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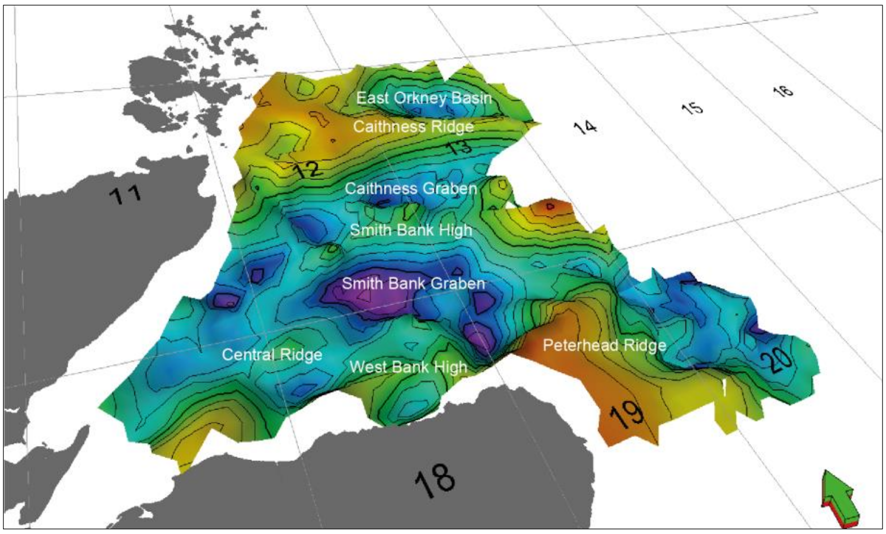
Seismic interpretation and generation of key depth structure surfaces within the Carboniferous and Devonian of the Orcadian Study Area, Quadrants 7-9, 11-15 and 19-21.

Energy and Marine Geoscience Programme

Commissioned Report CR/16/033



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Seismic interpretation and generation of key depth structure surfaces within the Carboniferous and Devonian of the Orcadian Study Area, Quadrants 7-9, 11-15 and 19-21.

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Report; Palaeozoic; Orcadian Basin, Seismic interpretation.

Front cover

3D image on Top Basement to illustrate structural summary of study area.

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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 Inner Moray Firth and western part of the Outer Moray Firth, East Orkney Basin and the Grampian High from seismic interpretation. The rationale for the interpretations made is given and the interpretation results are 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 geometry of the horizons. They are one of the key elements required to assess the petroleum prospectivity of the Palaeozoic sequence within the study area.

Acknowledgements

This report is a published product of the 21st Century Exploration Road Map (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.

In compiling this report, the authors readily acknowledge the assistance of several BGS colleagues, including Ian Andrews, Kirstin Crombie, Sandy Henderson, Mark Kassyk and Vanessa Starcher.

Nigel Smith is acknowledged for his contribution to construction of the updated pre-Permian subcrop map.

Seismic companies (TGS, CGG Veritas, PGS, Spectrum, Schlumberger/WesternGeco) are thanked for allowing reproduction of selected seismic lines and for agreeing to the release of a set of 5 km resolution grids. PGS are thanked for permitting the use of provided grids. Richard Milton-Worssell of OGA is thanked for requesting seismic data from companies.

Jo Bagguley (OGA) and Rosie Fletcher (Chevron) are thanked for technical review of this report.

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Executive Summary

This report details the rationale, methodology and results of a regional seismic interpretation of the 21CXRM Palaeozoic ‘Orcadian study area’, specifically the Inner Moray Firth and western Outer Moray Firth basins (Quadrants 11–15), the East Orkney Basin (Quadrant 13) and the Grampian High area (Quadrants 19–21). The aim of the interpretation was to create Two-Way Travel Time (TWTT) and depth 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 contribute a tectono-stratigraphic model of the Palaeozoic succession. Some 35,000 line kilometres of predominantly 2D seismic data have been interpreted and tied to key released wells in the study area.

In total, 8 depth structure maps of key horizons have been produced for the pre-Permian succession. The maps do not cover the entire study area as it was not possible to interpret a specific seismic reflector everywhere due both to seismic resolution and also current day extents (as a result of non-deposition and/or erosion). These maps provide a key element to aid assessment of the petroleum systems of the Palaeozoic sequence within the study area.

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

Inner and Outer Moray Firth and East Orkney Basin area

- Base Zechstein;
- Top Firth Coal Formation;
- Top Eday Marl Formation;
- Top Orcadia Formation;
- Base Orcadia Formation;
- Top Struie Formation;
- Top Basement.

The geological succession over the Grampian High area was such that only the following surfaces were generated:

- Base Zechstein;
- Base Carboniferous/ Top Devonian;
- Top Basement.

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 tectonic synthesis for the region (Leslie et. al., 2016).

A new pre-Permian subcrop map is presented here that builds on existing publications (Smith, 1985; Marshall and Hewett 2003) and incorporates relevant new well penetrations since the previous maps were published. The well dataset has been either validated or re-interpreted before being integrated with the new seismic interpretation. The map extends the interpretation of the pre-Permian subcrop northwards from the published Central North Sea map (Arsenikos et al., 2015).

General observations on the structures defined across the Inner and Outer Moray Firth:

- The thickest Devonian depocentres can be found in Quadrants 11, 12 and 14 in a relatively restricted corridor bounded to the north by the Caithness Ridge, to the east by the Halibut Horst and to the south by the West Bank and Grampian Highs;
- two important Palaeozoic depocentres underpin the Halibut Platform: in the west, in Quadrant 13, the depocentre is termed the Caithness Graben and to the east, in Quadrant 14 the depocentre is termed the Halibut Basin;

- the Smith Bank High was an intrabasinal high during Devonian times;
- the Halibut Horst, and the Caithness Ridge were major elevated areas by the middle Palaeozoic times, controlling deposition of Middle and (?)Late Devonian strata;
- across Quadrants 11 to 13 the regional basin trend is broadly ENE-WSW. Based on regional tectonic models, it is probable that there is also a deep pre-existing north-southerly trending structural grain but has been heavily overprinted by the more recent one from Permian onwards;
- most of the faults can be divided in two categories: low angle normal faults with growth strata and high angle horizontal slip faults with the presence of a transtensional component.

General observations across the East Orkney Basin:

- The East Orkney Basin is a Palaeozoic half-graben basin, with sediments buried at similar depths (between 2.0 seconds and approximately 2.7 seconds TWTT) to the Devonian basins observed in the Inner Moray Firth;
- The seismic reflector package within the East Orkney Basin is comparable to the Palaeozoic seismic reflector package observed in the Inner Moray Firth area. This suggests that Devonian strata may be present in the East Orkney Basin.

General observations over the Grampian High, NE Forth Approaches Basin and western edges of the Buchan basins:

- Much of the area covered by Quadrant 19 and northern part of Quadrant 20 is interpreted to have been a topographic high during Devonian and Carboniferous times;
    - Faults with a dominant WSW-ENE trend tip out westwards onto the Grampian High.
    - A Devonian succession has been mapped over much of the area. The succession is interpreted to be thin or absent on the footwall of the Banff Fault and immediately adjacent to and over the Grampian Spur (northern blocks of Quadrant 19 and Quadrant 20/01);
        - here Permian and younger successions rest on Lower Palaeozoic basement.
    - There is little evidence for thickening of the Devonian succession against faults within this area;
    - A Carboniferous succession thins westwards onto the Grampian high.
- The WSW-ENE trending Peterhead basins (principally Quadrants 19/9, 19/10, 19/15 and Quadrants 20/06, 20/11, 20/12) are interpreted to have formed principally during Late Jurassic rifting.
    - Significant thicknesses of Jurassic sedimentary rocks rest on either thin Triassic and Permian successions or directly on Devonian or Lower Palaeozoic strata.
    - The dominant fault trend (WSW-ENE) reflects Late Jurassic rifting.
- The NE part of Forth Approaches Basin (FAB) is interpreted to have only a relatively thin Carboniferous succession (200 ms TWTT ~400 m) resting on Devonian strata.
    - This explains the poor imaging on the seismic data compared to the SW part of the basin (northern part of Quadrant 26) where a thick Carboniferous succession can be interpreted;
    - A prominent unconformity of ?Late Devonian age, located within the NE part of FAB, is interpreted to mark an area of uplifted topography that separated Carboniferous successions of different thickness and facies to the south-west and north-east

1 Introduction

1.1 RATIONALE AND BACKGROUND

The Orcadian study area is an important hydrocarbon province with several large producing oil and gas fields. 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 Orcadian study area comprising the Inner Moray Firth and western Outer Moray Firth, the East Orkney Basin and the Grampian High; 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 Orcadian study area (Quadrants 7-9, 11-15 and 19-21), 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.

The study area comprises the Inner Moray Firth Basin (IMF) including the Smith Bank and West Bank highs and associated sub-basins, bounded to the north by the Caithness Ridge, and the Outer Moray Firth Basin (OMF) including the Halibut Horst and Platform and Witch Ground Graben. The East Orkney Basin and the offshore extent of the Grampian High, located to the north and south of the IMF respectively were also mapped (Figure 1). The structural trend within the IMF and Grampian High area is broadly NE-SW to ENE-WSW to E-W. The dominant structural trend within the OMF is NW-SE.

Key bounding faults in the area are the Great Glen Fault (GGF), the Helmsdale Fault and the Wick Fault to the north of the Moray Firth. To the south, the IMF is delineated by the Banff Fault and the Peterhead Fault (Figure 1). The Smith Bank Fault is a major intrabasinal fault.

The area has been subjected to major tectonic episodes during the Devono-Carboniferous, Permo-Triassic, Jurassic to Early Cretaceous and Late Cretaceous to Tertiary (Andrews et al., 1990). Regional Tertiary erosion played a major role in the area, with estimates of approximately 1 km of sediments being removed across the entire basin (Hillis et al., 1994). While development of the Devonian and Carboniferous basins is thought to have been controlled by strike-slip movement on the Great Glen and associated faults (Leslie et al., 2016), interpretation of offshore seismic data and onshore field observations show that during the Mesozoic the development of the IMF was the result of normal faulting in an extensional regime with a minimal strike slip component (Underhill 1991, Thomson and Underhill 1993). In the IMF area, the controlling fault was the Helmsdale Fault (situated west of the GGF along the Scottish coast) while the GGF played a minor strike-slip role (Andrews et al., 1990; Underhill, 1991).

Although there are a significant number of publications on the Palaeozoic intervals present in the study area, the majority discuss the onshore stratigraphy, facies analysis and the depositional environments of the Orcadian and the adjacent domains (e.g. Astin, 1985; Duncan and Buxton, 1995; Clarke and Parnell, 1999; Marshall et al., 2011).

The Offshore Regional Reports from Andrews et al., (1990) and the Devonian Chapter of the Millennium Atlas (Marshall and Hewett, 2003) provide the most complete overview of the offshore structures and the Palaeozoic structural configuration across the Orcadian study area, and have been utilised in this report. The Palaeozoic project benefited from access to a large amount of seismic data, in order to focus on Palaeozoic structures and investigate areas that have been unexplored or poorly understood.

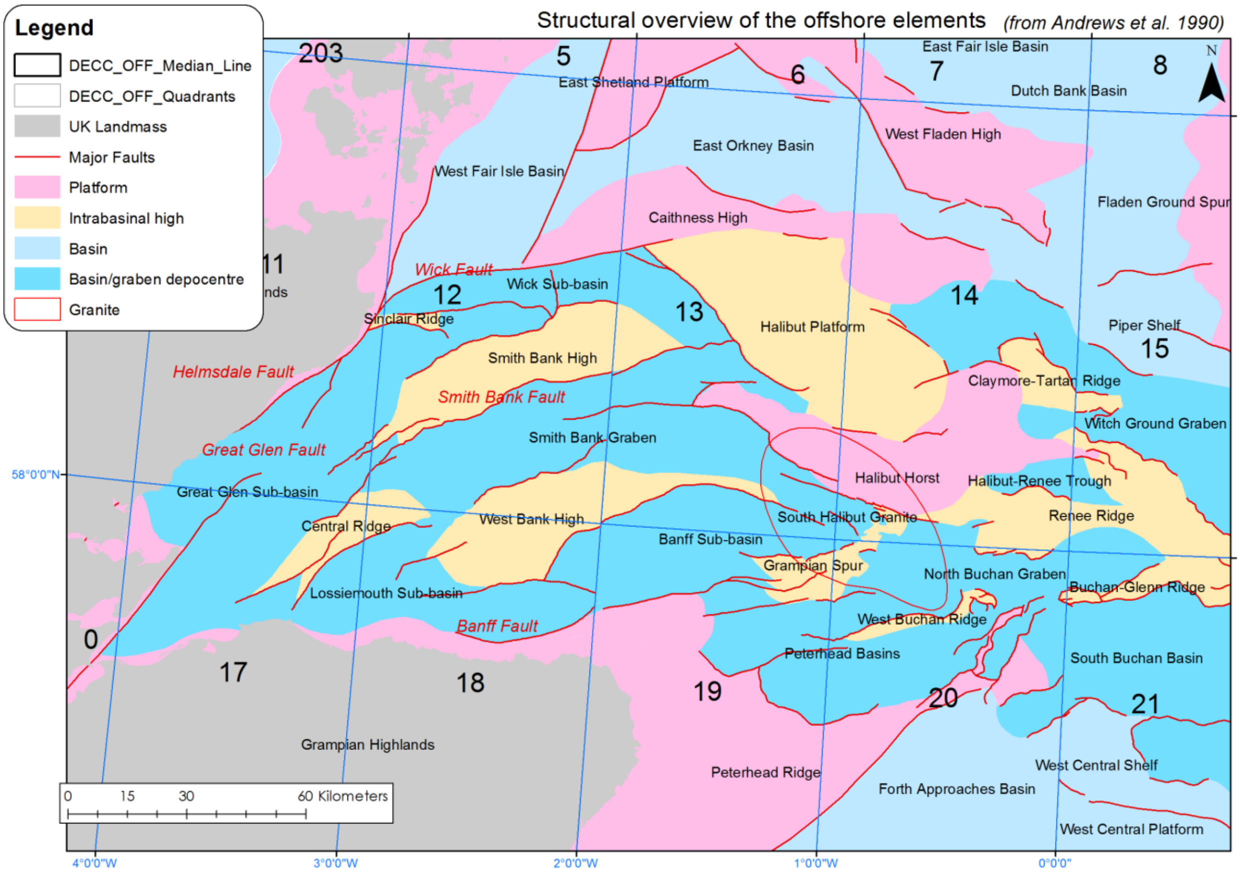


Figure 1. Structural diagram of the offshore domain illustrating the major structures in the study area (from Andrews et al., 1990).

1.2 RESOURCES AVAILABLE TO THE SEISMIC INTERPRETATION TASK

Approximately 800 2D lines and 19 volumes of 3D seismic data were consulted during the task. Released well information and accompanying reports, and published papers were also utilised (Section 2). The project objectives included regional-scale evaluation, not prospect-specific evaluations. In agreement with the seismic data vendor companies, all interpretations are released as grids with a 5000 m node spacing. More detailed interpretations using the 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 (Whitbread and Kearsey, 2016), source rock potential (Vane et al., 2016) and basin modelling (Vincent, 2016), was to undertake a regional scale petroleum systems analysis of the Palaeozoic. The depth surfaces, described in the following sections, are key components of the assessment of the petroleum potential of the Palaeozoic in the Orcadian 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 Quadrants 6 to 22. 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; 16 surveys comprising more than 800 profiles were used (Figure 2), amounting to approximately 35000 line kilometres of data. Nineteen 3D surveys were used as a source of information concerning the fault trends. PGS 3D volumes were used for more local interpretations of the Top Firth Coal across structurally complicated areas. These interpretations were consequently resampled over intersecting 2D lines spacing before inclusion in Two Way Travel Time and depth grids.

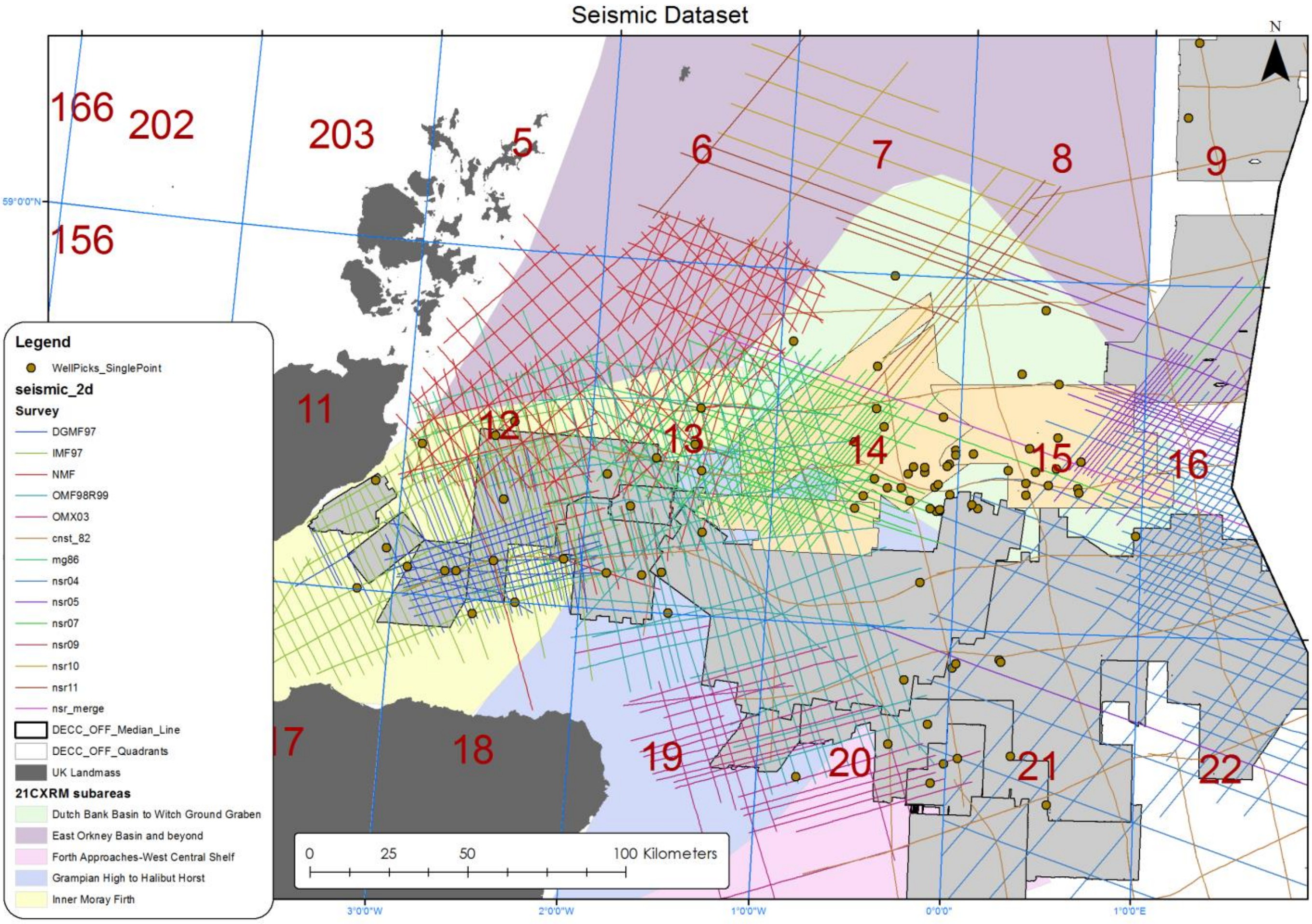


Figure 2. Basemap showing 2D data used during the project. PGS 3D seismic data (cream-coloured) were also used for seismic interpretation. The remainder of the 3D seismic data (grey) were consulted as source of confidential information through the DECC/BGS contract but was not interpreted for the Palaeozoic Project. Key wells used in the seismic interpretation are also shown.

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

Table 1 shows the 2D seismic surveys used for the interpretation of the Devonian and Carboniferous in the study area.

Survey	Owner
DGMF97	Spectrum
IMF97	Spectrum
OMF98	Spectrum
OMX03	Spectrum
CNST82	Schlumberger
MG86	Schlumberger
MP86MF	Schlumberger
NMF	Schlumberger
NSR	TGS and partners Spectrum
NSR03/NSR1 VOL 1 CDA	TGS and partners Spectrum
NSR04	TGS and partners Spectrum
NSR05	TGS and partners Spectrum
NSR07	TGS and partners Spectrum
NSR09	TGS and partners Spectrum
NSR10	TGS and partners Spectrum
NSR11	TGS and partners Spectrum

Table 1. List of 2D Seismic surveys used during the interpretation in the Orcadian Basin area.

The workflow was similar to the one utilised in the Central North Sea/Mid North Sea High area (Arsenikos et al., 2015). Seismic interpretation began from profiles close to wells which provided calibration of the seismic reflectors and was extended to areas less constrained by well information. The priority areas for seismic interpretation were agreed by the project Technical Steering Committee and focussed on underexplored areas of the East Orkney Basin, the Grampian High and the north-eastern end of the Forth Approaches. Nonetheless, in order to establish a better understanding of the area, seismic interpretation started from the better understood/calibrated area of the Inner Moray Firth. Absence of wells in the East Orkney Basin results in a lower interpretation confidence here; however distinct seismic reflectors were recognised and compared to areas with well coverage (see section 3.4.2).

A total of nineteen 3D Volumes were available for the project to use in confidence via the DECC/BGS contract, for better understanding of the complicated fault trends. These volumes cover the Inner and Outer Moray Firth area, and the transitional domain between the Forth Approaches and the area offshore the Grampian High:

3D Volumes consulted through the DECC/BGS contract – name as indexed by BGS	**Owner**
agea99	Aker Geo/via TGS
B14/25	BG
Caithness	Caithness Petroleum
ver_cns_north_25m (northern part of Cornerstone)	CGG Veritas
Captain	Chevron Texaco
EV06	Endeavour
Greater Dauntless	CGG Veritas
Blakeney	Spectrum
Greater Kittiwake	CGG Veritas
Moray_Firth_3D	Petro-Canada
Beatrice	Talisman
MF10_MF11	TGS
tq3d	Western Geco
MC3D-Q16-2013	PGS
MC3D-BYL2013M	PGS

3D Volumes used during interpretation and subsampled on 2D lines – name as indexed by BGS	**Owner**
MC3D_WGG2012M	PGS
MC3D_WGG2013M	PGS
MC3D-Q15-2015	PGS
MC3D Q14-06R	PGS

Table 2. List of the available 3D seismic surveys across the Orcadian study area. Only PGS 3D seismic data were interpreted and resampled based on the intersecting 2D profiles before being integrated in the gridding process.

