Structural development of the Devono-Carboniferous plays of the UK North Sea

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Abstract

Decades of oil and gas exploration across the North Sea, have led to a detailed understanding of its Cenozoic- Mesozoic structure. However, the deeper basin architecture of Palaeozoic petroleum systems has been less well defined by seismic data. This regional structural overview of the Devono-Carboniferous petroleum systems incorporates interpretations from more than 85,000 line-km of 2D seismic data and 50 3D seismic volumes, plus a gravity, density and magnetic study, from the Central Silverpit Basin to the East Orkney Basin. A complex picture of previously unmapped or poorly known basins emerges on an inherited basement fabric, with numerous granite-cored blocks. These basins are controlled by Devono-Carboniferous normal, strike-slip and reverse faults.

The main basins across Quadrants 29-44 trend NW-SE, influenced by the Tornquist trend inherited from the Caledonian basement. North of Quadrants 27-28, and the presumed Iapetus suture, the major depocenters are NE-SW (e.g. Forth Approaches Basin and Inner Moray Firth Basin) to E-W (e.g. Caithness Graben), and WNW-ESE-trending (e.g. East Orkney Basin), reflecting the basement structural inheritance. From seismic interpretation, there are indications of an older N-S fault trend in the Inner Moray Firth that is difficult to image, since it has been dissected by subsequent Permo-Carboniferous and Mesozoic faulting and rifting.

1 Introduction

The Central and Northern North Sea (CNS and NNS respectively) are key hydrocarbon provinces accounting for a large proportion of the UK's oil and gas production.

Running from late 2014 to early 2016, and ahead of the release of UK Government seismic data and the 29th Offshore Licensing Round, the 21st Century Exploration Roadmap Palaeozoic Project (21CXRM) aimed to stimulate hydrocarbon exploration of the Palaeozoic play across and around the Mid North Sea High (CNS study area; Quadrants 25-44; Fig. 1) to the Inner/Outer Moray Firth Basin and the East Shetland Platform (Orcadian study area; Quadrants 11-23; Fig. 1), focussing on Devonian and Carboniferous strata. This paper synthesises the systematic regional study undertaken by an interpretation of 85,000 line-km of the highest resolution seismic data (released and unreleased) across the study areas, integrated with gravity, magnetic, tectonics studies and onshore UK knowledge, to highlight key structural elements of the potential upper Palaeozoic petroleum systems.

More specifically, the Orcadian study area extends from the East Shetland Platform in the north (Quadrant 7) to Quadrants 14-15 and 22-24 in the south. Farther south, the CNS study area includes the Forth Approaches Basin (Quadrants 26-27), across the Mid North Sea High and southwards to the northern margin of the Carboniferous-Permian gas basin of the Southern North Sea (Quadrants 41-44; Cameron 1992; Cameron 1993; Cameron *et al.* 2005; Fig. 1).

The Upper Palaeozoic strata onshore UK have been heavily studied, reaching a broadly accepted understanding of the complex structural history of extension, transtension, transpression and inversion that these areas have undergone (Chadwick & Holliday 1991; Glennie & Underhill 1998; Underhill *et al.* 2008; Woodcock & Strachan 2012; Woodcock 2012) .

However, although the existence of potential offshore Devonian and Carboniferous petroleum systems across the study area has been previously documented (Evans *et al.* 2003; Hay *et al.* 2005; Doornenbal & Stevenson 2010; Milton-Worssell *et al.* 2010), regional seismic mapping and structural overview has been lacking, resulting in a poorly understood structural setting for the Palaeozoic basins.

Oil and gas production indicates that the majority of hydrocarbons are produced from Jurassic-sourced fields located in the heavily-explored Cenozoic and Mesozoic successions of the Central Graben and Moray Firth Basin (Abbotts 1991, Gluyas & Hichens 2003 and references therein). Across the 21CXRM Palaeozoic Project area, only a handful of fields (e.g. Buchan, Stirling, Claymore, Argyll/Ardmore) produce oil of assumed Jurassic source from a Devonian and Carboniferous reservoir, (e.g. Edwards 1991, Robson 1991), whilst the Beatrice/Jacky and Breagh fields exemplify Devonian and Carboniferous sourcing, respectively (e.g. Stevens 1991; Symonds 2016).

