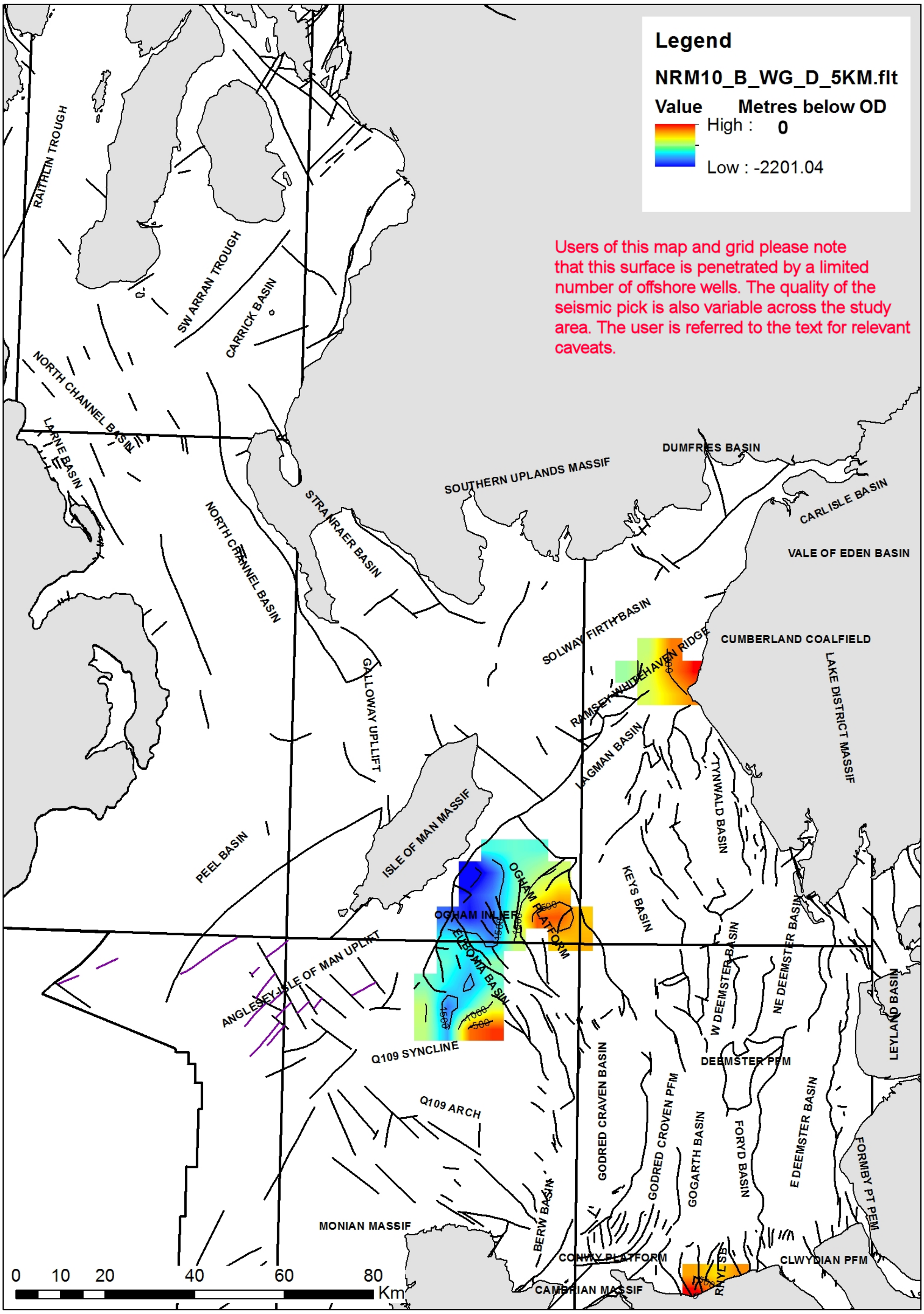