2.2 WELL INFORMATION AND SEISMIC CALIBRATION

2.2.1 Available wells database

A re-interpretation of wells picks was undertaken for the project (Whitbread and Kearsey, 2016). Notably, even though more than 320 wells penetrate Palaeozoic strata, very few penetrated the entire Devonian succession (four wells in and around the Inner Moray Firth).

2.2.2 Well to seismic ties

Seismic calibration was achieved both by the use of synthetics and the available time-depth pairs from checkshots. To add an extra degree of confidence in data calibration, synthetics were produced for a number of selected wells with good penetration of the Devonian and

Carboniferous strata (e.g. Figure 16). When compared with the synthetics, the time-depth pairs showed a very good fit. Subsequently, given the regional character of the study, the majority of the calibrations from wells to seismic were achieved using checkshot data.

Top Struie Formation	**Base Orcadia Fm. (well picks of Top Lower Strath Rory)**	**Top Orcadia Formation**	**Top Eday Marl**	**Top Firth Coal (including sand rich facies)**	
12/27- 1	11/30a- 10	11/25- 2	12/13- 1	14/13- 4	15/16- 16
12/27- 2	11/25- 2	11/30- 6	**12/30- 1**	14/15- 1	15/16- 3
12/29- 2	12/23- 1	11/30a- 10	**13/13- 1**	14/15- 2	15/17- 15
18/03- 1	12/26- 3	12/13- 1	**13/16a- 1**	14/19- 1	15/17- 16
	12/27- 1	12/18- 1	**13/17- 1**	14/19- 12	15/17- 1A
	12/27- 2	12/23- 1	**13/18- 1**	14/19- 2	15/18- 1
	12/28- 2	12/26- 3	**13/19- 1**	14/20- 1	15/18- 2
	12/29- 2	12/28- 2	**13/22- 1**	14/20- 11	15/18B- 3
	13/24- 1	12/29- 2	13/27- 1A	14/20- 13	15/19- 1
	18/03- 1	13/19- 1	**13/28- 1**	14/20- 2	15/19- 2
		13/22- 1	**13/28- 4**	14/20- 4	15/19- 3
		13/28- 4	9/16- 3	14/20- 6Z	15/21a- 7
		14/19- 10		14/20- 7	20/04A- 2
		14/19- 11		14/20- 8	20/09- 4A
		18/03- 1		14/20- 9	20/10A- 3
		8/04- 1		14/20B- 16	20/15- 1
		9/07- 1		14/20B- 17	20/15- 2
		9/16- 3		14/20B- 19	21/02- 7
				14/30- 1	21/11- 1
				15/07- 1	21/12- 2B
				15/08- 1	21/13B- 1A
				15/11- 1	26/07- 1
				15/12B- 2	26/08- 1

Table 3. Wells penetrations by the different formations interpreted in this study. Wells in BLUE text recorded both the Eday Marl and Eday Flagstone intervals.

3 Seismic Interpretation

3.1 SELECTED EVENTS

3.1.1 Selection criteria

The choice of the interpreted seismic events was based on two key-factors:

- The presence of high reflectivity seismic reflectors resulting from strong acoustic impedance contrasts between successions were preferentially mapped in order to obtain the most confident picking over large areas.
- The importance of the horizon picked as part of a functioning petroleum system. For example, the Devonian Orcadia and Carboniferous Firth Coal formations represent important potential Devonian and Carboniferous source rocks.

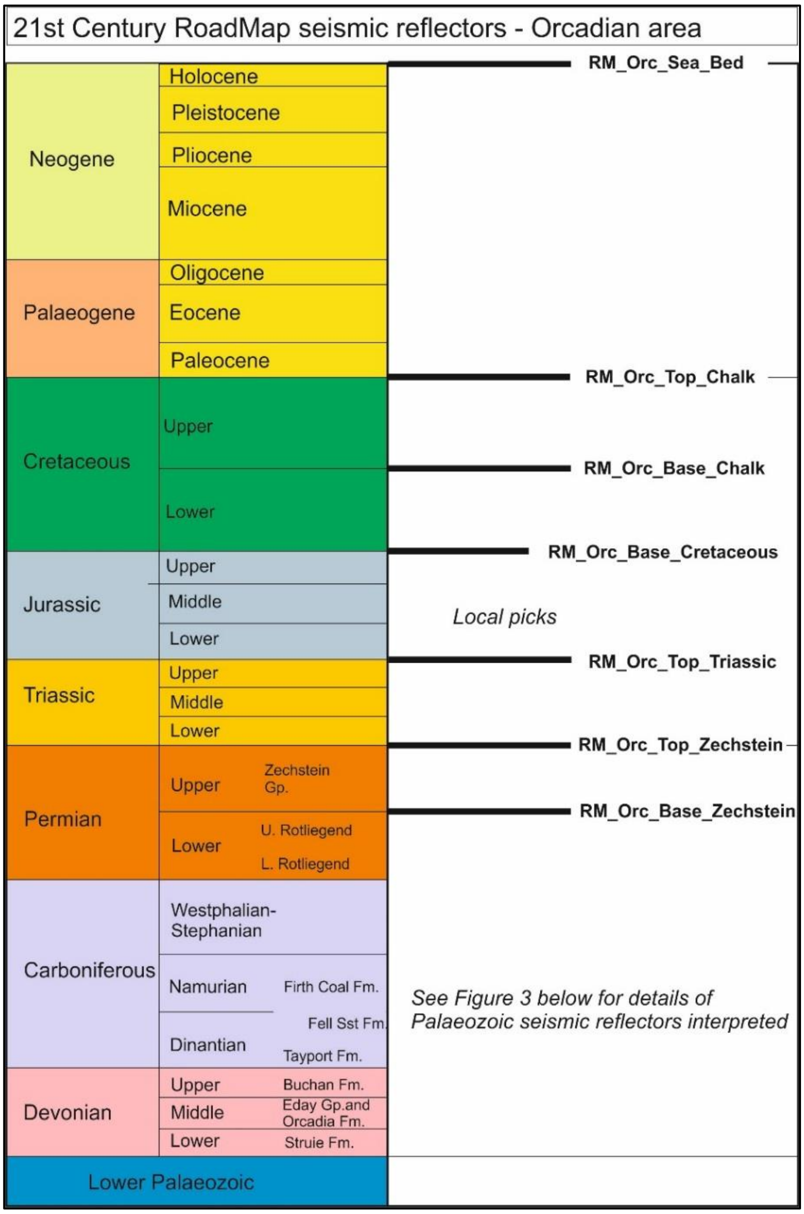


Figure 3. Summary of the key seismic horizons used in this study (black bold colour). The Mesozoic and Cenozoic horizons have been imported from previous confidential DECC/BGS studies and used for the purposes of depth conversion and production of surfaces of key pre-Permian events.

For this project, the Two Way Travel Time (TWTT) interpretations of the following events were carried out in SeisWorks™ and Decision Space™ software. Unless otherwise specified, events were only picked in Inner Moray Firth (IMF), Outer Moray Firth (OMF) and East Orkney basins:

- Base Zechstein – *All areas*;
- Top Firth Coal Formation;
- Base Carboniferous/ Top Devonian – *Grampian High area only*;
- Top Eday Marl Formation;
- Top Eday Group - *Grampian High area only*;
- Top Orcadia Formation;
- Base Orcadia Formation;
- Top Struie Formation;
- Top Basement - *All areas*.

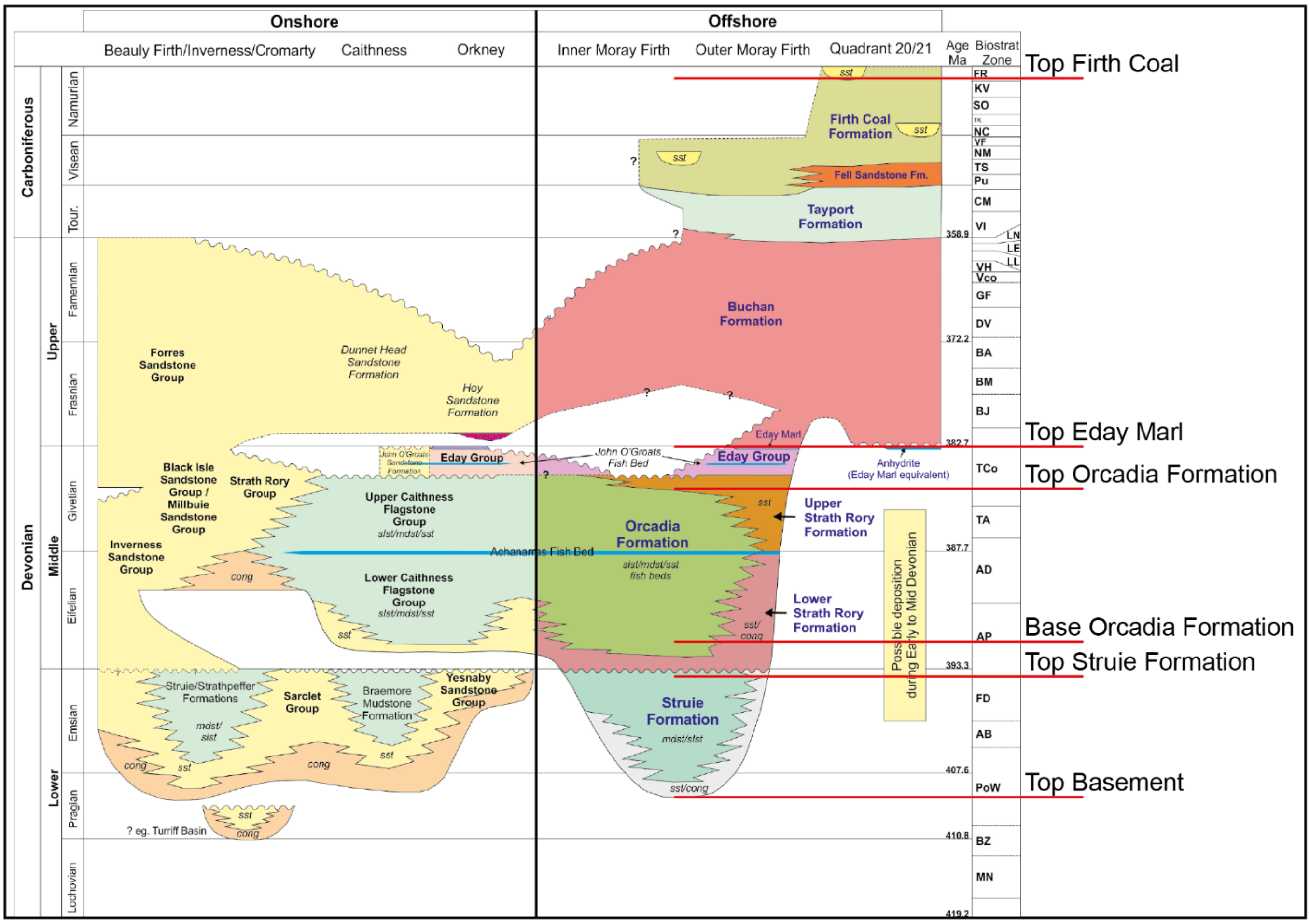


Figure 4. Key pre-Permian seismic reflectors interpreted in the Orcadian area placed on the regional Devonian and Carboniferous stratigraphic summary (Whitbread and Kearsey, 2016).

Seismic horizons from Base Zechstein and younger (Figure 3) were compiled from existing interpretations available within BGS (from the BGS-DECC/OGA contract) where possible, and then extended or infilled where no other interpretation was available. These overlying surfaces were also imported to Decision Space™ and gridded.

The TWTT grids were depth converted using the produced velocity model and the fits to the well tops database (see section 3.2).

The character of the seismic reflectors picked within the Devono-Carboniferous (Figure 4) is described below.

3.1.2 Near Top Basement

Basement is defined here as metamorphosed Lower Devonian or older Lower Palaeozoic and Precambrian rocks or granite. No single continuous seismic reflector defines the Top Basement over the study area. A near Top Basement pick may be located above a more transparent or featureless seismic package i.e. 'acoustic basement' immediately beneath Devonian, Carboniferous or younger successions (see deepest intervals in Figure 16 and Caithness High in Figure 20). It may also be represented by an angular unconformity. However, these characteristics cannot be used on their own to delimit the Top Basement as there may be relatively continuous seismic reflectors present within a likely basement package and an angular unconformity is certainly not present everywhere. The Top Basement interpretation was constrained by all available well penetrations and the bedrock occurring at sea bed, however, the depth structure map for this horizon must be viewed with the constraints outlined above in mind.

3.1.3 Top of the Struie Formation (Lower Devonian)

The lacustrine facies of the Struie Formation have been penetrated in 3 wells (Table 3) in the Inner Moray Firth and here it rests directly on Basement. The Struie Formation has been picked on the top of a seismic package comprising a series of high amplitude, relatively continuous reflectors and with reference to the Top Basement interpretation. Although predominantly comprising lacustrine mudstone, the Struie Formation penetrated in well 18/03-1 (shown in bold in Table 3) proved a conglomeratic succession with sandstone intercalations.

3.1.4 Top and Base Orcadia Formation

The Base Orcadia Formation pick was calibrated using the top of the Lower Strath Rory well surface picks (Table 3, Figure 4). In the seismic, it was interpreted at the base of the seismic package characterised by continuous seismic reflectors that define the Orcadia Formation. Furthermore, in many cases, especially in Quadrant 12, the Base Orcadia Formation represents an unconformity between the conglomerates of the Lower Strath Rory Formation and the initiation of stratified lacustrine sediments.

The Top Orcadia Formation has been penetrated in 18 wells across the Inner and Outer Moray Firth (Table 3). The interpretation followed the top of a package of high amplitude and relatively high frequency seismic reflectors. Locally, a boundary is resolvable in the seismic, between well-stratified, relatively continuous reflectors below, and more chaotic facies above. This is interpreted as the stratigraphic change between the top of the Orcadia Formation and the conglomerate and sandstone facies of the Upper Strath Rory Formation (where present and resolvable in the seismic).

One of the most representative examples of the Orcadia Formation can be seen in Figure 16. Equally, well 12/28-2 has penetrated the entire Orcadia Formation (see Whitbread and Kearsey 2016)

3.1.5 Top Eday Marl

The Eday Marl is typically picked as a bright, continuous seismic reflector usually recognised by a positive amplitude with negative amplitudes above and below. In most cases, where the Eday Marl is present, a deeper reflector interpreted as the Eday Flagstone is also present. The Eday Marl Formation is considered to be a marginal marine succession that is age equivalent to the Kyle Limestone. The Eday Flagstone Formation comprises a lacustrine succession of calcareous claystone and siltstone and minor sandstone and limestone (Whitbread and Kearsey, 2016). Table 3 shows the wells that have encountered the Eday Marl and the wells that have penetrated both the Eday Marl and Eday Flagstone in blue.

3.1.6 Base Carboniferous/ Top Devonian (picked in area immediately adjacent to Grampian High)

The near Base Carboniferous was interpreted at the base of a distinctive package of relatively strong and continuous seismic reflectors. Although a similar seismic package can be recognised where the Firth Coal Formation has been proven in wells (see section 3.1.7), it was not possible to use this observation to identify this Formation in the Grampian High area (see section 3.5.2). On some seismic lines it can be shown to be close to or coincident with an angular unconformity (see section 3.5.1.4). Where interpreted, the Top Eday Group seismic reflector helped constrain the interpretation of the Base Carboniferous. The Base Carboniferous seismic reflector becomes the near Top Devonian reflector when the former subcrops the Base Permian/ Base Zechstein (see section 3.5.1.4).

3.1.7 Top Firth Coal Formation

The Firth Coal has been picked regionally in Quadrants 14 and 15. The formation has been proven in numerous wells in the area (Table 3). It is resolvable in the seismic data as a small number of high amplitude reflectors, usually immediately below the Base Zechstein bright reflector. The formation is interpreted to have been deposited in a range of fluvio-lacustrine environments, including channels (Whitbread and Kearsey, 2016). Seismic interpretation shows that deposition was also fault controlled. In Quadrants 14-15, the Firth Coal Formation can be interpreted both on top of small-scale horsts and deeper basins. However, to the south and west of Quadrant 14 it is truncated and absent on regional highs, and is also absent further west in the Inner Moray Firth area. A representative example of this structural configuration can be found in Figure 23.

3.1.8 Base Zechstein Group (Upper Permian)

The Zechstein Group forms a regional cover across much of the study area but is absent in the far west of the Inner Moray Firth and over much of the Grampian High. Where present within the Inner Moray Firth, it comprises a clastic facies (Andrews et al., 1990). Further east into the Outer Moray Firth and east and south of the Grampian High it comprises the more familiar halite, anhydrite and carbonate succession. Here, 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 the distribution of its dolomite, anhydrite and evaporate lithologies. In some areas (e.g. northern edges of Quadrants 21, 22), the top of the Group is marked by the presence of distinctive halokinetic diapiric structures. The seismic character of the clastic deposits can be somewhat less bright than those of the dolomite, anhydrite and evaporite lithologies, but there is often still a relatively high amplitude, continuous reflector marking the top of the Group. The internal seismic character of the clastic deposits is typically fairly undisturbed, with parallel, relatively continuous reflectors comprising the seismic package (e.g. Figure 16).

3.2 DEPTH CONVERSION METHOD AND GENERATION OF DEPTH MAPS

3.2.1 Introduction

The mapped Palaeozoic 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 and differential compaction of the sediments. Where higher velocity layers are present, for instance due to significant thicknesses of Upper Permian Zechstein Group halite or Upper Cretaceous Chalk, it is particularly important to capture this variation in the depth conversion process.

Depth conversion provides a more realistic topography to interpret the basins' subsidence and uplift history. The depth converted surfaces provided input to the basin modelling calculations (Vincent, 2016).

There is a stepwise increase or decrease in velocity due to the contrasting lithologies and complex uplift and burial history down to the Carboniferous and Devonian surfaces. These variations are not easily described by a simple exponential increase in velocity with depth. Thus a layer cake method of depth conversion was applied.

3.2.2 General methodology

The following steps summarise the preferred depth conversion method:

1) Selection of all the available wells in the area of interest with a valid Time-Depth curve;
2) Selection of the wells with the most complete check shots and/or velocity logs;
3) Problematic wells with anomalously high or low velocities were removed;
4) Creation of the velocity model in Decision Space™ with the following parameters:
    a. Minimum velocity 1480m/s for the water column;
    b. 641 Time-Depth curves for wells spanning Quadrants 11 to 21;
    c. A layer cake model was defined by the following 14 Surfaces:
        i. Seabed;
        ii. Top Chalk;
        iii. Base Chalk;
        iv. Base Cretaceous/Cimmerian Unconformity;
        v. Near Top Triassic;
        vi. Top Zechstein (in contrast to the Central North Sea, due to absence of diapirs and extensive evaporitic facies, the velocity is not a function of the thickness of the Zechstein interval, see Arsenikos et al., 2015);
        vii. Base Zechstein Group;
        viii. Top Firth Coal Formation;
        ix. Top Devonian – Base Carboniferous (Grampian High only). Due to the absence of wells around the Grampian High with pre-Permian velocity information this surface was depth converted using a constant velocity of 4000 m/s (the same as the pre-Permian succession in the Central North Sea, Arsenikos et al., 2015);
        x. Top Eday Marl/Top Eday Group;
        xi. Top Orcadia Formation;

xii. Base Orcadia Formation;
xiii. Top Struie Formation;
xiv. Top Basement (granitic/metamorphic rock velocities were used for this surface).

5) The calculated 3D Volume was quality controlled visually against selected lines both across and along the basin;
6) Residual fit maps were produced as part of the velocity model;
7) This process was repeated until good correlation between modelled and measured depth in the wells was achieved.

An example from the final 3D velocity model is shown in Figure 5 below. The above surfaces, along with the interpreted faults were used to define the structural framework of the area. In areas where the interpretation of the Top Firth Coal Formation was derived from 3D data, the 3D picks were resampled to 2D line spacing for inclusion into the gridded surface.

3.2.3 Importing depth converted grids to Petrel

The TWTT and depth converted grids were imported into PETREL and checked for consistency. The grids were clipped to the Areas of Interest (AOI's) for each horizon and resampled from 1 km to 5 km. Any residuals due to the resampling and the curvature of the grids where corrected again to relevant wells in PETREL and the majority of overlaps resultant from the regridding process were removed.

