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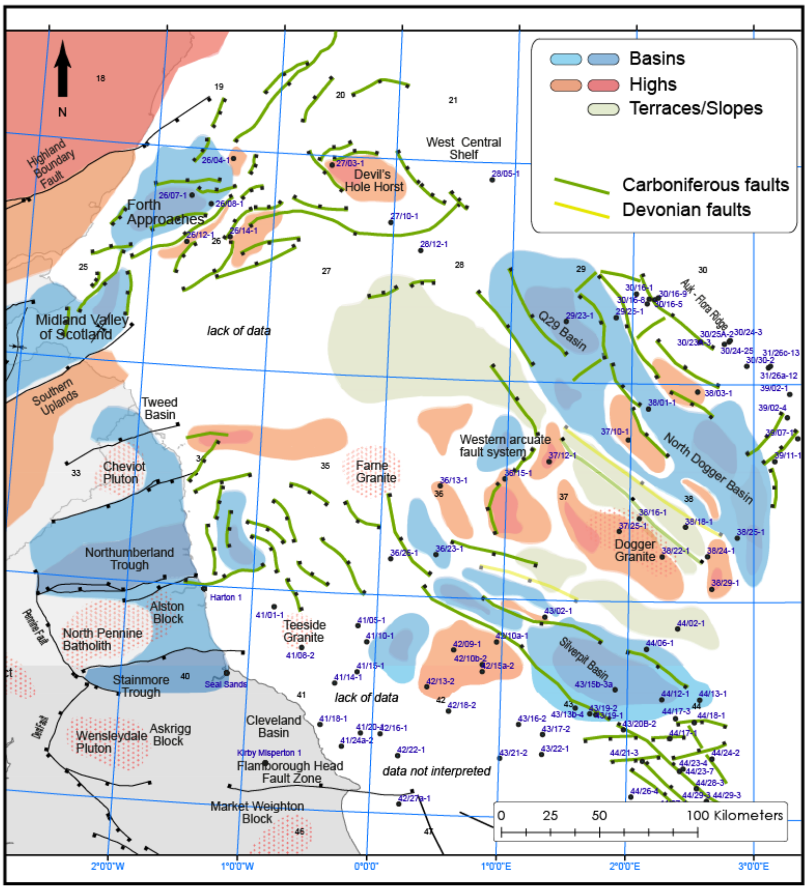
Seismic interpretation and generation of key depth structure surfaces within the Devonian and Carboniferous of the Central North Sea, Quadrants 25 – 44

Energy and Marine Geoscience Programme

Commissioned Report CR/15/118



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Seismic interpretation and generation of key depth structure surfaces within the Devonian and Carboniferous of the Central North Sea, Quadrants 25 – 44 area

S. Arsenikos, M.F. Quinn, T. Pharaoh, M. Sankey and A.A. Monaghan

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Foreword

This report describes the methodology of generation of a set of depth structure maps of horizons within the pre-Permian succession of the Mid North Sea High, western margin of the Central North Sea, offshore extension of the Northumberland Trough and Forth Approaches area, as well as the rationale for the interpretations made, and the interpretation results, presented as a set of maps. The work was carried out as part of the 21CXRM Palaeozoic project which itself is part of a larger endeavour to stimulate petroleum exploration in the United Kingdom Continental Shelf (UKCS). The work accessed a large seismic and well database through the BGS contract with DECC/OGA, plus data donated by industry and published peer reviewed papers. The depth structure maps resulting from this exercise are provided to industry participants at an agreed grid spacing of 5000 m and are thus necessarily a regional view of the topography of the horizons. They are one of the key elements required to assess the petroleum prospectivity of the Palaeozoic sequence within the study area.

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Executive Summary

This report details the rationale, methodology and results of a regional seismic interpretation of the western margin of the Central North Sea (CNS) area, specifically over the Mid North Sea High area, the offshore extension of the Northumberland Trough and the Forth Approaches area. The aim of the interpretation was to create maps that show the distribution of Palaeozoic basins and highs, and where possible interpret key Devono-Carboniferous surfaces and main structural elements in order to build a tectono-stratigraphic model of the Palaeozoic geology. Some 50,000 line kilometres of predominantly 2D seismic data have been interpreted and tied to key released wells in the study area. The seismic and well data were augmented by donated reports from sponsor companies.

A set of 5 depth structure maps of selected Palaeozoic horizons has been produced for the pre-Permian succession. These maps provide a key element to aid assessment of the petroleum prospectivity of the Palaeozoic within the study area.

The surfaces, with a grid spacing of 5000 m, give a regional view of the topography of the horizons, and comprise:

- Upper Permian Base Zechstein Group;
- Lower Carboniferous near Top Scremerston Formation;
- Lower Carboniferous near Top Fell Sandstone Formation;
- Lower Carboniferous near Top Cementstone Formation; and
- Middle Devonian near Top Kyle Limestone Group.

The regional structure map of the area constructed for this report and observations made from the seismic data, have been integrated with peer reviewed published information to describe a tectonostratigraphic model for the region (Leslie et. al., 2015).

A new pre-Permian subcrop map is presented here that builds on existing publications (Smith,1985a, b; Kombrink et al., 2010) and incorporates all relevant new well penetrations since the previous map was published. The well dataset has been either validated or re-interpreted before being integrated with the new seismic interpretation (Kearsey et al., 2015).

Figure 10 in Section 3.3.1 below summarises the regional structures referred to in the general observations listed below.

General observations on the structures defined across Quadrants 29, 30, 31, 37, 38 and 39:

- The Middle-Upper Devonian basins and highs follow a NW-SE trend across Quadrants 29-30 and 37-38;
- Lower Carboniferous sequences (Tournaisian and Visean) are interpreted to be present in depocentres across much of the area covered by Quadrants 29 to 38; wells, mainly drilled on the structural highs, constrain the edge of the Lower Carboniferous basins;
- There is a structurally complicated area in the southernmost part of Quadrant 38 which comprises a folded Visean and probably Namurian succession. The structure can be interpreted either as an anticlinal rollover on a low-angle fault, or as a compressional anticlinal fold (see Figure 17 below). The structure trends broadly NNE-SSW, plunging northwards into Quadrant 38;

  - the anticlinal structure is expressed on the pre-Permian subcrop map where progressively younger sequences are preserved below base Permian unconformity away from the anticlinal axis. The anticline is oblique to the general WNW-ESE trend of the Dogger Granite High;
- By analogy with mapped granitic intrusions onshore, the Dogger Granite High seems to influence the structural geometries of the Devono-Carboniferous sequences close to the south-west edge of Quadrant 38 where they gradually onlap;
- Interpretation of 3D seismic data shows evidence for a NE- trending strike-slip fault zone in the area between the southern edge of Quadrant 29 and the south-western part of Quadrant 30: to the northeast the fault zone is interpreted to terminate at the Auk Ridge. To the southwest, the fault zone continues into Quadrant 36; it is not observed farther south of Quadrant 36.

General observations across Quadrants 41-44:

- South of the Dogger Granite high, an E-W basin depositional trend is interpreted to have prevailed during mid to late Devonian times. This trend has been overprinted by a NW-SE to WNW-ESE fault trend (Quadrants 42-43) of possible Late Carboniferous age;
- Folding with wavelengths of 10-15 km, typically with a NW- trend, within the succession of Carboniferous age appears to be more concentrated in Quadrants 42-43 than in Quadrants 37-38-39;
- The majority of the anticlinal structures mapped have been truncated by the Base Permian Unconformity (e.g. Figure 14 below).

General observations over the offshore extension of the Northumberland Trough covering the southern blocks of Quadrants 34 and 35:

- Observation of the onshore succession and offshore wells adjacent to the area suggest that a thick succession of Carboniferous sandstone, coal, mudstone and limestone will probably be present within the offshore part of the Northumberland Trough;
- The majority of faults mapped in this area are steeply dipping;
  - a set of faults with an approximate N-S orientation, varying between a NNW-SSE to NNE-SSW trend with relatively small throws, sometimes reverse, have been mapped;
  - these faults are often associated with short wavelength folds and may provide evidence of strike-slip movement;
  - a major ENE-trending fault is interpreted as the offshore continuation of the Ninety Fathom/ Stublick Fault system that defines the southern boundary of the Northumberland Trough onshore. The fault has a large throw to the NW and extends approximately 40 km offshore.

General observations over the offshore extension of the Midland Valley of Scotland, the Forth Approaches area, covering Quadrants 25 to 27:

- The continuation of the onshore Southern Upland Fault has been mapped offshore and is interpreted to step to the north and continue with a ENE- trend towards Quadrant 27;
- Seismic data shows evidence of Variscan inversion and faults showing strike-slip movement;
- Seismic interpretation has defined an extensive (>7000 km^2) ENE-trending Carboniferous Basin within the Forth Approaches;
- The Carboniferous basin is unconformably overlain by a thick Upper Permian Rotliegend basin and a Zechstein succession including thick salt exhibiting halokinesis.

1 Introduction

1.1 RATIONALE AND BACKGROUND

The Central North Sea (CNS) area is a key hydrocarbon province accounting for a large proportion of the UK‘s oil and gas production. Exploration activity, as measured by drilling of exploration wells and acquisition of new seismic data, has been declining as the identification of relatively low risk, high return prospects has reduced and the oil price has lowered.

Following consultation with industry and other stakeholders, the 21CXRM Palaeozoic project was established to stimulate petroleum exploration over the UK Continental Shelf (UKCS) by assessing the petroleum prospectivity of defined areas and geological systems, specifically to:

- ***Focus interest in underexplored areas*** **-** for this report, the western margin of the Central North Sea (CNS) area, specifically over the Mid North Sea High area, offshore extension of Northumberland Trough and Forth Approaches area; and
- ***Provide a regional-scale understanding of the deeper Palaeozoic strata*** **-** for this report, the Devonian and Carboniferous succession.

This report provides an account of the seismic interpretation of the Central North Sea area (Quadrants 25-44), conducted as one of the tasks within the 21CXRM Palaeozoic project. One of the key deliverables for the project was production of a set of depth maps of selected pre-Permian surfaces. This report describes how these maps were generated, describes their main features, and endeavours to put the results of the interpretation into a regional geological context.

1.2 TIMESCALE AND RESOURCES AVAILABLE TO THE SEISMIC INTERPRETATION TASK

A large amount of 2D and 3D seismic data, released well information and accompanying reports, plus information provided by industry and published papers were utilised for this task (Section 2). The remit agreed with the steering committee was for a regional-scale evaluation and specifically was not to deliver prospect-specific evaluations. On agreement with the seismic data vendor companies, all interpretations are released as grids with a 5000 m node spacing. More detailed interpretations using the supplied 3D seismic data were re-sampled along 2D line locations.

The aim of the seismic interpretation, in conjunction with the other tasks in the project that studied stratigraphy, source rock potential and timing of migration modelling, was to undertake a regional scale petroleum systems analysis of the Palaeozoic sequence. The depth surfaces, described in the following sections, are key components of the assessment of the petroleum potential of the Palaeozoic in the CNS area.

2 Seismic and Well Dataset

The seismic dataset utilised in this study comprised 2D and 3D surveys provided to BGS under contract to DECC/OGA, covering the area from Quadrant 25 to Quadrant 44. Due to their regional coverage and their greater resolution of deeper sequences, the 2D surveys were the most important source of data for the study; 27 surveys comprising almost 1000 profiles were used (Figure 1), amounting to approximately 50,000 line kilometres of data. Four 3D surveys were available and used for more local interpretations across structurally complicated areas. At the request of seismic data providers, 3D surveys were resampled at 2D lines spacing before inclusion in Two Way Time and depth grids.

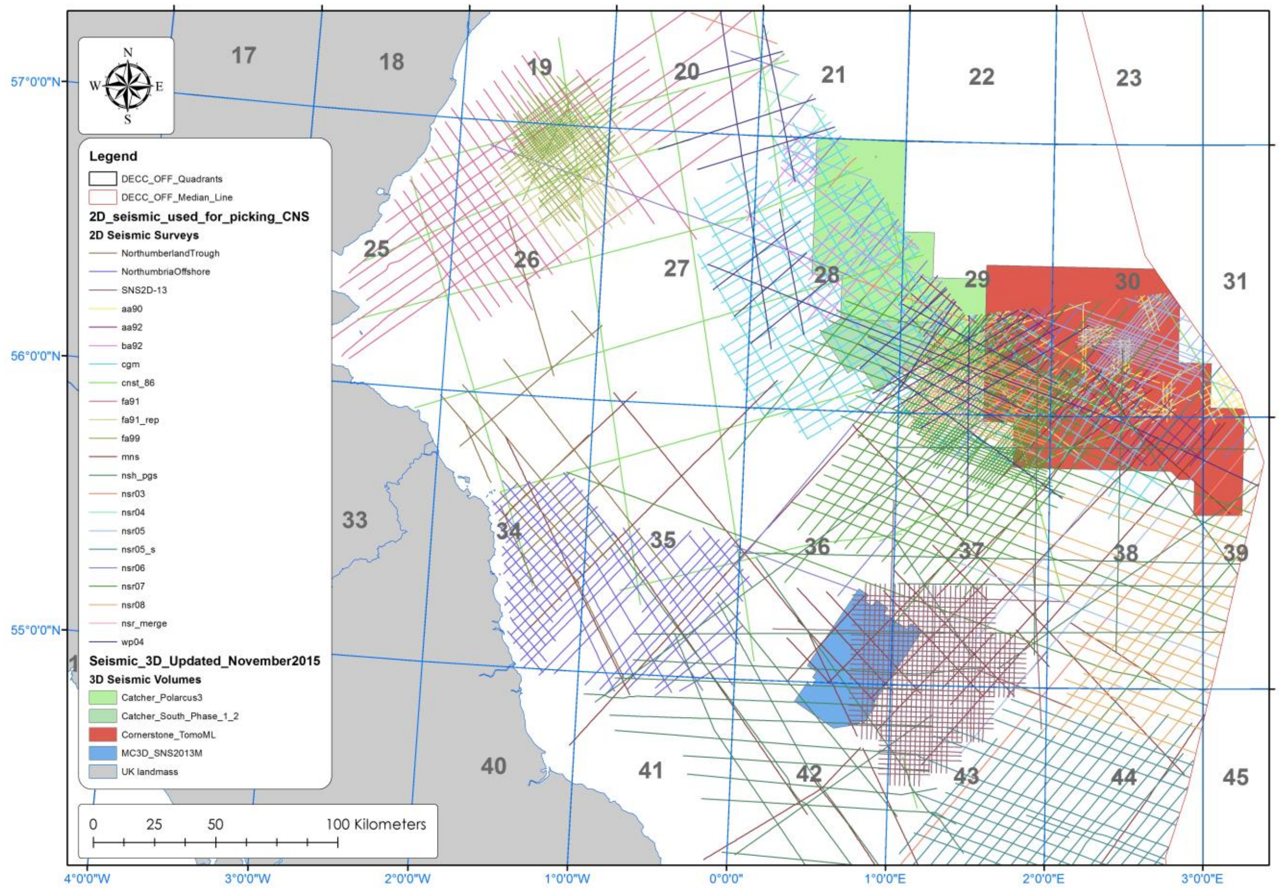

Figure 1. Basemap showing seismic surveys chosen for this study.

2.1 SELECTION OF THE SEISMIC SURVEYS (2D & 3D)

The 2D seismic profiles (with various grid spacing, ranging from 2 km up to 10 km wide) providing the best imaging of the deep Palaeozoic section (Table 1) used in the interpretation were:

Survey	Data supplier
FA99	Spectrum
WP04	Spectrum
NSH	PGS
AA90	Schlumberger
AA92	Schlumberger
BA92	Schlumberger
CGM	Schlumberger
MNS	Schlumberger
SNS2D-13	Spectrum
FA91_reprocessed	TGS
CNST86	WesternGeco via TGS
NSR03	TGS/ Spectrum
NSR04	TGS/ Spectrum
NSR05	TGS/ Spectrum
NSR07	TGS/ Spectrum
NSR08	TGS/ Spectrum
Northumberland Trough	WesternGeco
Northumberland Offshore	WesternGeco

Table 1. 2D seismic surveys utilised in the project interpretation.

The 3D interpretation focused on 4 surveys, especially over Quadrants 29 and 30 (Table 2):

Survey	Data supplier	Notes
Cornerstone_Tomo_ML	CGG	Interpretation of the Kyle Limestone
MC3D_SNS2013M	PGS	Use of the seismic to better constrain the Kyle Limestone depth
Catcher_Polarcus 3	Polarcus	Interpretation of the Kyle Limestone and the Pre-Permian sequences
Catcher_South_Phase_1	Polarcus	

Table 2. Key 3D seismic surveys utilised in the project interpretation.

The criteria for choosing which data to interpret were primarily those in closest proximity to wells, for stratigraphic calibration, and the seismic grid spacing. Regional lines were chosen as the primary framework, moving progressively further away from well calibrations when and where possible. The seismic coverage in Quadrants 27, 28, 34, 35, 41 and 42 was either sparse or of an older vintage, and as a result, seismic interpretation confidence is lower in these areas (Figure 1).

2.2 WELL INFORMATION AND SEISMIC CALIBRATION

2.2.1 Available wells database

Only 232 of the approximate count of 1331 wells in Quadrants 26-44 penetrate the Palaeozoic sequence (Figure 2; information from DECC/BGS databases). Only 58 of these 232 wells drilled the Lower Carboniferous sequence and even fewer (approximately 15) drilled more than a few tens of metres into pre-Westphalian strata.

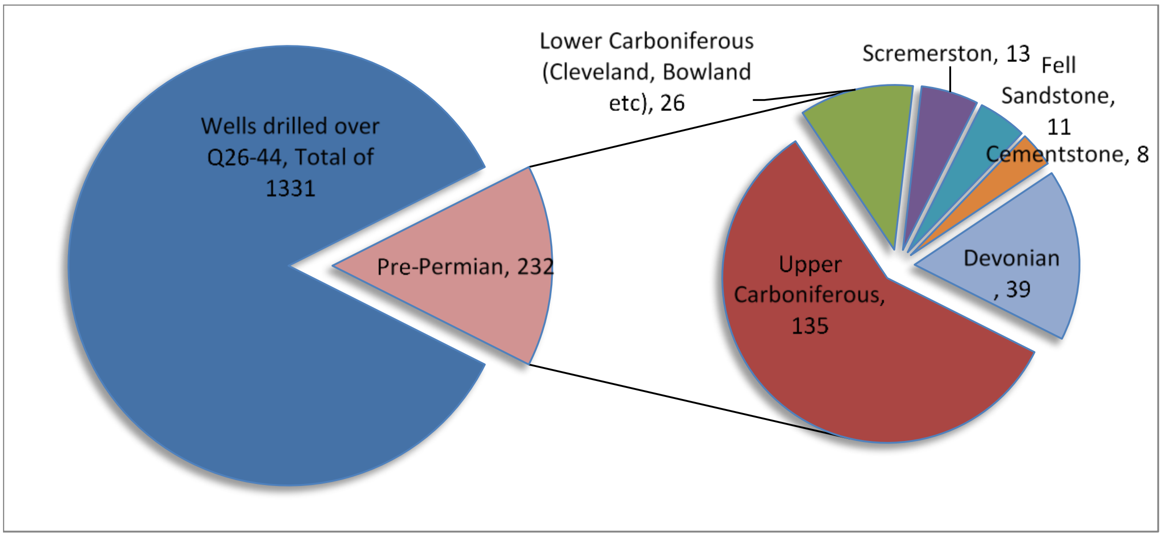

Figure 2. Pie-chart illustrating the number of wells that drilled the Middle/Lower Carboniferous across the study area.

2.2.2 Well to seismic ties

Well-to-seismic ties have been achieved using the available time-depth pairs for the wells and by comparing wireline log curves with the seismic (Figures 3 and 4). The study was focussed on regionally extensive, characteristic seismic picks, rather than at a detailed block/prospect level, and the well to seismic tie methodology was considered fit for purpose. A number of synthetic seismic ties were also produced in order to provide an extra degree of confidence in specific areas (Figures 3 and 4). These confirmed the validity of the regional picks observed from well-seismic ties and wireline log curves. The number of well ties to the Upper Carboniferous section is more significant than those to the Lower to Middle Carboniferous (Table 3). During this study the main focus was the pre-Namurian sediments, but the Westphalian well picks were integrated as a valuable information source.

Well	**Top Kyle Limestone**	**Top Cementstone Formation**	**Top Fell Sandstone Formation**	**Top Scremerston Formation**
26/07-1		X	X	X
26/08-1				X
30/16-5	X			
30/24-3	X			
30/25a-2	X			
37/12-1	X			

37/25-1		X		
38/03-1	X			
38/16-1			X	X
38/18-1			X	X
38/22-1		X		
39/07-1				X
41/01-1		X	X	X
41/10-1		X	X	X
42/10b-2		X	X	X
42/13-2				X
42/15a-2			X	X
43/02-1		X	X	X
44/02-1		X	X	X
44/06-1				X

Table 3. List of the key well ties used during the seismic interpretation of the key events.

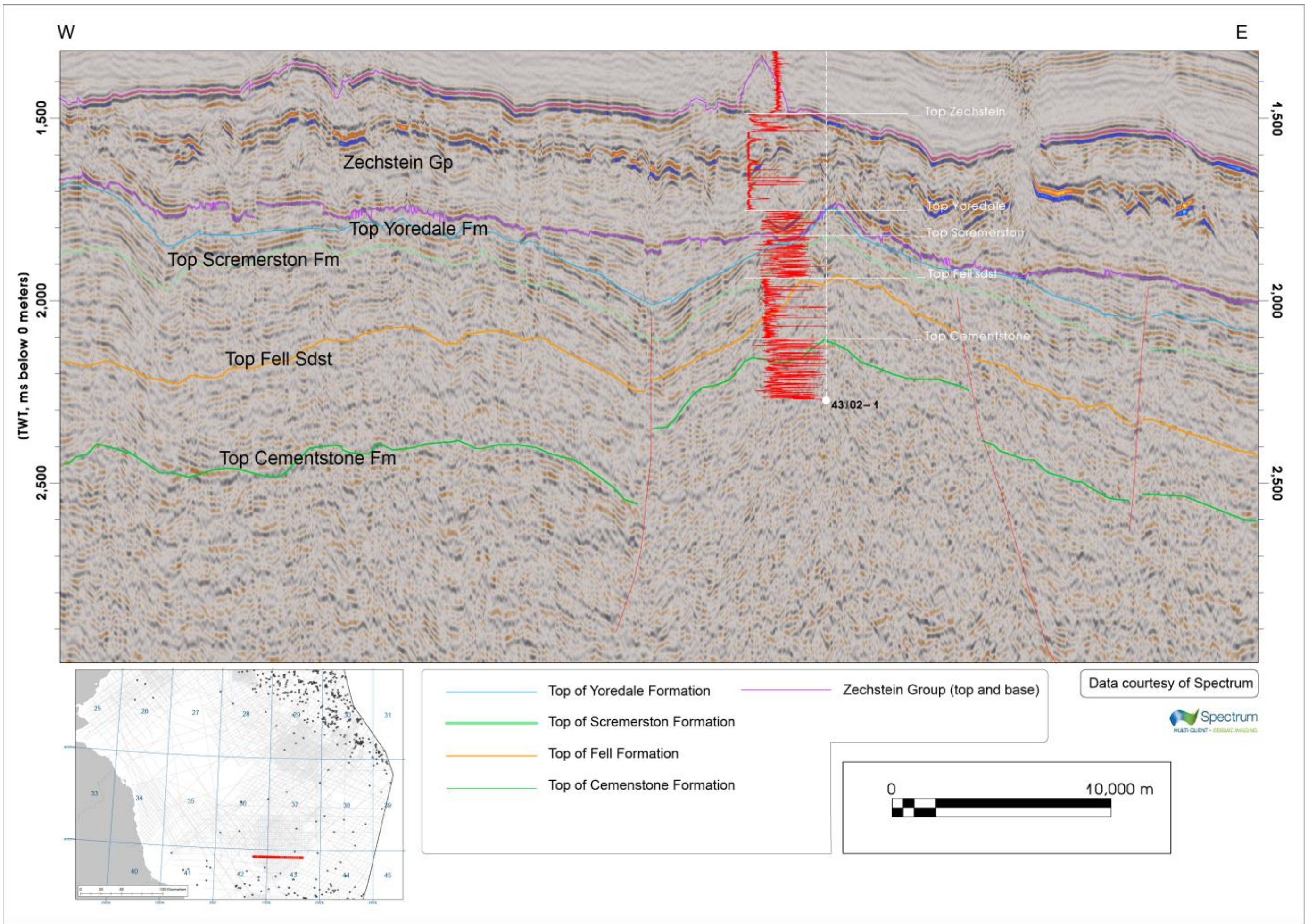

Figure 3. Seismic profile showing an example of well to seismic correlation. The red curve represents the Gamma ray curve.