2 Tectonic setting

Episodic, plate-scale tectonism between Laurentia, Baltica, Gondwana and Avalonia was active during the Upper Palaeozoic (Coward 1993; Domeier & Torsvik 2014). The tectonic framework of the study area is transitional between Iapetan and inherited Caledonian trends (NE-SW to ENE-WSW) in the north and Tornquist trends to the south (NW-SE) (British Geological Survey 1996; Pharaoh 1999). In Late Ordovician to Silurian times, Avalonia and Baltica were amalgamated by the closure of the Tornquist Sea (Pharaoh 1999; Torsvik & Rehnström 2003; Domeier & Torsvik 2014). By the Early Devonian, the Iapetus Ocean was closed, leading to a "soft collision" between Laurentia and Eastern Avalonia and the infill of the sedimentary basins with large volumes of clastic sediments (Woodcock 2012). The location of the offshore Iapetus suture has been a subject of numerous studies (e.g. Klemperer & Matthews 1987; Soper *et al.* 1992). The exact location is still debated, but it is in the vicinity of the northern Mid North Sea High, with the Forth Approaches Basin lying to its north.

The most relevant tectonic models for the project area come from Coward (1993) and Maynard et al. (1997). Ziegler (1990) and Cocks & Torsvik (2006) provide an overview of the wider palaeogeography of the region, local aspects of which have been updated through subsequent studies. According to Coward (1993), on the northern edge of the project area, during the Late Devonian to early Carboniferous the north-east expulsion of the Baltica microplate was accommodated by sinistral transtension in the vicinity of the Great Glen Fault, while the southern edge of the study area recorded dextral transtension as a combination of the Baltica microplate expulsion and the adjacent Variscan belt. Onshore southern UK, Late Devonian to early Carboniferous times were characterised by broadly N-S to NNW-SSE extension (Fraser & Gawthorpe 2003).

By late Carboniferous times, although Baltica moved back westwards leading to stress reversal (Coward, 1993), the regional transport direction (broadly NE-SW) would be expected to remain the same as during the early Carboniferous (*cf.* de Paola et al. 2005). This change in the stress field would be expected to have re-activated suitably oriented structures as part of a regional transpressive regime.

3 Datasets and methodologies

3.1 Seismic data

The seismic dataset utilised in this study comprised released and unreleased 2D and 3D surveys provided to the British Geological Survey under contract from DECC/OGA, covering the area from Quadrant 7 to Quadrant 44 (Fig. 1a). 85,000 line-km of 2D data including several regional-scale surveys were the most important source of information for the study, due to their coverage and better penetration of the Upper Palaeozoic sequences between approximately 0.5 and 4 seconds two-way travel time (TWTT). The line spacing was irregular, from 2 to more than 10 km (Fig. 1a), but was considered to be adequate for regional structural insights across the majority of the study area. Data spacing across the Mid North Sea High (Quadrants 26 – 36) was between 5 and more than 30 km; this area was the focus of a gravity backstripping study to elucidate Carboniferous and Devonian basins, and of a subsequent UK Government seismic survey (released 2016). Twenty-three 3D volumes were also consulted as source of information, and eight of them were partially interpreted, focusing on structurally complex areas. At the request of seismic data providers, these interpretations were resampled at 2D line spacing before inclusion in the 5-km resolution two-way travel time and depth grids.

3.2 Well data

Of the thousands of exploration and production wells drilled across the Central North Sea only 550 have reached pre-Permian strata, most of them terminating after a few tens of metres in that sequence. Approximately 180 wells penetrating the pre-Permian (both Carboniferous and Devonian) were stratigraphically re-interpreted during the 21CXRM Palaeozoic Project (Fig. 2 ; Kearsey et al, this volume, Kearsey *et al.* 2015, Whitbread & Kearsey 2016) and together with existing interpretations, these form the basis upon which the seismic and structural interpretations were made.