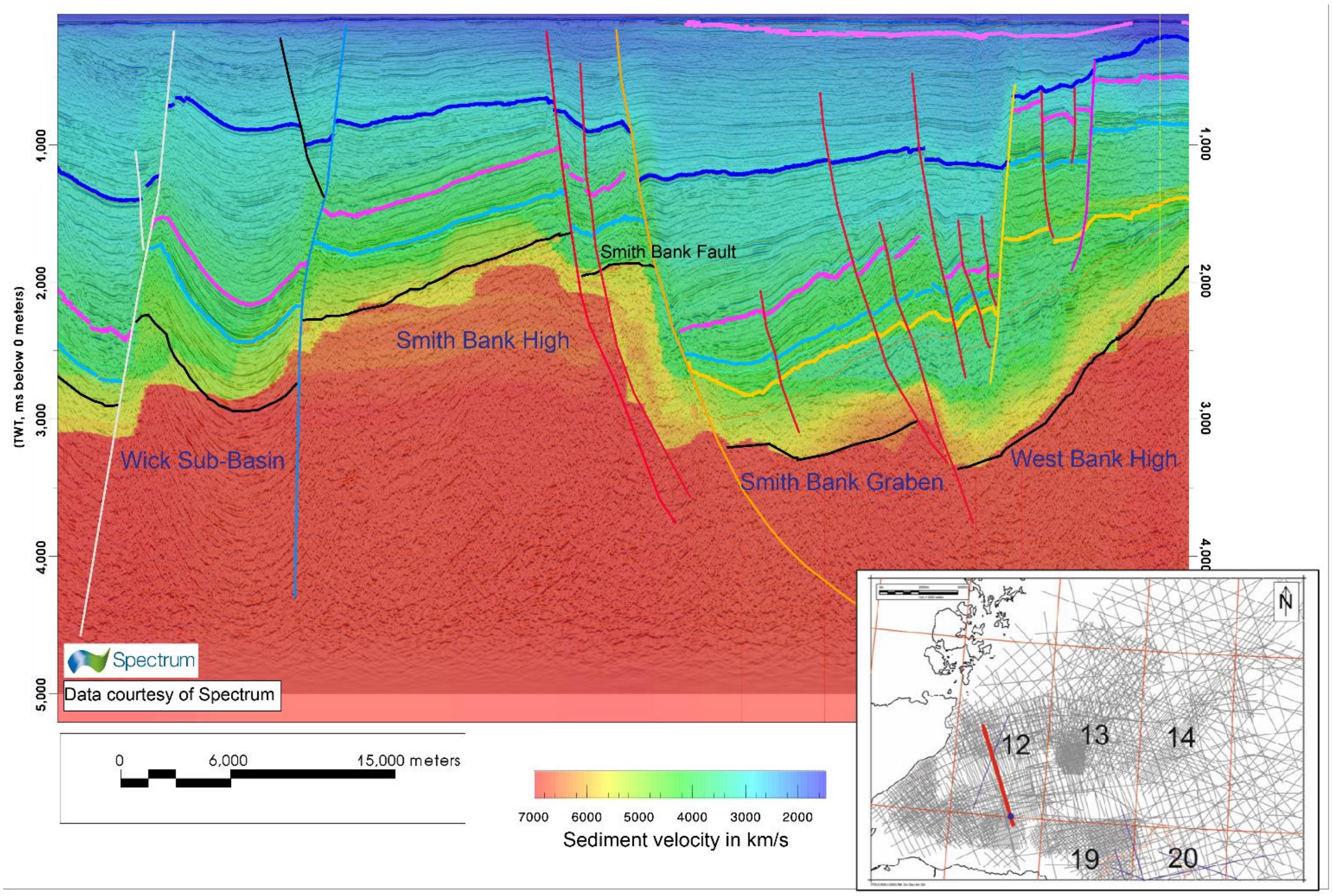


Figure 5. Seismic profile illustrating the variation in velocity both laterally and with depth (for horizon labels see Figure 16).

3.3 DEPTH SURFACES

This section presents images of the 5 km resolution depth converted surfaces which are available digitally. A set of TWTT surfaces complementing the depth surfaces shown in this report are also supplied in digital format. The surfaces are:

- Base Zechstein;
- Top Firth Coal Formation;
- Base Carboniferous/ Top Devonian (Grampian High and adjacent area only);
- Top Eday Marl Formation;
- Top Orcadia Formation;
- Base Orcadia Formation;
- Top Struie Formation;
- Top Basement (All areas).

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

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

The faults are supplied as generalised shapefiles. Faults were interpreted from a dense coverage of the available seismic data. The resulting detailed fault structure was simplified in order to fit with the 5,000 m grid spacing applied to the mapped surfaces.

3.3.1 Challenges during the interpretation

There proved to be six major challenges during seismic interpretation;

- limited well penetration of the Devonian and Carboniferous strata (typically the last 500-600 m before the well TD);
- restricted seismic coverage in areas such as the East Orkney Basin and the Grampian High area;
- low reflectivity of the deep Palaeozoic seismic interval;
- restricted interpretation time due to the project delivery timetable;
- complex tectonic framework with a strong control by Mesozoic and younger events;
- horst/ graben configurations spanning up to 15-25 km width, which sometimes prove difficult to represent on the agreed 5 km x 5 km grid spacing.

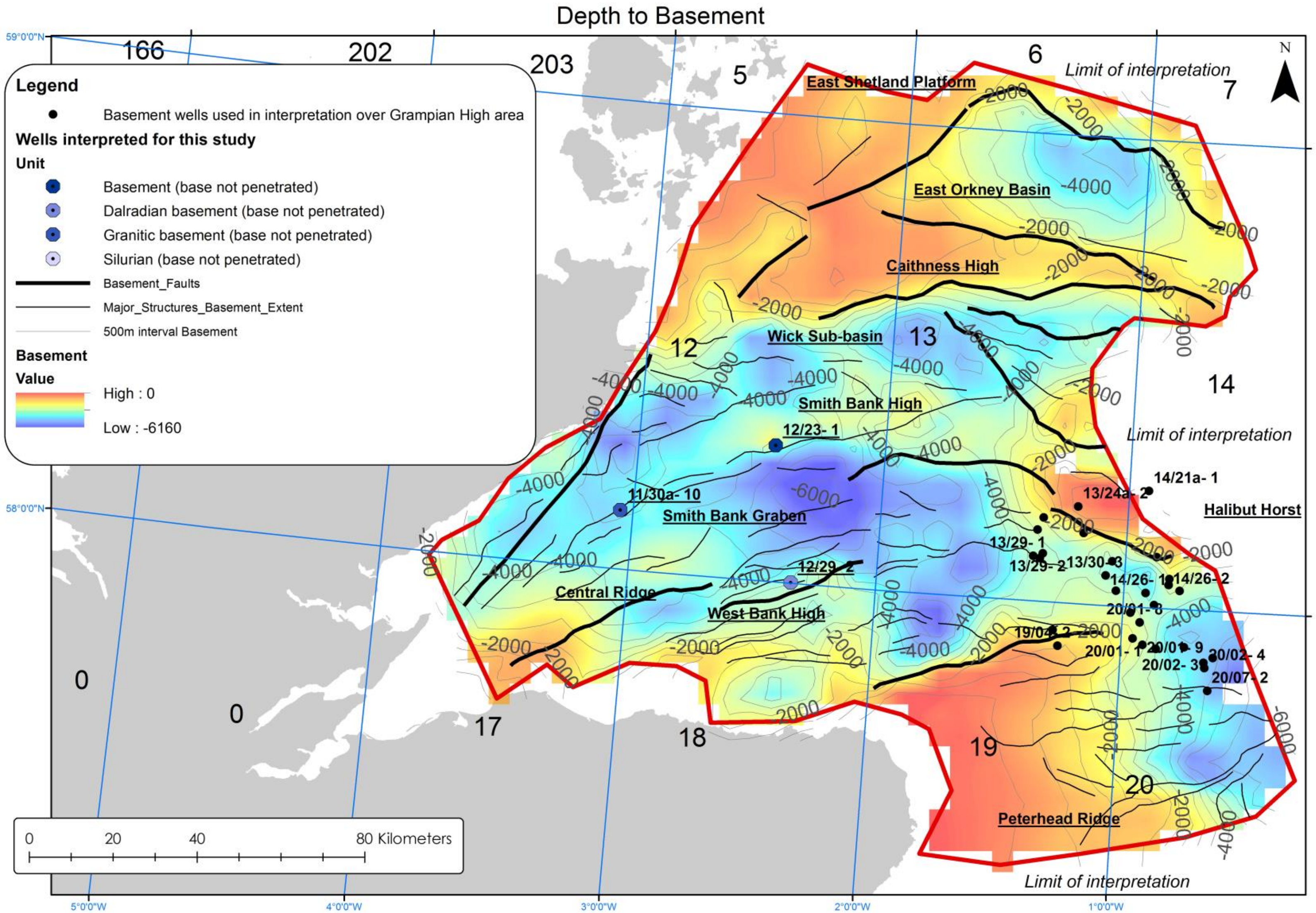


Figure 6. Depth to Top Basement in metres below mean sea level.

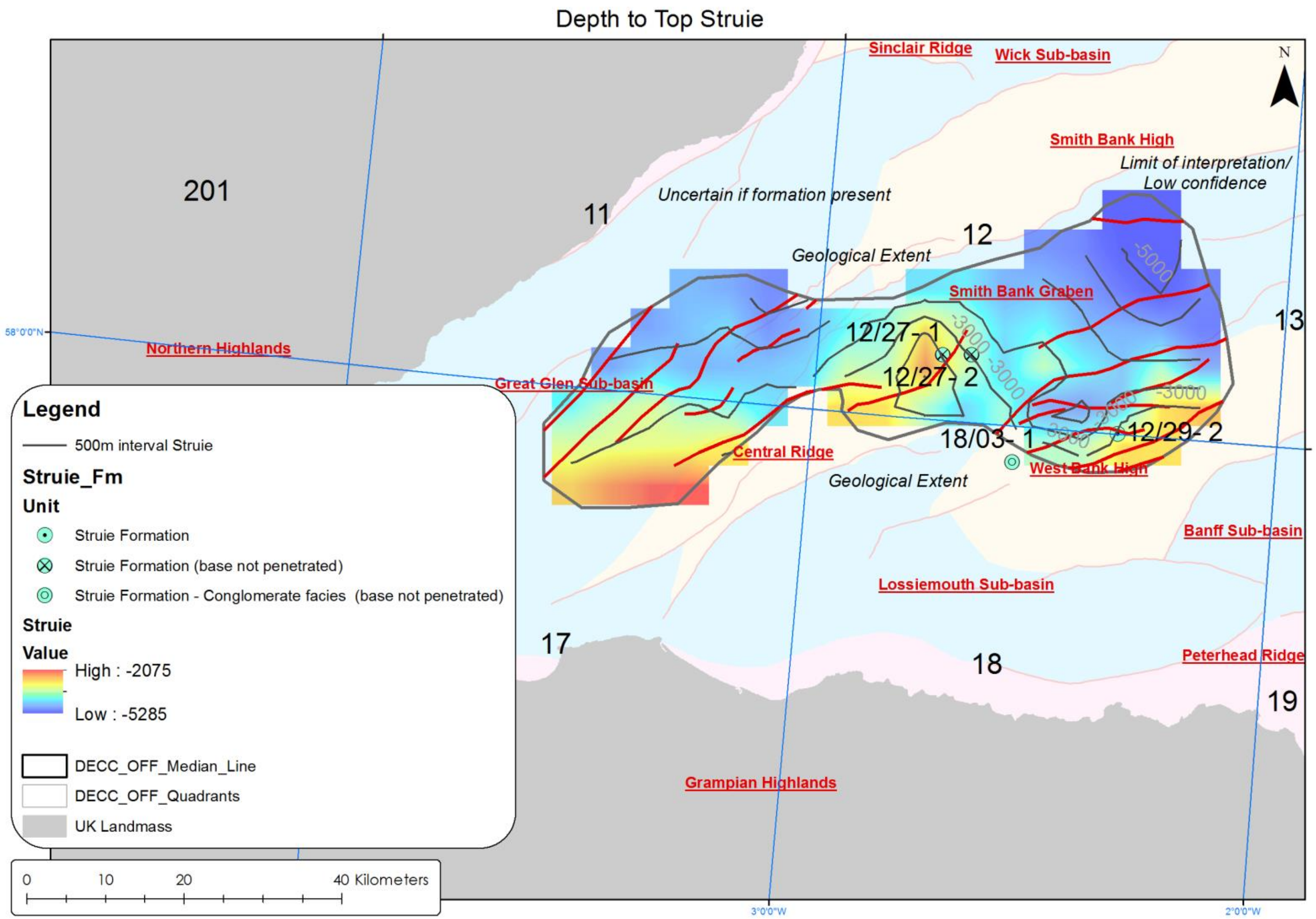


Figure 7. Depth to Top Struie Formation (Lower Devonian) in metres below mean sea level. The surface represents the lacustrine facies of the formation and not the conglomeratic synchronous deposits. 18/03-1 contains the conglomeratic facies and it has not been included in the surface. Pink colour illustrates the ridges, blue the basins and yellow/cream-coloured the highs.

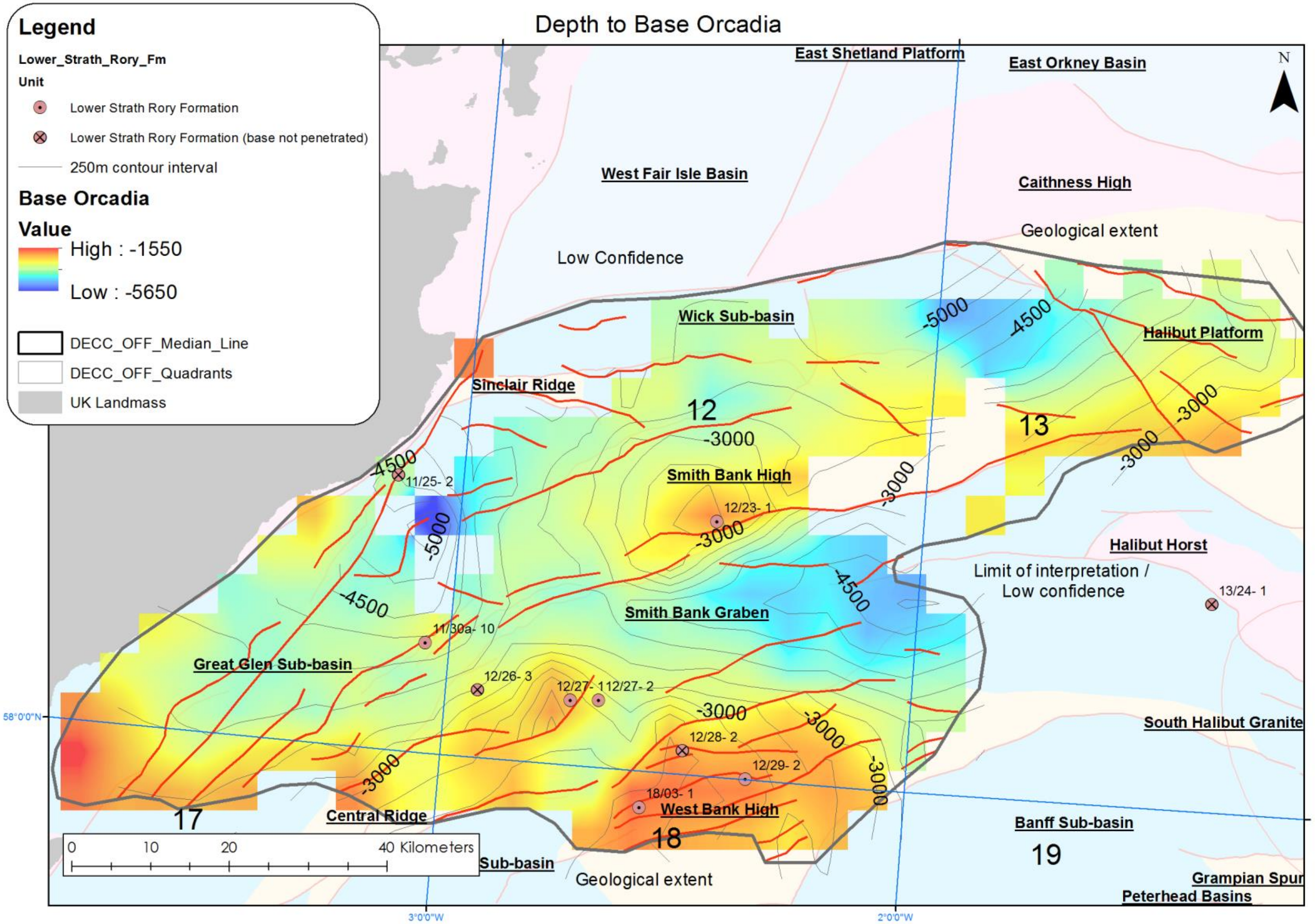


Figure 8. Depth to Base Orcadia Formation (Middle Devonian) in metres below mean sea level.

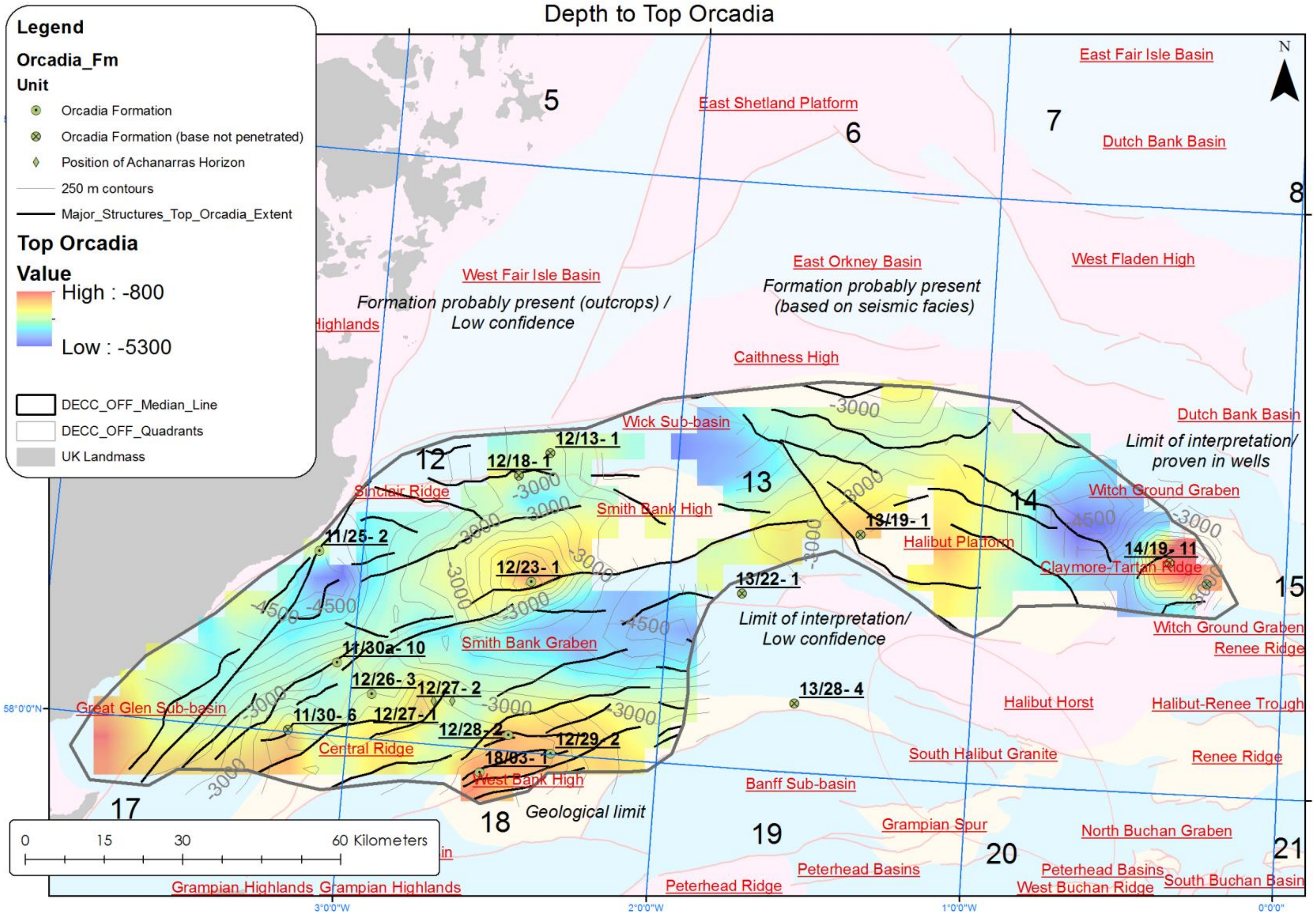


Figure 9. Depth to Top Orcadia Formation (Middle Devonian) in metres below mean sea level.