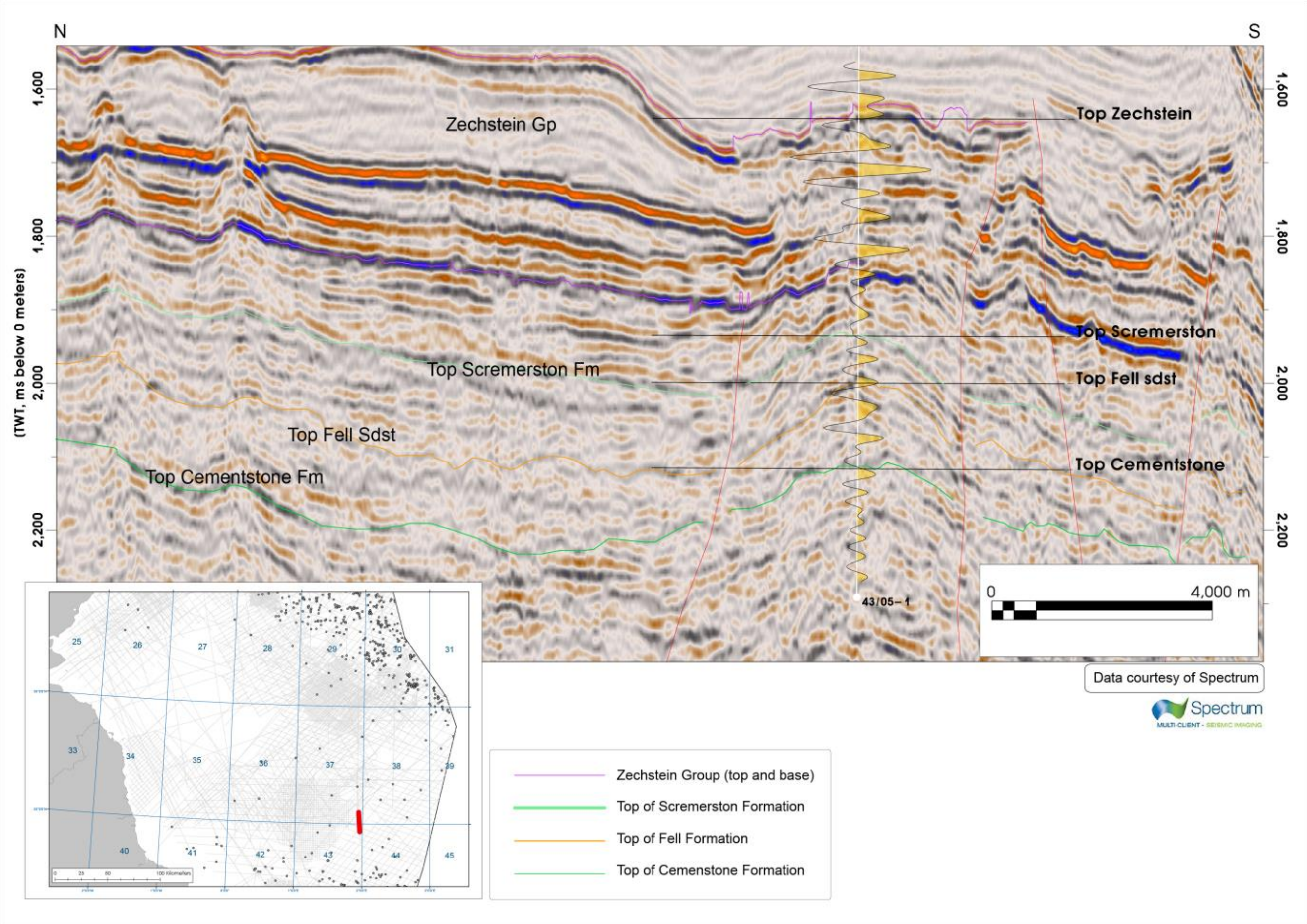

Figure 4. Example of synthetic curve compared to the seismic and the well picks illustrating the good correlation between the seismic amplitudes and the calculated peaks and troughs.

3 Seismic Interpretation

3.1 SELECTED EVENTS

3.1.1 Selection criteria

The choice of the interpreted seismic events (Table 4) was based on two key-factors:

- High reflectivity and acoustic impedance events were preferentially mapped in order to obtain the most confident picking over large areas between the successions. For example, the clearly visible high-amplitude/low-frequency event of the Top Kyle Group; and
- The importance of the event as part of a functioning petroleum system. For example, the Scremerston Coal Formation represents an important Lower Carboniferous source rock.

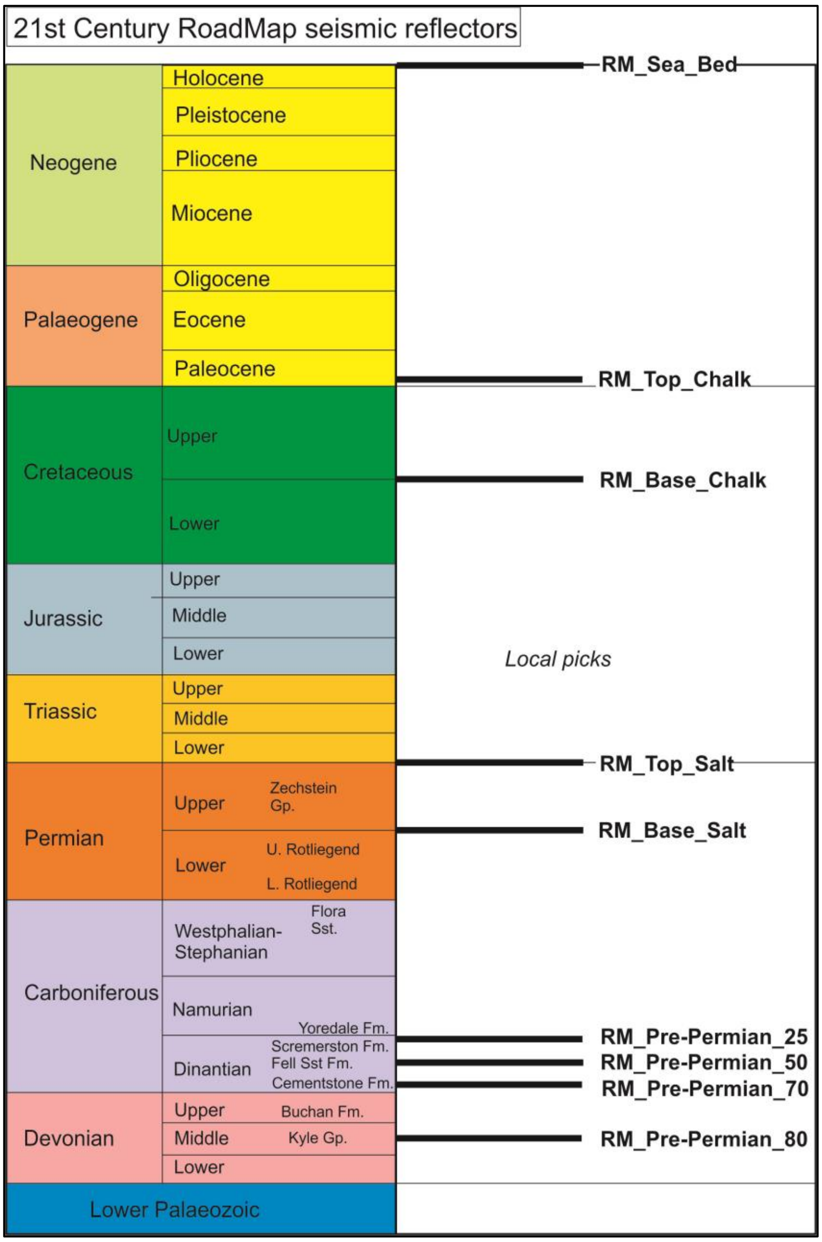

Table 4. Summary of the key seismic horizons used in this study (black bold colour). The Mesozoic and Cenozoic horizons have been imported from previous studies and used for the purposes of depth conversion and production of surfaces of key pre-Permian events.

The Two Way Travel Time (TWTT) interpretations of the following events were exported to ZmapPlus and gridded:

1. Top of the Kyle Limestone Gp (RM_Pre-Permian_80)
2. Top of the Cementstone Fm. (RM_Pre-Permian_70)
3. Top of the Fell Sandstone Fm. (RM_Pre-Permian_50)
4. Top of the Scremerston Fm. (RM_Pre-Permian_25)
5. Base Zechstein. (RM_Base_Salt).
6. Key overlying surfaces were also imported and gridded: Top Permian, Top and Base Chalk and Seabed.

Seismic events listed at 5 and 6 above were compiled from existing interpretations available within BGS (from the BGS-DECC/OGA's OGMRP contract) where possible, and then extended or infilled where no other data was available (see Section 4 for further detail).

The TWTT grids were depth converted and fitted to well tops (see Section 4).

The regional interpretation carried out for this study utilised a large number of diverse seismic datasets and the polarity convention may differ between the different 2D and 3D datasets used. For the pre-Zechstein seismic reflectors, a *specific* seismic reflector could only rarely be interpreted over long distances. Our interpretation methodology combined well to seismic ties, including some validation using synthetic seismic ties, coupled with consideration of the different seismic reflector package relationships.

The character of the seismic reflectors picked within the Devono-Carboniferous is described below.

3.1.2 Top of the Kyle Group (Middle to Upper Devonian) (RM_Pre-Permian_80)

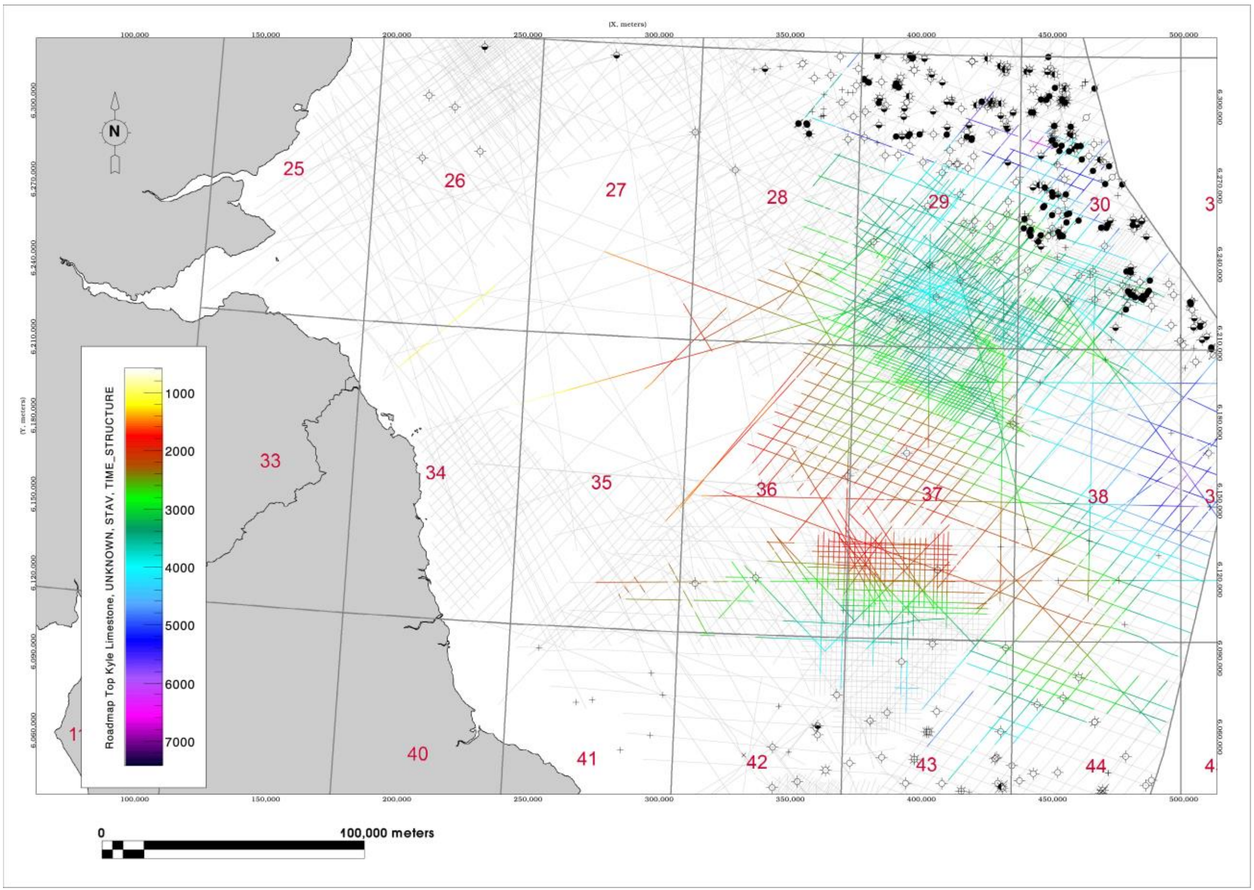

Figure 5 Extent of the seismic interpretation of the Kyle Group interval.

The Top Kyle limestone has been recognised in 5 wells in the study area (Table 2). The Top Kyle Group horizon generates a very distinctive high amplitude/low frequency seismic reflector (e.g. Figures 14 and 15) that has been interpreted across much of the study area (Figure 5). It represents the change upwards from a shallow marine environment characterised by intercalations between limestone and mudstone of the Kyle Group to a clastic upper Devonian succession.

The Kyle Group was chosen as the deepest seismic reflector picked for the study, although in certain areas deeper reflectors of probable Silurian or older age may be identified. These older events are termed the 'basement'.

3.1.3 Near Base Visean - Top Cementstone Formation (Lower Carboniferous) (RM_Pre-Permian_70)

The Top Cementstone Formation has been recognised in 8 wells in the study area (Table 2) and has been interpreted over much of the area (Figure 6). This horizon represents the contact between the top of the Cementstone Formation and the base of the Fell Sandstone Formation. The top of the Cementstone Formation is not defined by a single continuous seismic reflector rather it is marked by a change from a seismic package comprising higher amplitude relatively continuous reflectors to lower amplitude less continuous reflectors beneath (Figures14, 21 and 22). The upper part of the Cementstone Formation generally consists of intercalations of limestone, dolomite and sandstone.

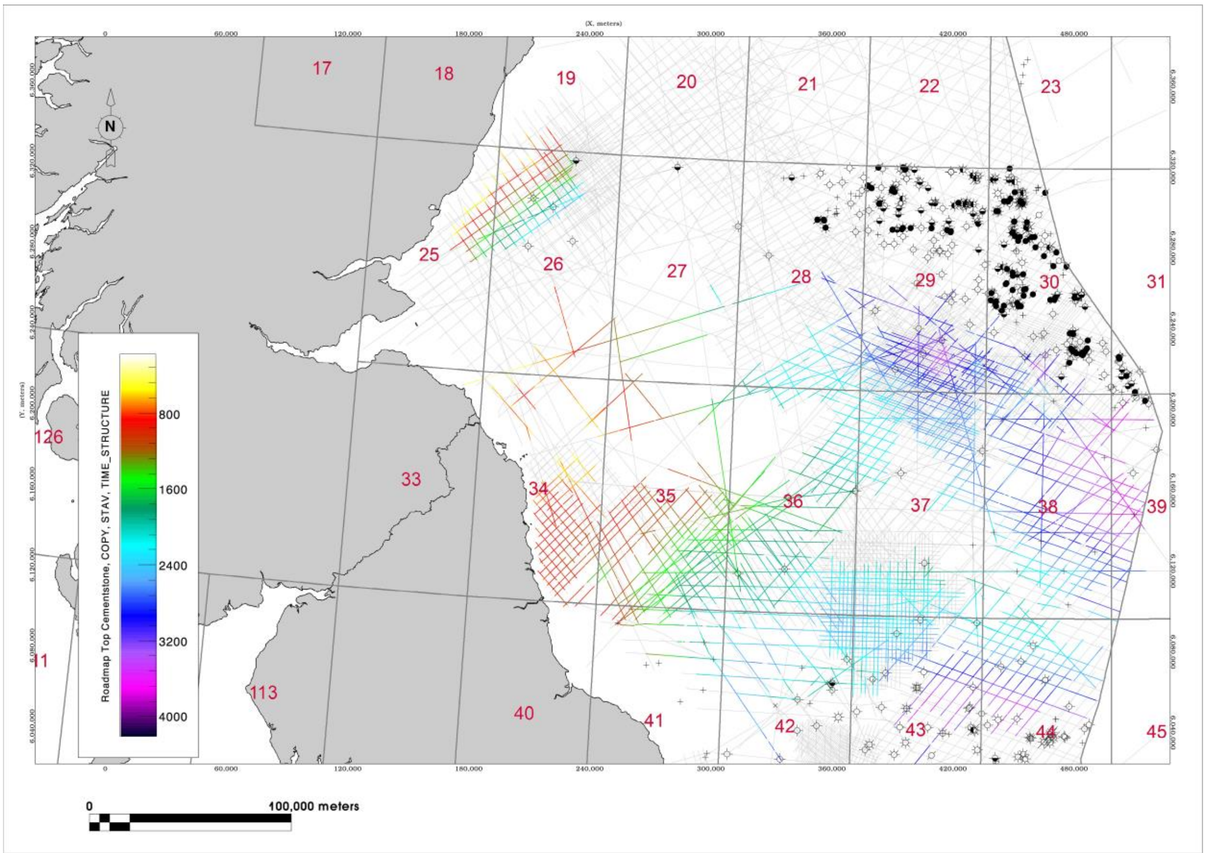

Figure 6. Extent of the seismic interpretation of the Cementstone interval.

3.1.4 Top of the Fell Sandstone Formation (Lower Carboniferous) (RM_Pre-Permian_50)

The Top Fell Sandstone Formation has been recognised in 9 wells in the study area (Table 2). The interpretation of this event was based on the contrast between the seismic response from the sandstone facies of the Fell Sandstone Formation and the response from coal facies of the overlying Scremerston Formation. (Figures 14 and 15). The Fell Sandstone is interpreted to be present over a large part of the study area, with highly variable thickness usually infilling the pre-existing topography (Figure 7). For example, it thickens southwards in Quadrants 42 and 43.

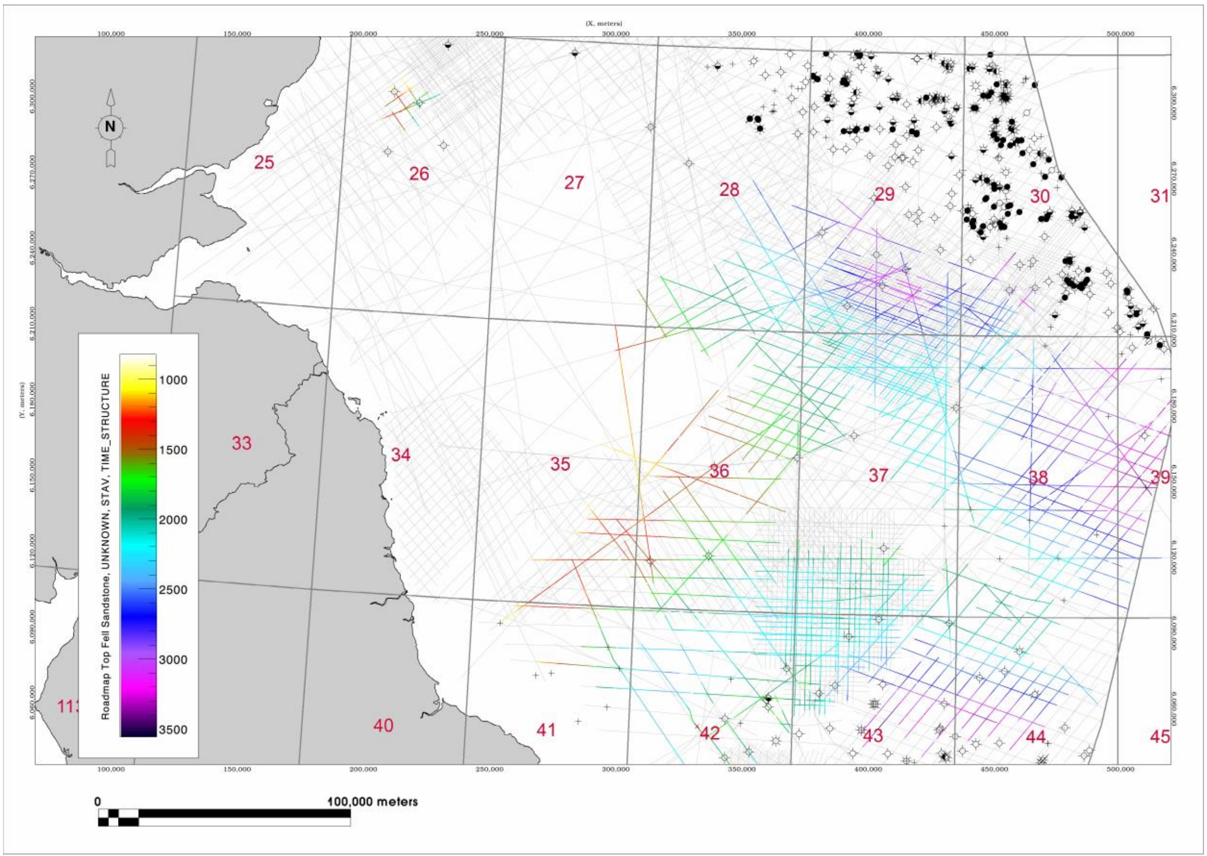

Figure 7. Extent of the seismic interpretation of the Fell Sandstone interval.

3.1.5 Top of the Scremerston Formation (Lower Carboniferous) (RM_Pre-Permian_25)

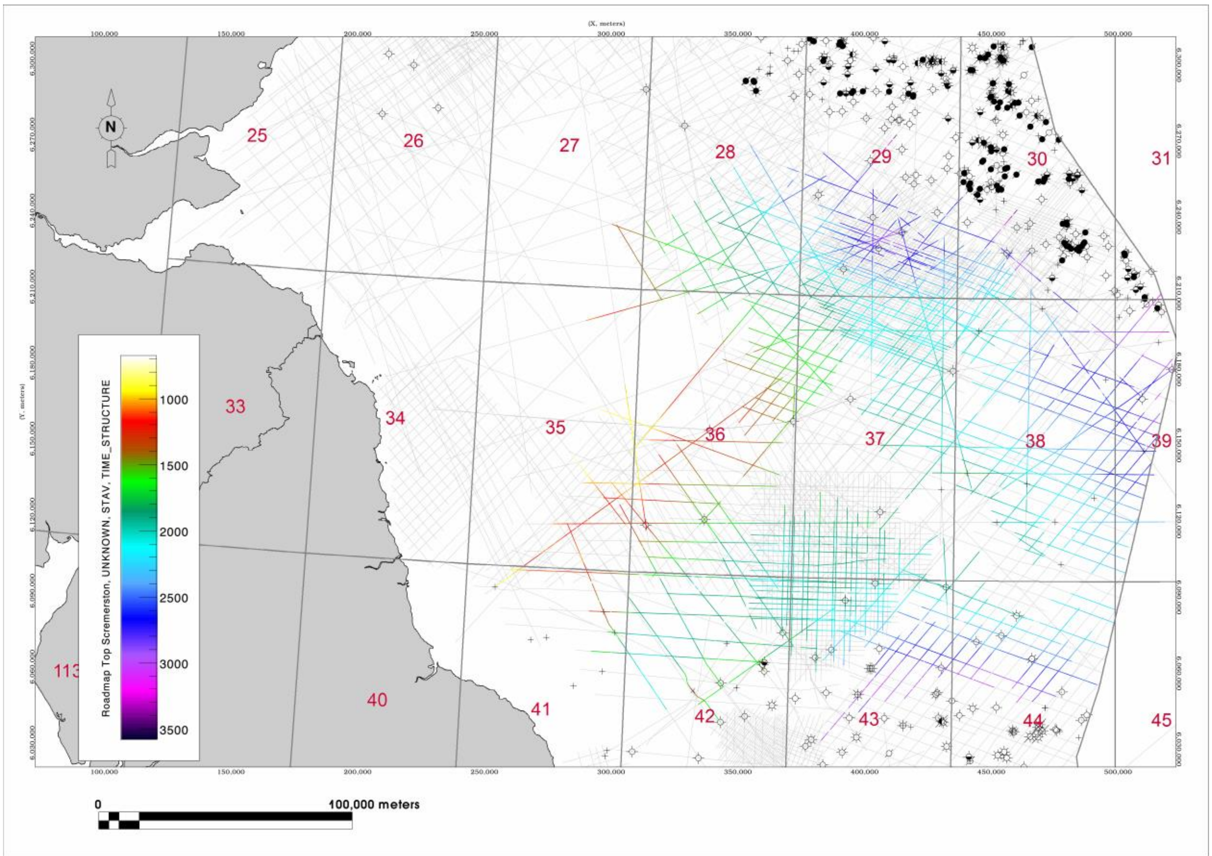

Figure 8. Extent of the seismic interpretation of the Scremerston Formation interval.

The Top Scremerston Formation has been recognised in 13 wells in the study area (Table 2). Where present, the Scremerston Formation is usually visible as a high amplitude/ high frequency reflector seismic package due to the presence of intercalated coals, and the horizon was picked on top of this package. In some cases Scremerston Formation strata have been folded and truncated by younger unconformities, such as the Base Permian Unconformity (e.g. in Quadrant 42).

3.1.6 Zechstein Group (Upper Permian) (RM_Base_Salt)

The Zechstein Group forms a regional cover over the pre-Permian strata across much of the study area. It has a distinctive seismic character, with high amplitude reflectors marking the top and base of the Group and relatively transparent seismic facies within the body of the Group, due to its dolomite, anhydrite and evaporite lithologies. In Quadrant 38, where the Group is thinnest, it consists primarily of dolomite and anhydrite (Kearsey et al., 2015). This thickness difference was a particularly important aspect that had to be taken into account during the depth conversion process, which is described in detail in Section 4. The top of the Group is marked by the presence of distinctive halokinetic diapiric structures.