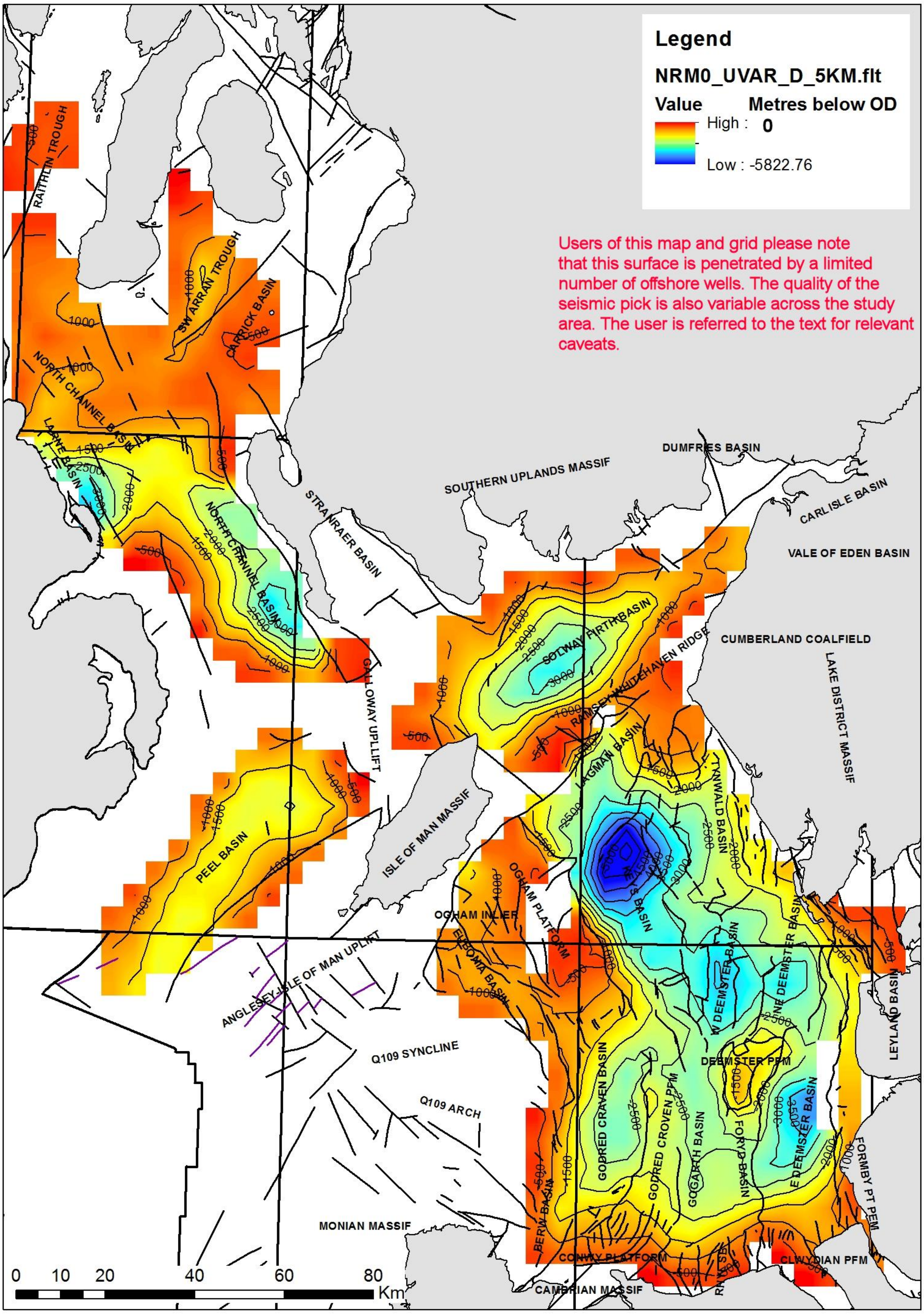