3.3 Calibration of well-to-seismic ties

Seismic calibration was achieved by the use of available time-depth pairs from downhole sonic logs and checkshots. Synthetic seismograms were produced for selected wells with a good penetration of Devonian and Carboniferous strata (e.g. 41/10-1 and 12/29-2). The comparison showed that there was a very good correspondence between the synthetic seismograms and the time-depth pairs.

3.4 Seismic interpretation / selected events

Ten seismic events were mapped through the Devonian, Carboniferous and Permian succession (Fig. 2). Events with the greatest acoustic impedance and greatest regional coverage were prioritised as were events which represented either important intervals delineating the deep basins (e.g. Middle Devonian), or intervals crucial for the better understanding of the petroleum system (e.g. Scremerston Formation and Middle Devonian source rocks). The study commenced by interpretation of a regional grid of well-calibrated seismic profiles. Additional lines were interpreted as the characteristic reflectivity for events and packages was established across different surveys and sub-basins. The most challenging aspects of the interpretation were the loss of reflectivity at depth (i.e. loss of impedance contrast), the complicated diapiric geometries of the Zechstein affecting seismic imaging underneath (especially in the Forth Approaches Basin) and the limited penetration of the Palaeozoic strata by wells.

3.5 Depth conversion methodology

The very large area of the project area encompassed highly heterogeneous lithologies and time-equivalent depositional units with different burial and uplift histories, resulting in laterally and vertically varying interval velocities. Regional depth conversion was therefore a crucial, yet challenging, procedure, which took into account variations in the interval velocities both laterally and vertically.

Given the regional extent and variability, the layer-cake depth conversion model was considered the most adequate approach. A 3D velocity model was constructed using 14 layers from the basement to the Cenozoic and defined by the most significant variations in velocity.

Velocity data were collected from over 700 wells with the most complete datasets of check-shots and/or velocity logs across Quadrants 11 to 44. Wells with anomalously high or low velocities were excluded.

In the northern part of the project area (Quadrants 11-22), the combination of the BGS well database, with the interpreted horizons and faults allowed for the creation of a full 3D Structural Framework™ and a 3D Velocity Volume in Decision Space™. The depth-converted surfaces were quality-controlled against the drilled depths in the wells and corrected as necessary.

The Upper Permian, Zechstein Group required to be treated differently between the southern and northern parts of the study. This is due to the presence of thick evaporite successions (halite, anhydrite, and gypsum) and diapirs and to the south (Quadrants 25-44) which gradually become more clastic-dominated to the north (Quadrants 11-22). The velocity of the Zechstein layer in the Netherlands is a function of its thickness rather than its burial depth

(Velmod-1, Velmod-2; Van Dalfsen et al. 2006). This applies also to the CNS study area and the method followed respects the relationship between thickness and velocity. For thicknesses more than 150 ms a constant velocity of 4500 m/s was used, while for thicknesses less than 150 ms a velocity function was applied based on the statistics from 65 wells in the CNS study area (Fig. 3)

Fig. 4 shows an example of the very good correlation of the final model between interval velocity, structures and depth-converted surfaces.

3.6 Gravity Modelling

Only an outline of the gravity modelling methodology is provided below; for full details see Kimbell & Williamson (2015, 2016). Gravity data acquired by the British Geological Survey (BGS 2017a, d) were employed, and the analysis of the results was supplemented by comparison with magnetic data (BGS 2017b, c).