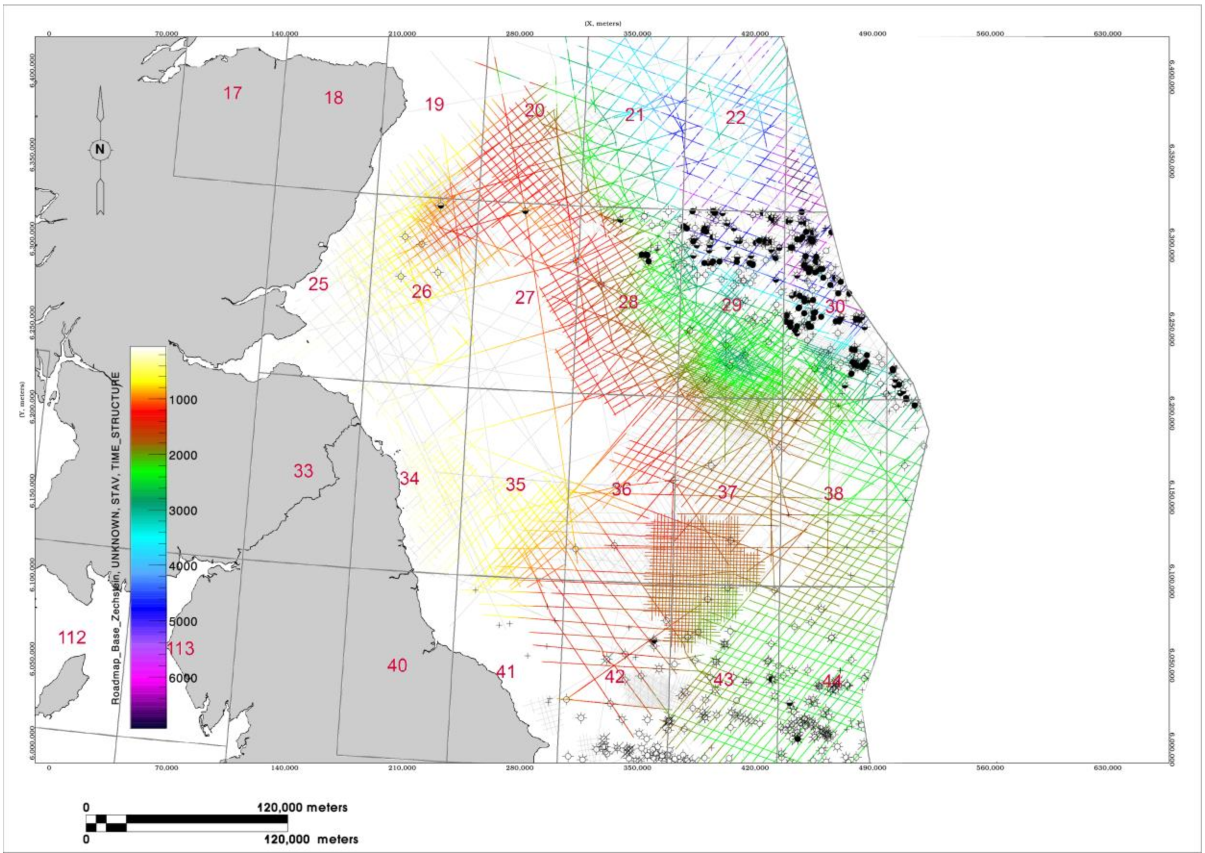

Figure 9. Extent of the seismic interpretation of the Zechstein interval.

3.2 CHALLENGES DURING THE INTERPRETATION

There proved to be six major challenges during seismic interpretation:

- Limited well penetration of the Palaeozoic sequence. Wells were usually drilled into the structural highs and typically contained one or more significant unconformities, for example Devonian strata at subcrop to the base Zechstein or base Permian;
- Poor seismic coverage over Quads 26, 27, 34, 35, 36, 41 (Figure 1);
- Low reflectivity of the deep, Palaeozoic seismic interval;
- Uneven seismic data spacing between the various surveys' profiles (spanning from 2 to >10km);
- Lack of velocity information and time-depth pairs for a number of wells, reducing the number of well ties to seismic;
- It was beyond the scope of the project remit to pick the often poorly-imaged Rotliegend succession, Base Permian Unconformity and locally extensive horizons of the Carboniferous (e.g. top Yoredale Formation, horizons within the Coal Measures).

3.3 SEISMIC INTERPRETATION OF SOUTH, CENTRAL AND EASTERN PART OF CENTRAL NORTH SEA AREA (QUADRANTS 28-30, 35-44)

3.3.1 Previous work

The area included in these Quadrants has been described previously by Cameron et al. (1993), Gatliff et al. (1994), Hay et al. (2005) and Milton-Worssell et al. (2010). However, there is little published information about the Palaeozoic interval and most structural maps are blank or lack detail north of Quadrants 36 to 44. Regionally, the area is characterised by an elevated sub-surface topography, the Dogger Granite High, which separates deeper basins to the north and to the south of the granite. The stratigraphy of the southern basin is analagous to the Southern North Sea province where Carboniferous (Westphalian) gas has been one of the major targets of the oil industry. The northern basin (North Dogger Basin) remains relatively unknown in the area between the granite high and the Auk/Flora Ridge in Quadrants 29-30.

The North Dogger Basin has been characterised as a deep Palaeozoic basin (Milton-Worssell et al., 2010) and shows indications for hydrocarbon presence:

- shallow gas chimneys – Hay et al. (2005);
- gas shows – well 38/16-1; and
- poor oil shows – well 39/07-1.

The focus of the study was to better constrain the Palaeozoic structure and the geometry of the Devono-Carboniferous intervals. Figure 10 shown below summarises the regional structure based on the seismic interpretation carried out for this study.

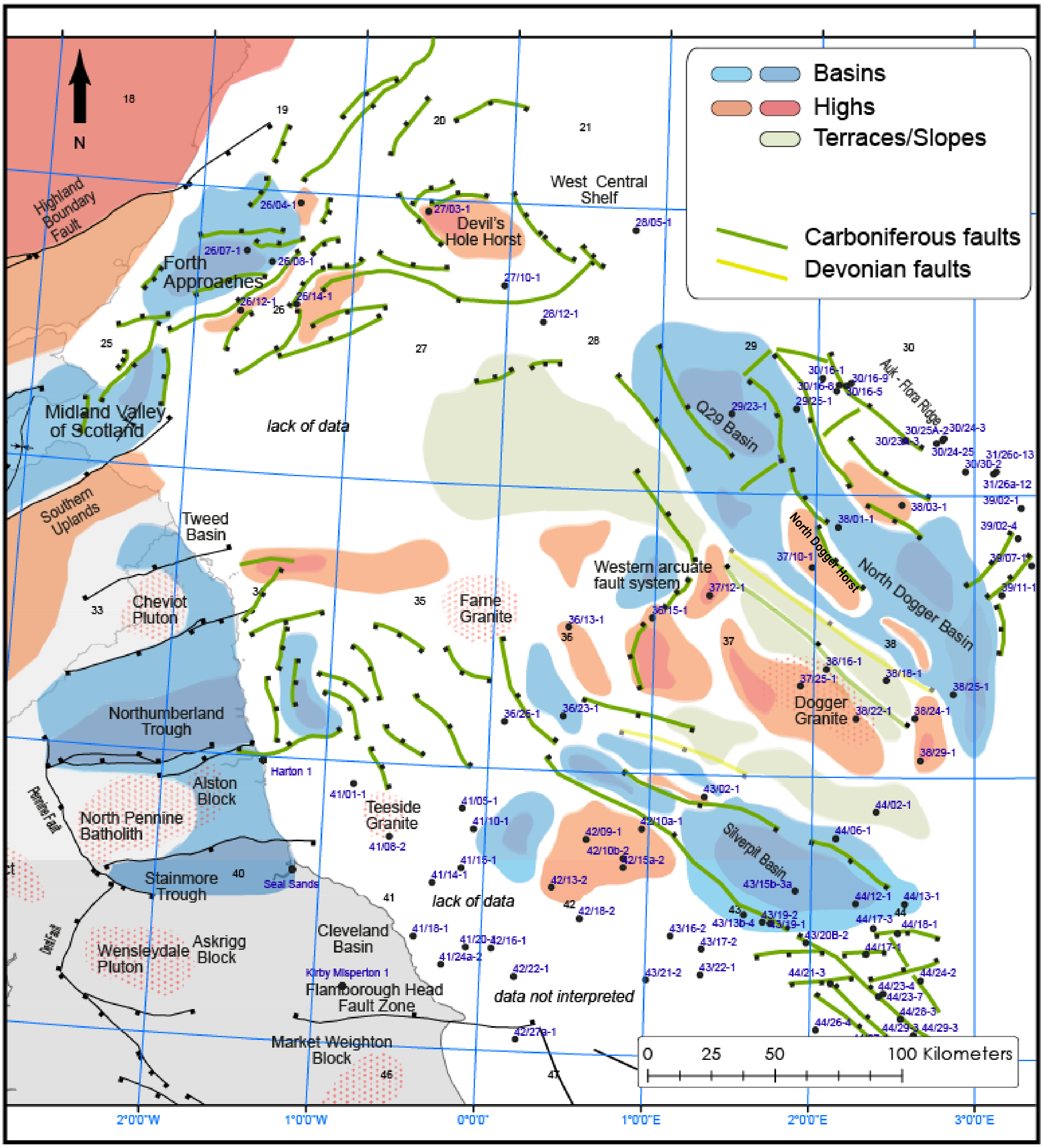

Figure 10. Regional structural diagram of the Central North Sea based on the seismic interpretation of the present study.

3.3.2 Selected Seismic Profiles

Four seismic profiles have been selected as representative of the Palaeozoic geometries of the area (Figure 11).

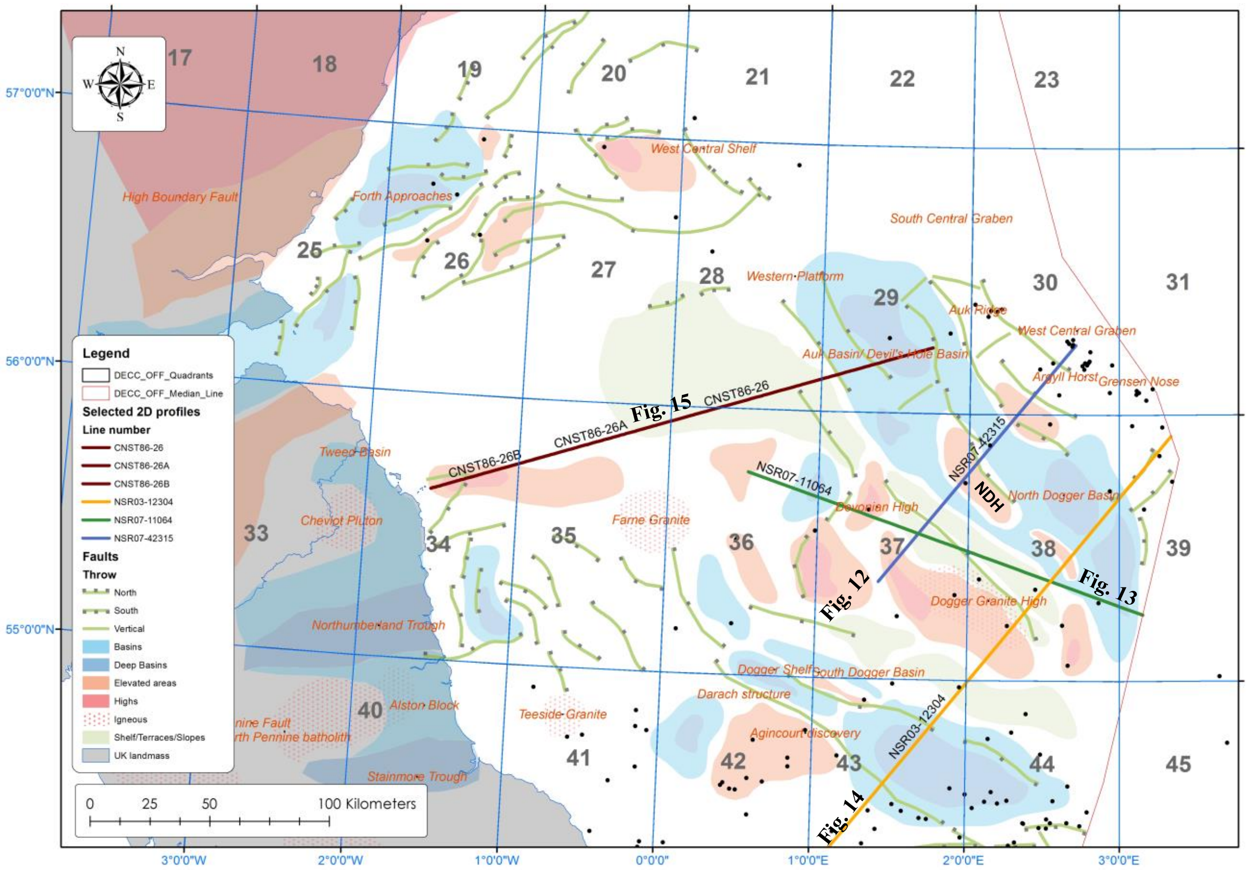

Figure 11. Basemap showing the location of selected seismic profiles over study area. Figures in which profiles are shown are numbered. NDH is the North Dogger Horst.

Quadrants 37, 38 and 30

Figure 12 shows a key seismic line drawing, based on seismic line NSR07-42315, representing a typical geometry of the area, with condensed sequences on the highs and significantly thicker successions in the basins. Intervals of Upper Devonian and Lower/Middle Carboniferous infill the available accommodation space.

The line drawing (Figure 12) cuts SW-NE across the northern edge of the Dogger Granite High, into a deep basin, the North Dogger Basin, an intra-basinal horst block (named here the North Dogger Horst) and the Auk Ridge. The main features of note are the deep Devono-Carboniferous basin of up to 2-2.5 TWT seconds thickness, and the intra-basinal structural high. Stratigraphic constraint on the top Scremerston pick is approximately 50km away in well 39/07-1. Stratal growth/fault growth is interpreted between the Upper Devonian and Visean (Fell Sandstone) intervals.

Quadrants 36, 37, 38, 39

This line drawing, based on seismic profile NSR07-11064 runs in a WNW-ESE direction along the Dogger Granite High and crosses its eastern flank (Figure 13). Starting from the WNW the main elements are the thick Carboniferous basin and the Dogger Granite High where the Carboniferous intervals onlap on the High. The basin and the High are offset by a high angle fault, which forms part of a NE trending strike slip fault-zone. Towards the ESE edge of the line is a substantial (>1000 ms) thickness of the Upper Devonian and Lower Carboniferous sediments to the east of the Dogger Granite High.

Quadrants 43, 38, 39

The selected SE – NW profile (seismic section NSR03-12304), cuts across the Dogger Granite High, illustrating both its southern and northern flanks (Figure 14). The most notable features in this profile are the deep Devono-Carboniferous basins on both sides of the Dogger Granite. The well control is better on the southern flank of the High. Fault movements can be dated as primarily late Devonian/earliest Carboniferous, followed by reactivation induced by Variscan inversion and the development of NW trending folds. Finally, some of these faults were reactivated in Permian times, and offset the Zechstein intervals. Northeast of the high, steep normal faults are interpreted rooting in the deep basin northeast of the High, resulting in downstepping of the Palaeozoic picks.

Quadrants 35, 28 and 29

The selected composite profile, based on seismic lines CNST86-26, 26A and 26B, runs in a WSW-ENE direction (Figure 15) across the Mid North Sea High. Devono-Carboniferous reflectors defining a 1500 ms thick basin in Quadrant 29 gradually thin and shallow to the southwest. Well control on pre-Permian reflectors is poor in the southwestern part of the area; the nearest wells being in Quadrant 36 (36/13-1 and 36/15-1), approximately 50 km away.

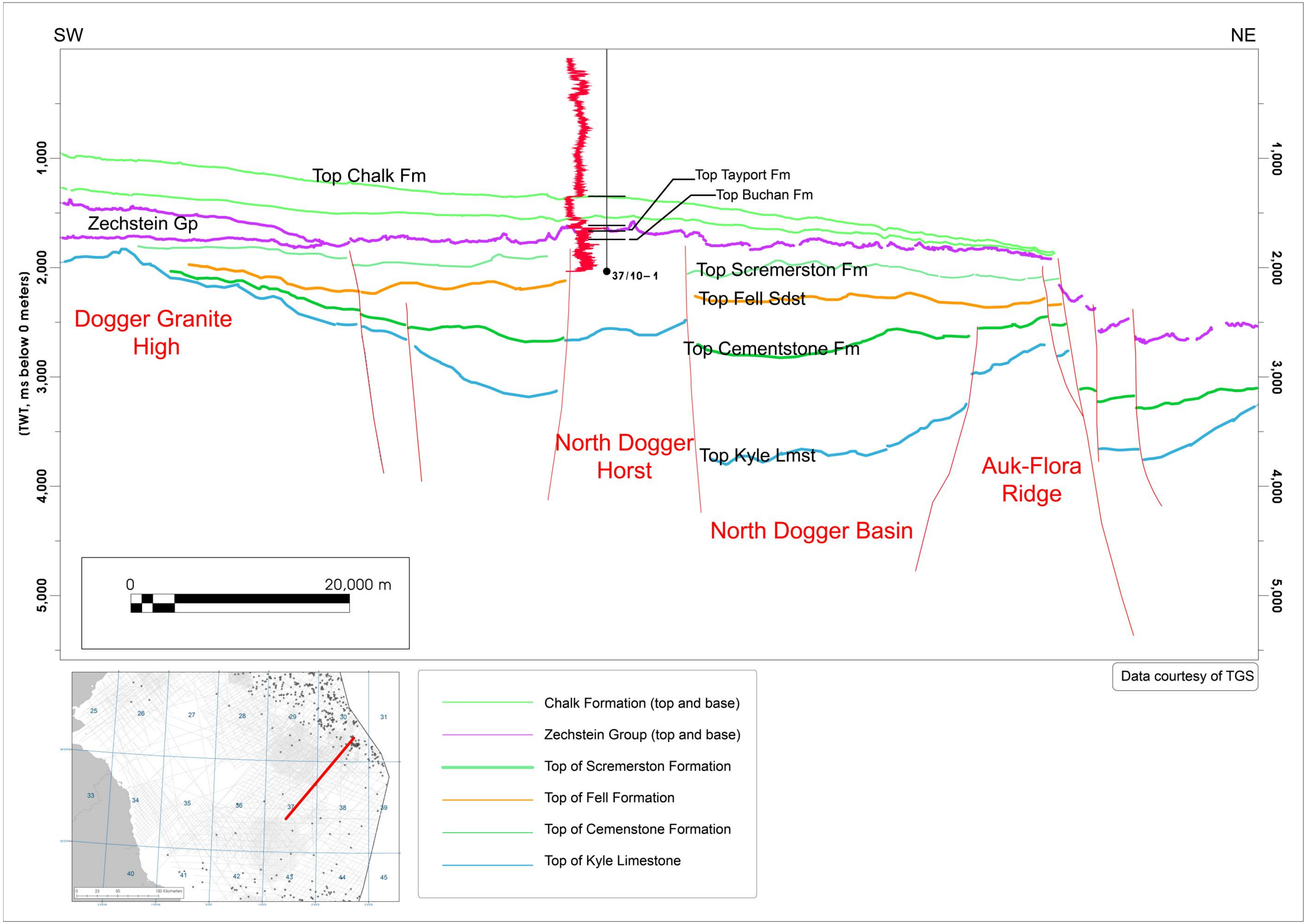

Figure 12 Selected profile cutting across Quadrants 37, 38 and 30. See Figure 11 for profile location in structural context.

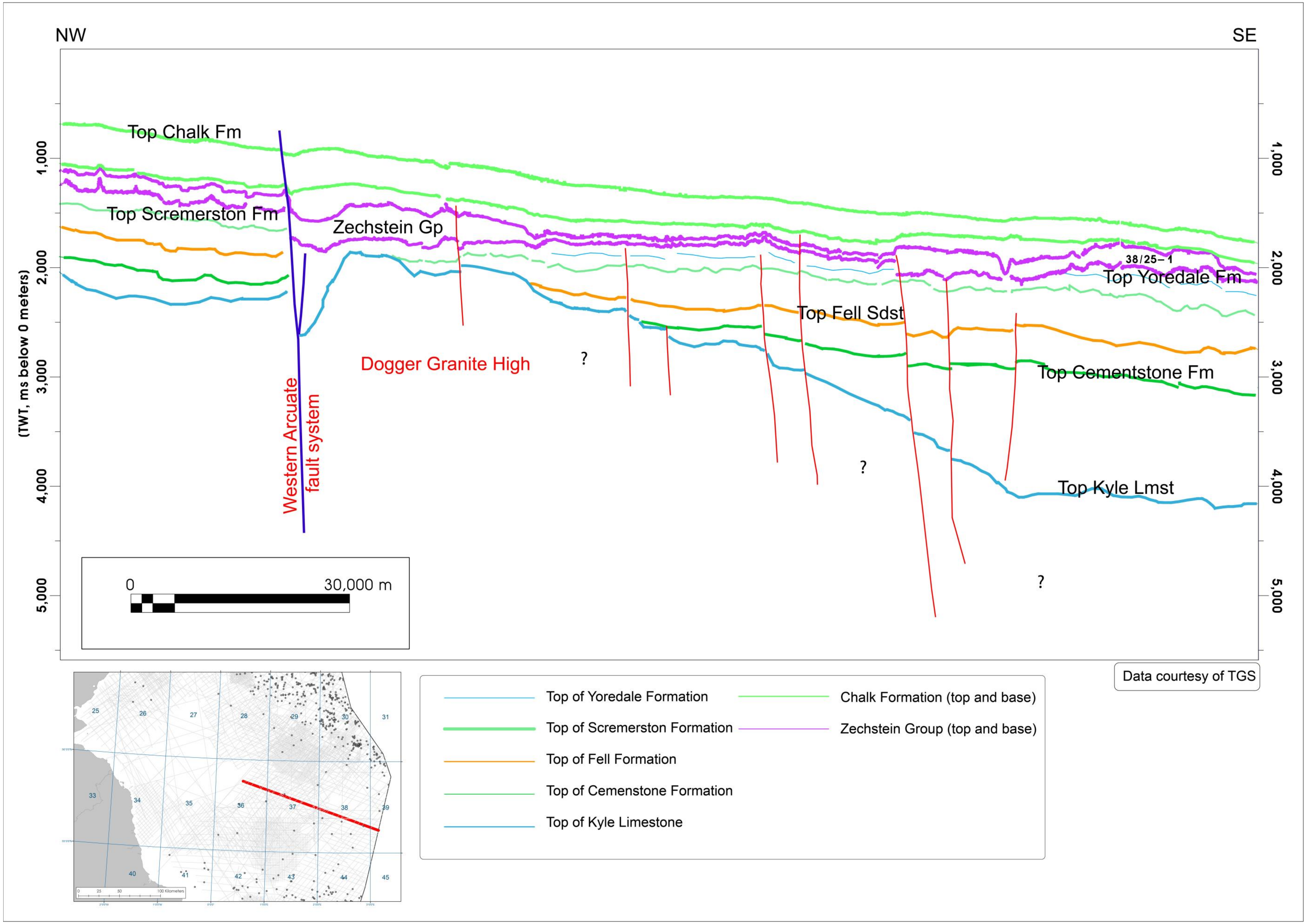

Figure 13 Selected profile cutting across Quadrants 36 to 39. See Figure 11 for profile location in structural context.

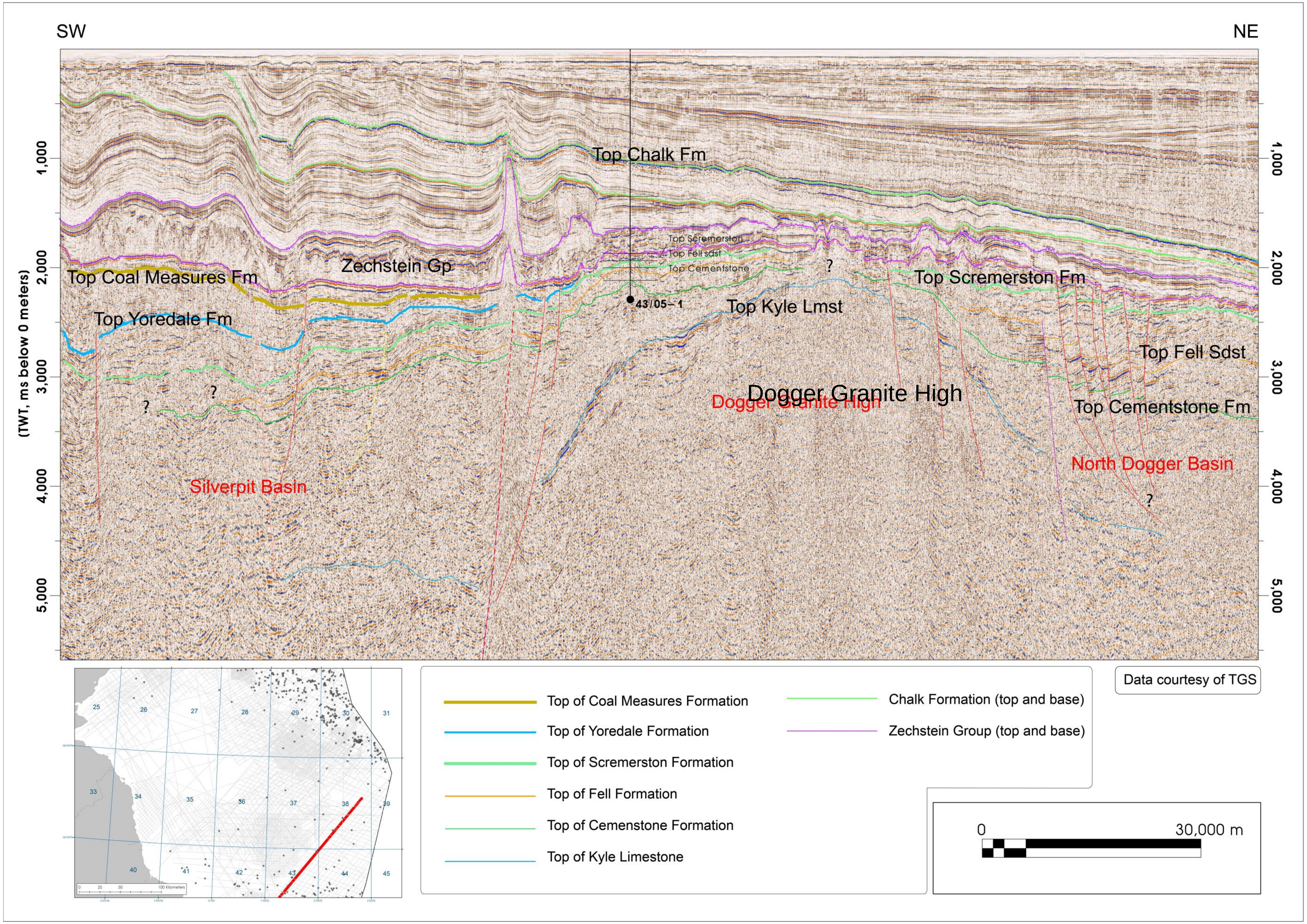

Figure 14 Selected profile cutting across Quadrants 43, 38 and 39. See Figure 11 for profile location in structural context.