Figure 36 Structure map in depth (metres sub sea level) for the Top of the Namurian (Base Coal Measures) with simplified fault pattern for the Top Namurian.



Users of this map and grid please note that this surface is penetrated by a limited number of offshore wells. The quality of the seismic pick is also variable across the study area. The user is referred to the text for relevant caveats.

Figure 37 Structure map in depth (metres sub sea level) for the Base of the Warwickshire Group.



Users of this map and grid please note that this surface is penetrated by a limited number of offshore wells. The quality of the seismic pick is also variable across the study area. The user is referred to the text for relevant caveats.

Figure 38 Structure map in depth (metres sub sea level) for the Variscan Unconformity.

5.3 ISOPACHS

Isopach maps can easily be generated from the depth surfaces provided. An example is shown in Figure 39 below.

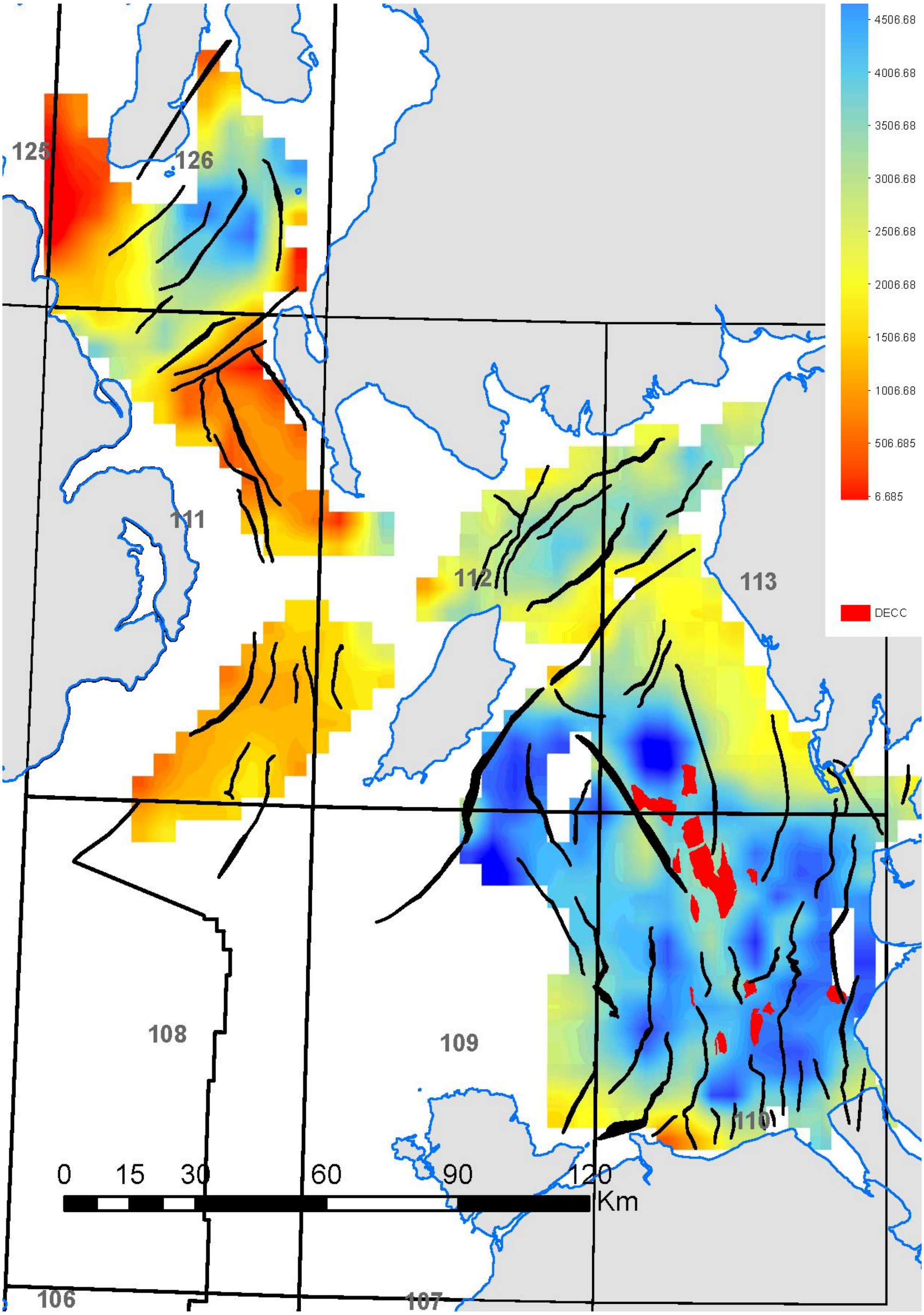


Figure 39 Example of an isopach map: Total preserved Carboniferous thickness (metres).

6 Conclusions and future work

This study has carried out a regional seismic interpretation of the Irish Sea basins, from Anglesey to the Highland Boundary Fault. The project has generated a set of two-way time and depth structure maps and a new pre-Permo-Triassic subcrop map (see Pharaoh et al., 2016b), also delivered in digital formats. The interpretation has been used as a key input to the assessment of the Palaeozoic petroleum prospectivity (Pharaoh et al., 2016b).

About 40,000 km of 2D seismic reflection data have been interpreted, with ties to a validated well database, allowing a comprehensive assessment of the structural evolution and petroleum systems of the region to be undertaken. Major, previously undescribed Carboniferous tectonic elements are postulated, both syndepositional basin elements, and Variscan inversion structures. The geometrical relationship of these elements to structures in the Permo-Triassic cover is demonstrated.

The variable data quality, and sparsity of deep well control, have hindered interpretation, particularly of the deeper Carboniferous picks. The interpretation of these surfaces, which are not penetrated by wells, contains a strong model-driven element, evidenced by the onshore relationships and areas where seismic picks can be made with the greatest confidence.

Key structural inferences are:

The presence of a major Carboniferous extensional half-graben in Quadrant 109, extending into the Eubonia Basin, and farther east, beyond the Keys Fault, where it was abruptly terminated by Variscan inversion and subsequent Permian-Mesozoic graben formation.

The recognition of a fold/thrust belt extending SW-NE across the region from the Quadrant 109 Arch, across the Godred Croven Platform to the Formby Platform and (onshore) the Ribblesdale Fold Belt.

Both of the above represent areas with enhanced Variscan, and reduced Alpine, inversion, which it is inferred, represent the most favourable areas for exploration of the late Palaeozoic hydrocarbon system.

Recommended future work includes:

- Detailed mapping of the Intra-Namurian and Top Namurian picks, which are the key to understanding the distribution of Pennine Coal Measures strata and the geometry of Variscan inversion structures.
- Mapping potential reservoir structures to establish four way closure and integrity
- New seismic acquisition to include a denser network of 2D in Quadrants 108, 109 and 125, and a patch of 3D south of the Isle of Man to map the key Variscan inversion structures there.

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