Downhole density logs from 146 wells in the Central North Sea study area and 179 wells in the Orcadian study area were analysed. The logs were divided into units separated by the seismically-defined boundaries which would be used in subsequent gravity modelling. The sampling in the Central North Sea study area was relatively poorly distributed, so a predictive model was used to simulate the density of the post-Zechstein sequence in that area. The model employed compaction trends and burial anomalies based on analysis of the available log data and integration with the results of previous studies. Compaction trends were derived from the shale and chalk models of Sclater & Christie (1980) and burial anomalies were based primarily on the results of Japsen (1998, 1999, 2000). The efficacy of the predictions was tested at the well sites and, as a result, overcompaction effects were incorporated in full but thresholds were applied to the influence of undercompaction (overpressure) to avoid overcorrection. There is an inverse correlation between the average density of the Zechstein Group in the Central North Sea study area and its thickness, which results from a greater proportion of low-density halite where the unit is thick and higher-density dolomite and anhydrite where it is thin. This relationship was used to develop a density model for this sequence based on regression kriging, with well logs (where at least 60% of the sequence was sampled) as primary control and the relationship between thickness and density as secondary drift.

Compaction trends and burial anomalies were used to estimate densities in the post-Chalk sequence in the Orcadian study area, but the older strata were relatively well-sampled and their density was modelled by empirical Bayesian kriging. In both areas, densities of 2.75 Mg/m^3 and 1.03 Mg/m^3 were assumed for basement and seawater respectively.

The gravity modelling involved the removal ('stripping') of the effect of the shallower part of the sequence in order to isolate that of underlying structure. It was conducted using GM-SYS 3D routines within the Geosoft Oasis Montaj software package. In the Central North Sea study area the stripping extended to the base of the Zechstein Group, but in the Orcadian study area it only extended to the top of the Zechstein because of limitations in the information available on the thickness of that unit. The structural inputs to the gravity stripping were depth-converted grids from the seismic interpretation. For the purposes of gravity modelling the 5-km grids were resampled at 2.5-km node spacings to allow improved resolution where the structure was smoothly varying, although this does not circumvent the resolution limits where the seismically-defined structure contains short wavelengths. Both models included boundaries at seabed, Top Chalk, Base Chalk and Top Zechstein; the CNS study area model also included the base Zechstein surface and the Orcadian study area model included the base Cretaceous (Cimmerian Unconformity) and Top Triassic surfaces.

Stripped gravity fields were produced for both study areas, and these contained pronounced regional gradients relating to deep crustal structure (in particular a reduction in depth to Moho and increase in deep crustal density towards the central axis of the North Sea). These effects were removed in the form of a regional field which was constrained, in a generalised fashion, where there was sufficient control (good evidence of depth to basement in areas remote from major granite plutons) and allowed to vary smoothly in between. Subtraction of the regional trend resulted in a residual stripped gravity field which was employed in further analysis. In the case of the Orcadian study area this analysis was qualitative, but with the Central North Sea study area a further quantitative step was undertaken which involved inversion of the residual stripped anomalies in terms of a new depth interface. The density assumed for the unit between base Zechstein and the gravity inversion surface was based on a generalised model of the density of the pre-Zechstein, Upper Palaeozoic rocks, so the surface provides a simulation of the depth to top basement. This is not the case, however, where basement density contrasts, and in particular low-density granite plutons, affect the inversion. Although it is possible to excise the influence of granites from the results of gravity inversion (e.g. Milton-Worssell *et al.* 2010), in the present study we omitted this step in order to: (i) facilitate the integrated (seismic/gravity/magnetic) analysis of areas where granites and basins were in close proximity and partitioning of their effects was difficult; and (ii) avoid pre-judging the interpretation where intrusive bodies were identified with less confidence. The gravity inversion surface was converted into a horizon in two-way-travel-time and imported into the seismic interpretation environment to aid this integration.

The apparent thickness between base Zechstein and the gravity inversion surface in the Central North Sea study area is illustrated in Fig. 5a and residual stripped gravity anomalies in the Orcadian study area are illustrated in Fig. 5b.

4 Devonian and Carboniferous basin geometry and evolution

The mapping of the Palaeozoic basins from the entire project area is described in two major study areas with eight sub-areas/basins. The CNS study area includes the North Dogger Basin, the Mid North Sea High, the Silverpit Basin, the offshore Northumberland Trough and the Forth Approaches Basin. The Orcadian study area includes the Inner Moray Firth Basin, the East Orkney Basin and the Outer Moray Firth. Fig. 6 provides the regional synthesis of the individual mapped basins, their trends and their geographical relationship with onshore.