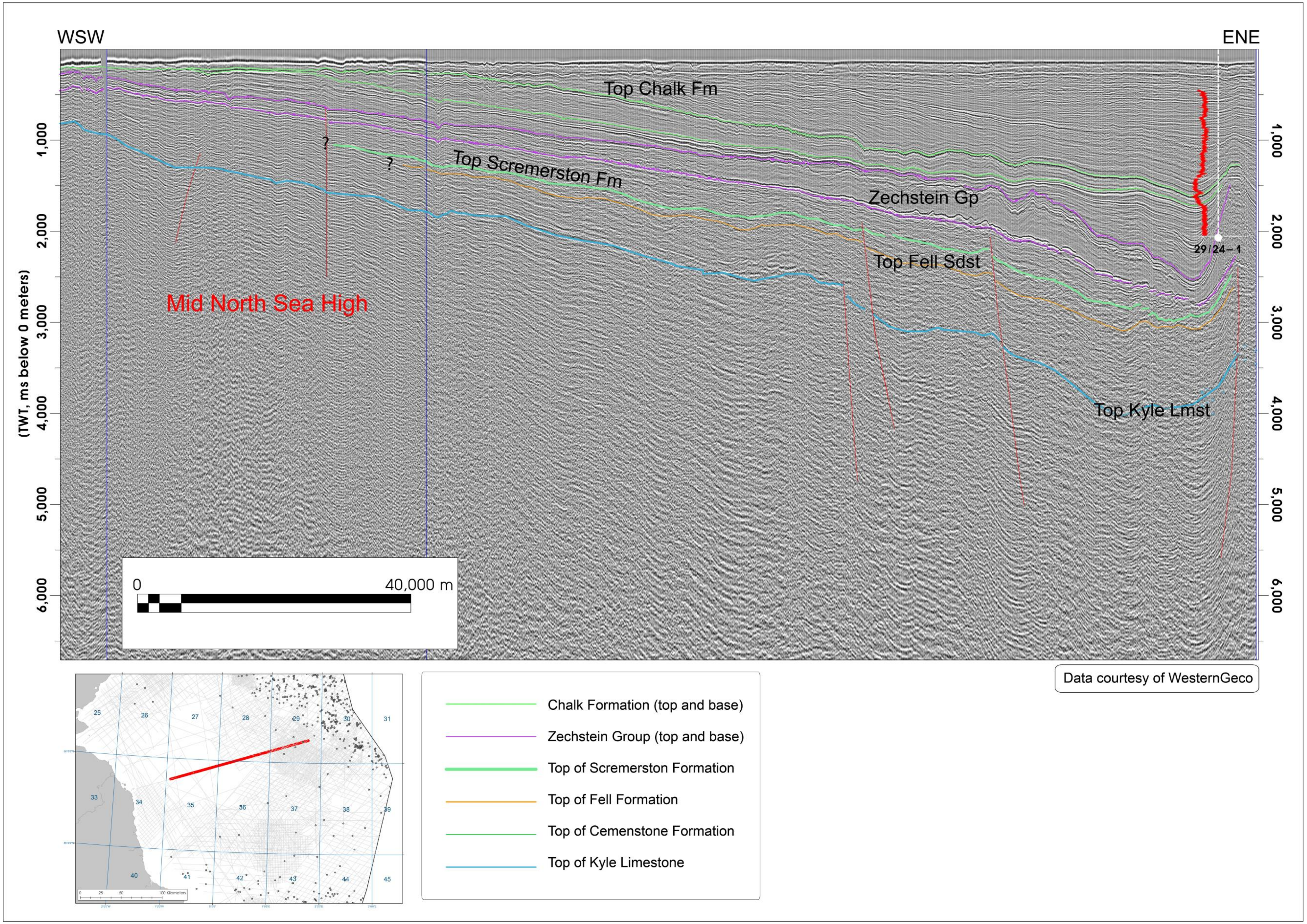

Figure 15 Selected profile across Quadrants 35, 28 and 29. See Figure 11 for profile location in structural context.

3.3.3 Structural Observations

Some general observations on the structures defined across Quadrants 29, 30, 31, 37, 38 and 39 include:

- The Middle-Upper Devonian basins and structural highs follow a NW-SE trend across Quadrants 29-30-37 and 38;
- A significant number of wells were drilled into the structural highs where the Devonian subcrops the Permian. Lower Carboniferous sequences (Tournaisian and Visean) are unpenetrated but the seismic interpretation work indicates strongly their presence in the adjacent depocenters across much of the Quadrant 29 to Quadrant 38 area (for example the well 37/10-1 in Figure 12). Wells 38/16-1, 38/18-1, 38/22-1 and 38/24-1 penetrate the Carboniferous and constrain the edge of the Lower Carboniferous basins. The 37/10 -1 intra-basinal high, the North Dogger Horst, separates the deep graben which is present in the intersection of Quadrants 29, 30, 37 and 38 into two smaller sub-basins (Figure 12);
- The North Dogger Horst is located at the northeast corner of Quadrant 37 and the southeast extremity of Quadrant 29 and is a buried positive structure following a NNW-SSE trend. This has a similar geometry to the Auk ridge. Interpretation of the 37/10-1 well drilled on this ridge shows that Upper Devonian and Lowermost Carboniferous rocks lie directly below the Permian. There are two possible scenarios to explain this hiatus:
    - the favoured scenario is that the structure was emergent during Middle-Upper Carboniferous times (thus controlling the depocentres) with no or minimal deposition of Carboniferous sediments followed by burial in Early Permian;
    - alternatively, the Devonian interval may be interpreted to have been faulted post deposition (Figure 12) and provides evidence for another possibility, namely that Lower Carboniferous rocks were deposited and then eroded during Variscan inversion;
- There is a structurally complicated area in the southernmost part of Quadrant 38 comprising a folded Carboniferous Visean, and possible minor Namurian succession. A detailed interpretation has not been resolved from the seismic, and the structure can be interpreted either as an anticline rollover on a low-angle fault, or as a compressional anticlinal fold. The structure trends broadly NNE-SSW, plunging northwards into Quadrant 38 (Figure 16 and Figure 17).

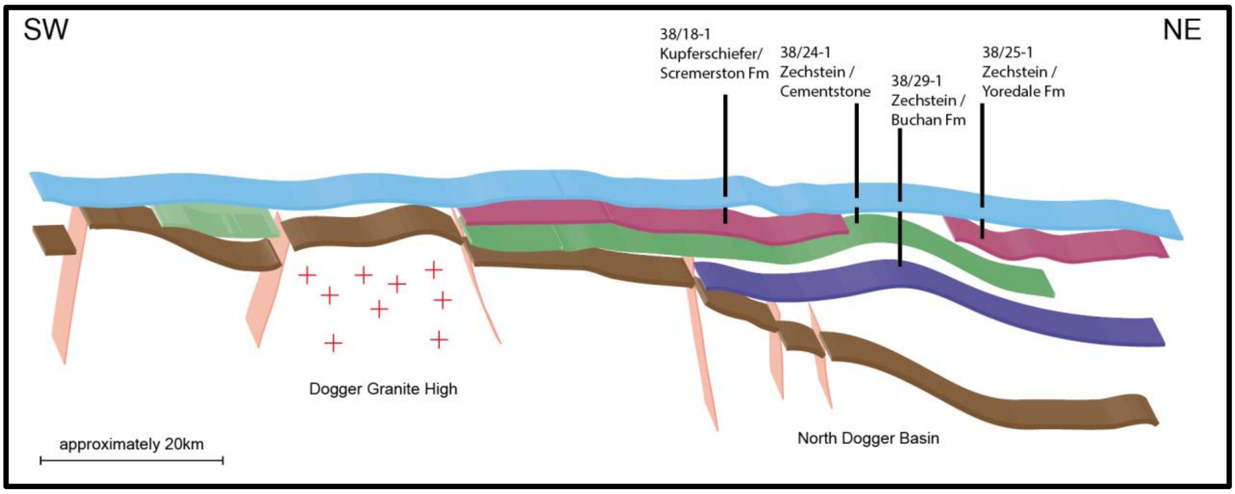

Figure 16. 3D sketch illustrating the anticlinal structure over the northern flank of the Dogger Granite High in southern part of Quadrant 38. Approximate line of sketch shown as dashed line in Figure 17.

- This NNE-trending anticlinal structure is expressed in the pre-Permian subcrop map (Figure 17), whilst away from the crestal part of the anticline, younger sequences are preserved below base Permian unconformity. The interpretation has reasonable well control with identified Tayport Formation in well 38/29-1, Cementstone Formation in well 38/22-1, Scremerston Formation in well 38/16-1 and the Yoredale Formation in well 38/25-1 (Figure 17). The anticline is oblique to the general WNW-ESE trend of the Dogger Granite High;

- The granite high seems to influence the structural geometry of the Devono-Carboniferous succession close to the south-west edge of Quadrant 38, where it gradually onlaps. Similar control by granitic intrusions have been observed onshore; an example is the Cheviot Pluton as it appears to constrain the locus of folding (Leslie et al., 2015);

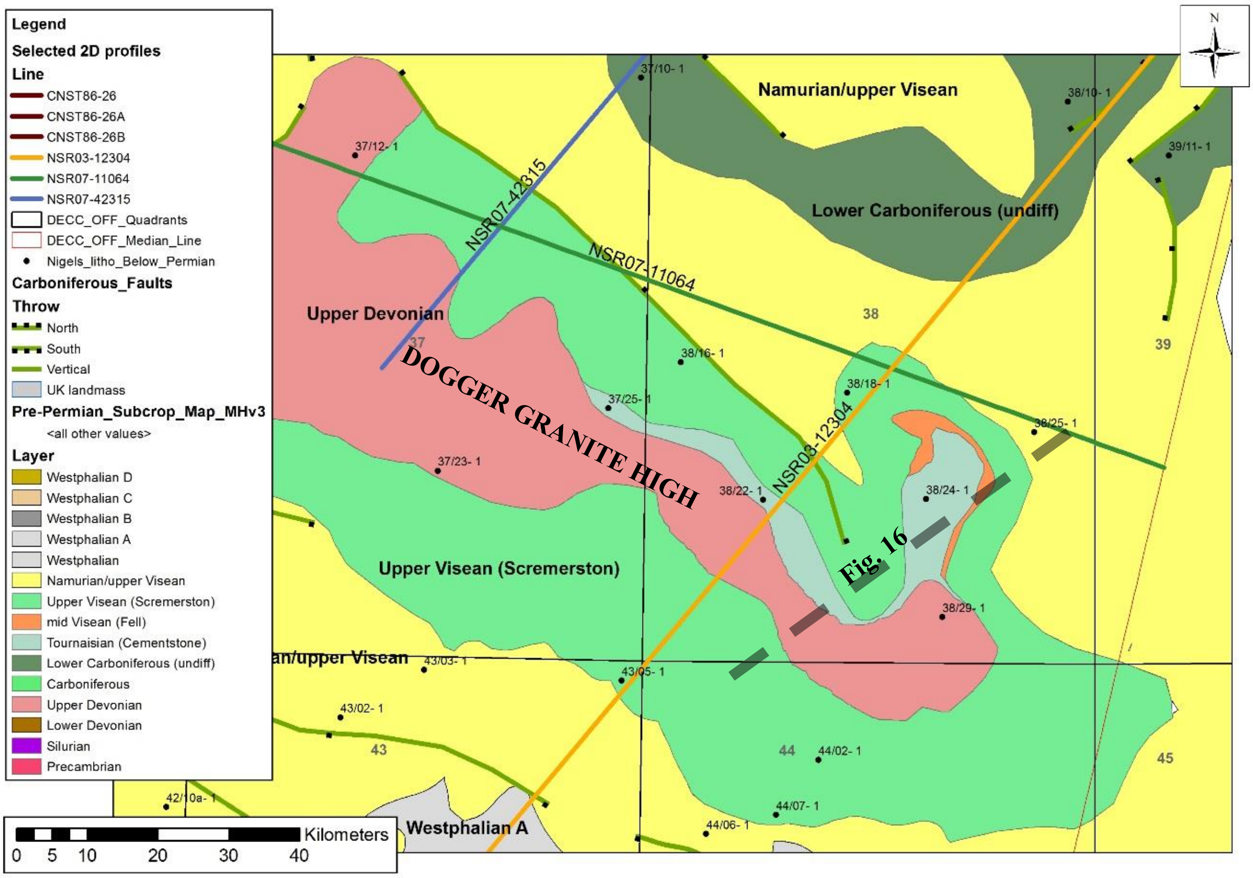

Figure 17. Detail from the pre-Permian subcrop map illustrating the NNE-trending anticlinal structure at a high angle to the Dogger Granite High in Quadrants 37 and 38.

- In the Dutch sector, just east of the median line in Quadrant 39, structures similar to the anticline are interpreted as transpressional (EBN, personal communication);
- Based on structural interpretation of 3D seismic volumes, there is evidence for a strike-slip fault zone trending NE-SW in the area between the southern edge of Quadrant 29 and the south-western domain of Quadrant 30 (Figure 10). To the northeast the fault is interpreted to terminate at the Auk Ridge. To the southwest, this fault continues into Quadrant 36 (the major vertical fault illustrated in Figure 10 and Figure 13). This fault system has been previously described as the “Western arcuate fault system” by Jenyon et al., 1985; it is not observed further south than Quadrant 36.

Across Quadrants 41-44, the geometry of the structures interpreted from seismic data include:

- South of the Dogger Granite high, the basin depositional trend was broadly E-W during Middle-Upper Devonian. It has been overprinted by a NW-SE to WNW-ESE fault trend (Quadrants 42-43) of questionable Late Carboniferous age (Figure 10);
- Small scale folding (wavelengths of 10-15km) of the Carboniferous strata is more concentrated within Quadrants 42 and 43 than Quadrants 37, 38 and 39 (example in

Figure 14). Typically, the fold axes trend NW-SE. In most of the cases the crestal area of the anticlinal structures have been truncated by the Base Permian Unconformity.

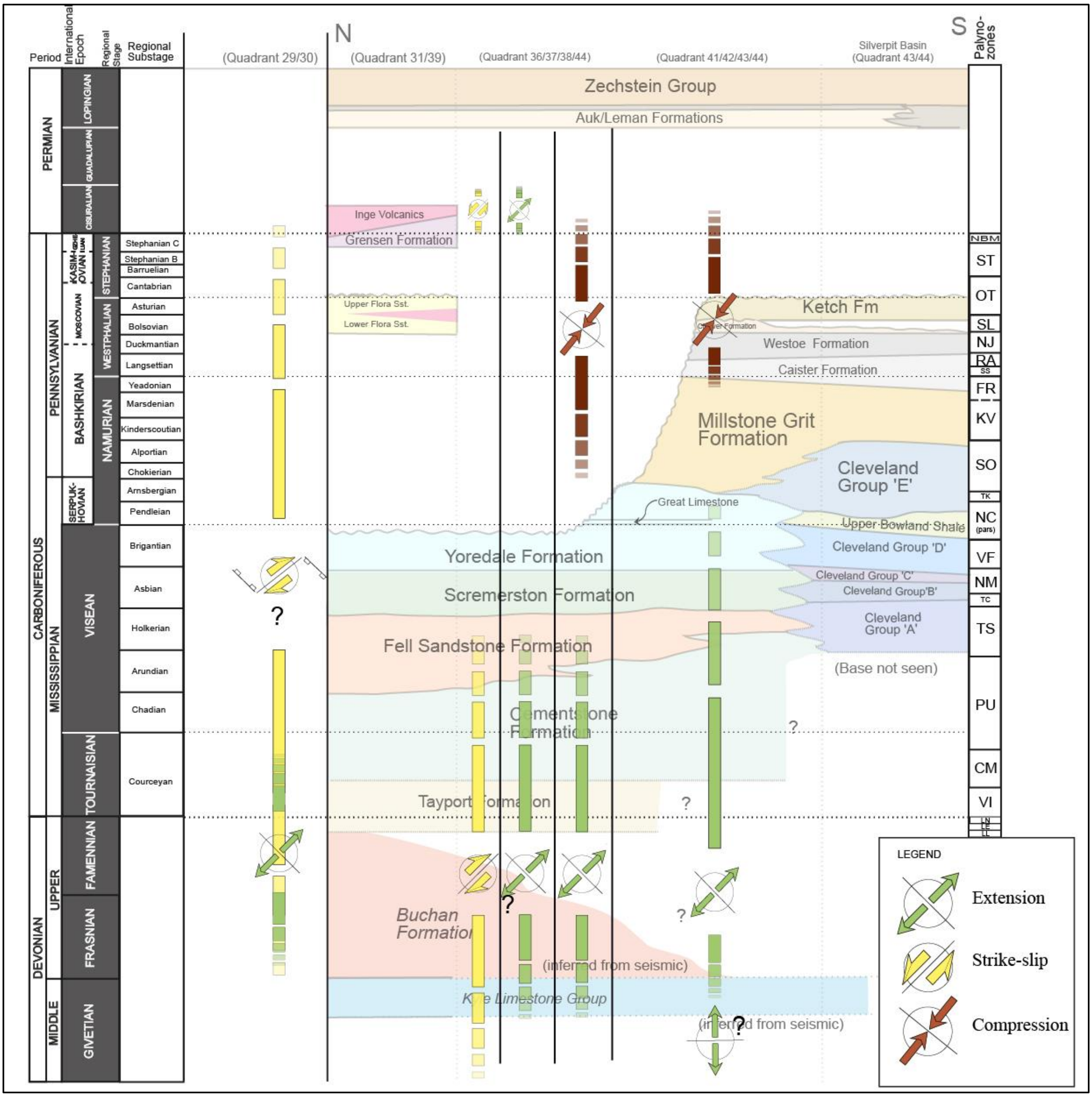

Figure 18. Tectono-stratigraphic framework summarising the timing and general trends of the structures observed on seismic profiles.

3.4 SEISMIC INTERPRETATION OF THE OFFSHORE EXTENSION OF THE NORTHUMBERLAND TROUGH

3.4.1 Previous work

The Northumberland Trough is an ENE-trending early Carboniferous Basin bounded to the north and south by structural highs (the Cheviot and Alston blocks respectively), the latter underpinned by low density granitic intrusions (Kimbell et al., 1989; Chadwick and Holliday, 1991; Figure 10). The offshore extension of the Northumberland Trough covers the southern blocks of Quadrants 34 and 35 (Figure 19).

A Caledonian shear-zone, interpreted onshore by Chadwick and Holliday (1991) was reactivated during crustal extension in latest Devonian to early Carboniferous times (Collier, 1989). Subsidence of its hangingwall block was accompanied by the formation of E- to ENE- trending syn-sedimentary faults (e.g. the *en-echelon* Stublick and Ninety Fathom faults) (Figure 19 and Figure 20), and initiation of the Northumberland Trough (Chadwick and Holliday, 1991; DePaola et al., 2007). The Stublick and Ninety Fathom faults (Figure 19 and Figure 20) mark the southern margin of the Basin and display syn-depositional extensional faulting in the Lower Carboniferous strata, with up to 4 km of Dinantian sediments adjacent to the fault system contrasting with only 1.5 km of coeval strata to the north (Kimbell et al., 1989; DePaola et al., 2007).

Rifting ceased by the end of the Dinantian (after Brigantian times) and Namurian and Westphalian sediments were deposited in a thermally subsiding basin. Post-Westphalian, pre-Permian compressional deformation and inversion took place with the formation of NE- to NNW- trending folds and faults (Collier, 1989). The folds do not deform the overlying Permian succession and are therefore related to Variscan compression (Collier, 1989). De Paola et al. (2007), through detailed interpretation of onshore outcrops, suggested a single phase of dextral transtensional deformation to account for the distribution and orientation of the mapped structures formed during this Variscan inversion episode. The relatively wide spacing of the interpreted seismic data precludes definitive comparison, but our evaluation strongly suggests strike-slip movement on faults.

NE-SW extension, related to the development of the Northern North Sea Basin, dominated the basin evolution from ?Early/Late Permian through to the Tertiary (Collier, 1989).

3.4.2 Dataset

The seismic interpretation was carried out on two nearshore surveys (prefixed NT- and NO-) and a small number of more regional 2D lines to infill data gaps in seismic coverage (Figure 19). There are no wells drilled within the offshore extension of the Northumberland Trough.

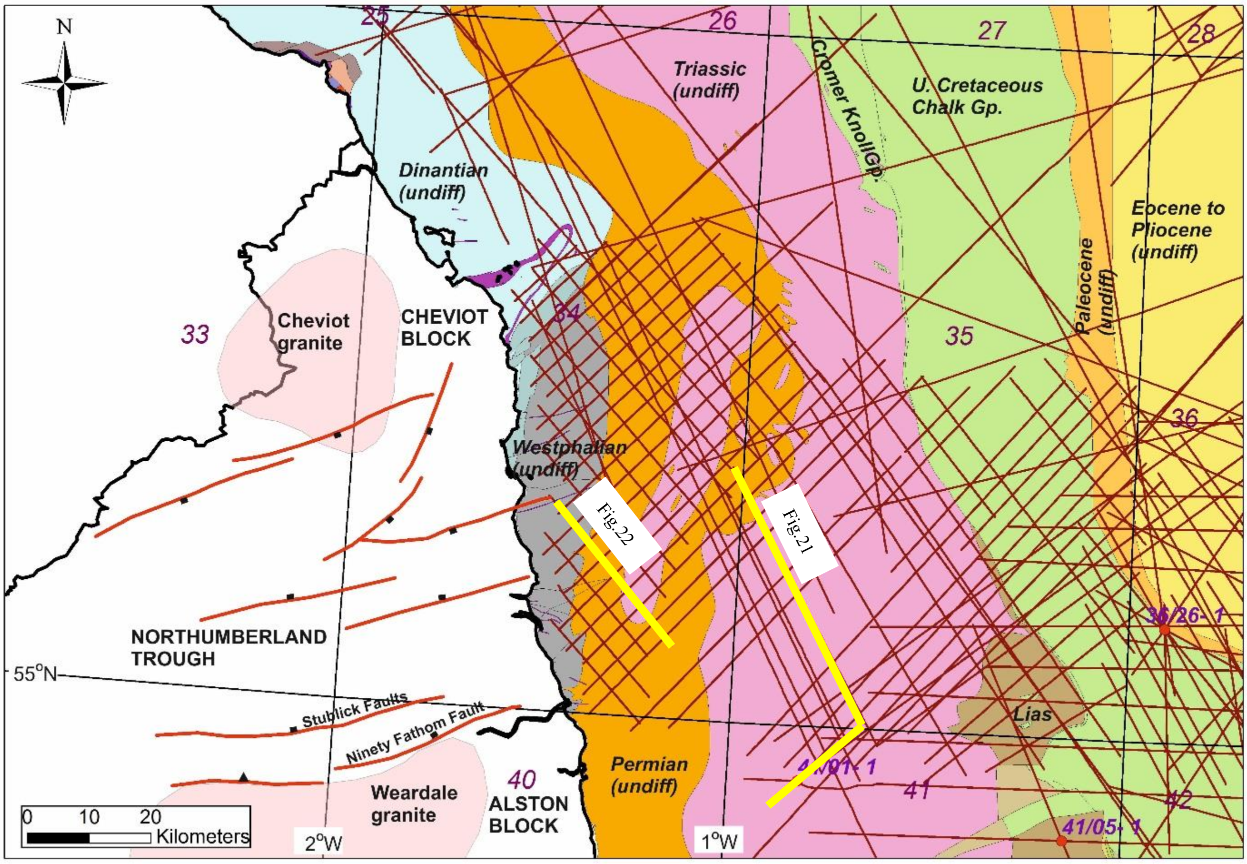

Figure 19. Seismic and well dataset utilised in the interpretation of the offshore extension of the Northumberland Trough. Also shown is bedrock at sea bed. Selected structure onshore taken from Chadwick and Holliday, 1991.

Geological horizons were tied to Well 41/01-1 south of the basin, which reached the Lower Carboniferous Cementstone Formation. An understanding of the offshore succession was gained with reference to onshore wells and several publications.

3.4.3 Seismic interpretation

Carboniferous rocks subcrop the sea bed adjacent to the Northumberland coast and are succeeded by Permian and Triassic, Jurassic and Cretaceous successions eastwards (Figure 19). Where present, Top Chalk, Base Chalk, Top Zechstein and Base Zechstein seismic reflectors were interpreted for the purposes of depth conversion (Section 4).

The pre-Permian subcrop map shows Westphalian and older Carboniferous rocks including a North trending syncline (Figure 20). The nearest well to the study area, 41/01-1, lies to the south and records a Carboniferous succession comprising 159 m of Cementstone Formation sediments overlain by 128 m of Fell Sandstone Fm, 380.5 m of Scremerston Fm. and 777 m of Visean Yoredale Formation. By analogy with onshore successions and 41/01-1, it is expected that a thick succession of Carboniferous sandstone, coal, mudstone and limestone will be present within the offshore part of the Northumberland Trough.