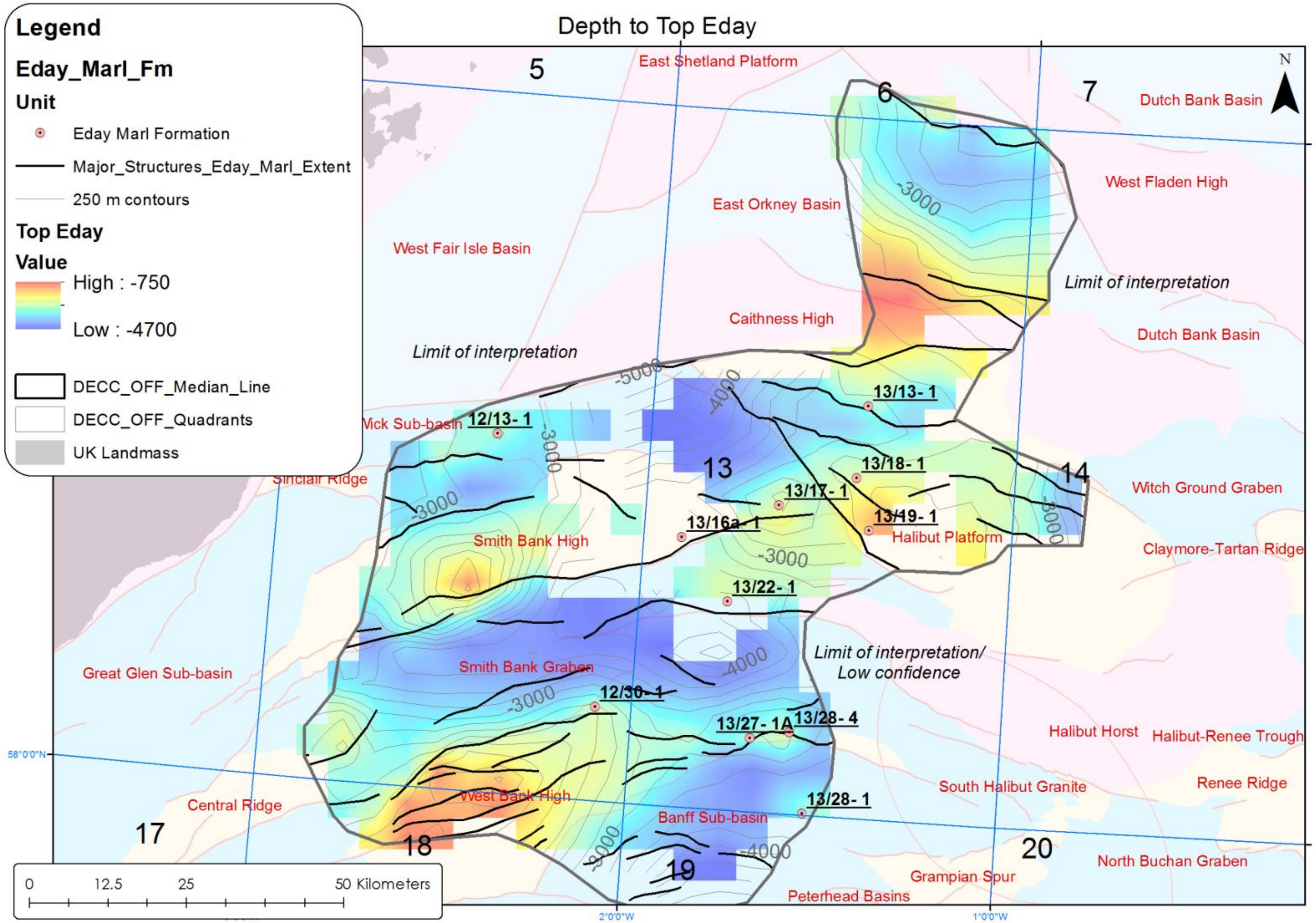
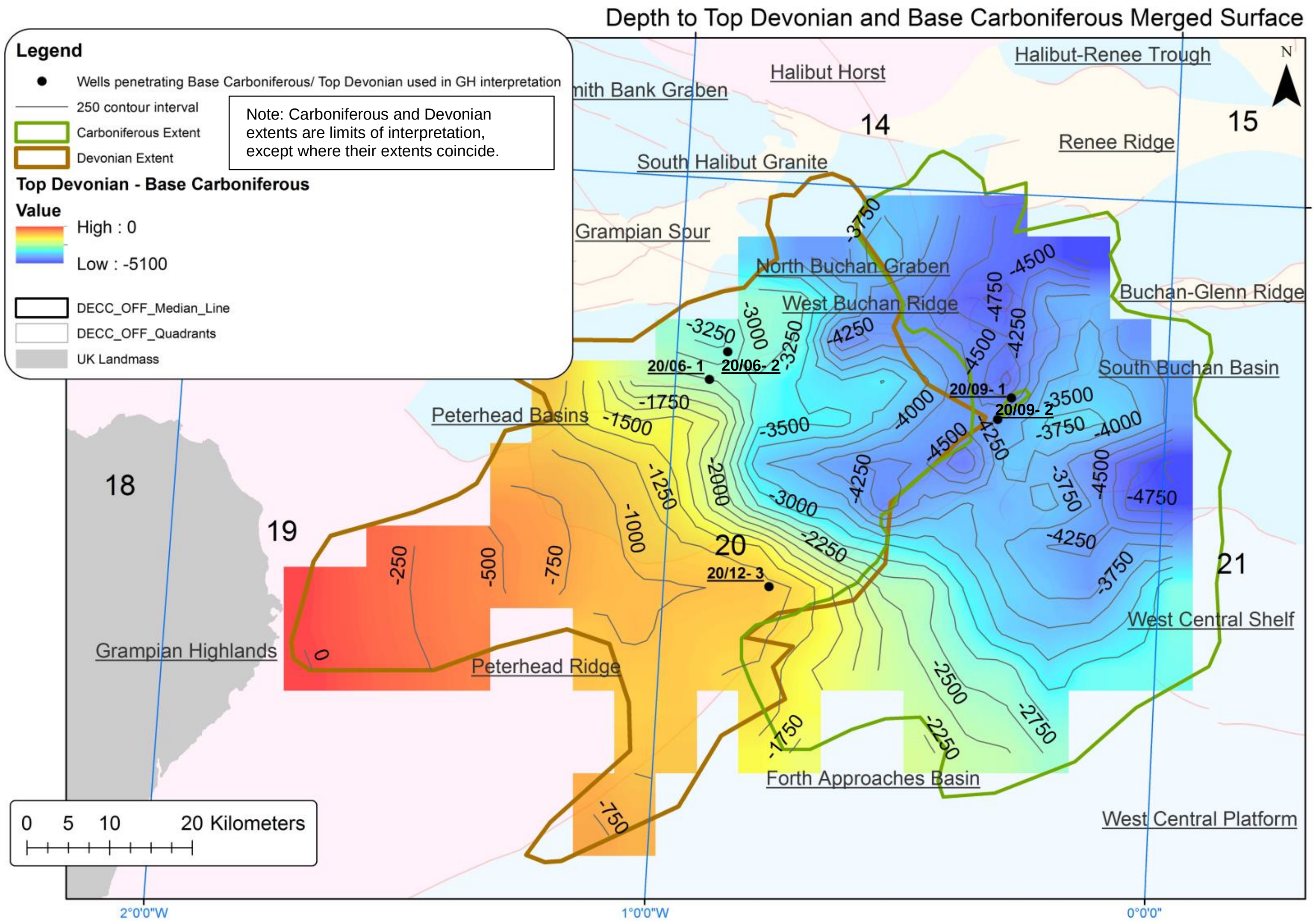


Figure 10. Depth to Top Eday Marl Formation (Mid/ Upper Devonian) in metres below mean sea level. All wells shown penetrate the Eday Marl. However, the 5 km subsampling means that sometimes values are absent close to faults e.g. wells 13/16a-1 and 13/22-1.



g.

Figure 11. Depth to Top Devonian/ Base Carboniferous in metres below mean sea level. The map comprises a Base Carboniferous pick merged with Top Devonian where the Carboniferous succession is interpreted to be absent. 'GH' referred to in key is Grampian High.

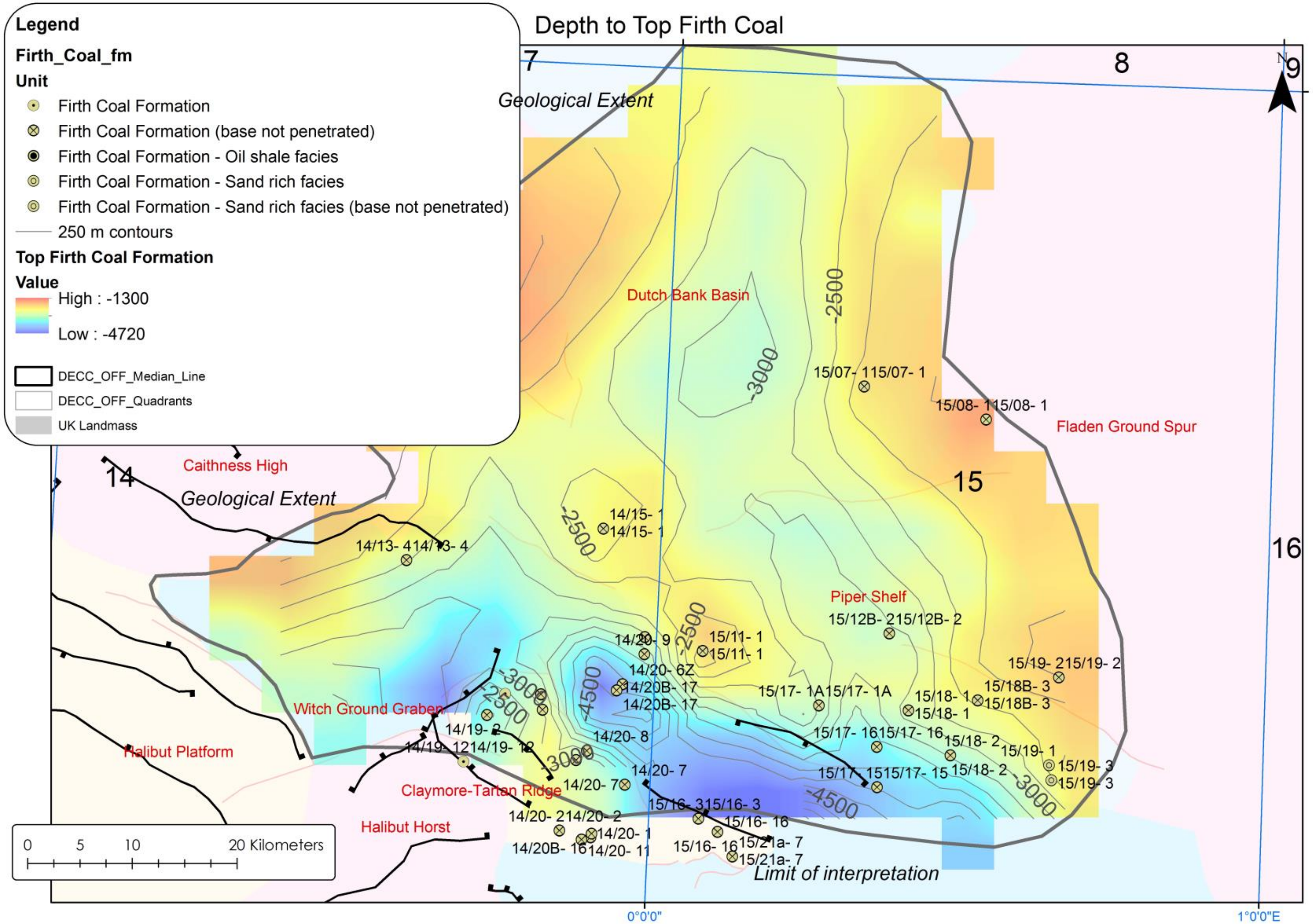


Figure 12. Depth to Top Firth Coal in metres below mean sea level.

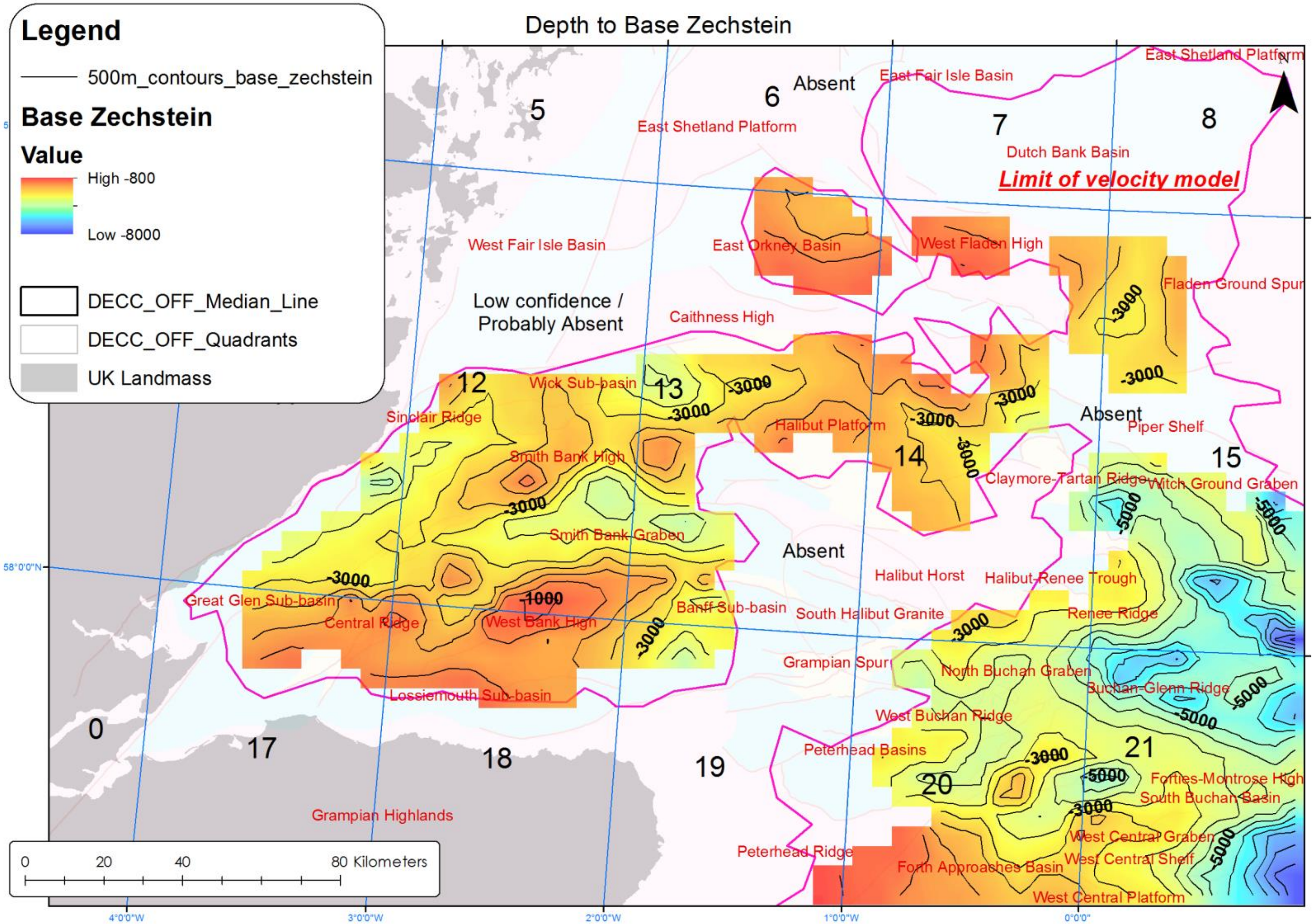


Figure 13. Depth to Base Zechstein Group (Upper Permian) in metres below mean sea level. Well points not shown due to large number of wells penetrating the interval.

3.4 SEISMIC INTERPRETATION AND STRUCTURAL OBSERVATIONS OF THE INNER AND OUTER MORAY FIRTH

Figure 14 below shows the location of seismic profile figures that have been used to illustrate aspects of the seismic interpretation carried out in this study.

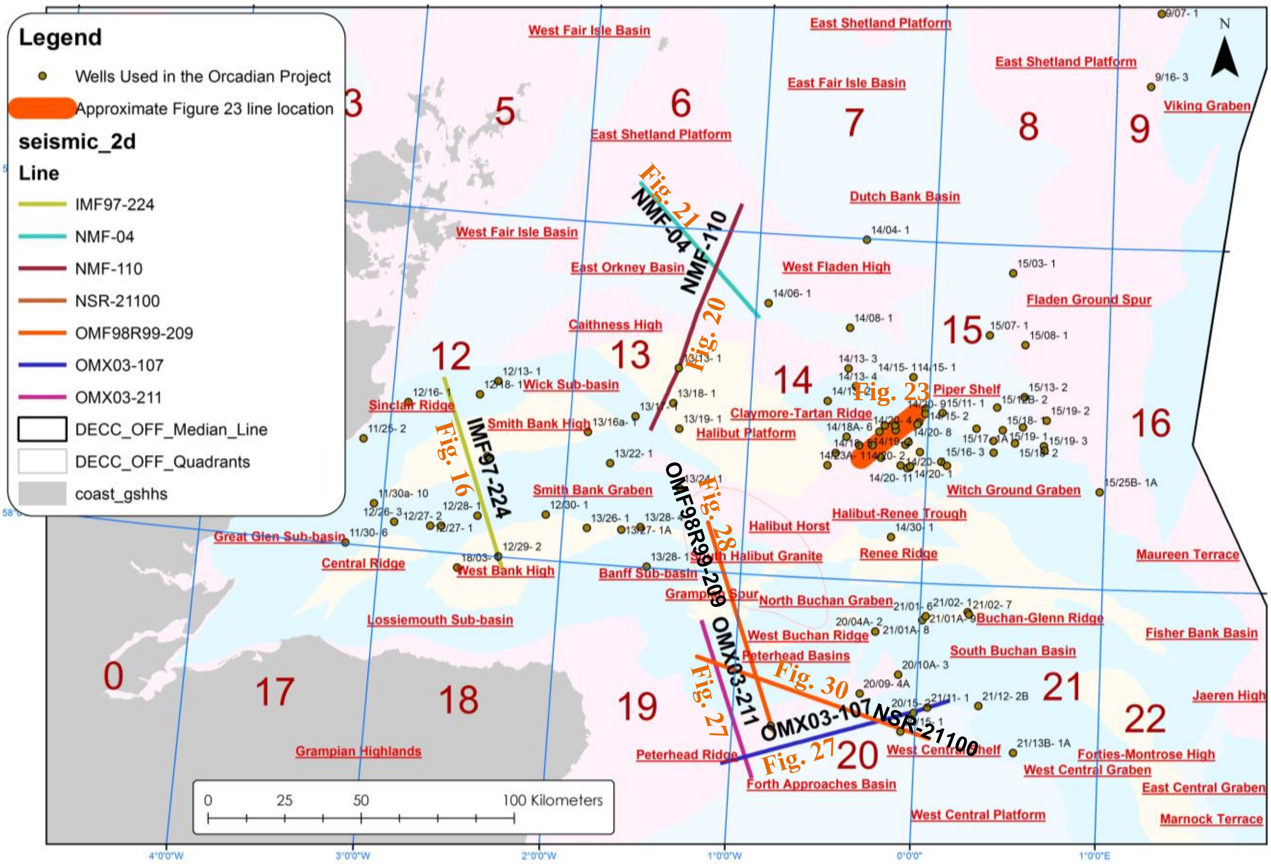


Figure 14. Location of seismic profiles presented as figures in this report. Blue areas represent the basins and depocentres, shelves and terraces are in yellow and the highs are in pink.

Figure 15 illustrates the major structural elements of the Palaeozoic succession as they have been recognised in the seismic data. Sections 3.4.1 to 3.4.4 describe these elements and provide seismic examples.

3.4.1 Inner Moray Firth

Figure 16 illustrates an interpreted NNW-SSE trending seismic profile across Quadrant 12. At the SSE end of the profile, the elevated West Bank High is covered by a thick Lower/ Middle Devonian succession which plunges north-westwards to more than 3 seconds TWTT/ 4000 m (see Figure 9) in the Smith Bank Graben. North of the Smith Bank Fault, thinner Devonian strata are present, suggesting that the Smith Bank High likely existed as an intrabasinal high at this time. This Devonian succession continues northwards and in the Wick Sub-basin reaches a TWTT of around 3 seconds/ >3.5 km. It is possible that what has been interpreted as Basement in Figure 16 is still part of the Devonian sequence, thus making the latter thicker than the current interpretation (approx. 300-400 ms).

From a petroleum systems point of view, this line shows that a thick, deeply buried succession of potential Devonian source rock is present. Faults are a key risk to the play in this area (especially the Smith Bank Fault) as they are interpreted to breach the Mesozoic and Cenozoic strata. However, where the faults do not reach seabed, similar configurations have shown proven plays (e.g. Beatrice field, Stevens, 1991).

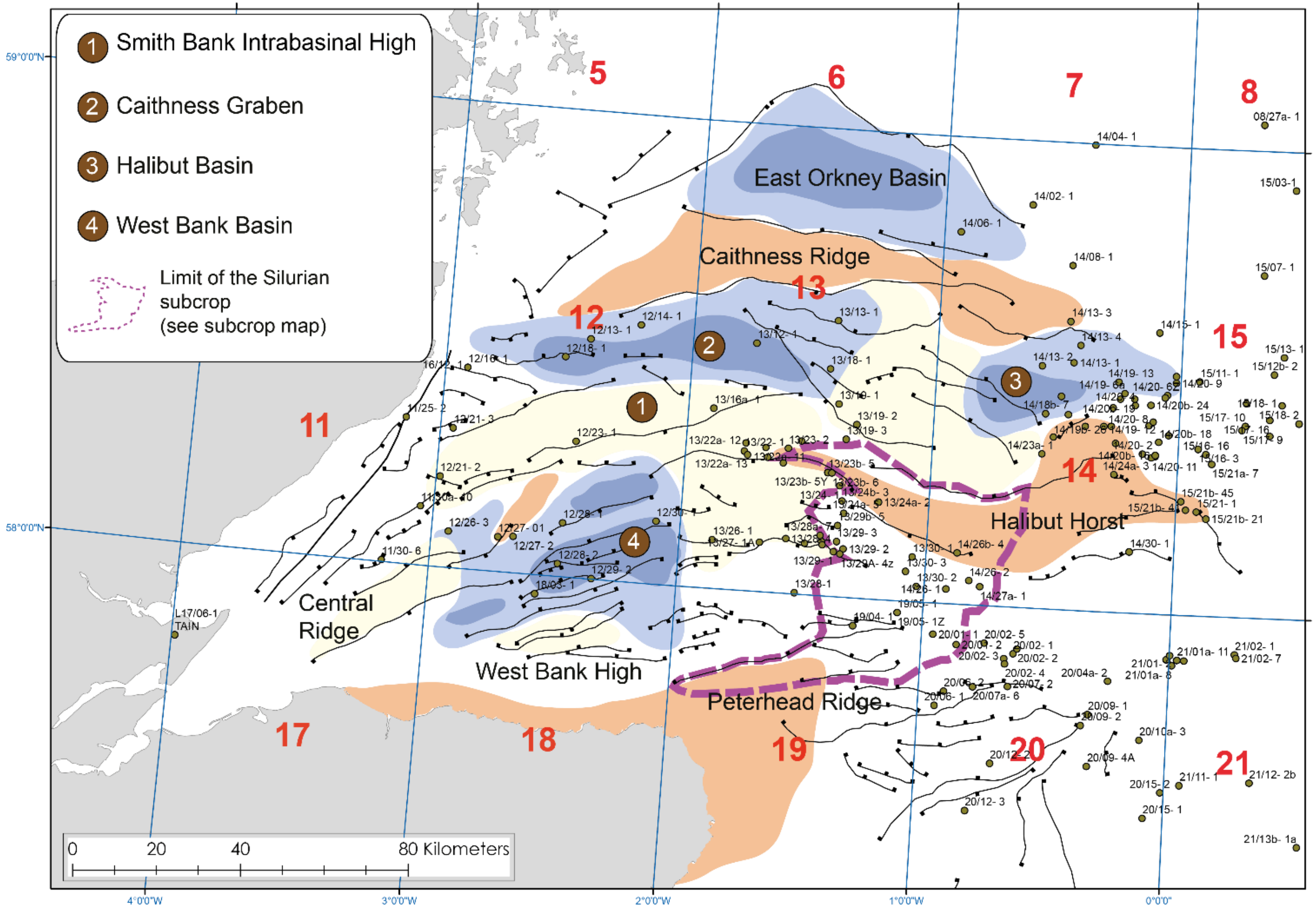


Figure 15. Structural diagram with the major Palaeozoic structural elements shown. Blue areas are the basins/ depocentres, cream coloured are the terraces/ shelves and orange areas are the highs/ ridges.