4.1 North Dogger Basin

The North Dogger Basin, initially described as a deep Carboniferous basin by Milton-Worssell *et al.* (2010), trends in a NW-SE direction, from the southern edge of Quadrant 29, across the northwest corner of Quadrant 37 and into the central part of Quadrant 38 (Fig. 6). To the north-northeast, the basin margin is delineated by the Auk Ridge (Trewin & Bramwell 1991; Gatliff *et al.* 1994) and well-resolved in the gravity model (Fig. 5a; Tornquist trend). The basin is delineated by the Dogger Granite High to the southeast. The Dogger Granite is clearly identifiable in the gravity modelling results (and has a strong magnetic effect) with possible N-S and E-W extensions identifiable in both gravity and magnetic data (Fig. 5a ; Kimbell & Williamson 2015). The basin continues into the Dutch sector north of the Elbow Spit Platform (Wride 1995; Ter Borgh *et al.* 2016). The Top of the Middle Devonian Kyle Group is the most prominent reflector in the Devonian-Carboniferous sequence, defining the geometry of the North Dogger Basin, proven in wells 30/16-5, 30/24-3, 30/25a-2, 37/12-1 and 38/03-1surrounding the basin (Fig. 7). Although the interpretation is based on the strong, characteristic Kyle Group reflector on the highs, it is possible that the Middle Devonian is represented by deeper-water facies into the basin. Lower and middle Carboniferous strata are proven in 11 wells and can be mapped across the basin. The limited number of well ties across Quadrants 29, 30, 37 and 38 remains the biggest constraint for a more detailed tectonostratigraphic model of the North Dogger Basin The Scremerston Formation (lower Carboniferous) has been interpreted in an area more extensive than previously mapped and it has been interpreted based on its characteristic seismic signature across the basin (high frequency, high amplitude reflectors) in agreement with previous studies (Hay *et al.* 2005) .

The North Dogger Basin is separated into two sub-basins by a prominent elevated block, the NW-SE-oriented North Dogger Horst (Fig. 7), which is constrained by well 37/10-1 proving uppermost Devonian and basal Carboniferous stratigraphy (Tayport and Buchan formations, see Kearsey et al. this volume and Kearsey *et al.* 2015). The North Dogger Horst is also identifiable as a high in the gravity model and as a magnetic anomaly (Fig. 5a).

The second sub-basin is located in Quadrant 29 (Fig. 6 and Fig. 7) and is considered to be a fault-controlled Devono-Carboniferous depocentre (this study and Milton-Worssell *et al.* 2010). The varying levels of well control in the basin have an impact on the certainty of interpretation but seismic data clearly show deep reflectors which define a 1.5 s TWTT thick basin under the Permian sequences. Devonian and Carboniferous sequences are eroded (or non-deposited) on top of the regionally extensive Dogger Granite High in Quadrants 37 and 38, reaching a thickness of over 1 s TWTT around 50 km NNE of the high into the basin. The Top Kyle Group seismic pick plunges in depths of more than 7 km (3.5 s TWTT) in the centre of the North Dogger Basin (Quadrant 38; Fig. 8) until imaging is unclear. In the Auk-Flora Ridge area, reflectors of the well-calibrated Kyle Group (wells 30/16-5, 30/24-3 and 30/25a-2) are clearly visible on seismic data, offset by major normal faults trending broadly NE-SW (Fig. 7). The presence of Upper Devonian and Carboniferous strata in wells 37/10-1, 37/12-1, 38/16- 1, 38/18-1, 38/22-1, 38/24-1 and 39/07-1, combined with seismic data, indicates that the Upper Devonian and lower-middle Carboniferous intervals have infilled the available space of the North Dogger Basin. On seismic data, these are condensed sequences which appear to onlap onto the Dogger Granite High, and to the NE of the granite in Quadrant 38 they become thicker and deeper infilling an under-filled basin (Fig. 8).