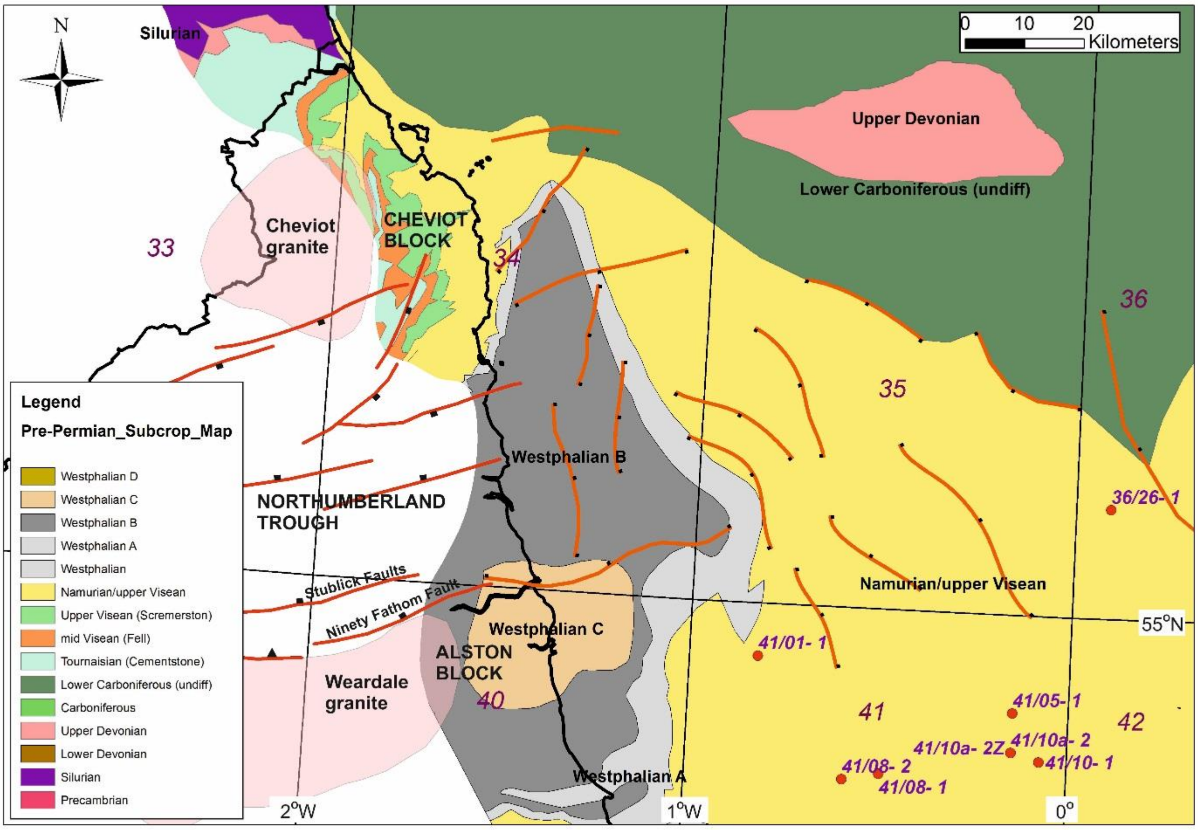

Figure 20. Pre-Permian subcrop map in offshore extension of Northumberland Trough. Selected structure onshore taken from Chadwick and Holliday, 1991.

The quality of the seismic image on the two main selected surveys (NT- and NO-) was fair. Variation in amplitude and continuity of seismic reflectors within the pre-Permian succession enabled seismic packages to be differentiated and hence faults and fold structure within the pre-Permian section to be identified (Figures 21 and 22).

A horizon interpreted to represent Near Top Cementstone Formation was picked over the area to define faults, basins and highs. The top of the Cementstone Formation has been interpreted to occur close to the terminal depth in well 41/01-1, at 1.028 seconds TWTT. There is no clear seismic reflector defining the pick on seismic data at the well, but the approximate top of the Cementstone Formation is marked by a change in the seismic reflectivity, from higher amplitude more continuous reflectors above, to a more transparent package beneath (Figure 21). This change in character between seismic packages was pervasive northwards into the offshore Northumberland Trough (Figure 22). Therefore, there remains uncertainty regarding the absolute definition of the near Top Cementstone pick, and hence ultimately its depth. However, this interpretation was of adequate detail to enable delineation of basins and highs, and the trend and throw of the main faults in the area.

Although younger Carboniferous rocks, including a succession of Westphalian sediments (Figure 20), are interpreted to be present in the area, the lack of local well ties and the discontinuous nature of the seismic reflectors precluded the interpretation of shallower surfaces.

The major basin bounding faults that define the Northumberland Trough onshore continue a short distance offshore (Figure 20). The eastwards continuation of the ENE-trending Ninety Fathom Fault can be mapped approximately 34 km offshore (Chadwick and Holliday, 1991). The Cementstone Formation seismic surface varies in depth from approximately 1500 m down to ~2500 m below mean sea level (bmsl) within the hanging wall of, and close to, the eastward extension of the 90-Fathom Fault. The northern boundary is not so distinctly defined as it is composed of two ENE-trending faults, offset from each other with opposing throws and extending in total approximately 38 km offshore (Figure 20).

The seismic data reveals both long (Figure 21) and short (Figure 22) wavelength folding within the pre-Permian succession. Between the bounding ENE-trending faults, the dominant fault trends appear to be between NNW and NNE. These faults tend to be steep to vertical and have relatively small throws (usually <150 m), sometimes with reverse displacements that are related to the tight folds within the pre-Permian succession (Figure 22). Some of the fold/ fault relationships could be interpreted as flower structures and provide evidence for the overall strike-slip tectono-stratigraphic model proposed by Leslie et al., 2015.

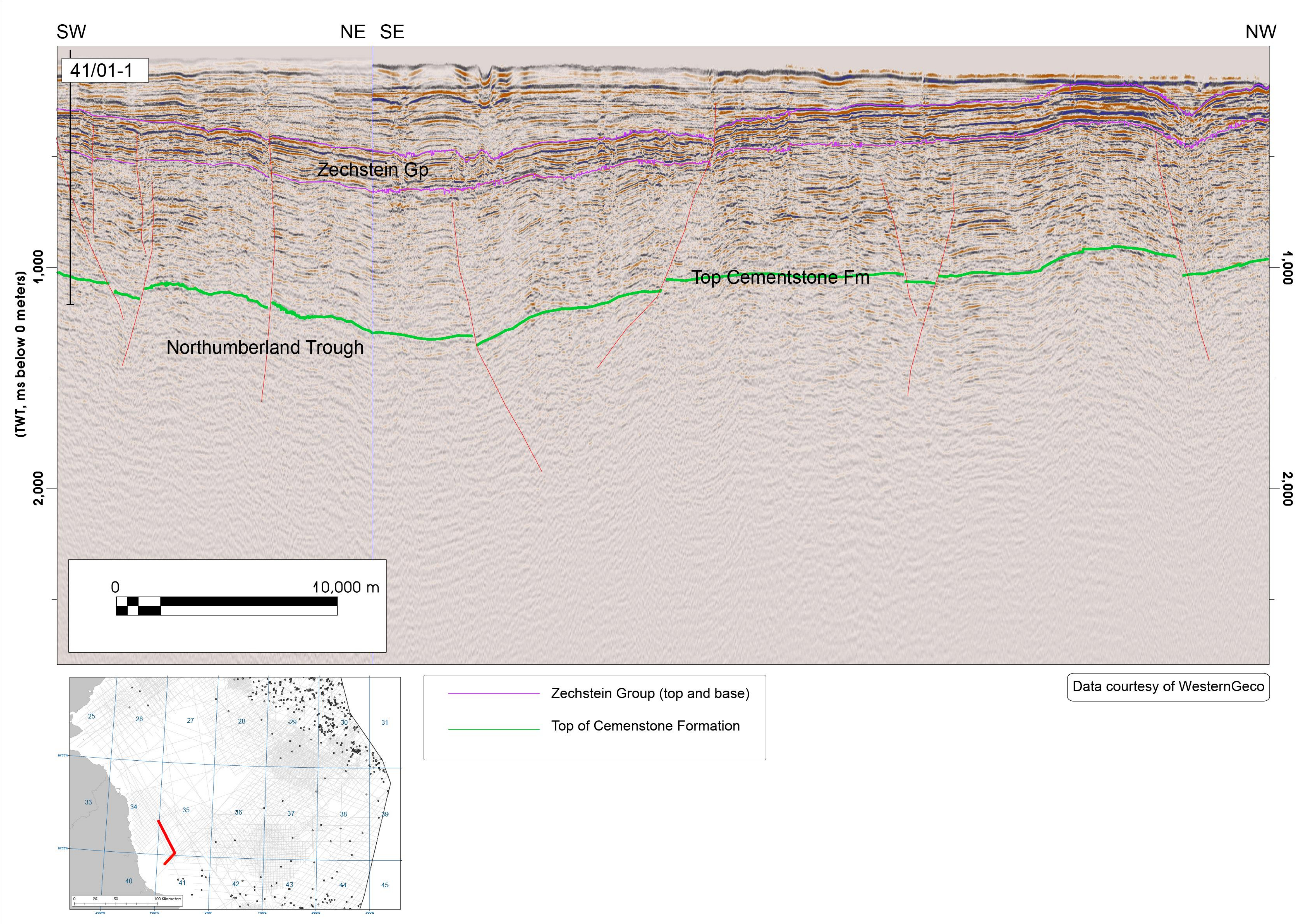

Figure 21. Multipanel seismic profile showing tie from well 41/01-1 into offshore extension of the Northumberland Trough. See Figure 19 for detailed location.

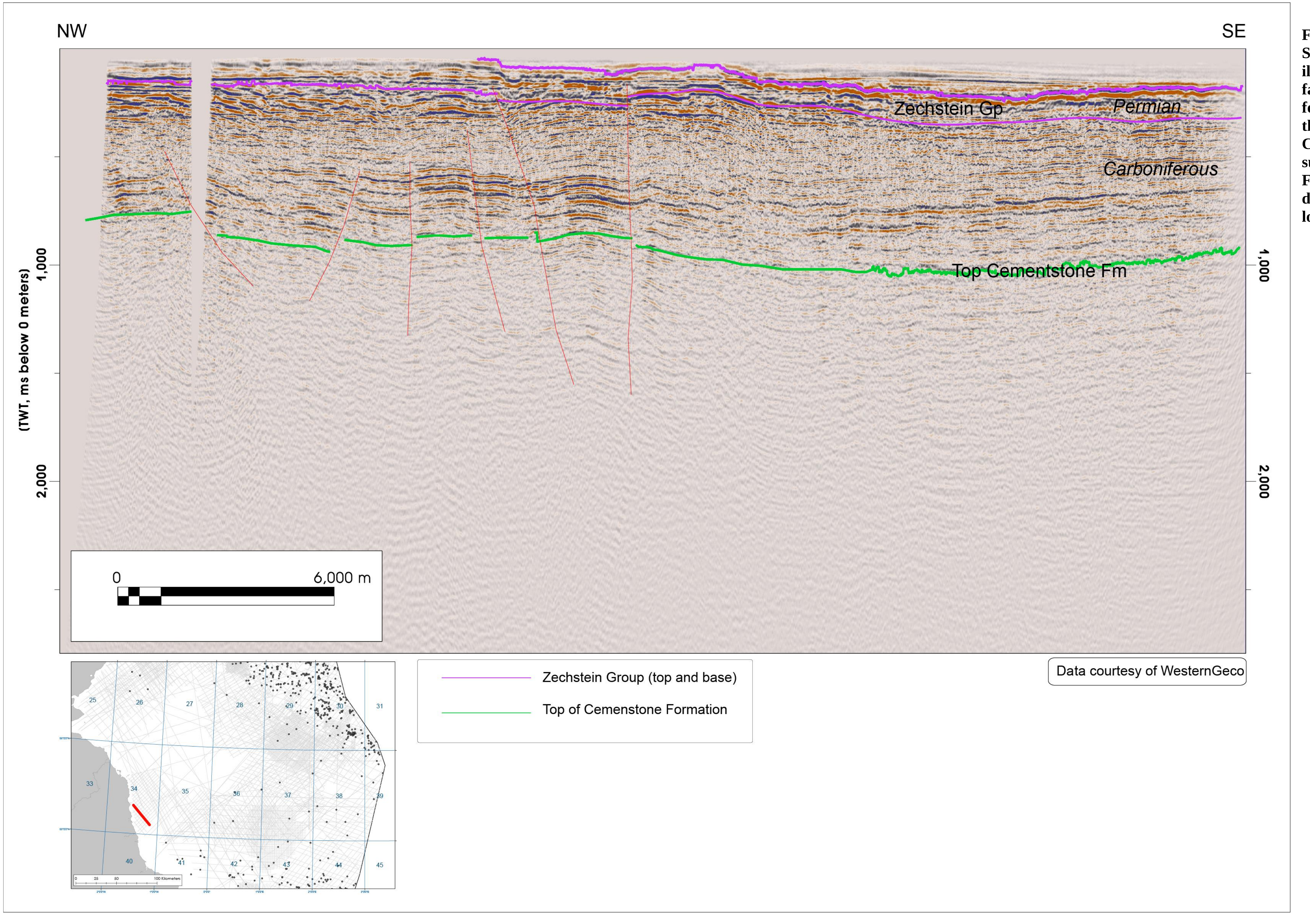

Figure 22. Seismic profile illustrating fault related folding within the Carboniferous succession. See Figure 19 for detailed location.

3.5 SEISMIC INTERPRETATION OF FORTH APPROACHES BASIN

3.5.1 Previous work

The Forth Approaches Basin is the offshore north-easterly extension of the Midland Valley of Scotland (MVS), bounded to north and south by offshore continuations of the Highland Boundary and Southern Upland faults respectively (Figure 23). In the Midland Valley of Scotland, during the later stages of the Caledonian Orogeny, the generally compressive regime was succeeded by a period of extension and continental sediments were deposited locally in small basins with deposition becoming more extensive during the Early Devonian (Marshall and Hewett, 2003). To the north of the Highland Boundary Fault, the Orcadian Basin was fully developed by mid-Devonian times whereas the Midland Valley of Scotland and offshore Forth Approaches area was a region of uplift and there is no evidence of deposition of mid-Devonian sediments. Post-rift subsidence in the Orcadian Basin dominated from latest mid-Devonian and late Devonian times and fluvial coarse grained clastic sediments spread south of the Highland Boundary fault into the study area. An overall left-lateral (sinistral) regime was active during the Devonian and into the early Carboniferous, strike-slip faulting is thought to have been dominant throughout most of the Carboniferous (Read et al., 2002).

A series of N to NNE-trending Carboniferous synclines and anticlines have been mapped in the Firth of Forth (Ritchie et al., 2003; Underhill et al., 2008) and to the east in the Forth Approaches; the pre-Permian subcrop map and seismic data show a syncline of similar orientation in the southern part of Quadrant 25 (Figure 23 and Figure 24). These syn-sedimentary structures are orientated at a high angle to the ENE-trending Southern Upland and Highland Boundary faults and are interpreted to have formed in a predominantly dextral strike-slip regime during the middle to late Carboniferous following initiation of the MVS in the Early Carboniferous (see discussion in Underhill et al., 2008). Underhill et al. (2008) note a late Carboniferous tightening of folds that conforms with observations made by Cartwright et al. (2001) on offshore seismic data of possible inversion of a Carboniferous half-graben during Variscan, pre-Permian, inversion.

The seismic mapping for this project confirms previous work in the Forth Approaches Basin (Cartwright et al., 2001) that identifies thickening of a Carboniferous succession against a NE- trending fault forming a NE-trending half-graben (Figure 25). The controlling fault appears to be the northern offset extension of the Southern Upland Fault. Overall, the distribution of Carboniferous sediments within the Forth Approaches Basin area is controlled by the Highland Boundary Fault and offshore extension of the Southern Upland Fault (Bruce and Stemmerik, 2003).

Significant thickening of Rotliegend sandstone observed in wells 26/07-1 and 26/08-1 (152 m and 390 m respectively) towards the ENE-trending fault bounding the Carboniferous basin is interpreted to result from syn-rift deposition during a phase of early Permian extensional reactivation that followed the Variscan compression and inversion (Cartwright et al., 2001; Underhill et al., 2008).

3.5.2 Dataset

The area benefits from good 2D seismic data coverage. Key surveys are prefixed FA-91, UK99, AB-, CNST86- and UK20-. The FA-91 survey has been partially reprocessed. There are six offshore wells drilled within the Forth Approaches area and several publications were used to gain insights into this area (Figure 26).

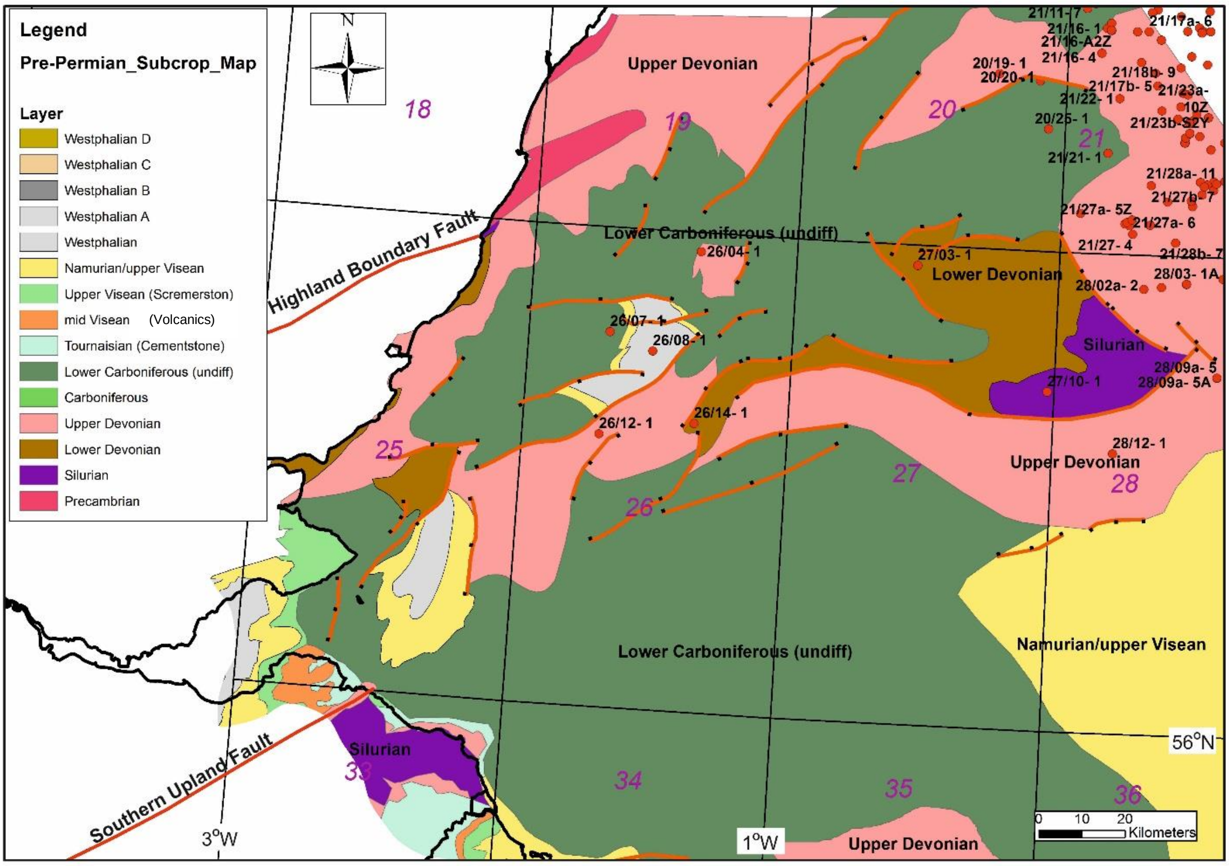

Figure 23. Detail from pre-Permian subcrop map over the Forth Approaches area showing a large ENE-trending Carboniferous basin and Carboniferous synclines within and adjacent to Firth of Forth. Upper Devonian and older rocks border the basin.

3.5.3 Seismic interpretation

Early Carboniferous rocks are present adjacent to the Fife coast and the Firth of Forth. The subcrop at the seabed is an eastward younging sequence of Permian, Triassic, Lower and Upper Cretaceous and Cenozoic deposits (Figure 26). A narrow band of Neoproterozoic to Upper Devonian rocks subcrop sea bed close to the Aberdeenshire coastline. Where present, Top Chalk, Base Chalk, Top Zechstein and Base Zechstein were interpreted for the purposes of depth conversion.

Within the Carboniferous, a horizon interpreted to represent Near Top Cementstone Formation was picked over the area to define faults, basins and structural highs. Other intra-Carboniferous horizons were interpreted locally but could not be extensively picked to produce gridded surfaces. The pre-Permian succession in the SW part of the basin has been drilled by wells 26/07-1 and 26/08-1 enabling some understanding of the Carboniferous succession in relation to the seismic data. Well 26/07-1 proved a Lower Carboniferous succession comprising 565m of Firth Coal (Scremerston equivalent) Formation mudstone with frequent thin beds of coal, limestone and sandstone resting on 515 m of the Fell Sandstone Formation. Close to the total depth penetrated by this well (2375 m below kelly bushing (bkb)), the Top Cementstone Formation is interpreted at a measured depth bkb of 2365 m (2340 m bmsl) corresponding to a TWTT of approximately 1.35 seconds. Well 26/08-1 proved 773 m of Westphalian sediments resting on 128 m of Millstone Grit

Formation and reaching total depth within the Firth Coal (Scremerston equivalent) Formation.

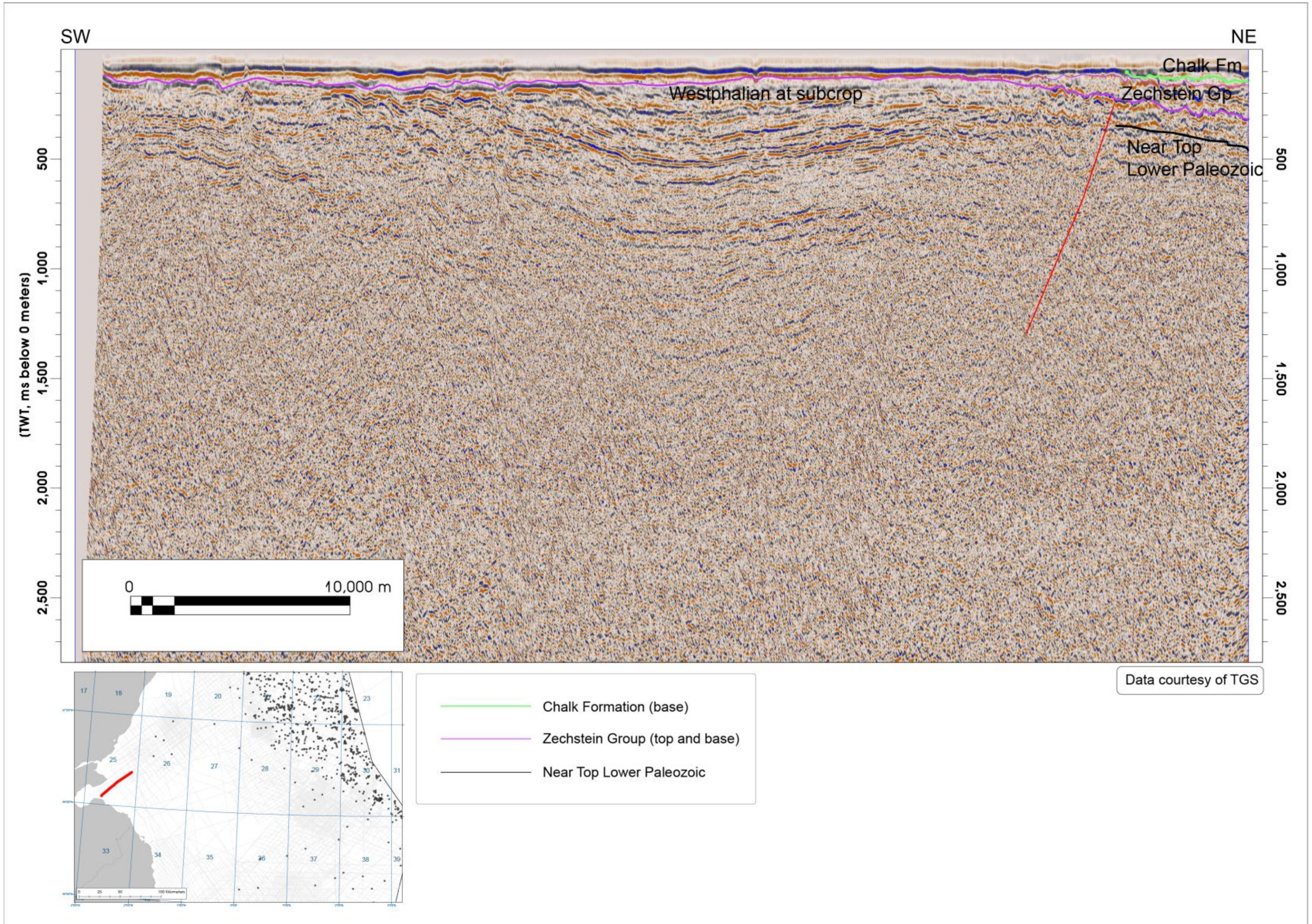

Figure 24. Seismic profile showing NNE-trending syncline with a subcropping Westphalian succession just east of the Firth of Forth. See Figure 26 for detailed location.