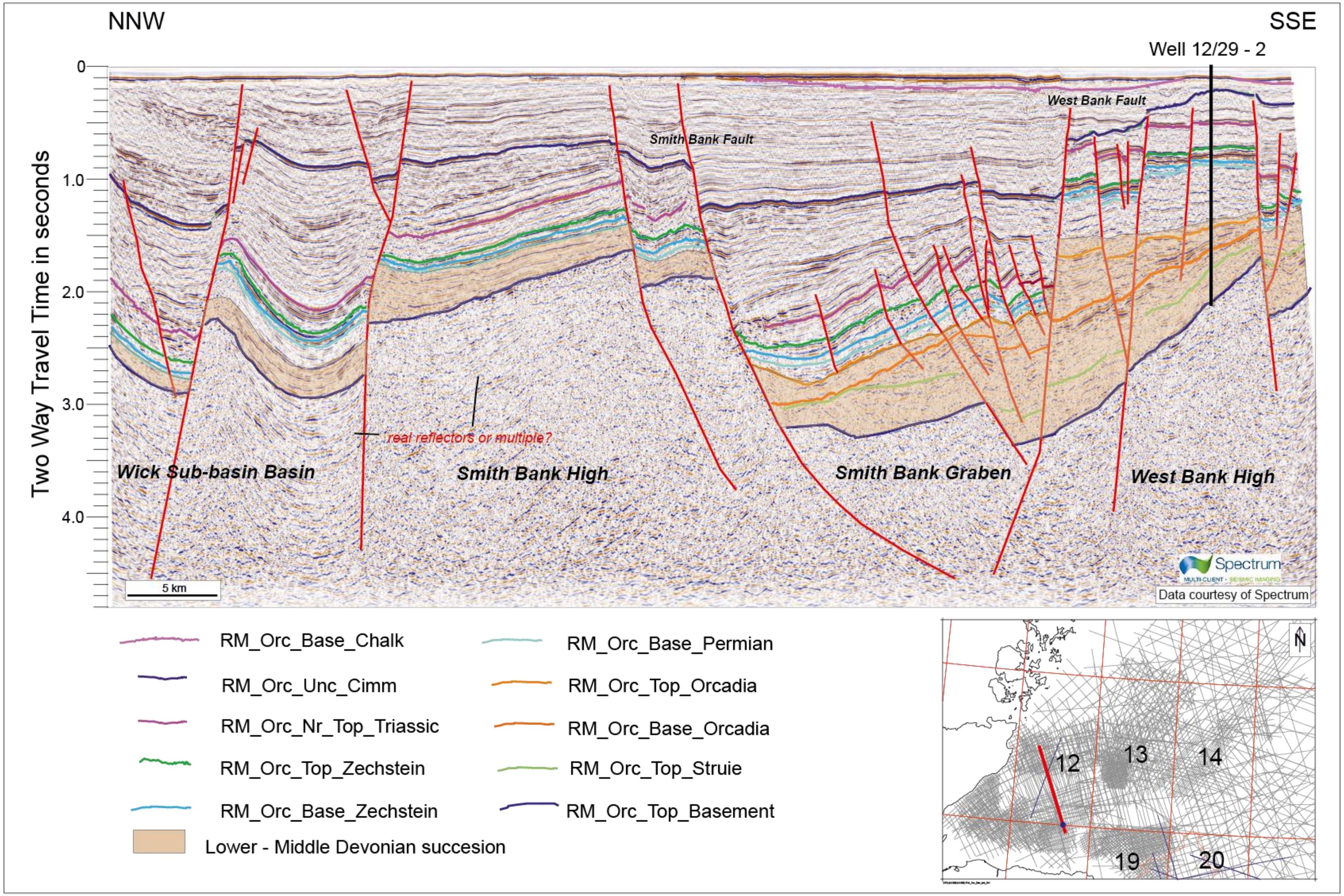


Figure 16. NNW - SSE trending seismic profile across the Inner Moray Firth, Quadrant 12

The Lossiemouth - West Bank Fault zone is primarily responsible for the thick Devonian strata on the southern edge of Quadrant 12 (e.g. 12/29-2).

Syn-depositional growth is observed into the Lossiemouth and West Bank faults during Lower/Middle Devonian times (see Figure 16). Both segments were probably part of the same fault zone running broadly ENE-WSW, throwing south-eastward (Figure 17).

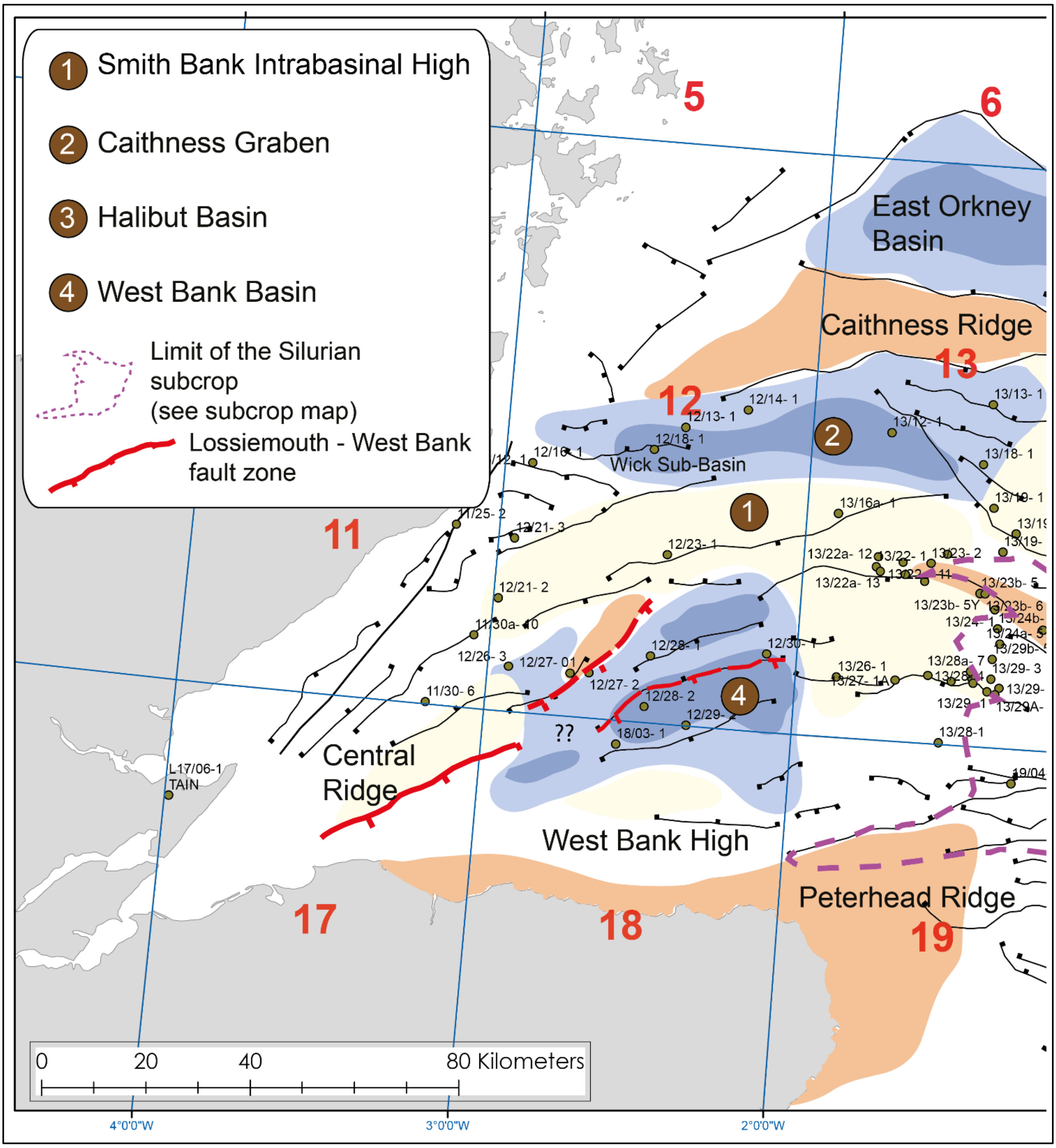


Figure 17. Detail of the structural diagram presented Figure 15 with the Lossiemouth/ West Bank Fault zone highlighted in red. Dashed red lines indicate deep faults interpreted in the seismic but with low confidence as to their exact location.

Seismic interpretation suggests that during the Mesozoic, the fault antithetic to the Palaeozoic segment of the West Bank Fault became dominant, truncating the southward throwing Palaeozoic fault, and becoming the north-bounding fault to the West Bank High. A possible mechanism which could explain this configuration is the migration of the faulting activity from the West Bank area to the Smith Bank High (establishing the West Bank Fault as a major antithetic fault to the Smith Bank Fault zone during the Mesozoic and Cenozoic, Figure 18).

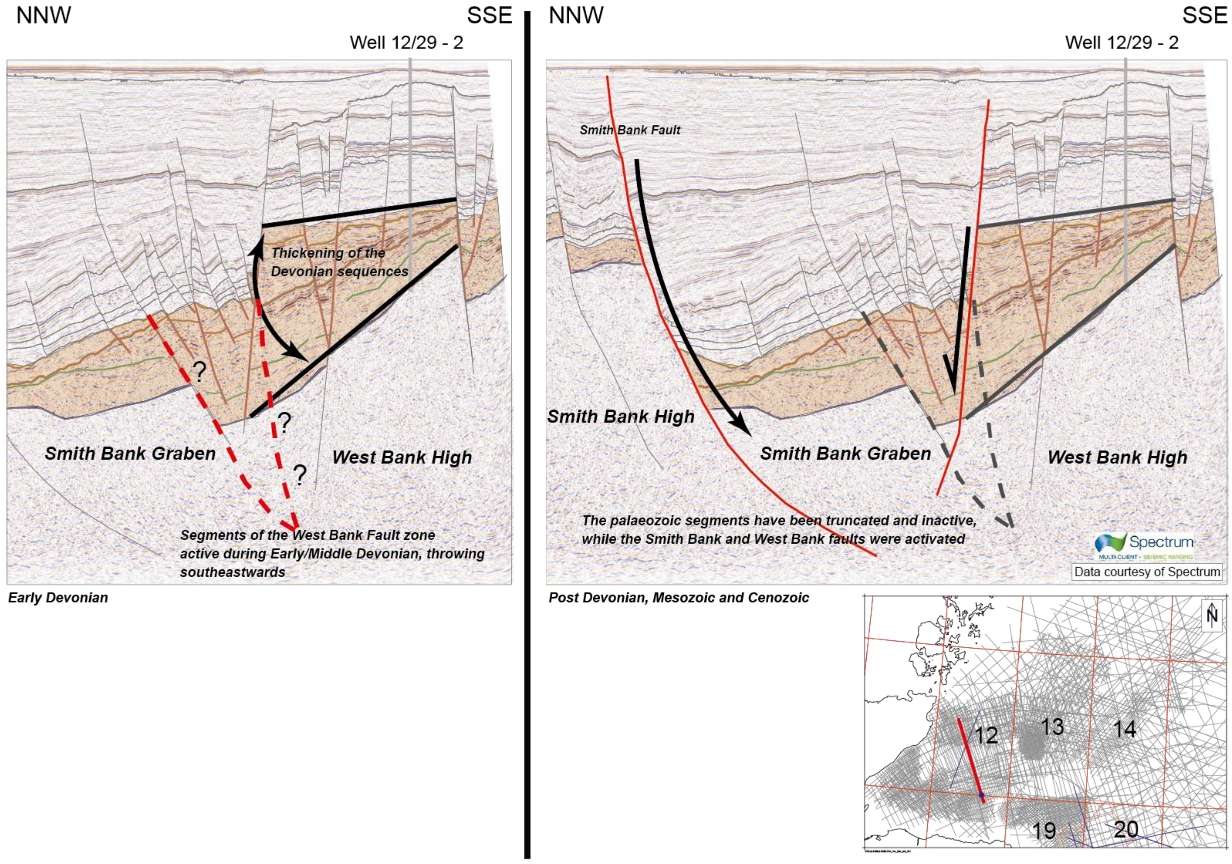


Figure 18 Sketch illustrating the possible evolution of faulting activity in the West Bank area.

The Devono-Carboniferous intervals occur at depths of more than 2.5 seconds TWTT, and as a result seismic interpretation confidence was low, and could not provide definitive evidence as to whether there was significant thickening along the Great Glen Fault (GGF). The majority of the tectonic activity during this time appears to have been accommodated by normal faulting with a transtensional component and pull-apart configurations (e.g. Wick Sub-basin, Lossiemouth basin trending broadly ENE-WSW to E-W for location see Figure 1 and Figure 17).

Figure 17 illustrates a NE-SW trending “ridge” where well 12/27-1 has been drilled. This is a Palaeozoic elevated feature which has been buried in Mesozoic times. Seismic data coverage does not allow for mapping of a linkage to the Central Ridge, but these two elements certainly follow the same trend. These structural elements are interpreted to be evidence of NNE-SSW to NE-SW normal faulting suggested during Devono-Carboniferous tectonics (Leslie et al., 2016). This ridge is also visible in the thickness map between Base Zechstein and Top Basement (Figure 19) and can be identified in the correlation panels from Whitbread and Kearsey (2016).

Figure 19 illustrates the thickness between the Base Zechstein and Top Basement surfaces. Since the majority of the wells drilled in the area have penetrated thin Lower Permian and no Carboniferous, the map is indirectly illustrating the Devonian thickness interval.

The most prominent feature is the thick West Bank Basin depocentre to the south of Quadrant 12. The geometry of this depocentre fits very well with the Devono-Carboniferous structural configuration as it has been described by Leslie et al. (2016), where the expulsion of Baltica during Late Devonian-Early Carboniferous would produce intracontinental stress and extension in the directions shown in the strain ellipse inset.

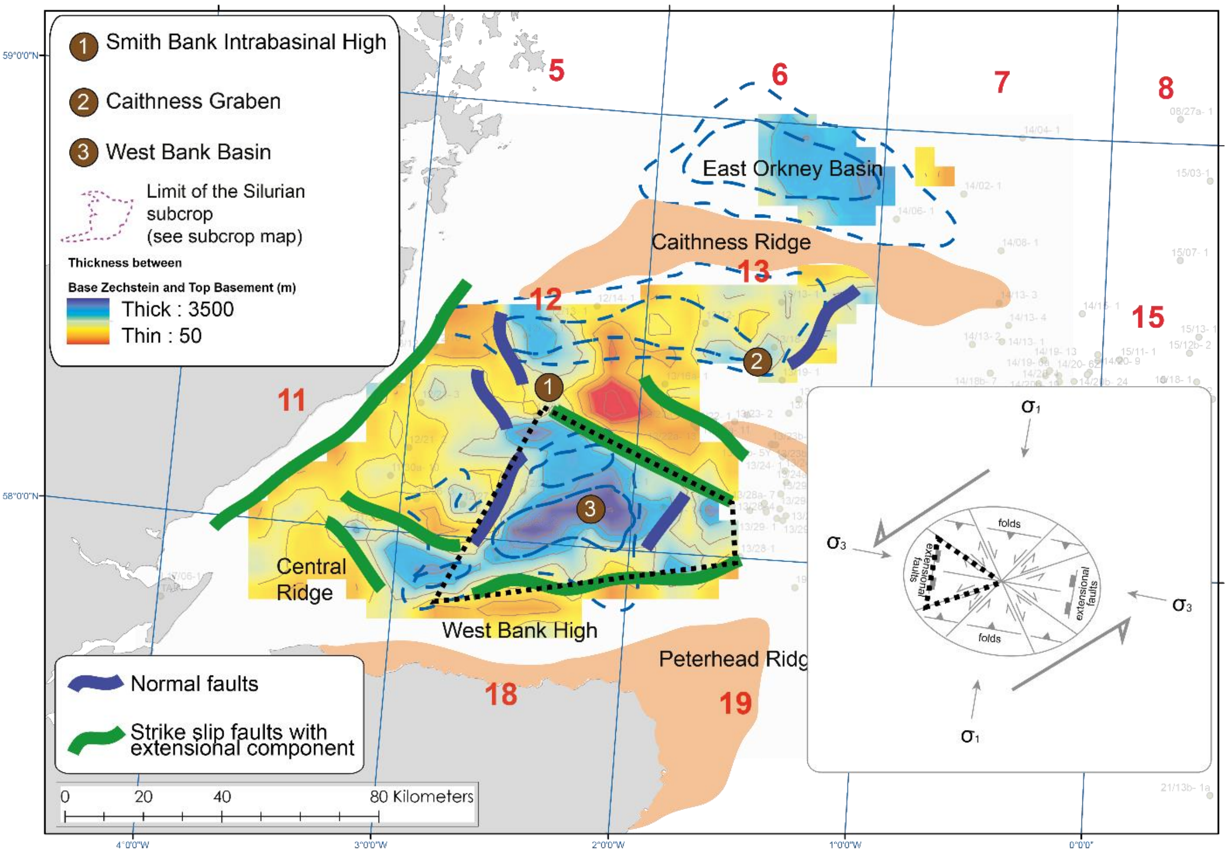


Figure 19 Thickness map between the Base Zechstein and the Top Basement. The dashed blue outlines are the basinal domains shown in Figure 15 and Figure 17. Green trends illustrate zones with primarily strike-slip faulting and blue trends primarily normal extensional faulting. Note that the thickest sequences are deposited inside the dotted triangular area, which fits well with the model based on the strain ellipse representative of Late Devonian – Early Carboniferous times (inset).

3.4.2 East Orkney Basin

Figure 20 shows an interpreted seismic profile running SSW-NNE across Quadrant 13. From the NNE, the seismic profile traverses the East Orkney Basin, the Caithness Ridge and the Halibut Platform respectively.

Based on correlation with the Inner Moray Firth and wells from surrounding areas, the East Orkney Basin shows characteristic deep reflectors of probable Devonian age. Apart from the Eday Marl and the Eday Flagstone, the highlighted Devonian succession may also include the Orcadia Formation. This cannot be verified directly as no wells have been drilled in this basin however, abundant outcrops on the Orkney Islands and well penetrations in wells further northeast (8/04-1, 9/07-1, 9/16-3) strengthen the possibility that Orcadia Formation rocks are also present in the basin.

Importantly, published oil seep surveys (Richardson et al., 2005) indicate that there is a functioning source rock at depth. This information, in addition to the fact that any Jurassic source present would be expected to be immature to early mature in the area (Kubala et al., 2003), points towards a Devonian source rock. The lacustrine Orcadia Formation is a good candidate for that hypothesis, which, although it has not been drilled and interpreted inside the East Orkney Basin, it has been recognised in wells around the area further to the north-east and to the south-west.

In terms of petroleum plays, both the East Orkney Basin and the Caithness Graben are not explored. These basins both illustrate equally deeply buried Devonian source rocks at the present day (at approximately 2.5 seconds TWTT), that seismic evidence indicates to be at depths similar to the Devonian source rocks adjacent to the Beatrice Field where a Devonian source is thought to have contributed to the hydrocarbon charge. Reservoirs could be found either in the Palaeozoic succession (e.g. sandstone-rich Devonian strata) or higher in the Mesozoic sequence.

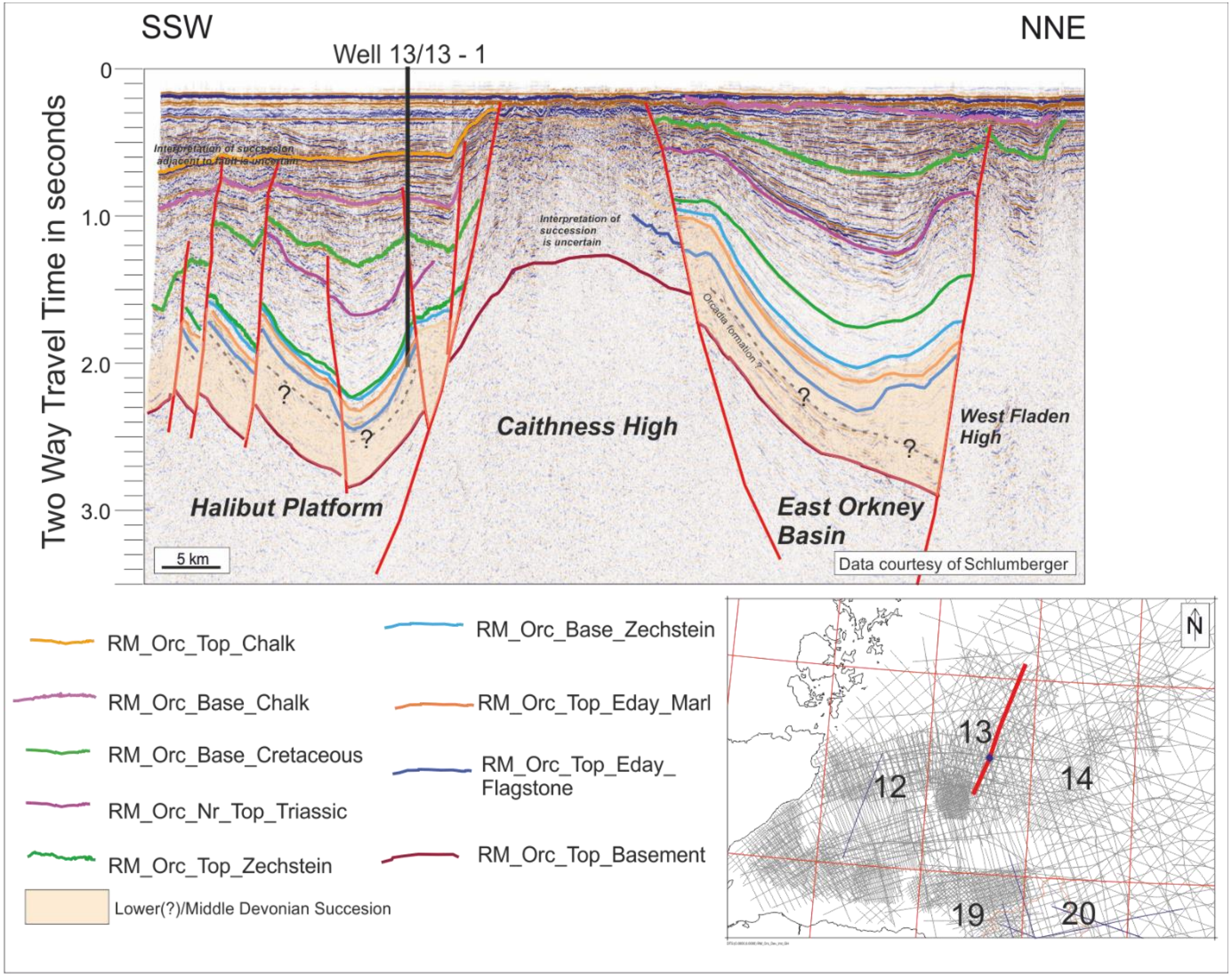


Figure 20. NNE-SSW trending seismic profile across the East Orkney basin, the Caithness Ridge and the Halibut Platform

Cross sections along the East Orkney Basin (Figure 21) are indicative of the relatively continuous character of the deep Devonian strata.