In summary, the North Dogger Basin is interpreted as having an overall (N)NW-(S)SE structural trend with more than 2.5 km (more than 1.2 s TWTT) of Upper Devonian-lower Carboniferous sediments.

4.2 Mid North Sea High – Dogger Granite High

The term Mid North Sea High, initially used in the description of the palaeogeographic division of the northern and southern Permian basins (Donato *et al.* 1983; Jenyon *et al.* 1984), is also used for the geographical area across Quadrants 27-28 and 35-36 (Fig. 6). Tectonic and summary maps are lacking detail (British Geological Survey (BGS) 1996; PESGB 2017), due to several kilometres spacing of legacy seismic data (in places more than 20 km) and very limited well penetrations. As part of the CNS study area, seismic mapping across the deepest parts of the Mid North Sea High has added detail and defined a 'high' across Quadrants 26-28 and 35-36 that is less extensive than previously thought along with a series of highs and basins to its north, east and south margins (Fig. 6; largely in the area of the offshore Southern Uplands).

The gravity model indicates structures with ENE-WSW trends crossing the Mid North Sea High (e.g. the offshore continuation of the Pressen-Flodden-Ford line, the Oldhamstocks Basin, and a possible basin spanning the Quadrant 26-27 boundary; Fig. 5a). Magnetic features associated with Permo-Carboniferous dykes also follow this trend (Kimbell & Williamson 2015).

In Quadrants 26-27-28 and 34-35-36, regional mapping of three interpreted intervals (Top Cementstone Formation – lower Carboniferous/Tournaisian, Top Fell Sandstone Formation – lower/middle Carboniferous/Visean and Top Scremerston Formation – middle

Carboniferous/Visean), constrained by wells to the north and to the south of it, shows that the Mid North Sea High is a relatively flat, tilted terrace deepening eastwards with post?-Permian onlapping sequences. In more detail, this geometry is mapped across Quadrant 28 and northern Quadrant 36, and becomes truncated by the fault-controlled North Dogger Basin in Quadrant 29 and northern Quadrant 37. Moving west towards the UK coast (Quadrants 27 and north 35), Palaeozoic (i.e. Kyle Group or time-equivalent) seismic reflectors are interpreted as dipping up towards shallower depths in the sub-surface. The northern margin of the Mid North Sea High is marked by several ENE-trending faults that downthrow northwards to the Forth Approaches Basin and the Devil's Hole Horst block and granite.

At the boundary of Quadrants 36 and 37, the south-eastern extremity of the Mid North Sea High is characterised by the Western Arcuate Fault described by Jenyon *et al.* (1984). It consists of a near-vertical NE-SW trending fault mapped towards the NW-SE trending faults bounding the North Dogger Basin (Fig. 6 & Fig. 7). On the east side of Quadrant 36, a restricted Devono-Carboniferous (pull-apart?) basin is mapped. The gravity and magnetic modelling confirms the presence of this feature and the NE-SW trend identified as the Western Arcuate Fault (Fig. 5a). 3D seismic interpretation and coherence volumes over the northern North Dogger Basin (Quadrant 29) suggest an along strike NE-SW trending structure at approximately 3-4 s TWTT depth, offsetting the NW-SE trending faults and with some evidence of pop-up flower structures (Fig. 7). This may represent an extension of the Western Arcuate Fault, or a similarly oriented system and is consistent with the regional Devono-Carboniferous structural grain (e.g. Coward 1993, British Geological Survey (BGS) 1996, Coward *et al.* 2003, Fraser & Gawthorpe 2003, De Paola *et al.* 2005 and references therein). Further detailed structural mapping and analysis is required to deduce whether Devono-Carboniferous strain-partitioning resulted in wrench- and extension-dominated domains across the Dogger Granite High and North Dogger Basin as a result of an oblique regional transport direction (NNW-SSE; Coward, 1993; *sensu* De Paola *et al.* 2005; Leslie et al., 2015) and resolve the timing of the observed NW-SE and cross-cutting, NE-SW ?oblique slip faults.