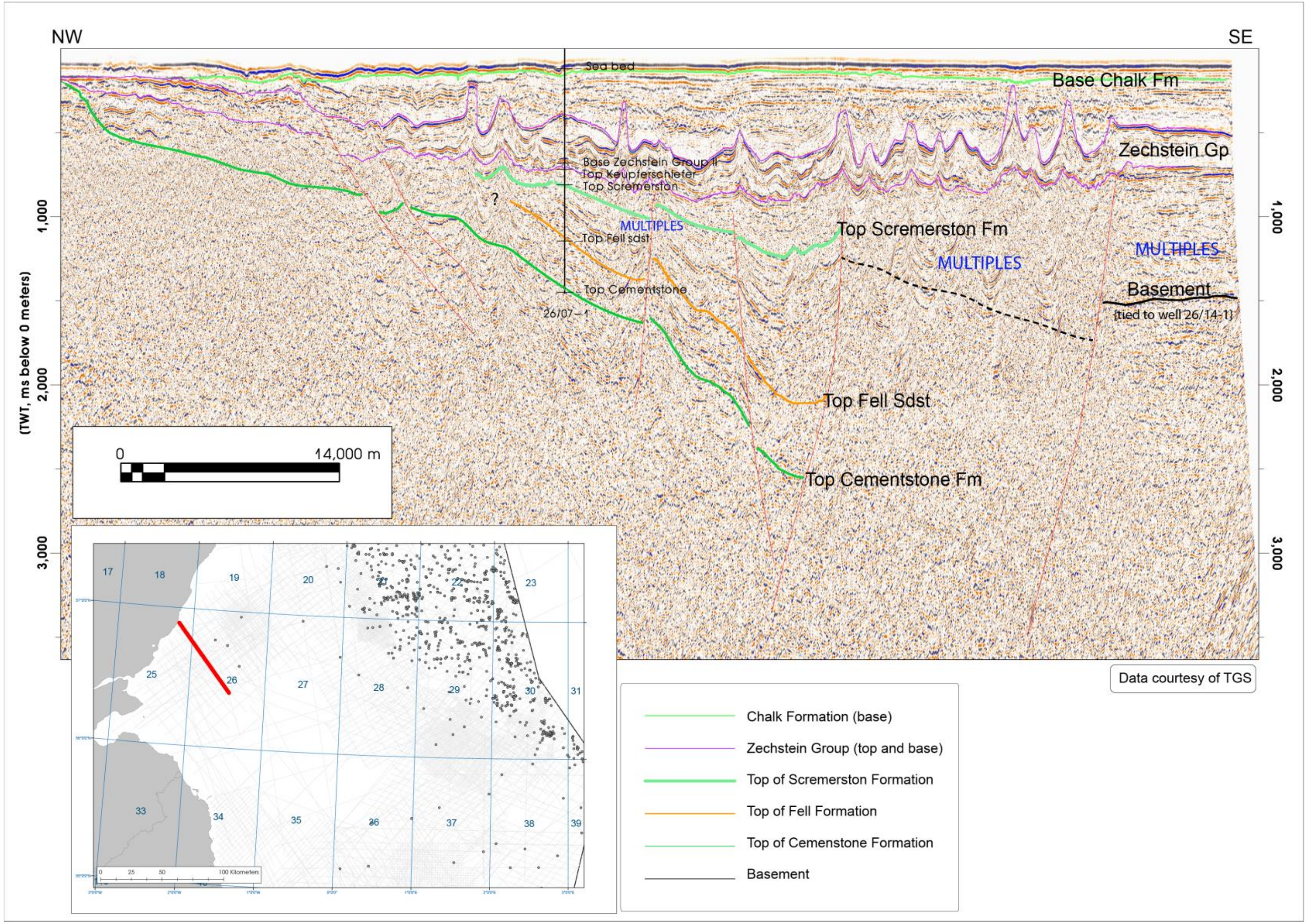

Figure 25. Seismic profile showing thick Carboniferous succession preserved in the hanging wall of major ENE-trending fault. The profile intersects with Well 26/07-1. See Figure 26 for detailed location.

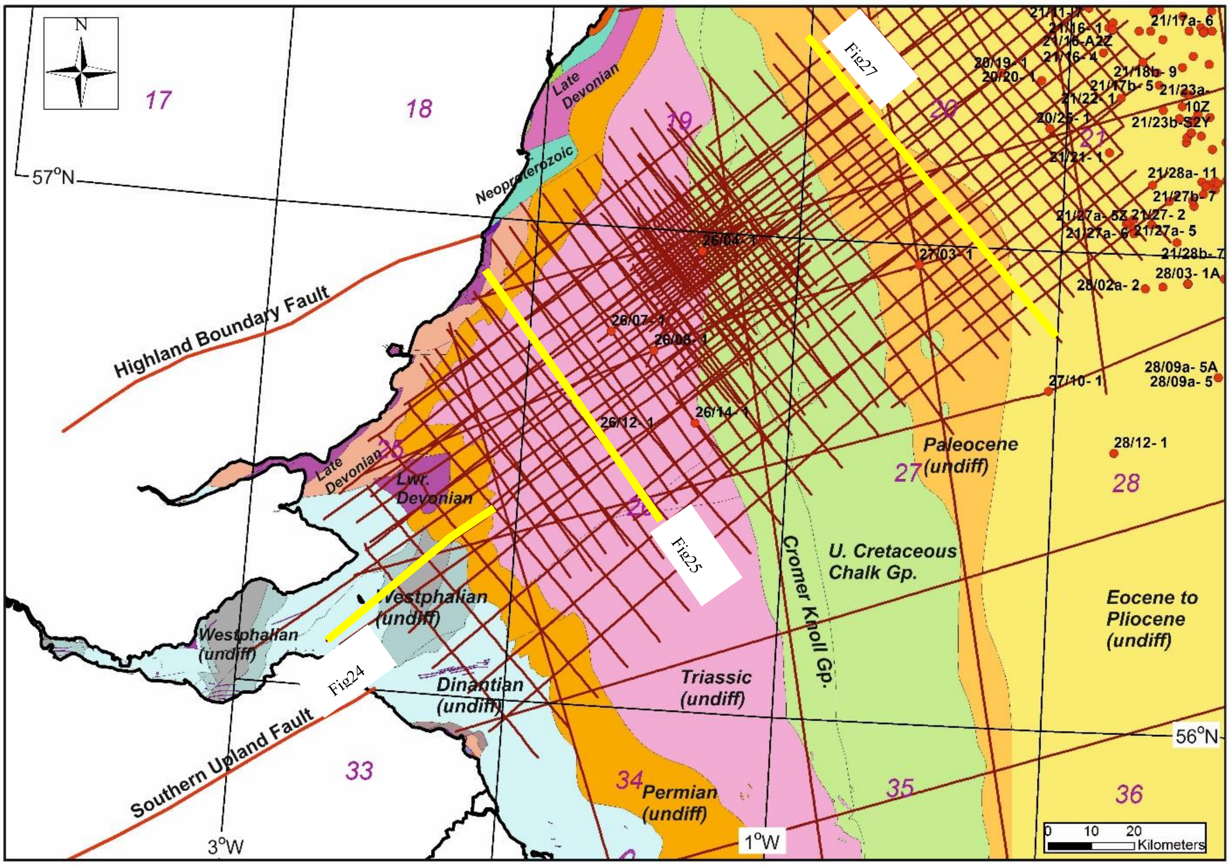

Figure 26. Bedrock offshore showing outcrop of progressively older successions towards the west. Seismic and well dataset utilised in the interpretation of the Forth Approaches Basin.

An extensive (>7000 km^2) ENE-trending Carboniferous Basin within the Forth Approaches has been identified during the seismic interpretation exercise. The basin is bounded to the south by ENE- trending *en echelon* faults totalling more than 140 km in length that are interpreted to represent the offshore extension of the Southern Upland Fault (Figure 23 and Figure 26). The SW part of the basin has a Carboniferous succession ranging from Tournaisian to Westphalian in age (Figure 25). Here, the fault defining the southern boundary of the basin trends ENE is approximately 66 km in length with a displacement of at least 2500 m. At Well 26/12-1, located 15 km to the SW on the footwall of the ENE-trending fault, the Base Permian Unconformity/ Top Devonian lies at a depth of 928 m bmsl. Immediately adjacent, in the hanging wall of this fault the Top Cementstone lies at an interpreted depth of approximately 4000 m bmsl suggesting a 3000 m displacement at this location. However to the NE, the basin is poorly imaged on seismic data and it was not possible to interpret a continuous Carboniferous reflector (Figure 27). It was possible however, to interpret fault displacements that define the possible limits of the NE part of the basin.

The new pre-Permian subcrop map (Figure 23) shows the main ENE-trending Carboniferous basin bounded to the south by a faulted block comprising Upper Devonian Buchan Formation sandstone, Lower Devonian sandstone and mudstone, and Silurian metasediments. To the south-west, in southern part of Quadrant 25, the fault trend changes to a N to NNE orientation and here a marked NNE-trending syncline (Figure 24) can be interpreted on the seismic data, similar in trend to those mapped in the Firth of Forth (Ritchie et al., 2003). The change in fault trend is interpreted to mark the step northwards of the Southern Upland Fault system from its more southerly onshore location to its interpreted position in the Forth Approaches.

A Lower Palaeozoic horizon was also interpreted over part of the area constrained by well 26/14-1, that proved Lower Devonian resting on Silurian at a depth of 1206 m bkb (1181 m bmsl). Wells 27/03-1 and 27/10-1 prove undifferentiated Lower Devonian/ Silurian and were used in conjunction to calibrate the seismic interpretation to construct the pre-Permian subcrop map in this area.

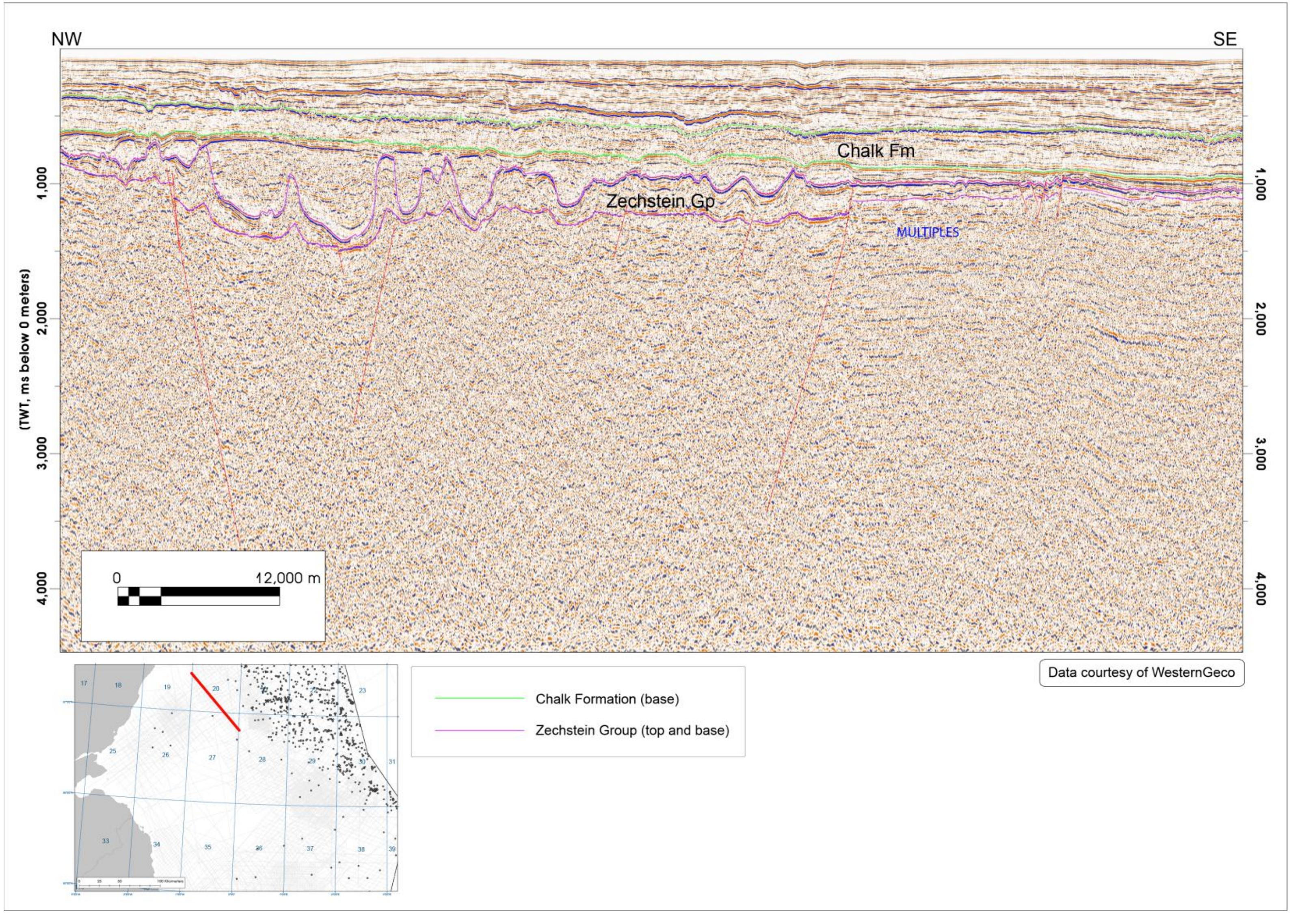

Figure 27. Seismic profile illustrating the lack of seismic reflector continuity beneath the Zechstein group. However, the quality of the seismic data did allow interpretation of some of the major ?basin bounding faults in this area. See Figure 26 for location.

4 Depth conversion method and generation of depth structure maps

4.1 INTRODUCTION

The mapped Devonian and Carboniferous Two-Way-Travel-Time (TWTT) horizons were converted to depth in order to remove distortions in the time surfaces as a result of numerous lateral and vertical changes in velocity within the overlying layers. These changes in interval velocity are due to heterogeneous lithology, compaction of the sediments and halokinesis, the latter specifically in the Upper Permian Zechstein layer. Depth conversion provides a more realistic topography, and has been used to generate isopach thickness maps and to interpret the basins' subsidence and uplift history. The depth converted surfaces, and basin history analysis, provided input to the petroleum systems modelling calculations to deliver ultimately estimates of hydrocarbon maturation (Vincent, 2015).

The various velocity trends, the contrasting lithologies and the complex uplift and burial history of the Carboniferous and Devonian successions are not easily described by a simple exponential increase in velocity with depth. Thus a layer cake method of depth conversion was applied.

The geological succession is divided into the minimum number of layers, mainly a function of lithology, to create the simplest possible model whilst retaining sufficient detail to capture adequately the various velocity-depth relationships. The number of layers selected was in part dependant on the availability of interpreted horizons that define top and base of the layers in the existing BGS-DECC/ OGA project database. As the surfaces were derived from several different projects they were merged with additional interpretation and extended were necessary, to provide the surfaces that define the layers in the Depth Conversion. The surfaces were gridded, contoured and viewed in ARCGIS, but no reinterpretation was performed above Permian level due to time constraints on the project. The following steps summarise the layer cake method:

- the top and base of layers, defined by the interpreted TWTT surfaces, were subtracted from each other to provide time isopachs;
- the variation of interval velocity for each layer was calculated in different ways depending on the layer in question (see **Section 4.1.1** below);
- the time isopachs were converted to thickness with the application of a suitable interval velocity;
- the thickness of the layers was summed to produce depth to key horizons.

This method takes into account the contrasting velocities expected between each layer and the variation in interval velocity within some layers both vertically and laterally. Six layers were defined (Figure 28):

1 Water
2 Cenozoic (Sea Bed to Top Chalk)
3 Upper Cretaceous (Top Chalk to Base Chalk)
4 Lower Cretaceous, Jurassic, Triassic (Base Chalk to Top Zechstein)
5 Upper Permian Zechstein (Top Zechstein to Base Zechstein)
6 Palaeozoic (Base Zechstein to mapped Palaeozoic reflector)

4.1.1 Utilisation of velocity data and generation of velocity grids

Velocity data points from wells within and immediately adjacent to the area of interest were extracted from the existing DECC well database. The points were plotted against depth in Excel and their distribution showed a general increase in interval velocity with depth (Layers 2, 3 and 4). Interval velocity values from available wells and TWTT of the base of the appropriate layer were modelled with the trendform option in ZmapPlus to generate a velocity grid that reflects variation in velocities away from well points. For Layer 5, the Upper Permian Zechstein interval, the variation in velocity is due to vertical and lateral changes in lithology; the variation in velocity can be defined by a curve and associated equation (see **Section 4.2** below). For Layer 6 (pre-Permian), no interval velocity/depth relationship could be discerned from the available data points and consequently a constant velocity was utilised for layers beneath the Base Zechstein (see **Section 4.2** below).

4.2 GENERAL METHODOLOGY

The Depth Conversion workflow is summarised in Figure 29. TWTT surfaces in milliseconds (ms) define the top and base of the layers that were used in the depth conversion. Each interpreted surface successively subcrops recent sediments in a generally westerly direction (Figure 28). In order to fully constrain each Layer, the top of each surface was interpreted beyond its subcrop until it intersected with the next surface deeper in the succession (Figure 28). This enabled the thickness of each layer to be calculated even when its depositional top has been truncated. The extent of each surface is constrained by an area of interest (AOI) polygon and these were used in blanking and clipping the surfaces.

ZmapPlus was chosen as the gridding program because of its proven capability to produce geologically realistic grids at a regional scale using widely spaced, variable data.

Depth maps are presented in metres below Mean Sea Level, and water depth (***Layer 1***) was added to the first depth converted thickness layer (***Layer 2***). All grids were set to the same XMIN, YMIN, XMAX, YMAX coordinates, and grid spacing set to 500 m. Depth converted surfaces at a spacing of 500 m were imported to PETREL and resampled to an agreed grid spacing of 5000 m for delivery to sponsors. Pre-Permian surfaces were gridded with faults.

Layer 1, the water layer, varies in depth over the area between <10 m to 160 m. The sea bed surface was derived from Digbath 250k (http://www.bgs.ac.uk/products/DigBath250/home.html) reprojected to ED50 UTM31N and imported into ZmapPlus as a grid. The imported grid was resampled in Zmap to ensure X Y grid spacing and XMIN, YMIN, XMAX, YMAX matched the other gridded surfaces.

Layers 2, 3, and 4 were converted to thickness in metres using the trendform modelling function in ZmapPlus. This method generates a velocity grid from well data points and the TWTT to base of the Layer (Figure 30), taking into account the geometry of the TWTT surface and adjusting the velocity values with reference to the magnitude in TWTT. The resulting velocity grid reflects compaction of the sediments with increasing depth.

The One-Way-Travel-Time (OWTT) isopach in seconds of Layers 2, 3, and 4, multiplied by the relevant Interval Velocity grid in metres per second (ms^{-1}) was used to generate a thickness of the Layer in metres. Adding the thickness to the overlying depth generates an Initial Depth for the base of the Layer.

The Initial Depth for each of these Layers was corrected in turn by creating a 'depth difference grid' from back-interpolated well depths using the Trendform modelling function in ZmapPlus (see Section 4.2.1 below).

Layer 5, the Upper Permian Zechstein, required a different method (Van Dalfsen et al. 2006) for deriving its thickness as it varies from between <50 msecs to >700 msecs in TWTT thickness and comprises a frequently varying succession of salt, dolomite, carbonate and shale. A plot of Interval Velocity against OWTT thickness of Layer 5 displays high velocities of between 4700 ms^{-1} and 5900 ms^{-1} where the layer is thin and where lithologies are dolomite, anhydrite and shale (Figure 31). The velocity decreases to a minimum of around 4500 ms^{-1} where the layer is predominantly a thick halite succession. The velocity change can be defined by an exponential equation that was used to generate a velocity grid for Layer 5.

Layer 6, represents the succession between the Base Zechstein surface and each of the interpreted pre-Permian horizons (Top Scremerston, Top Fell Sandstone, Top Cementstone and Top Kyle) interpreted for this study. Twenty seven data Interval Velocity data points were available and the resultant plot of Interval Velocity against TWTT to base of Palaeozoic (generally TD of well) (Figure 32) shows no obvious correlation with depth. With no observable Interval Velocity/ TWTT to base relationship, a constant Interval Velocity of 4069 ms^{-1} (an average of all the available data points) was applied to the Layer 6 time isopach to generate thickness of pre-Zechstein to interpreted Carboniferous and Devonian surfaces.

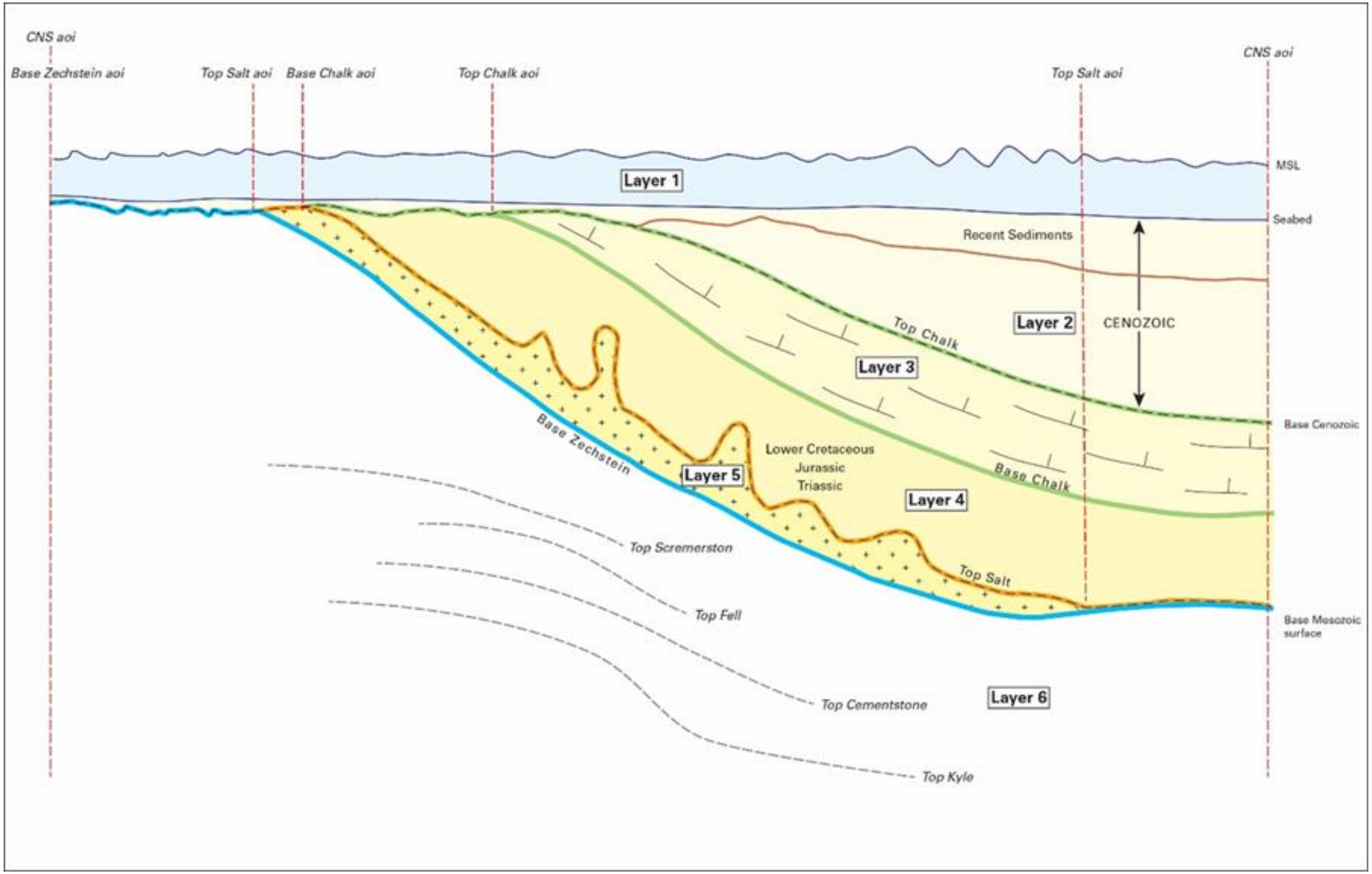

Figure 28. Cartoon showing the layers and the defining surfaces used in the depth conversion process.

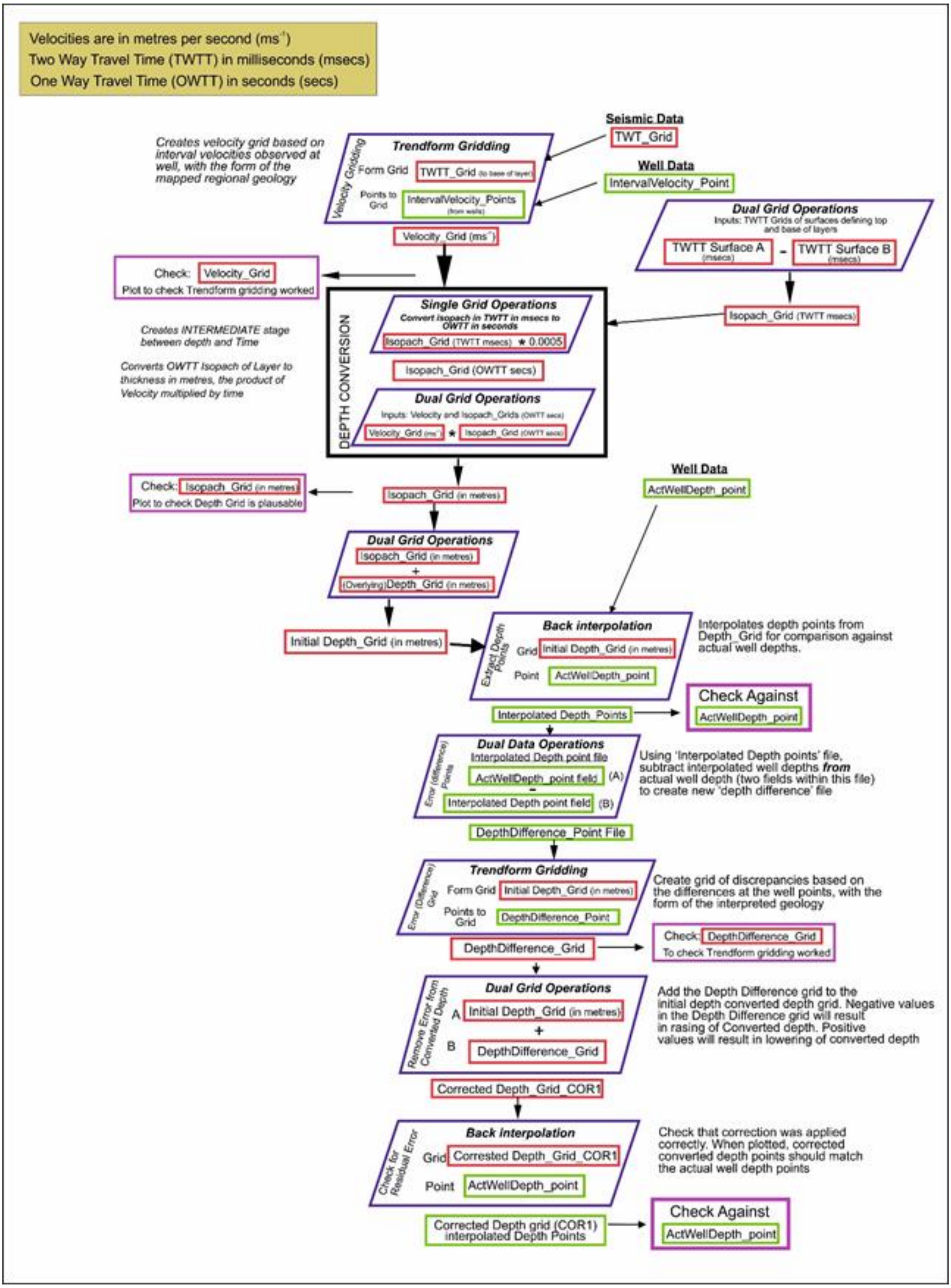

Figure 29. Flow diagram summarising the 'Layer Cake' depth conversion process carried out in the Central North Sea area.