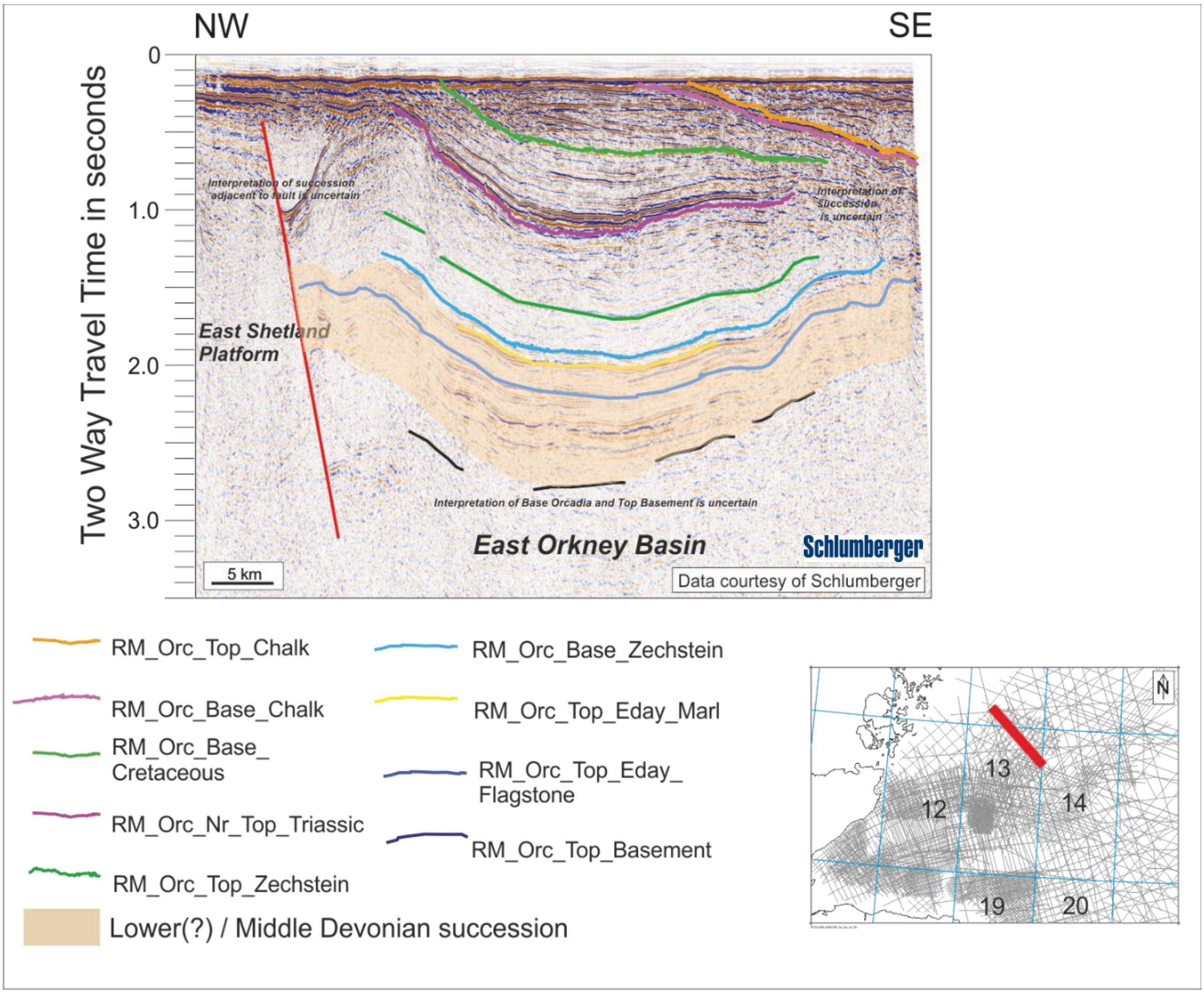


Figure 21. Seismic profile along the East Orkney Basin. Note the deeply buried sequences of probable Lower/Middle Devonian age.

There are striking similarities in the seismic character between the deepest visible sequences of the East Orkney Basin and the southwest area of the Caithness Ridge (Wick Sub-basin/ Halibut Graben, see Figure 22). Despite the absence of wells proving Devonian, this suggests that the East Orkney Basin was also a depocentre during Palaeozoic times, accommodating Devonian strata. The sequences are buried at comparable depths with the strata deposited in the Wick Sub-basin which lies south of the Caithness Ridge.

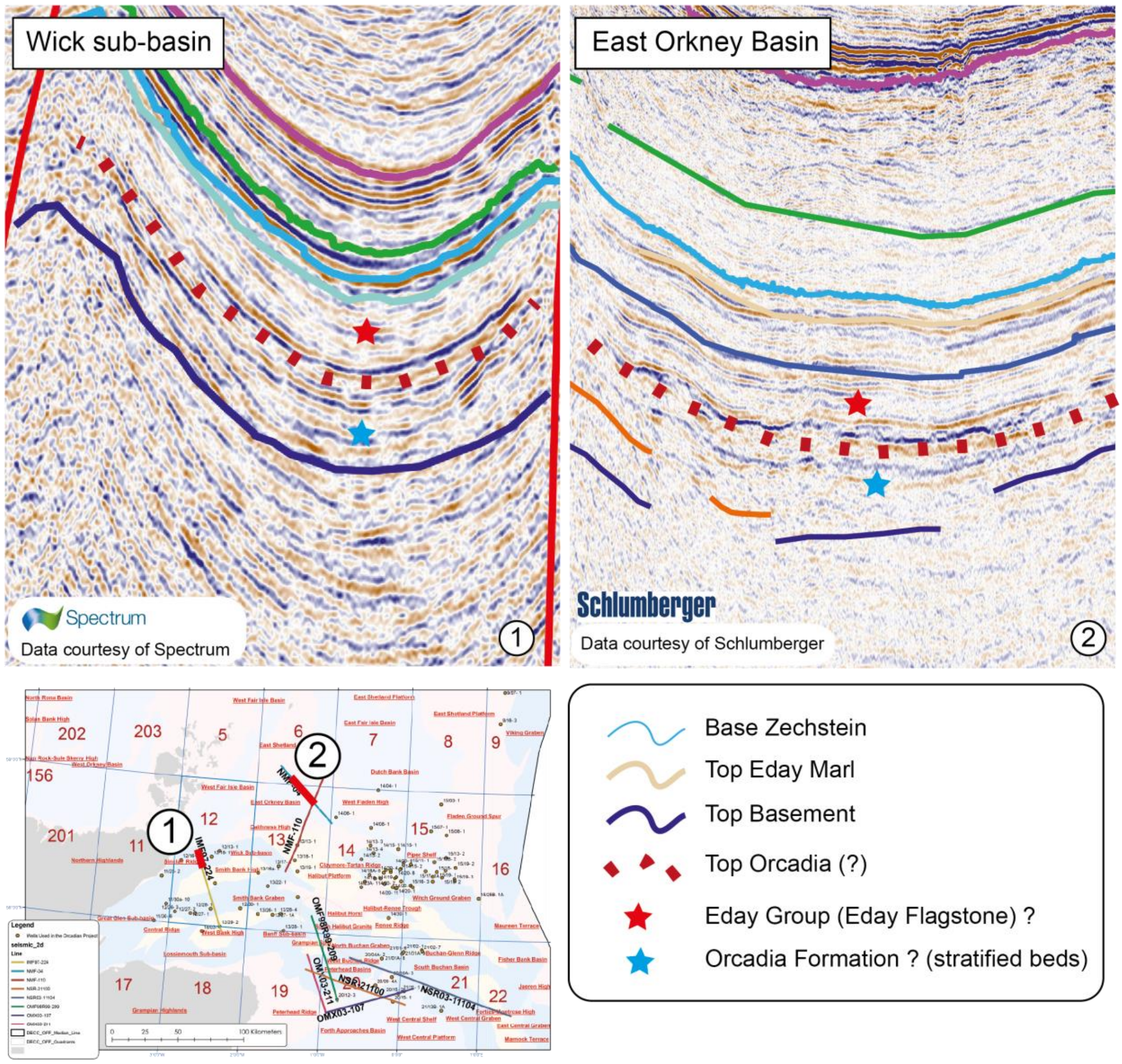


Figure 22. Detail from two seismic profiles, one along the East Orkney Basin and the second across the Wick Sub-basin illustrating the very similar seismic character of the pre-Permian strata. The red, dotted line separates two comparable stratified sequences. The red and blue stars could be interpreted as either the Lower Devonian Struie Formation overlain by the Orcadia Formation, or as the Orcadia Formation and part of the Eday Group.

3.4.3 Smith Bank High, Caithness Ridge, Halibut Platform

The Smith Bank High is interpreted to have been an intrabasinal high during Devonian times that controlled sediment deposition (thinner sequences on top of the high than to the south and to the north of it). It is possible that during the Lower Devonian, the Smith Bank intrabasinal High was part of the northernmost boundary of the lacustrine successions of the Struie Formation (Lower Devonian, see Whitbread and Kearsey, 2016). It is unclear if the lower Devonian was deposited north of the Smith Bank intrabasinal High, as the lacustrine facies cannot be picked in basins, and confidence in seismic interpretation reduces northwards.

The Caithness Ridge is interpreted to have been a high during Devonian times. The nature of the sediments on top of the Caithness Ridge remains unknown. Locally some similarities in the seismic character of the Devonian reflectors can be interpreted, but there is a lack of any well penetration. The presence of numerous multiples on top of the Caithness Ridge (related probably both to very shallow waters and fast/ dense sediments) diminishes the seismic interpretation confidence and resolution.

To the SSW of the profile shown in Figure 20, the Halibut Platform (Figure 14 and Figure 15) is underpinned by a deep graben accommodating Palaeozoic sequences which include relatively thick (600-700 milliseconds) Devonian strata. The graben is named here the Caithness Graben, contrasting with Caithness Ridge lying a few kilometres to the north and delineating the depocentre.

The Caithness Graben (Figure 15) consists of at least 400 milliseconds of deeply buried Devonian sediments (depths >2 seconds TWTT). Based on the seismic facies and wells close to the area, these are probably lacustrine sediments of the Orcadia Formation overlain by the Eday Marl Formation. The Caithness Graben was probably an eastern extension of the Wick Sub-basin (Figure 15 and Figure 17).

3.4.4 Northern Outer Moray Firth

To the east of the Halibut Platform, the thick Middle Devonian sedimentary sequence continues into Quadrant 14, where it has been proved in wells (> 700 m in well 14/19-11, Whitbread and Kearsey, 2016). This basin is named here the Halibut Basin (Figure 15) and represents at least 700 milliseconds of thick deeply buried Devonian strata (> 2 seconds TWTT).

The major bounding faults of the Caithness High and West Fladen High offset the Devonian strata in deep basins (>3 seconds TWTT, see Figure 20). Seismic interpretation for this study and by Reid and Patruno (2015) shows the extent of the Devonian to continue east across Quadrant 14, having undergone deformation and erosion.

The Firth Coal Formation has been interpreted as present in local deep basins and grabens (Figure 12) in Quadrants 14 and 15 in the Witch Ground Graben area with good well constraint (Table 3, well tops spreadsheet). A representative example is shown from the Claymore-Tartan area (Figure 23), illustrating a configuration of Firth Coal strata present both on top of the highs (where it has been proven as early mature for oil) and in deeper basins (following a NW-SE axis trend).

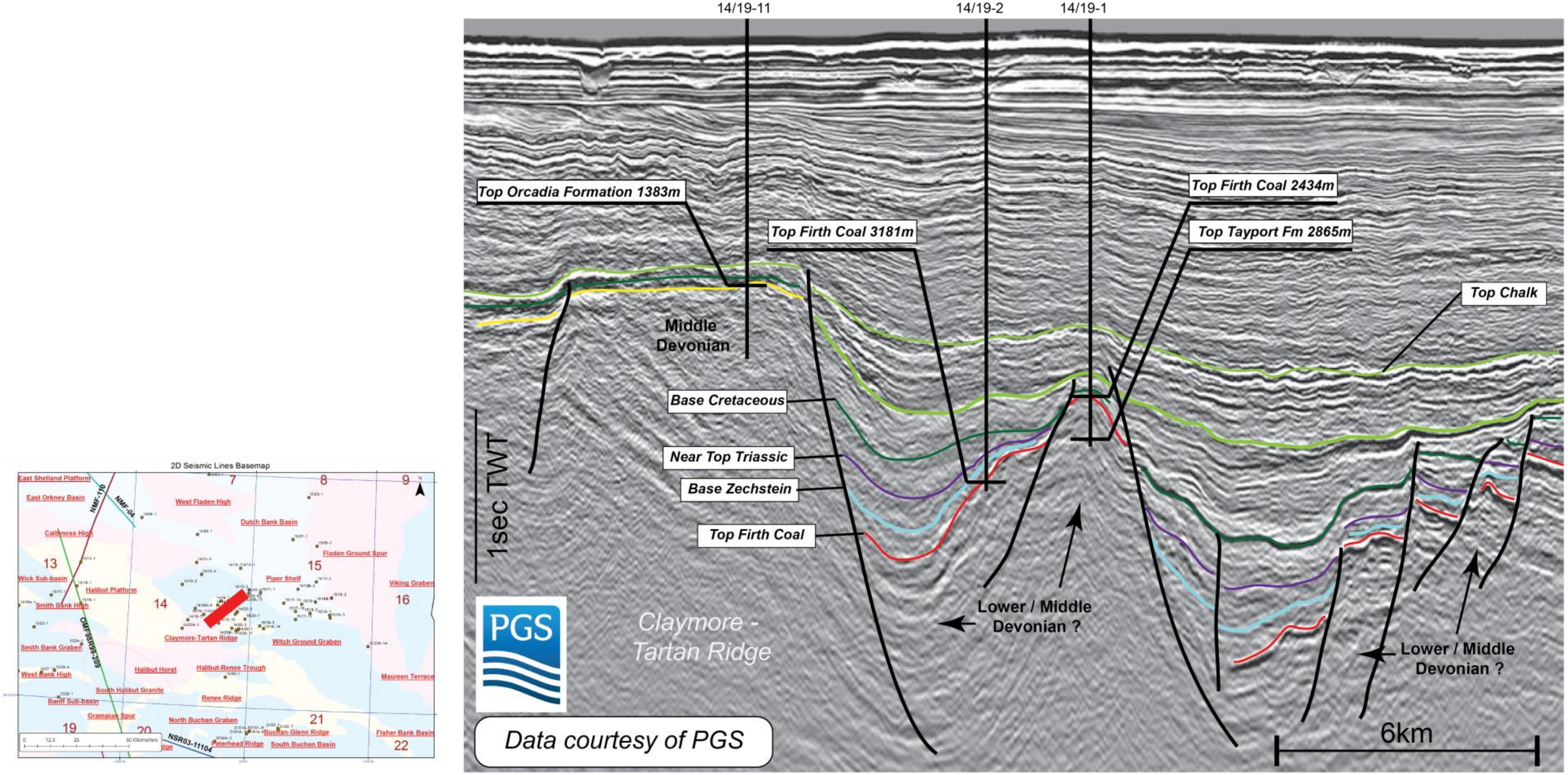


Figure 23. Seismic line from the Claymore Tartan Ridge area in Quadrant 14. The top Firth Coal Formation (black) is interpreted as present both on the footwall highs (where it has been penetrated by wells, e.g. 14/19-1) and in the deeper basins. It is absent on the regional highs, e.g. Caithness High and the Fladen Ground Spur (Figure 12).

PGS has donated to the project a selection of TWTT grids based on their in-house seismic interpretation of recently acquired 3D Volumes covering the East Shetland Platform and the Outer Moray Firth. These grids were compared with the output of the seismic interpretation carried out from BGS for the purposes of the 21st Century Palaeozoic Roadmap. The donated interpreted horizons include, amongst others, the Top Basement, Upper Devonian and Top Permian surfaces. The results show a very good fit between the BGS and PGS grids.

The most important conclusion from this exercise is that the Middle to Late Devonian sequences form part of a regional system which is present in Quadrants 7 to 9 and 11 to 15. The direct consequence of this observation is the presence of the lacustrine Middle Devonian source rocks, which were also identified in a number of wells in Quadrants 7, 8 and 9 (Marshall and Hewett, 2003; Whitbread and Kearsey, 2016).

Figure 24 illustrates the geometry of the Middle/Upper Devonian intervals. It is a product of the merge between the top of the Orcadia Formation TWTT grid and the subsampled TWTT grid of Upper Devonian donated from PGS.

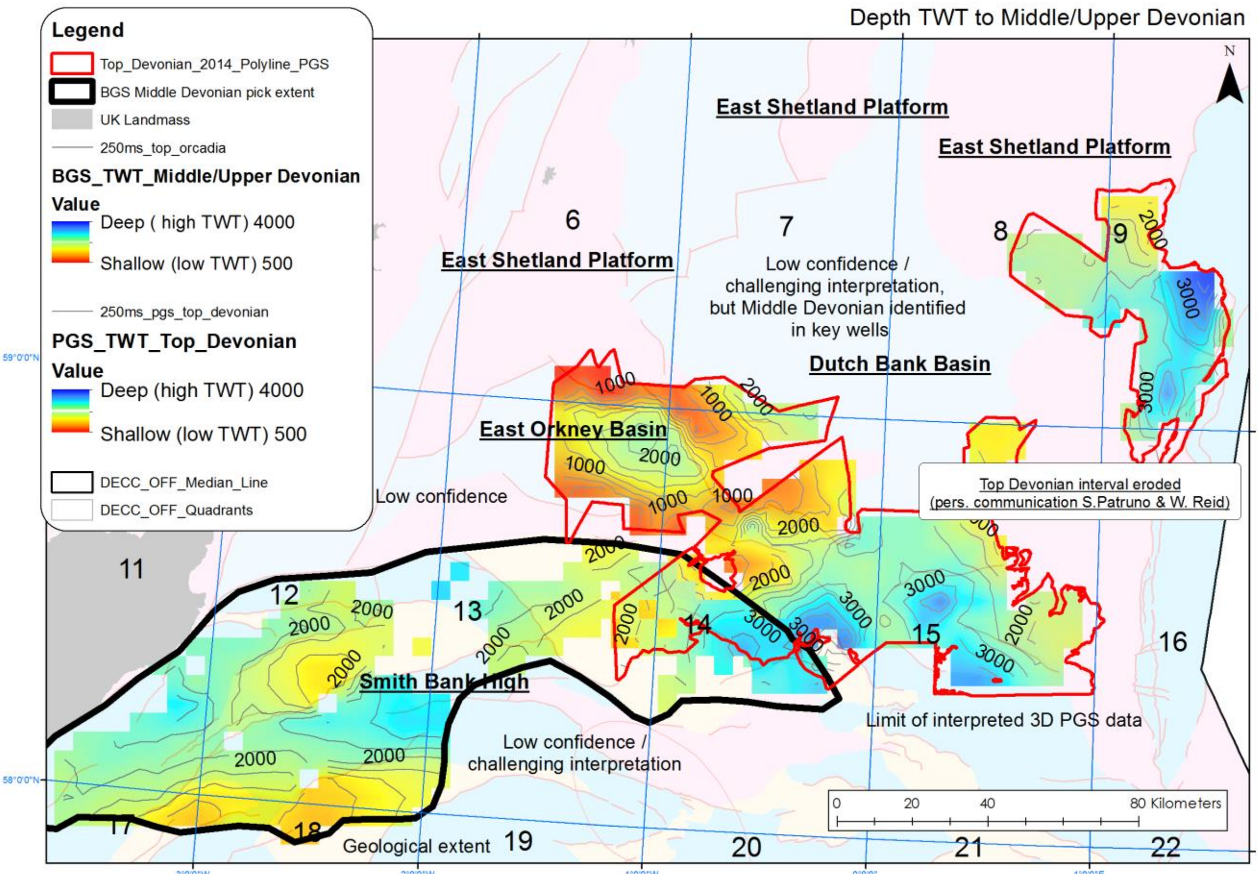


Figure 24. TWT map of the Middle/Upper Devonian across the Orcadian study area. Grids inside the red polygons illustrate data from PGS, and the grid inside the black polygon from BGS (this study).