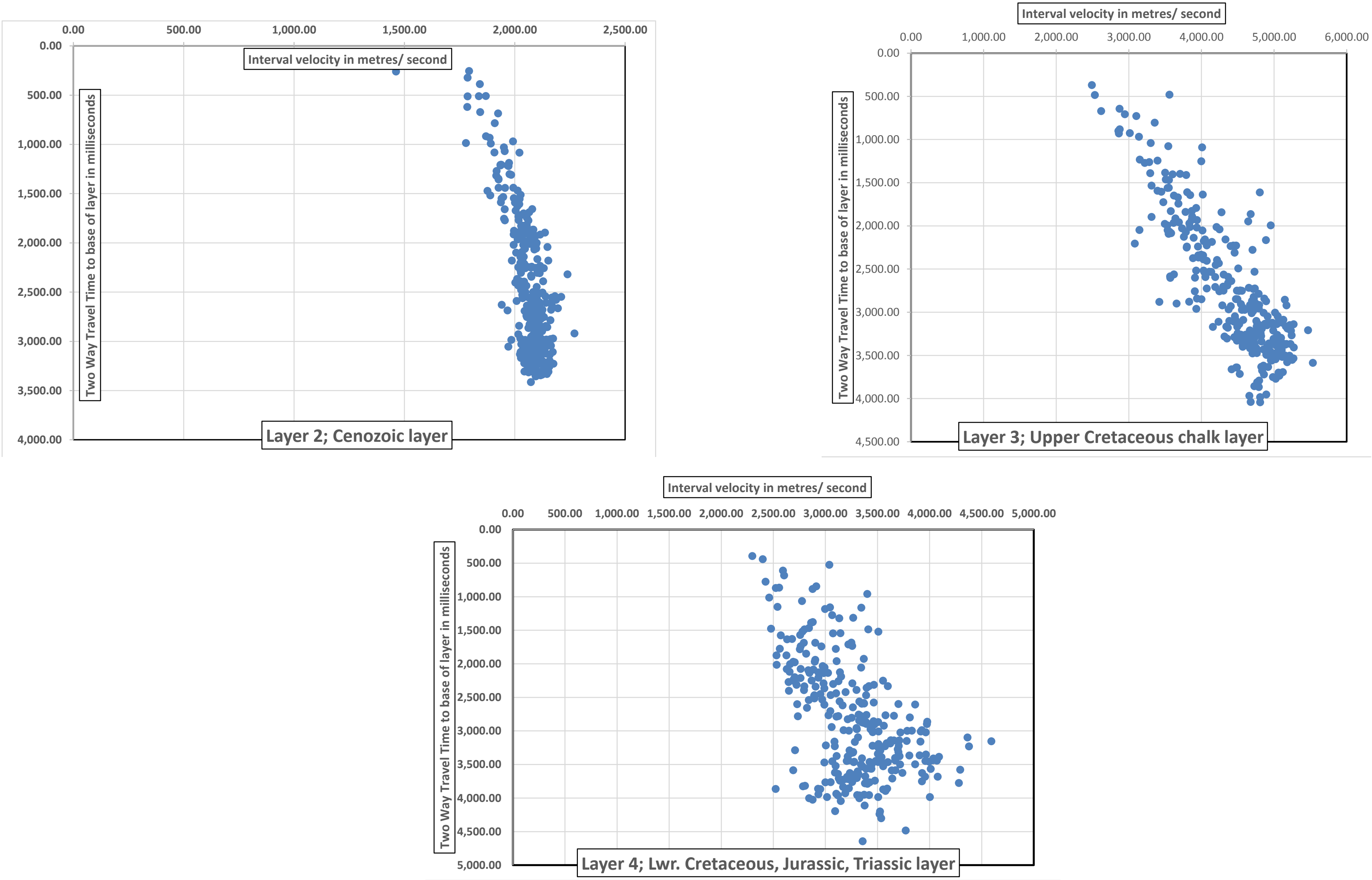

Figure 30. Velocity vs. TWTT to base of Layers 2, 3 and 4. Velocity and TWTT data were inputs for the trendform modelling function that generated a velocity grid for each layer.

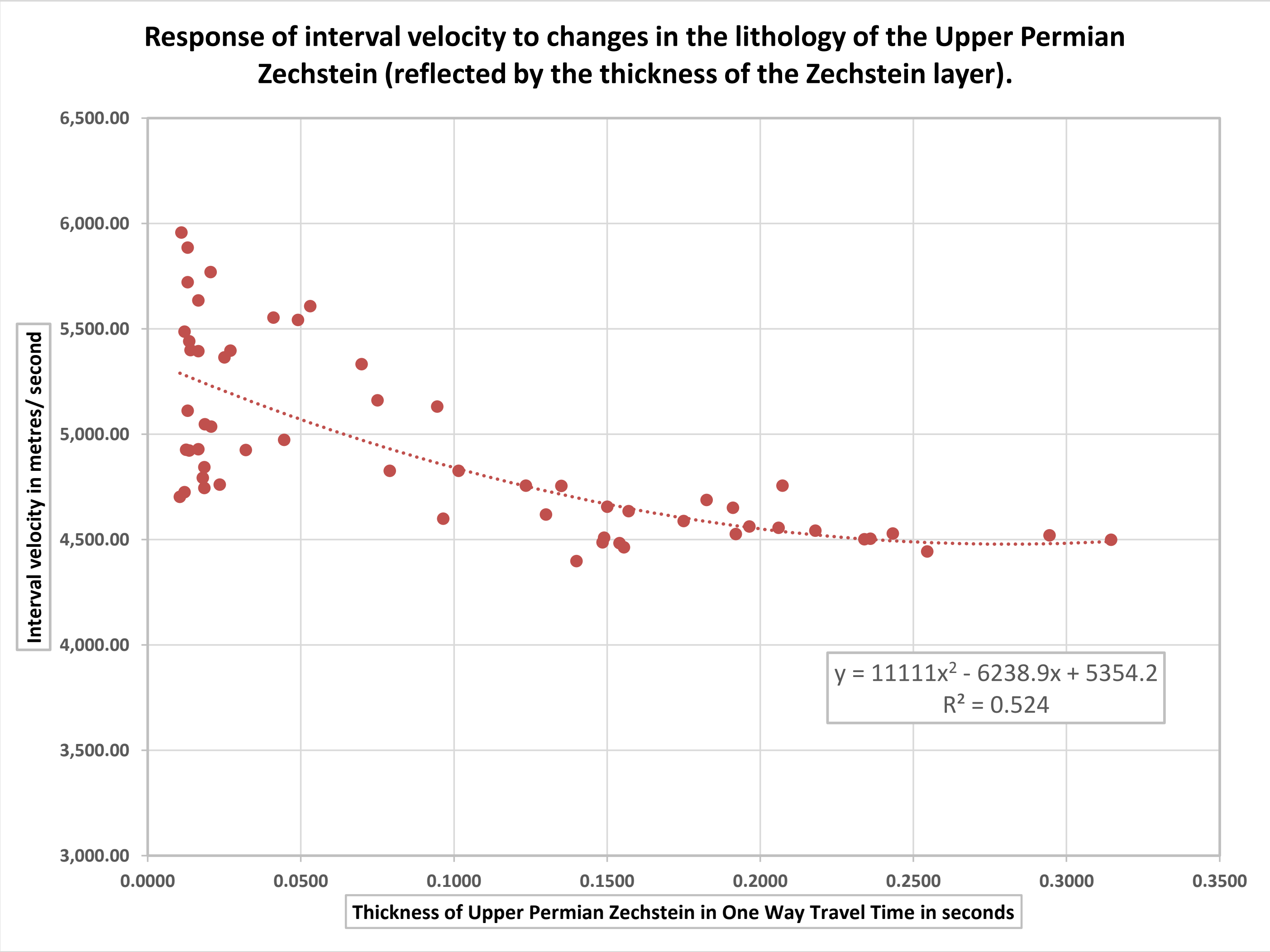

Figure 31. Velocity vs. OWTT thickness of Layer 5, Upper Permian Zechstein. The distribution of data can be described by the equation of the curve shown above and this was used to generate a velocity grid for Layer 5.

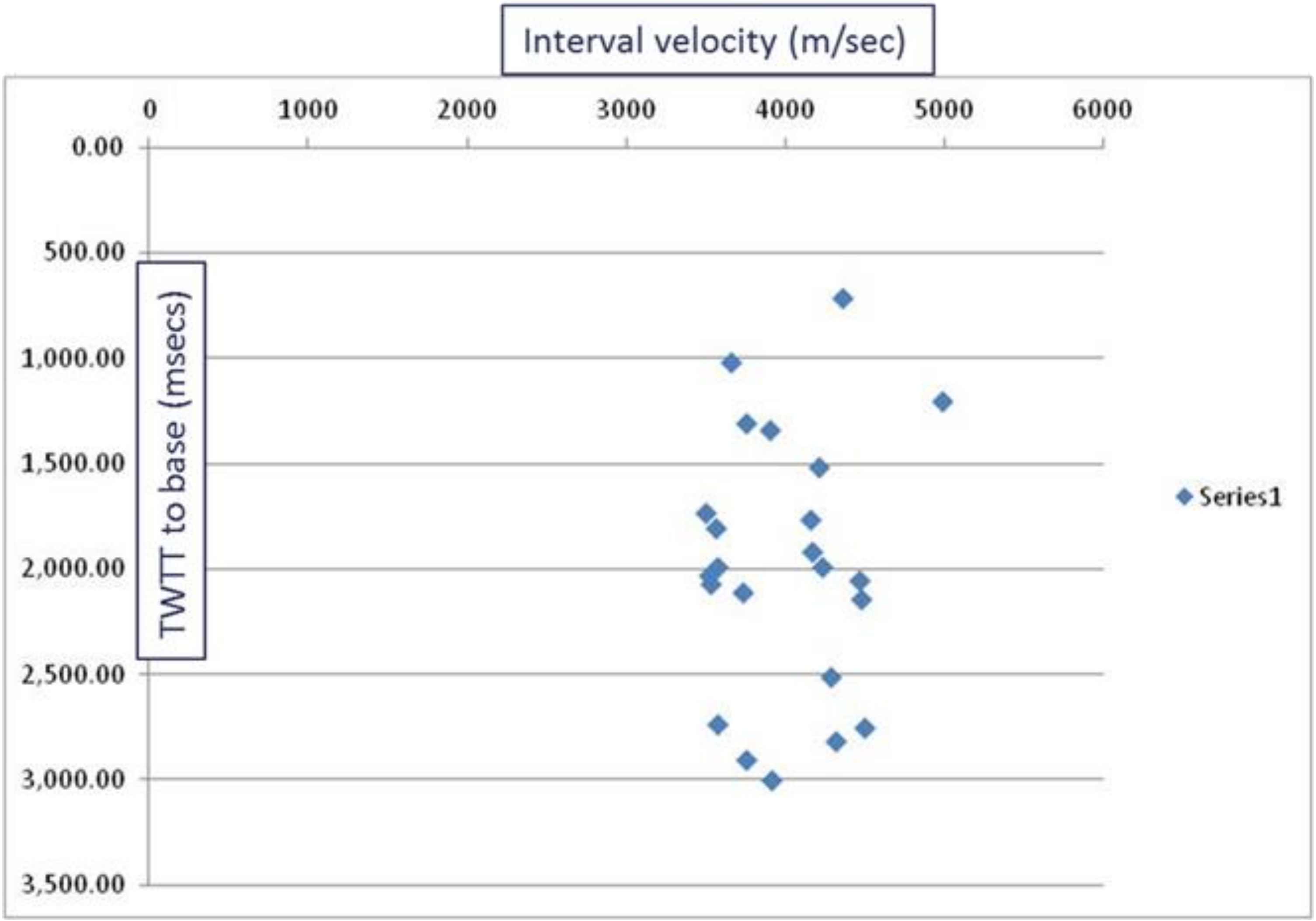

Figure 32. Interval Velocity vs. TWTT to base (TD of wells) for Devonian and Carboniferous strata showing no clear relationship between increase in depth and velocity.

4.2.1 Depth checking, residual production and final depth surfaces

After the initial depth converted surface grid was created (those down to and including the Base Zechstein) each was subjected to the following process:

1. Initial back interpolation to derive a calculated depth at a well location.
2. A ‘depth difference’ file was generated from interpolated and actual well depths.
3. Using the ‘Trendform modelling’ function in ZmapPlus, a ‘depth difference grid’ was generated using the ‘depth difference’ file trended to the initial depth grid.
4. The ‘depth difference grid’ was then added to the initial depth grid to produce a corrected depth converted surface.

The corrected depth converted surface forms the surface to which the calculated thickness of the layer beneath was added to derive an *initial* depth converted surface grid of the base of that layer. The steps 1 to 4 above were then repeated to create the next corrected surface down the section.

4.2.2 Palaeozoic surfaces and uncertainties

After the initial depth conversion of each Palaeozoic surface, depth differences at wells were identified (steps 1 and 2 above) and investigated to identify their cause.

Initial depth differences at wells may be due to a number of reasons either together or singly:

1. Poor or missing velocity log from the well which affects the extracted TWTT data.
2. Mistie between the well pick and the seismic pick due to:
    a. interpretation of the formation top in the well does not agree with seismic interpretation tied from other wells in the area;
    b. error in the seismic interpretation.
3. Cumulative error in depth conversion through the different overlying surfaces and using the constant velocity for the Palaeozoic surfaces.

Trendform modelling (to generate a depth difference surface) is only effective if there is a good spread of data points over the area; the low number of points and their uneven spread makes trendform modelling, to create a depth difference surface, ineffective for the Palaeozoic surfaces. Therefore, for the 4 Palaeozoic surfaces, the seismic well ties were investigated and corrections to the initial interpretation were carried out to minimise the differences. Revised depth maps and the associated depth difference (at the wells) maps were generated. Remaining depth differences, assumed to be due to the cumulative effect of errors in overlying depth converted layers and/or use of constant velocity for the Palaeozoic, were corrected in PETREL by applying corrections at the specific wells. These depth differences, not due to 1, 2 above, are shown in **Table 5** below.

Kimbell and Williamson (2015) note anomalously high densities in the Upper Devonian of well 42/10b-2. These would result in equivalent higher interval velocities within the Upper Devonian and highlights the likelihood of both lateral and vertical variation in velocities within the Palaeozoic and a possible source of error in using a constant interval velocity for the Palaeozoic succession.

	26/07-1	38/03-1	41/01-1	41/10-1	42/10b-2	43/02-1	44/02-1
Top Scremerston Fm.			-71 m	71 m	85 m	73 m	
Top Fell Sandstone Fm.			-41 m	257 m	141 m	164 m	
Top Cementstone Fm.	-160 m		8 m	154 m	211 m	123 m	94 m
Top Kyle Group.		44 m					

Table 5. Depth differences at wells within pre-Permian succession that were applied to depth converted surfaces imported to PETREL to generate final corrected surfaces.

In conclusion, the absolute depths for the four Palaeozoic surfaces are prone to error from the following:

1. Incorrect interpretation away from well ties;
    a. Particularly vunerable where seismic and/ or well data is sparse (Figure 1 and Table 3).
2. Cumulative error from thickness of overlying layers that together contribute to depth to base Zechstein;
3. The use of a constant velocity for calculation of thickness of all Palaeozoic surfaces.

These sources of potential error are not easily quantifiable and the user of these results should be aware of these potential errors in generated surfaces.

4.2.3 Importing depth converted grids to Petrel

The TWTT and depth converted grids were imported into PETREL and checked for inconsistencies. Palaeozoic surfaces were corrected to relevant wells in PETREL. The grids were clipped to the AOI’s for each horizon and resampled from 500 m to 5000 m.

5 Results

The images of the depth converted surfaces and isopachs delivered to sponsors are presented in Figures 33 to 39. A set of TWTT surfaces complementing the depth surfaces shown in this report will also be supplied. The surfaces are:

- the top of the Middle Devonian Top Kyle Limestone Group;
- near top of the Lower Carboniferous Cementstone Formation;
- near top of the Fell Sandstone Formation;
- near top of the Scremerston Formation;
- the Upper Permian Base Zechstein Group.

The isopachs are:

- pre-Permian to Top Kyle Limestone Group;
- Top Scremerston to Top Cementstone Formation.

The preceding sections in this report detail how these surfaces were generated and should be read in conjunction with the digital products delivered to sponsors and shown below. The original grid spacing was 500 m and depth conversion of the surfaces was carried out at this resolution. Following agreement with owners of the seismic data used in the interpretation, final deliverables are at a grid spacing of 5000 m.

5.1 PRODUCTS

The steering committee asked that the surfaces are supplied in a digital format suitable for import to:

- PETREL;
- ZmapPlus format for import to Kingdom software;
- ARCGIS software packages.

Please note that interpreted fault polygons are supplied only as shapefiles and are not included in the supplied depth map images and grids due to scaling differences. The faults were interpreted for a 500 m grid resolution and upscaling the resulting fault structure to 5000 m grid resolution results in an apparent mismatch due to the scale difference.

5.2 DEPTH SURFACES

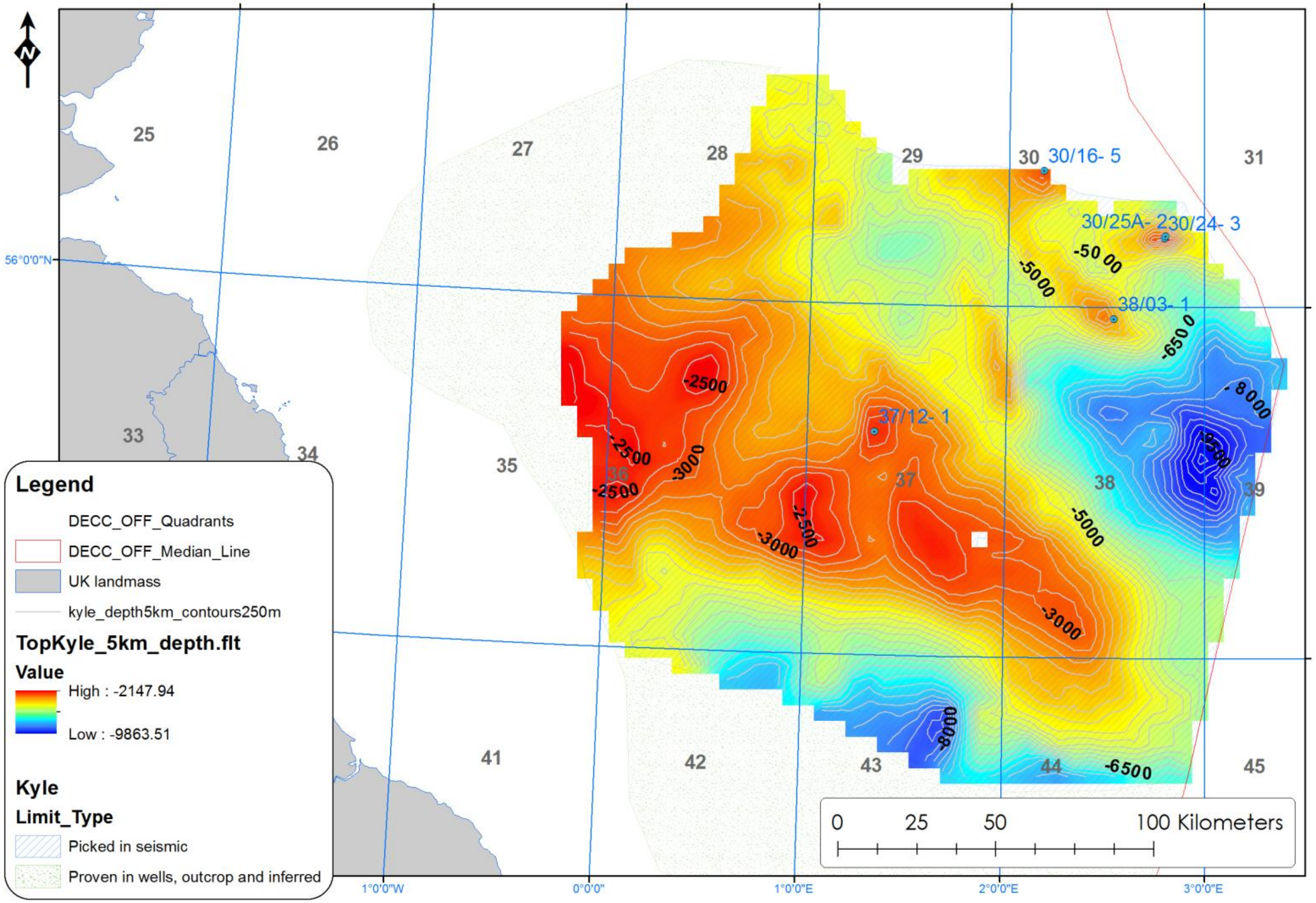

Figure 33. Depth to Top Kyle Group in metres below mean sea level.

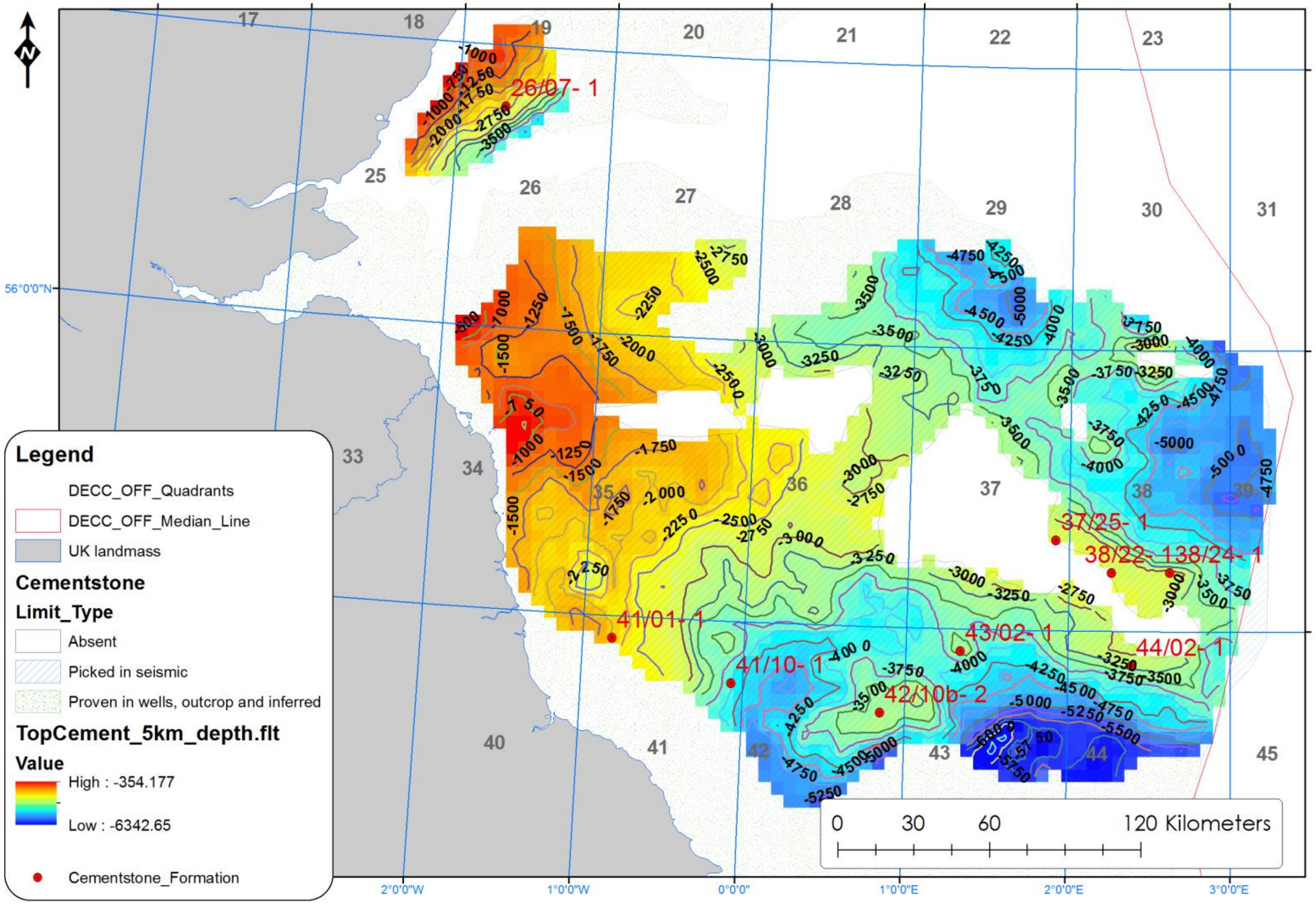

Figure 34. Depth to near top Cementstone Formation in metres below mean sea level.

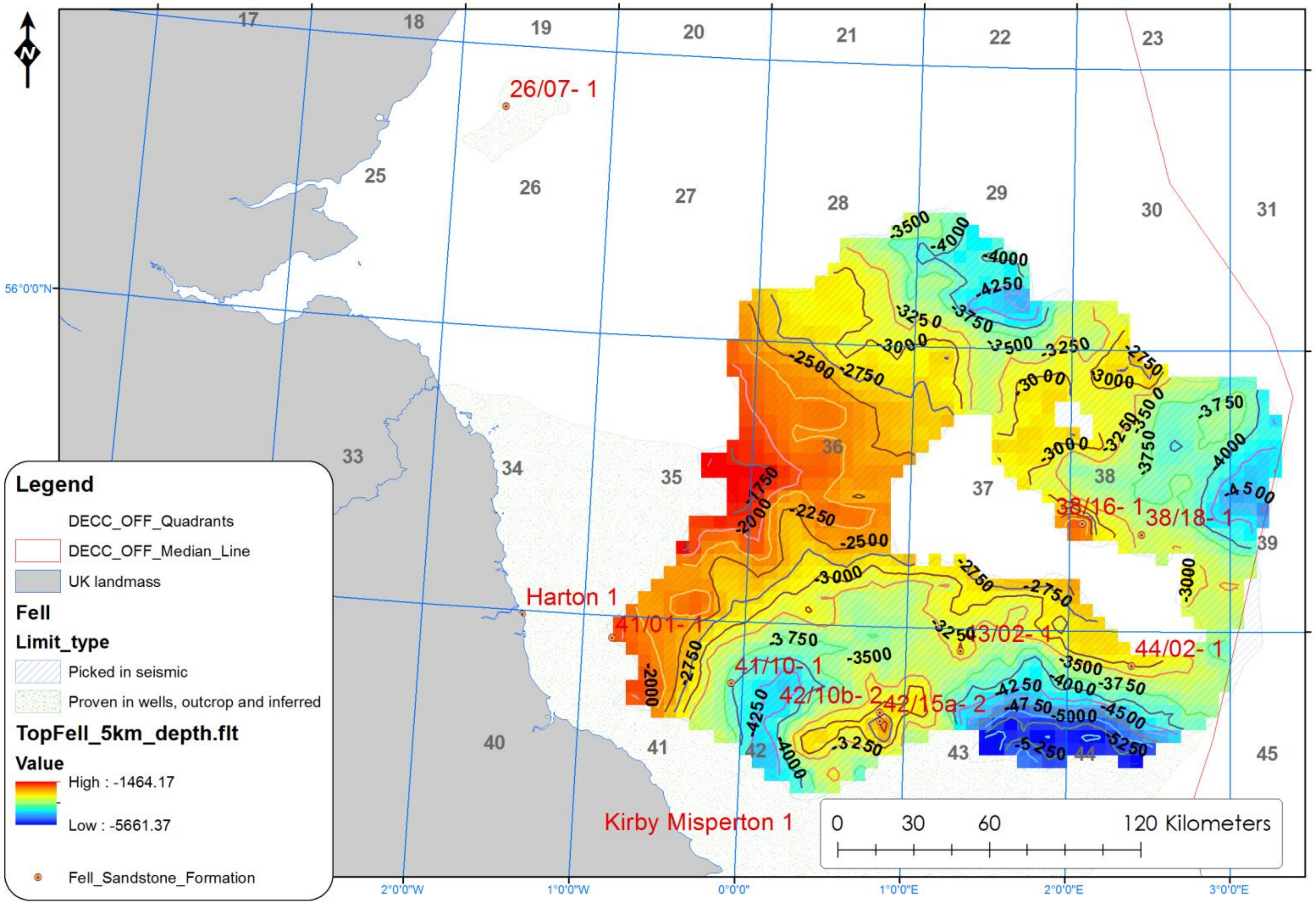

Figure 35. Depth to near top Fell Sandstone Formation in metres below mean sea level.

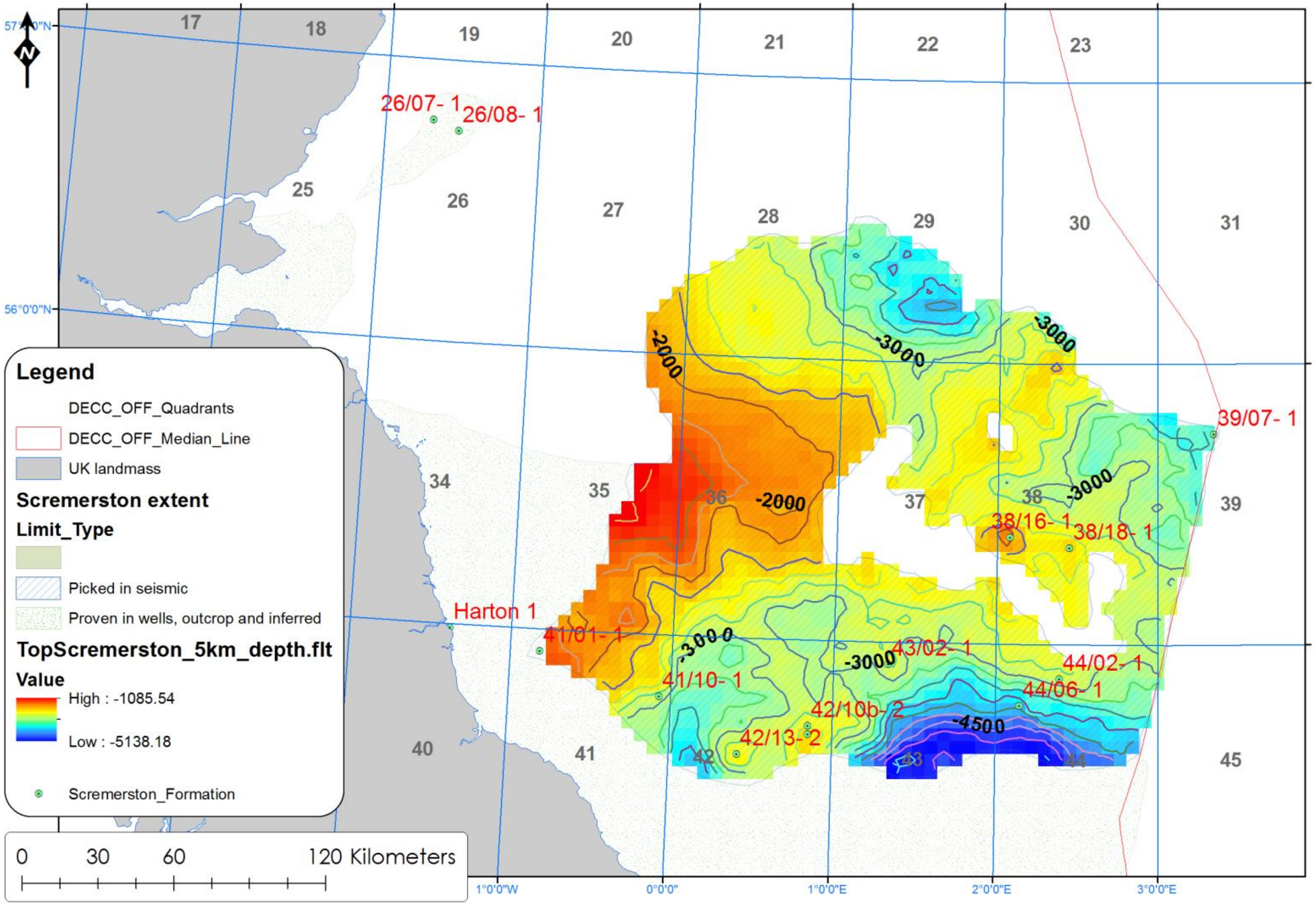

Figure 36. Depth to near top Scremerston Formation in metres below mean sea level.

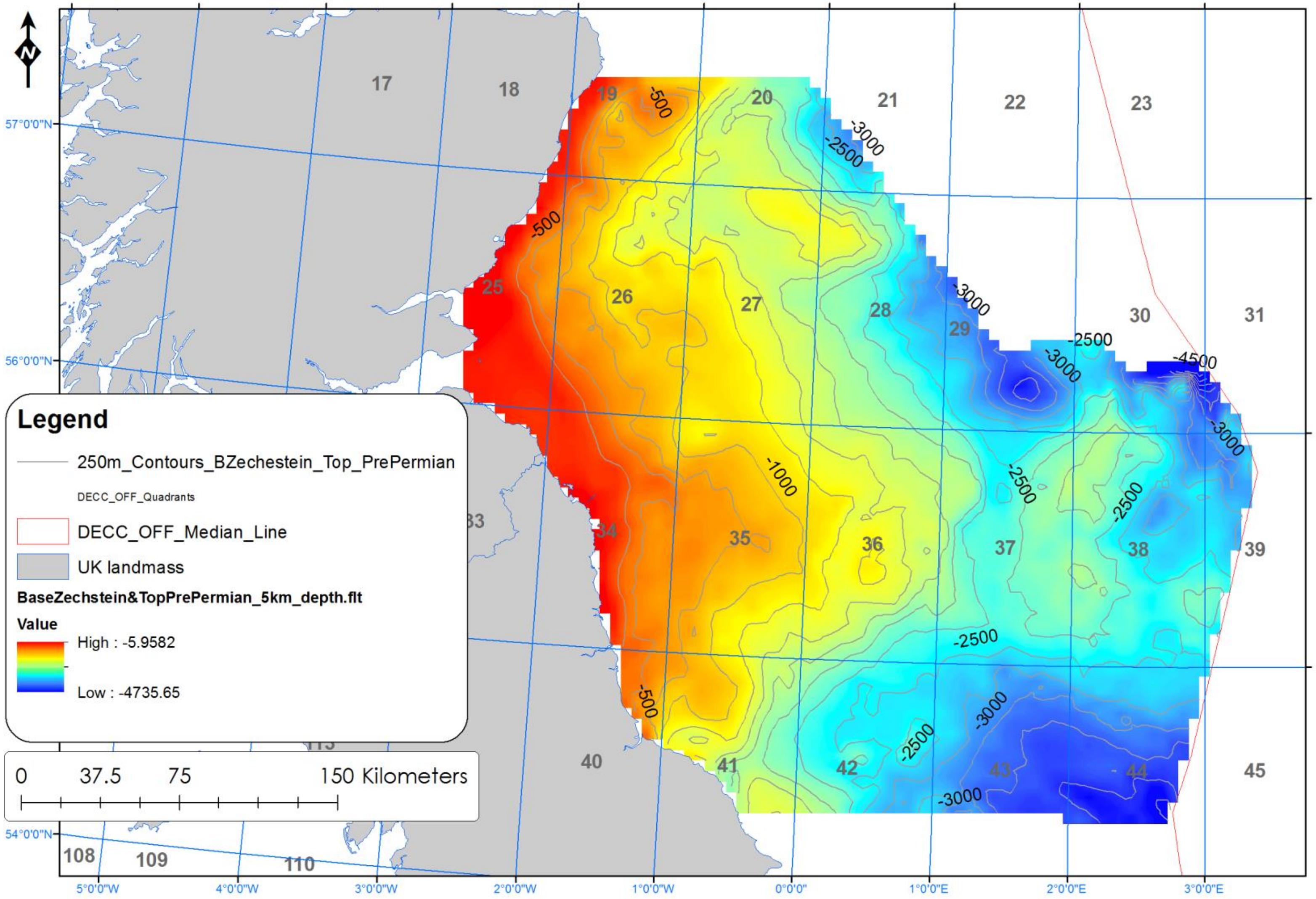

Figure 37. Depth to Base Zechstein in metres below mean sea level.

5.3 ISOPACHS

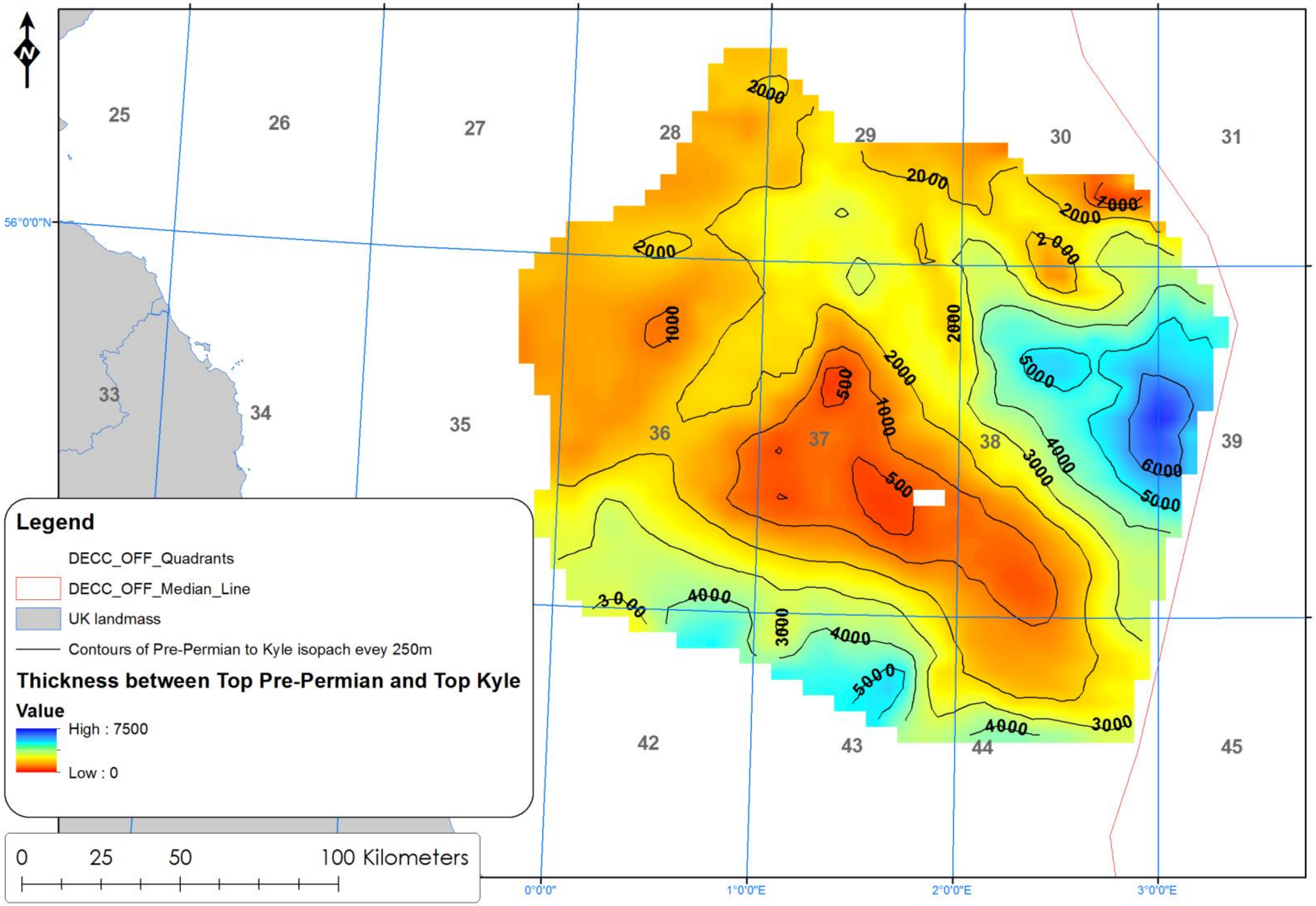

Figure 38. Isopach of the pre-Permian to Top Kyle Group interval. Contour interval is 250 m.

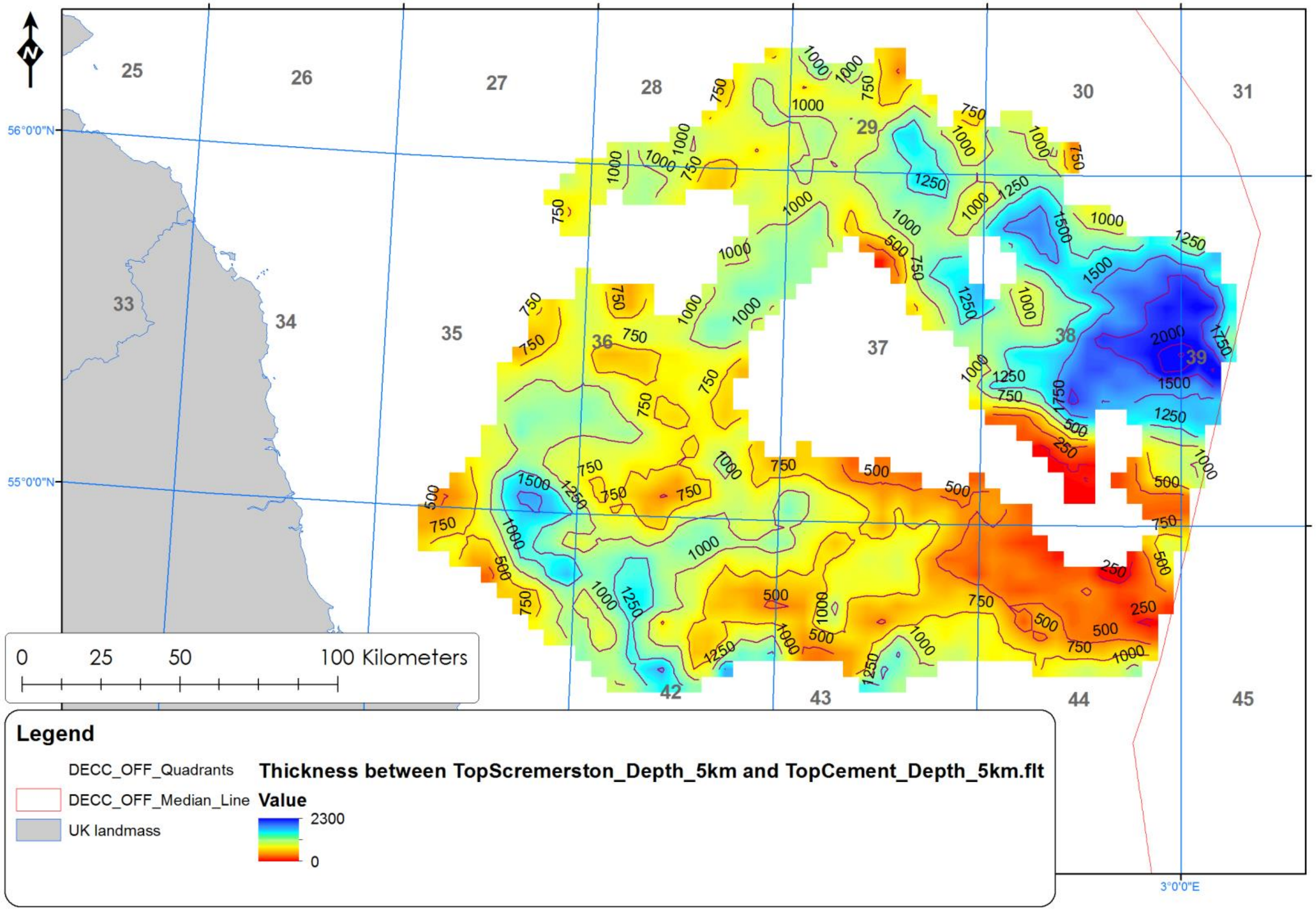

Figure 39. Isopach of the Top Scremerston to Top Cementstone interval. Contour interval is 250 m.

5.4 PRE-PERMIAN SUBCROP MAP

The starting point for revision of the pre-Permian subcrop of the CNS area (Figure 40) was the Pre-Permian Geology of the United Kingdom map produced by Smith (1985a, b). The subcrop map published in the Southern Permian Basin Atlas (Kombrink et al., 2010) superseded the interpretations of Smith (1985a, b) in that area.

The updated pre-Permian Subcrop map has been produced from the integration of:

- Well data;
    - a high proportion of which have been validated or re-interpreted;
    - including recent well results;
- The new seismic interpretation carried out in this project;
- The onshore geology.

Pre-Permian Subcrop Map

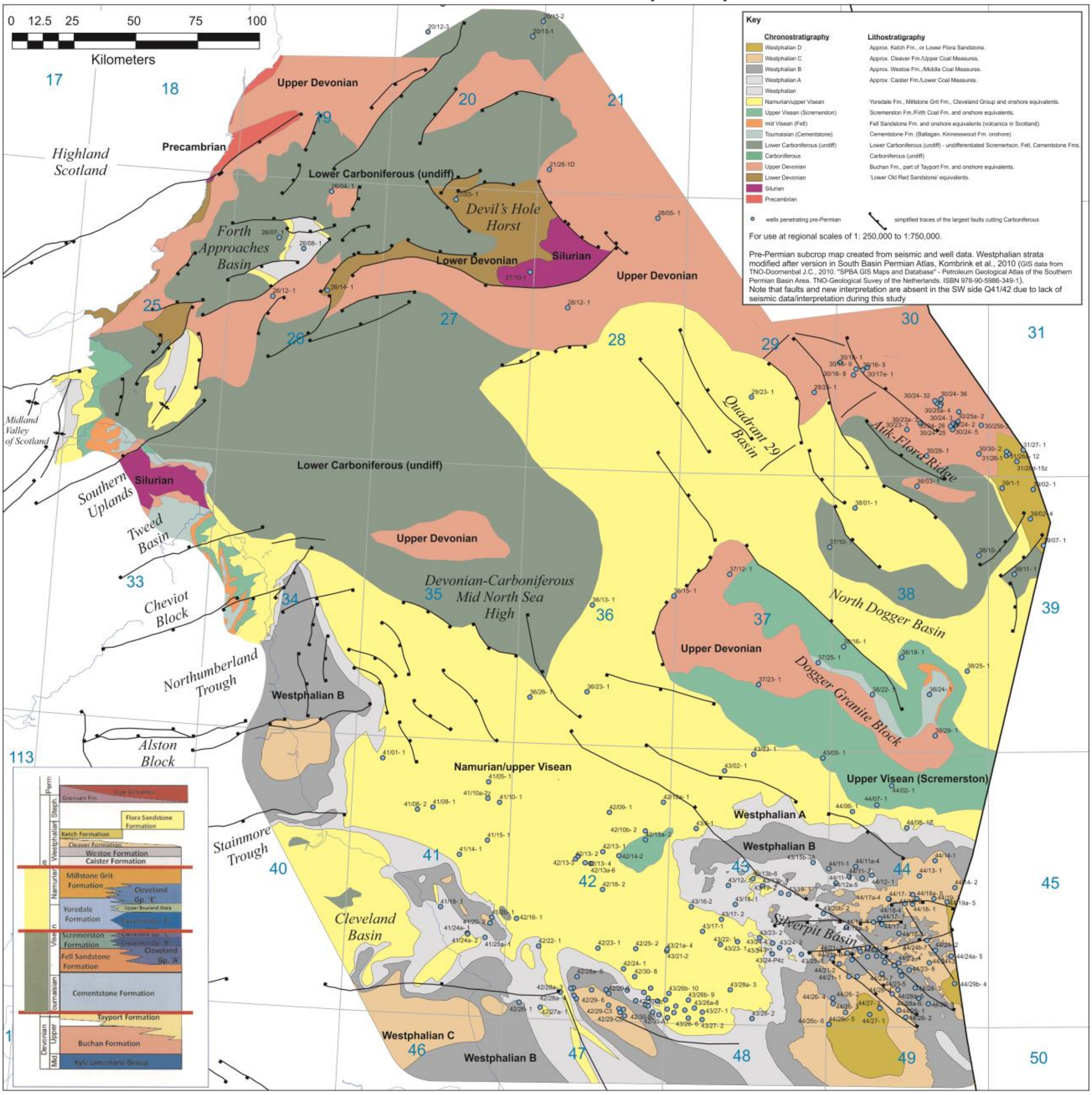

Figure 40. Updated Pre-Permian subcrop map.

6 Conclusions and future work

A regional seismic interpretation of the western margin of the Central North Sea (CNS) area was carried out, specifically over the Mid North Sea High area, offshore extension of Northumberland Trough and Forth Approaches area. A set of time, depth structure and isopach maps and a new pre-Permian subcrop map have been generated and delivered to sponsors digitally. The maps have been used as key inputs to an assessment of the petroleum system and prospectivity of the Palaeozoic succession (Monaghan et al., 2015).

Interpretation of around 50,000 line km of 2D seismic data, together with ties to an extensive well database, has allowed a complex series of Devono-Carboniferous basins to be defined on and around the area known as the 'Mid North Sea High'. The largest and thickest Devono-Carboniferous basins are the NW trending North Dogger Basin, the approximately E-W basins to the south of the MNSH and the Forth Approaches Basin.

The new structural interpretation has been summarised (Figure 10) and used in the compilation of a tectono-stratigraphic model of the area (Leslie et al., 2015; Figure 18). Key observations from the seismic interpretation that contribute to this model are:

- A dominant NW to NNW structural trend in the Dogger region;
- A major NE- trending vertical fault interpreted as a strike-slip fault zone located NW of the Dogger Granite;
- Granitic intrusions are interpreted to influence the structure constraining folding of surrounding Devono-Carboniferous successions;
- Steep faults with relatively small displacements with some exhibiting reversal of throw associated with short wavelength folds observed in offshore extension of Northumberland Trough;
- A deep half-graben in the Forth Approaches area associated with the offshore extension of the Southern Upland Fault that steps northward and is interpreted to have had a strike-slip component of movement during the Late Devonian early Carboniferous.

6.1 FUTURE WORK

Future work could usefully:

- examine areas of Quadrants 41-43 where interpretation was constrained by limited seismic data availability;
- focus on mapping of local reflectors and structures in more detail; and
- provide a more complex depth conversion model.

The new Government seismic survey, available from March 2016, will be a significant asset for any future work undertaken. The new survey provides good regional coverage over the study area and, importantly, will provide modern and deep imaging over some areas not adequately covered by available existing seismic profiles.

7 References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

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