3.5 SEISMIC INTERPRETATION OF THE GRAMPIAN HIGH AND ADJACENT AREAS (QUADRANTS 19 AND 20)

The aim of the seismic interpretation in this area was to map the structural transition between the Grampian High, the offshore extension of the Grampian Highlands (Figure 25), and north-eastern part of the Forth Approaches Basin and the western part of the Outer Moray

Firth Basin, specifically the western extremities of the North and South Buchan basins (Figure 25). Additionally, the limit of the Carboniferous and Devonian successions westwards onto the Grampian High towards the onshore in Quadrant 19 was mapped where possible. Interpretation therefore extends from the NE part of the Forth Approaches Basin, over the Highland Boundary Fault and onto the Grampian High, including the Peterhead Ridge, the Peterhead sub-basins and northwards to the Banff Fault (Figure 25).

The Grampian High is located in the northern part of offshore Quadrant 19 immediately NE of the town of Peterhead and the Grampian Highlands (Figure 25). The existence of the high is due in part to the presence of a low density granite intrusion, the South Halibut Granite (Trewin and Thirlwall 2002; Marshall and Hewett, 2003) that is penetrated by several wells for example, 13/30-1, 14/26a-8, 19/04-2 and 20/01-2 and defined on gravity data (Kimbell and Williamson, 2016). The granite is located on the northern part of the Grampian High and is Silurian or Lower Devonian in age. The high was in existence during the Devonian and Carboniferous (Whitbread and Kearsey, 2016) and sediments are interpreted to onlap the high as well as having had their original depositional thicknesses reduced by subsequent erosion. Erosion of the South Halibut Granite shed Middle Devonian sandstone and conglomerate to the north e.g. sediments seen in well 13/24-1 (Trewin and Thirlwall, 2002). The Grampian High is bounded to the north by the NE-trending Banff Fault (Figure 25). Southwards, a series of ENE-trending faults, including the Peterhead Fault, that has a significant throw to the WNW, tip out onto the Grampian High. The Grampian High is bounded to the south by the Forth Approaches Basin (Figure 25).

The Forth Approaches Basin, in the northern part of Quadrant 26, is a NE-trending half-graben containing a thick preserved Carboniferous succession that is well imaged on the seismic data (Arsenikos et al., 2015). Gravity data indicated that there was a possible basin located in the NE Forth Approaches Basin (Figure 31 in Kimbell and Williamson, 2015) and seismic interpretation resulted in basin bounding faults being delineated (Arsenikos et al., 2015). However, it was noted that the existing seismic data did not resolve many seismic reflectors within the NE part of the interpreted limits of the basin (Arsenikos et al., 2015). Either the succession in this area is not the same as to the SW (i.e. a thick Carboniferous succession) or seismic data processing either targeted the post Zechstein successions or failed to image the deeper successions (see section 3.5.2.1 below).

Interpretation of near Base Carboniferous, near Top Devonian and near Top Basement events enables:

- the limit of the Carboniferous succession onto the Grampian High to be defined;
- the top of the Devonian and the extent of the Devonian succession;
- the location of Basement rocks subcropping the Permian to be mapped.

All the elements necessary to form a Palaeozoic hydrocarbon play are interpreted to be present over the Grampian High and adjacent area (Monaghan et al., 2016). The north-eastern side of the Grampian High includes three Jurassic reservoired hydrocarbon fields including the Buzzard Field (Figure 25) that has plateau oil production of 200,000 barrels of oil per day (Ray et al., 2010). The Upper Jurassic Kimmeridge Clay source rock is generally in the range immature to early mature over most of the Grampian High and only mid-mature within the western part of the North Buchan Graben, immediately north of the West Buchan Ridge and east of the Buzzard Field (Kubala et al., 2003). However, as shown by the presence of the Buzzard Field, hydrocarbons have migrated westwards towards the Grampian High. In addition, potential Lower Devonian Struie and Orcadia formation source rocks are located to the north of the Grampian High and potential Carboniferous source rocks lie to the east.

Potential reservoir rocks are present within the Devonian succession with faulted highs adjacent to sub-basins providing the possibility of structural traps in the area. However, generating prospects on the Grampian High will require acquisition of a denser grid of bespoke seismic data in order to properly image structural relationships and better define the Palaeozoic and younger successions.

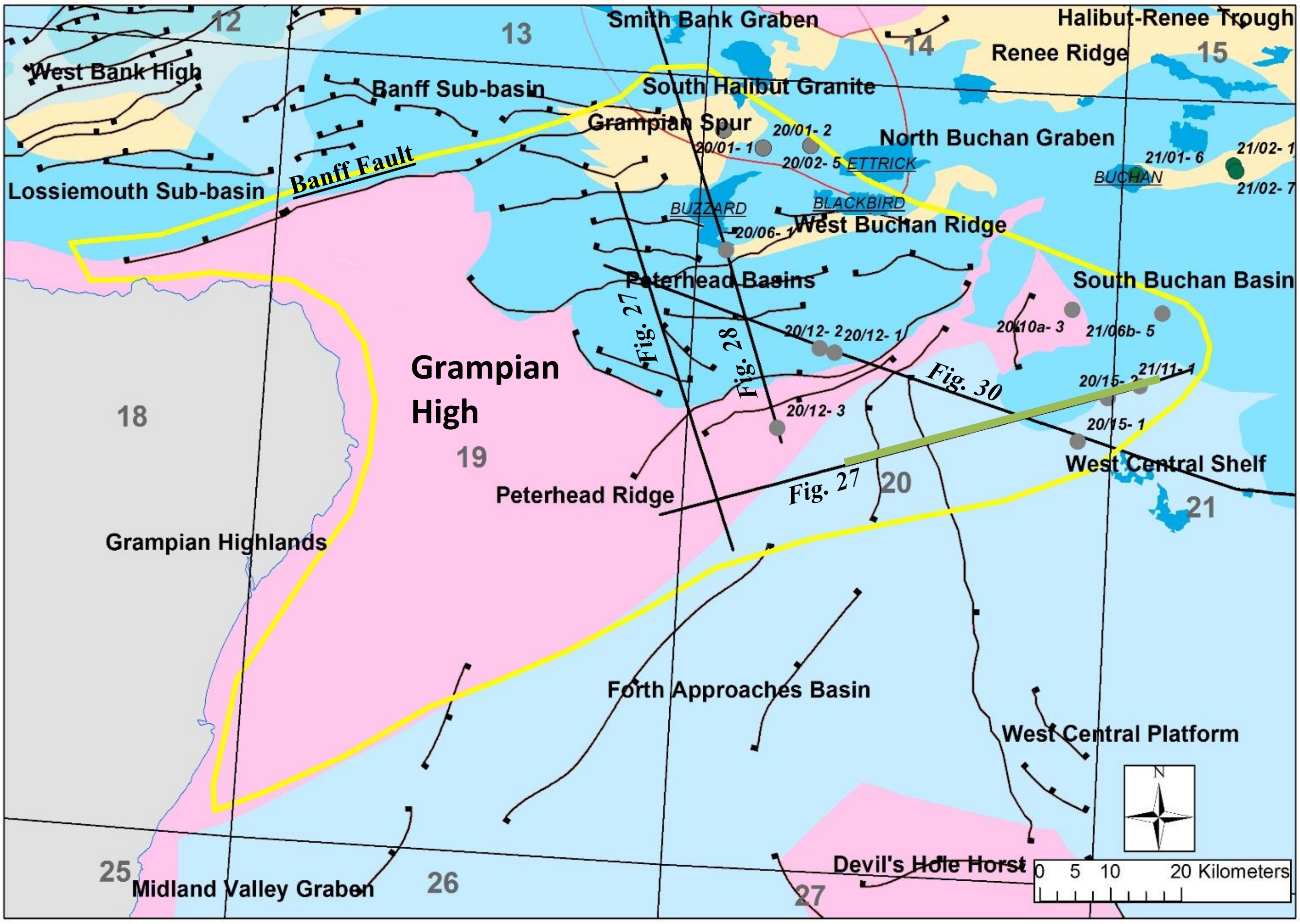


Figure 25. Location of seismic profiles and wells referred to in text in the Grampian High area. Extent of Figure 29 is shown in green. Yellow polygon shows approximate limit of seismic interpretation.

3.5.1 Depth Structure maps generated over the Grampian High and adjacent area

In this area, the following seismic reflectors were interpreted with a view to producing depth structure maps:

3.5.1.1 Near Top Basement - Map generated (Figure 6)

Basement rocks are directly overlain by progressively younger successions where the South Halibut Granite impinges on part of the northern edge of the Grampian High, specifically immediately adjacent to and over the Grampian Spur (Northern blocks of Quadrant 19 and Quadrant 20/01) and also in the footwall of the Banff Fault (Figure 26). A Lower Devonian granite, the South Halibut Granite, is penetrated in several wells in Blocks 19/04, 20/01, 20/02 and 20/07. For instance, well 20/02-5 within the North Buchan Graben, on the flanks of the South Halibut Granite, proves 50 m of probable Upper Devonian resting on granitic basement. Moving progressively westwards, well 20/01-2 proves Triassic on granitic basement while further west again, well 20/01-1 penetrated Upper Jurassic resting on granitic basement (Figure 25). Seismic data also shows progressively younger sediments onlapping the Grampian Spur and although Devonian has been interpreted within the Peterhead sub-basins north of the West Buchan Ridge it may be thin (see 3.5.2.2 below).

3.5.1.2 Near Top Eday Group

Well 20/12-3 proves a thin (60 m) succession of Rotliegend Group claystone and sandstone resting on 230 m of sandstone and siltstone of the Upper Devonian Buchan Formation. A 15 m succession of anhydrite at 1489 m below Kelly Bushing (1.1926 secs TWTT) is interpreted to be Top Kyle Group equivalent (Whitbread and Kearsey, 2016; Marshall and Hewett, 2003). This change in lithology generates a relatively distinct seismic response on the seismic data due to a marked increase in velocity within the underlying anhydrite layers (Figure 28 and Figure 29). The near Top Eday Group seismic reflector has been mapped where possible but the seismic response is quite variable and it was not possible to generate a depth surface in this area. However, where present, interpretation of the Top Eday Group enables better understanding of the age of the Devonian succession and importantly constrains the interpretation of near Base Carboniferous surface. Well 20/12-3 reaches Total Depth (TD) in sandstone and siltstone of Middle or Lower Devonian age.

3.5.1.3 Near Top Devonian – Map generated (Figure 11)

Where the Carboniferous is absent, Permian Rotliegend or younger rocks rest unconformably on Devonian sediments. For instance, well 20/09-1 reached TD in Devonian (Zechstein on Devonian or possible Permian Rotliegend) and well 20/09-2 proved Rotliegend on Devonian. The near Base Carboniferous seismic reflector (see below) and the near Top Devonian seismic reflector beyond the subcrop of the Carboniferous were merged to generate a depth to near Top Devonian map.

3.5.1.4 Near Base Carboniferous – Map generated (Figure 11)

Well 20/15-1 penetrated a 381 m Carboniferous succession comprising Firth Coal, Fell Sandstone and reaching TD after proving 159 m of Tayport Formation. The near Base Carboniferous was interpreted beneath this well at the base of a distinctive package of relatively strong and continuous seismic reflectors. This can be interpreted onto other seismic lines and is shown to be close to or coincident with an angular unconformity (Figure 29). Where interpreted, the Top Eday Group seismic reflector helped constrain the interpretation of the Base Carboniferous (e.g. Figure 29 and Figure 30). The Base Carboniferous seismic reflector becomes the near Top Devonian reflector when the former subcrops the Base Permian/ Base Zechstein.

3.5.2 Seismic interpretation

The geological succession becomes progressively less complete and more prone to unconformities from the Forth Approaches and Outer Moray Firth basins onto the Grampian High. There are no wells in the immediate area that prove the Carboniferous/ Devonian boundary. Wells 21/01-6, 21/02-1 and 21/02-7 drilled close to the Buchan Field (Figure 25) penetrate the Base Carboniferous and reach total depth in the Devonian, but it was not possible to interpret a Base Carboniferous seismic reflector away from these wells and onto the Grampian High. However, well 20/15-1 (Figure 25,Figure 30) reached total depth in the Carboniferous proving 159 m of Tayport Formation and this well was used to constrain a Base Carboniferous pick in the area (See section 3.5.1.4 above). Where the Carboniferous succession pinches out onto the Grampian High a Top Devonian pick was continued where possible (See section 3.5.1.4 above). Merging the Base Carboniferous and Top Devonian interpretations resulted in generation of a Top Devonian surface over some of the area (Figure 11). The Top Eday Group has been interpreted in well 20/12-3 (Whitbread and Kearsey, 2016) and has been picked on some seismic lines in the area. However, interpretation was not extensive or dense enough to generate a depth surface from this horizon (See section 3.5.1.2 above). East of the Grampian High, the Firth Coal Formation has been proven in two wells, one immediately to the east of the west Buchan Ridge and the other at the north-eastern end of the Forth Approaches Basin. However, the seismic package could not be interpreted away from these wells and as a result it was not possible to generate a map of the Top Firth Coal Formation surface in the area to the east of the Grampian High.

Seismic interpretation shows Permian (either thin Rotliegend or Zechstein) resting on Carboniferous or directly on Devonian (Figure 26 and Figure 27). On the Grampian Spur a Permian or younger succession rests directly on granitic basement or Dalradian metasediment (Figure 26 and Figure 28).

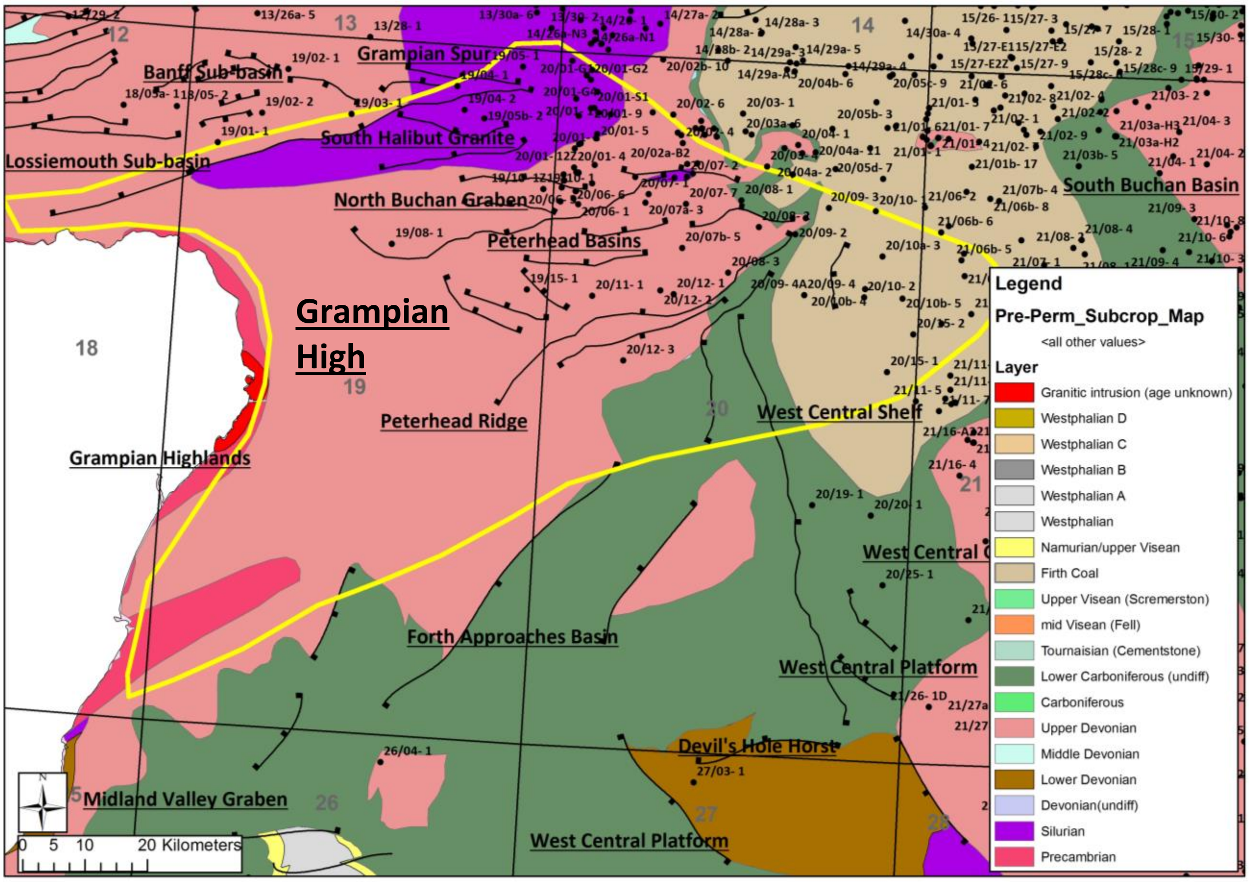


Figure 26. Pre-Permian subcrop over Grampian High and adjacent area. Yellow polygon shows approximate limit of interpretation.

The Devonian and Carboniferous succession thins onto the Grampian High. The Carboniferous is interpreted to thin and pinch-out along the southern edge of the Peterhead Ridge and is interpreted to be absent in the Peterhead Sub-basins. A Devonian succession is interpreted to be present over much of the area (Figure 26 and Figure 27) but thins and is absent adjacent to and over the South Halibut Granite and part of Grampian Spur (Figure 28).

The Peterhead sub-basins are interpreted to have formed during Late Jurassic rifting and prior to this, the area adjacent to the South Halibut Granite would have been a high and subjected to significant erosion. In some areas of the Peterhead sub-basins, Permian and younger rocks are interpreted to rest upon Basement (see 3.5.2.2 below).

3.5.2.1 North-east Forth Approaches Basin (FAB) and Grampian High transition

It was noted in the seismic interpretation report for the Central North Sea (Arsenikos et al., 2015) that the seismic character of the pre-Permian in the NE part of the Forth Approaches Basin (FAB) was comparatively featureless with relatively low amplitude, discontinuous seismic reflectors (see Figure 27 in Arsenikos et al., 2015) compared to the SW FAB. It was suggested that this was due to either unsuccessful processing of the seismic data to these depths or a different pre-Permian succession in the NE FAB (Arsenikos et al., 2015). Interpretation for the Grampian High area included examination of 2D seismic lines traversing the High and the NE FAB. On one of the seismic profiles, a prominent unconformity can be identified in the hanging wall of the NW bounding fault of the NE FAB that is interpreted to comprise a Carboniferous succession resting on an eroded Middle to Upper Devonian succession (Figure 29). The Top Eday Group seismic reflector is truncated by the unconformity and shows the eroded Top Devonian surface, in the hanging wall, to become older towards the north-west bounding fault of the Forth Approaches Basin at this location. The Top Eday reflector is interpreted again in the footwall of the fault. These observations suggest that the uplift increases in magnitude towards the fault, and that movement on the fault is likely to have been a controlling factor in the uplift of the Devonian in this area.

Uplift is interpreted to have taken place sometime during the Upper Devonian, prior to deposition of the Carboniferous. The extent of the unconformity could not be mapped on the available seismic data however it is suggested that the uplifted Devonian, overlain by thin Carboniferous, explains the different pre-Permian seismic character in the NE FAB. In addition, it is suggested that the NE FAB could have been an area of elevated topography in the earliest Carboniferous and had a controlling influence on its paleogeography. Specifically, it might have been a control in the change from a marginal marine environment with a thick sedimentary succession to the SW to a fluvial environment with relatively thinner sedimentary succession to the NE (Whitbread and Kearsey, 2016).

3.5.2.2 Peterhead and West Buchan highs and Buchan basins

The ENE-trending Peterhead and West Buchan ridges are defined by steep faults with pronounced throws to the NW and SE that tip out onto the Grampian High. The intervening Peterhead sub-basins are interpreted to have formed during Late Jurassic rifting. The sub-basin immediately NW of the Peterhead Ridge shows a Jurassic succession that thickens towards the fault bounding the NW edge of the Peterhead Ridge. A thick Devonian succession is interpreted resting on Basement but no significant thickening to the fault can be seen (Figure 28). The NW fault bounding the West Buchan Ridge also shows a thickening Jurassic succession but the variation in thickness of the Devonian is interpreted to be erosional occurring before the major movement of the fault in the Jurassic (Figure 28). Both ridges are interpreted to be capped by Devonian successions although the Devonian succession may be thin or absent adjacent to the Grampian Spur. Here, intrusion and uplift of the South Halibut Granite resulted in erosion of the pre-Permian succession such that the Devonian may be thin or absent in the area immediately south of the Grampian Spur (Figure 26 and Figure 28).

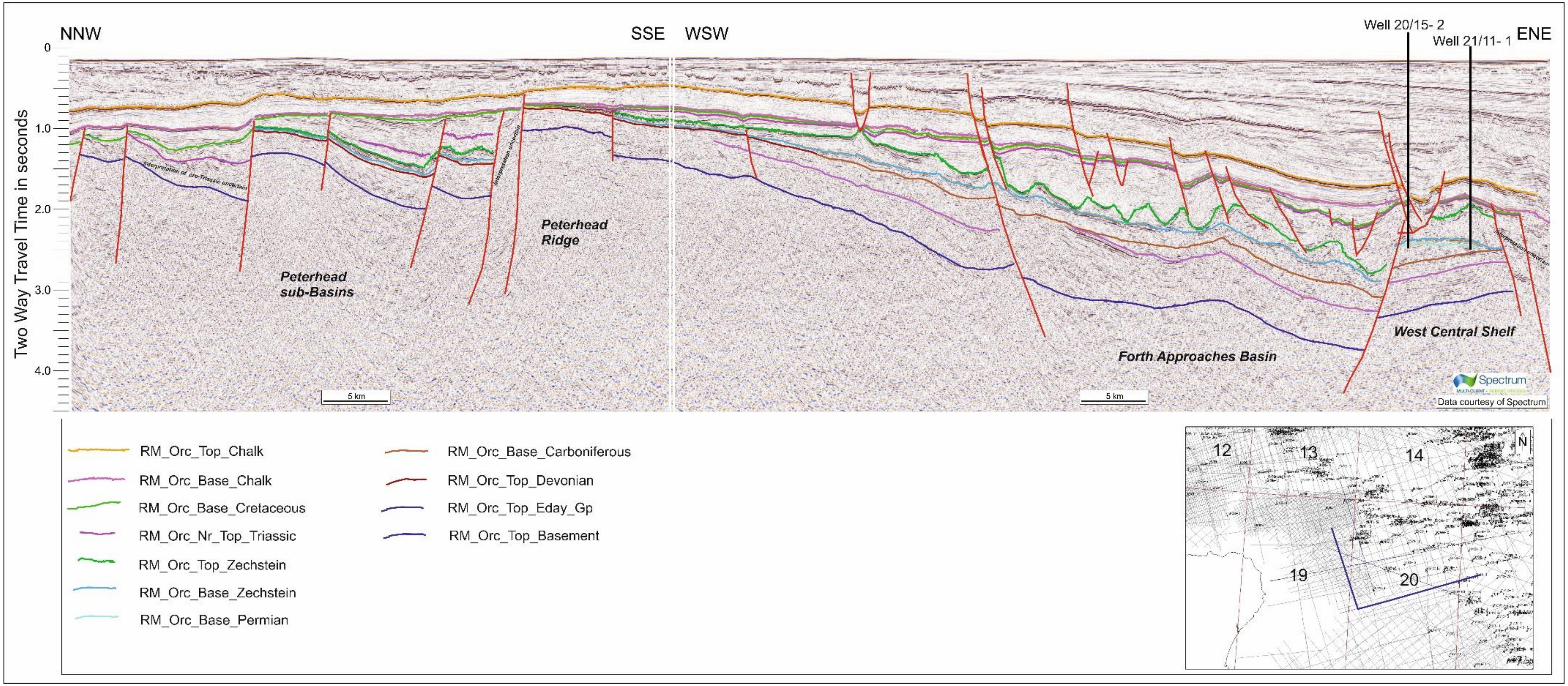


Figure 27. Two seismic profiles traversing the NE Forth Approaches Basin, the Peterhead Ridge and Peterhead sub-basins. For location in relation to structure, see Figure 25.

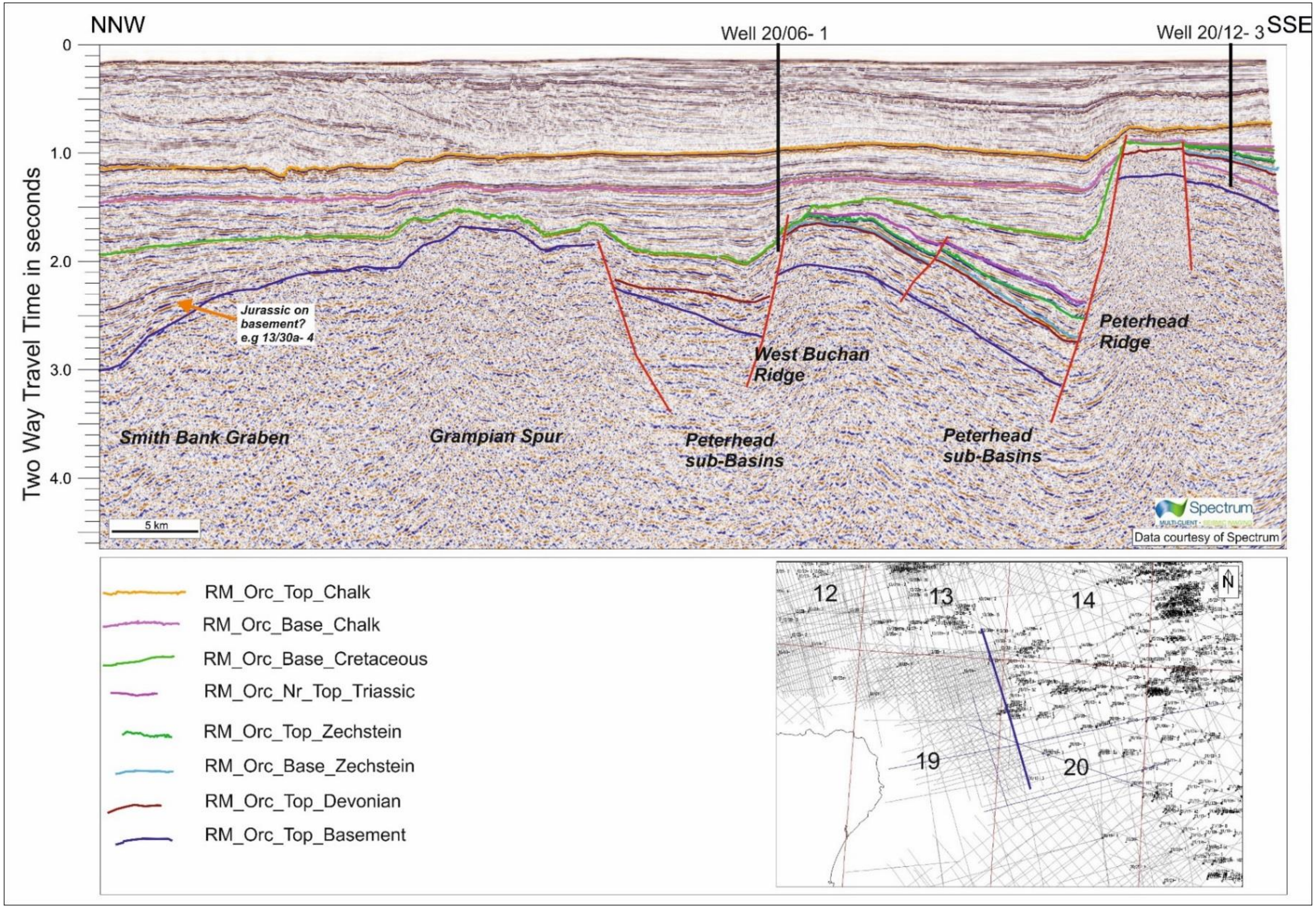


Figure 28. Seismic profile traversing the Peterhead and West Buchan ridges and over the Grampian Spur. For location in relation to structure, see Figure 25.

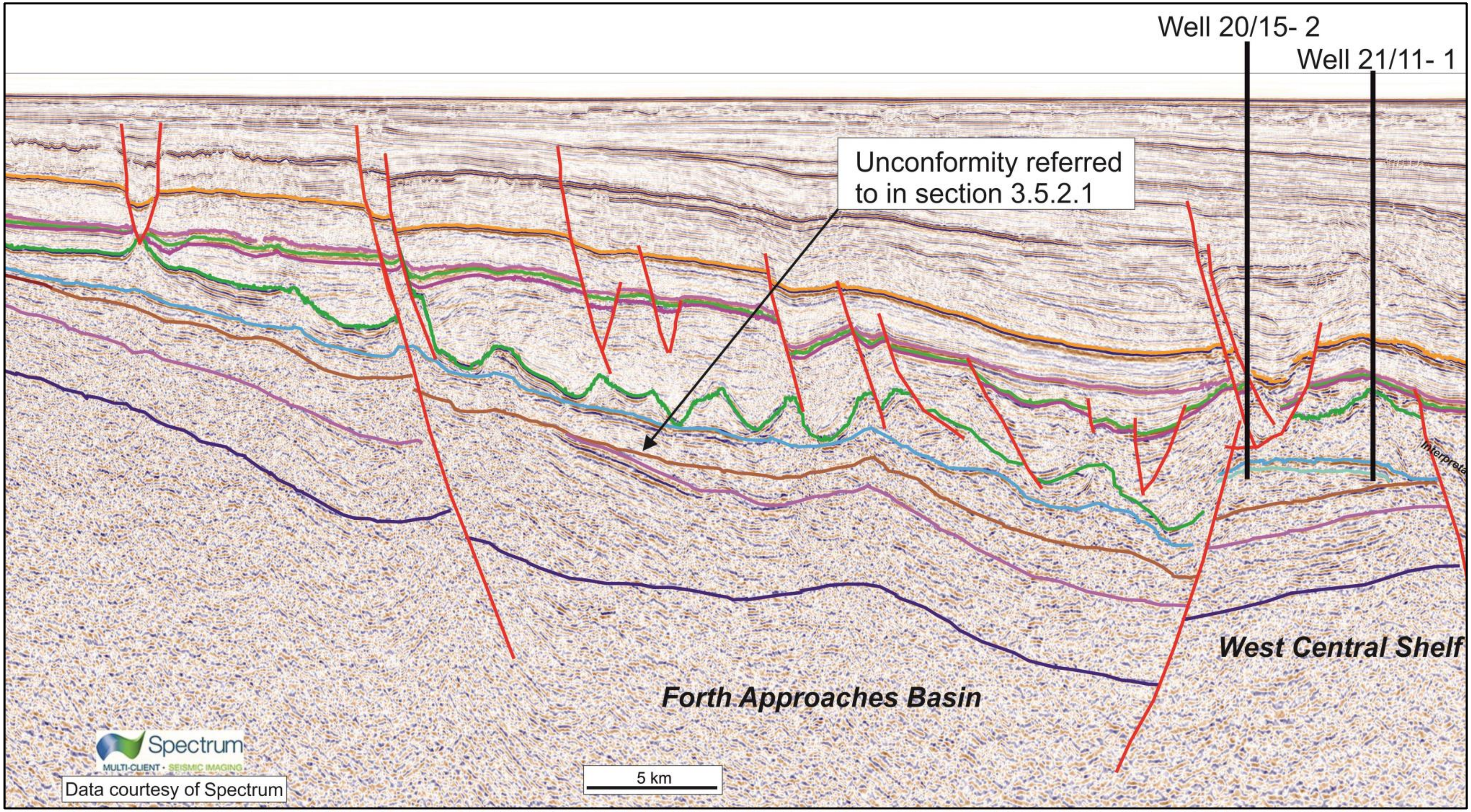


Figure 29. Detail from seismic profile shown in Figure 27 illustrating a prominent unconformity between the Devonian and Carboniferous succession. Brown pick is Base Carboniferous, light Purple is Top Eday Gp. pick, dark Purple is Top Basement pick.

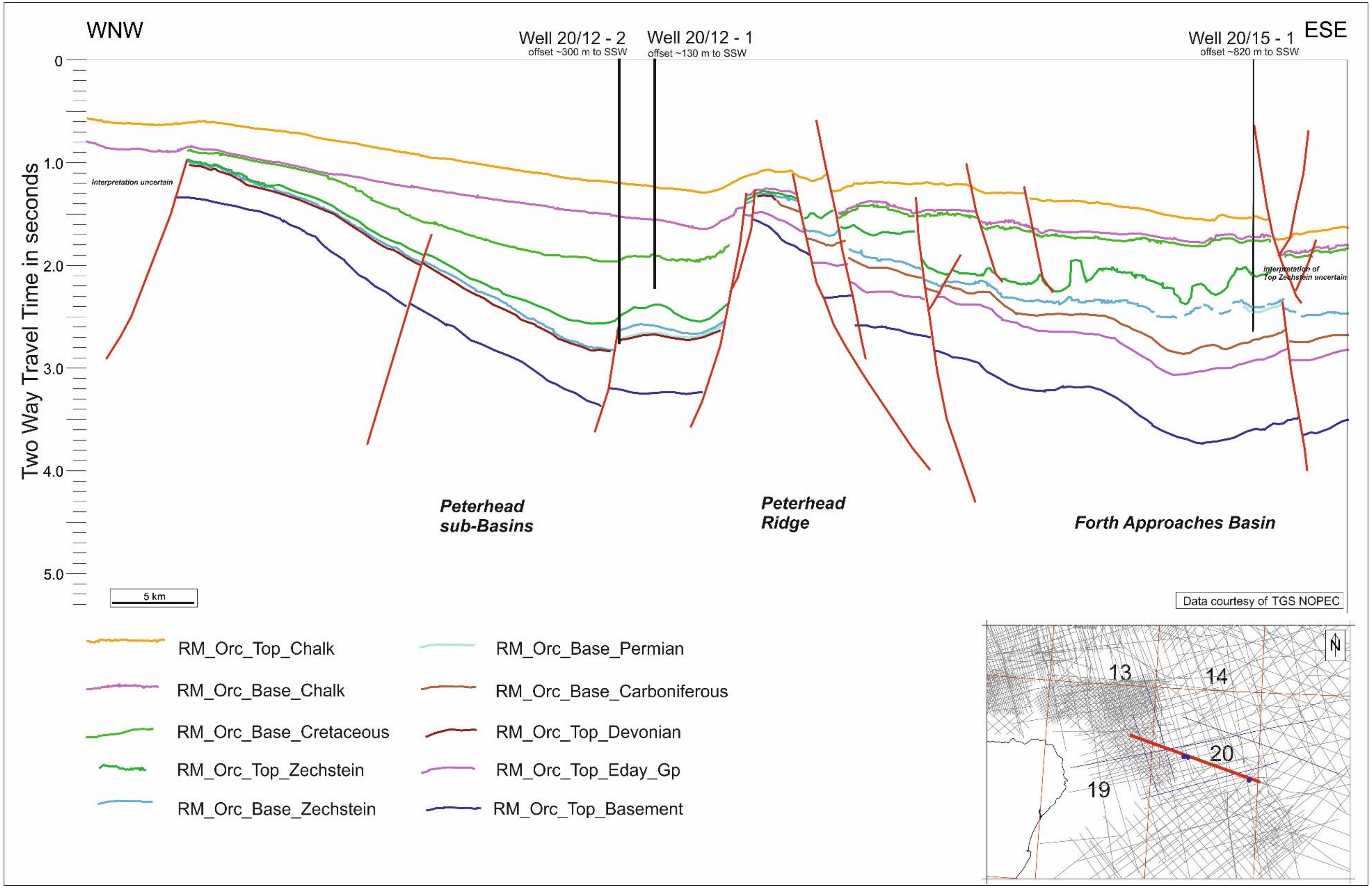


Figure 30. Line drawing of an interpretation of a seismic profile beginning in the NE Forth Approaches Basin and running over the Peterhead Ridge and into the Peterhead sub-basins. For location in relation to structure, see Figure 25.

3.6 PRE-PERMIAN SUBCROP MAP

The starting point for revision of the pre-Permian subcrop of the Orcadian area was the pre-Permian Geology of the United Kingdom map produced by Smith (1985).

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;
    - wells drilled since previous versions of the subcrop map;
- the new seismic interpretation carried out in this project;
- offshore BGS sea bed geology maps;
- the onshore BGS geology;
- information from the Millennium Atlas.

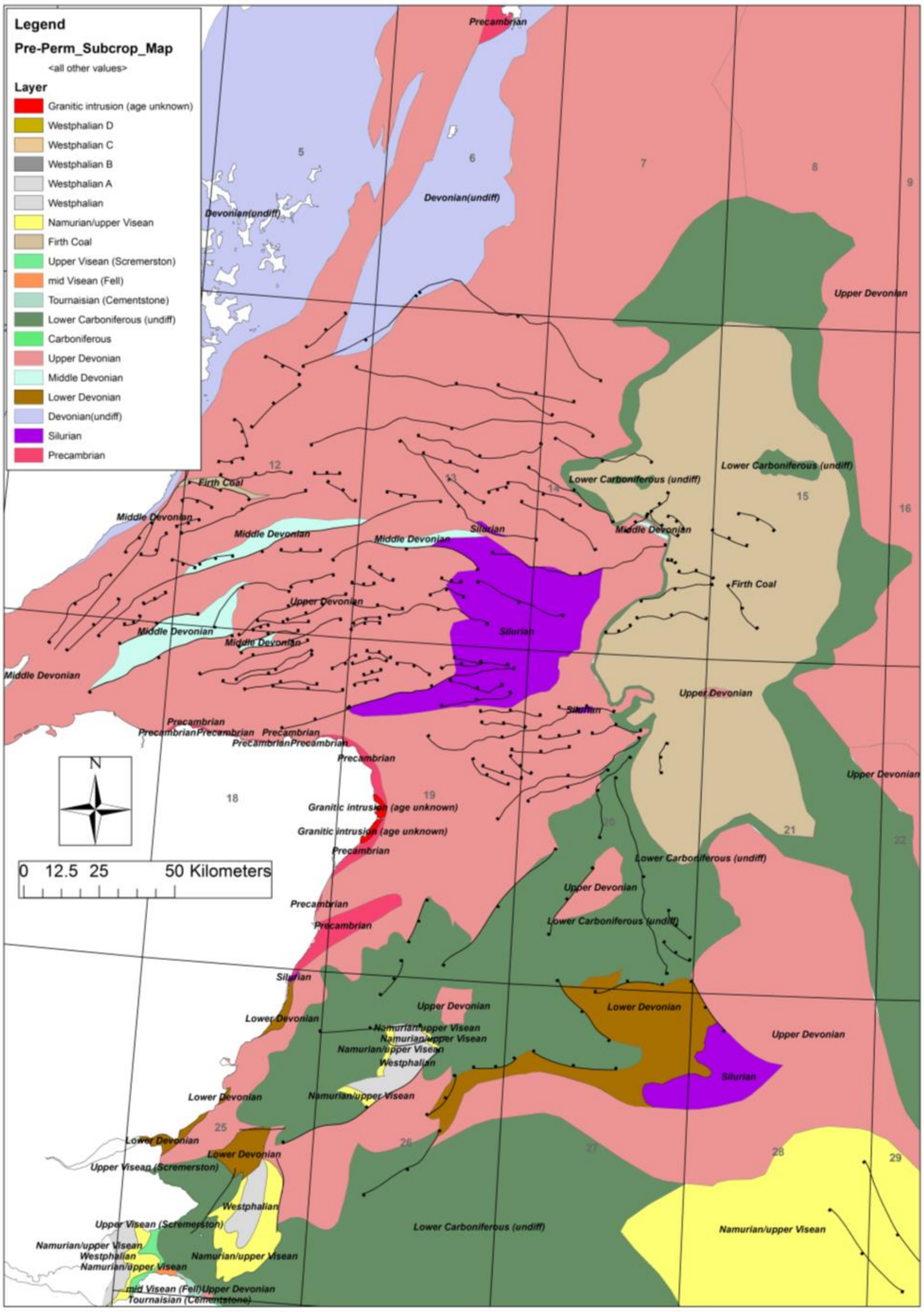


Figure 31. Updated Pre-Permian subcrop map.

4 Conclusions and future work

This report describes a regional seismic interpretation of the 21CXRM Palaeozoic Project Orcadian study area. Specifically, the Inner Moray Firth (Quadrants 11-13W and 17N-19N), the western Outer Moray Firth (Quadrants 13E – 15), the East Orkney Basin and adjacent highs and the Grampian High and adjacent areas. The study has generated a set of time and depth structure maps that are available digitally. The pre-Permian subcrop map has been extended northwards from the Central North Sea/Mid North Sea High study (Arsenikos et al., 2015). The maps have been used as key inputs to an assessment of the petroleum systems of the Palaeozoic succession in this area (Monaghan et al., 2016).

Some 35,000 line kilometres of predominantly 2D seismic data have been interpreted and tied to key released wells in the study area. This has allowed the delineation of Devonian and Carboniferous 'block and basin' structures in the Moray Firth, East Orkney Basin and Grampian High areas.

A new Palaeozoic structural interpretation has been summarised (Figure 15) and placed in regional tectonic context by Leslie et al. (2016). Key observations from the seismic interpretation that contribute to the Palaeozoic tectonic model are:

- The thickest Devonian depocentres can be found in Quadrants 11, 12 and 14 in a relatively restricted corridor bounded to the north by the Caithness Ridge, to the east by the Halibut Horst and to the south by the West Bank and Grampian Highs;
- Two major Palaeozoic depocentres have been mapped, the Caithness Graben and the Halibut Basin in Quadrants 13 and 14 respectively.
- The Smith Bank High, the Halibut Horst, and the Caithness Ridge were major elevated areas by the middle Devonian times, controlling deposition of Devonian strata;
- The East Orkney Basin is a Palaeozoic basin with sediments buried at similar depths to the basins observed in the Inner Moray Firth;
- The Grampian High area, covered by Quadrant 19 and northern part of Quadrant 20, is interpreted to have been a topographic high during the Devonian and Carboniferous.
    - Faults with a dominant WSW-ENE trend tip out westwards onto the Grampian High.
    - A Devonian succession has been mapped over much of the area. The succession is interpreted to be thin or absent on the footwall of the Banff Fault and immediately adjacent to and over the Grampian Spur;
    - There is little evidence for thickening of the Devonian succession against faults within this area and main movement on faults is interpreted to have been late Jurassic in age.
    - A Carboniferous succession thins westwards onto the Grampian high.
- The WSW-ENE trending Peterhead basins (principally Quadrants 19/9, 19/10, 19/15 and Quadrants 20/06, 20/11, 20/12) are interpreted to have formed principally during Late Jurassic rifting.
- The NE part of Forth Approaches Basin (FAB) is interpreted to have only a relatively thin Carboniferous succession (200 milliseconds TWTT or ~400 m) resting on Devonian strata.

    - This explains the poor imaging on the seismic data compared to the SW part of the basin (northern part of Quadrant 26) where a thick Carboniferous succession can be interpreted;
    - A prominent unconformity of ?Late Devonian age, located within the NE part of FAB, is interpreted to mark an area of uplifted topography that separated Carboniferous successions of different thickness and facies to the south-west and north-east.
        - However, the extents of the area affected cannot be confidently mapped due to a lack of seismic lines on which it can be interpreted.

4.1 FUTURE WORK

The 2015 Government-funded seismic survey provides new regional cover in Quadrants 20 and 21 and could be utilised in any future work identified in the area.

Future work could usefully:

- Extend the interpretation of the Base Carboniferous unconformity at the NE end of the Forth Approaches Basin;
- Extend the Devonian and Carboniferous seismic interpretation further to the east and north e.g. Quadrants 8, 9 16 and 21 to investigate the likely extent of source and reservoir rocks over a larger area, as well as characterising trapping styles;
- focus on mapping of local reflectors and structures in more detail;
- provide a structural reconstruction model across key areas the Inner Moray Firth.

5 References

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