4.3 Silverpit Basin

Forming one of the major structures of the Southern North Sea Carboniferous gas basin, the Silverpit Basin is oriented NW-SE across Quadrants 43-44, extending northwards into Quadrant 36 (Bailey *et al.* 1993; Cameron 1993; Cameron *et al.* 2005; Fig. 6) . Since the margin of the basin is characterised by the presence of the Breagh Field (blocks 42/13a and 42/12a; Symonds 2016), the rest of the basin margin is also a key zone for understanding the Visean-Namurian sedimentation and potentially prospective petroleum systems (Monaghan *et al.* 2015). Well-calibrated seismic interpretation combined with the gravity model (Fig. 5a) provide a good outline of the basin margins. On the north-eastern basin margin Middle (?)/ Upper Devonian and lower Carboniferous sequences onlap the south-western flanks of the Dogger Granite High. Carboniferous strata tied to wells in Quadrants 42-43-44 constrain phases of Late Devonian/earliest Carboniferous normal faulting, mid-Carboniferous post-rift sedimentation, followed by Variscan inversion and the development of NW-trending gentle folds. Some NW-SE trending faults were reactivated in post-Permian times, offsetting the Zechstein Group.

4.4 Offshore Northumberland Trough

The onshore Northumberland Trough (Fig. 6) is an ENE-trending Carboniferous basin, bounded to the north and south by structural highs (the Cheviot and Alston Blocks respectively) that are underpinned by low density granitic intrusions (Kimbell *et al.* 1989; Chadwick & Holliday 1991; De Paola *et al.* 2007). Offshore, Carboniferous rocks subcrop the seabed adjacent to the Northumberland coast and are succeeded by Permian and Triassic, Jurassic and Cretaceous successions eastwards. Seismic interpretation was poorly constrained in this area as the nearest deep offshore well (41/01-1) lies to the south of the area (Fig. 9). A thick Carboniferous succession comprising sandstone, coal, mudstone and limestone is expected to be present within the area by analogy with well 41/01-1 and the onshore succession within the Northumberland Trough. The Near Top Cementstone Formation (lower Carboniferous) reflector was interpreted across southern Quadrants 34 and 35 (Fig. 9) in order to define faults, basins and highs, while where present Top and Base Chalk, Top and Base Zechstein were interpreted to facilitate depth conversion. Well 41/01-1, 25 km south of the area, penetrates 159 m of Cementstone Formation sediments. Although there is no clear seismic reflector defining the top of this formation, a contrasting juxtaposition of the seismic packages above and below the boundary (higher amplitude, more continuous reflectors above with a more transparent seismic package below) enabled an interpretation and delineation of a primarily early Carboniferous basin infill into the area to be made (Fig. 10). Outcrop onshore and penetrations by offshore BGS shallow boreholes have allowed the offshore subcrop of Westphalian strata to be mapped but a lack of well ties, along with erosion due to Variscan inversion, resulted in discontinuous picks and precluded the interpretation of upper Carboniferous surfaces in the offshore Northumberland Trough.

Onshore, the major bounding faults to the south of the Northumberland Trough are the ENE-trending Stublick and Ninety-Fathom Faults. They show evidence of syndepositional extensional faulting in the lower Carboniferous strata, with up to 4 km of Tournaisian and Visean sediments being deposited adjacent to the faults (Kimbell *et al.* 1989; De Paola *et al.* 2007). Offshore, the eastward continuation of the Ninety-Fathom Fault can be mapped for approximately 30 km (Fig. 6 & Fig. 9). The northern margin of the basin is characterised by an ENE-trending fault which can be mapped for approximately 20-25 km offshore in

Quadrant 34, a continuation of the Hauxley Fault of Kimbell *et al.* 1989. Between the ENE-trending basin-bounding faults, a system of typically steep to vertical NNW to NNE-trending faults with small throws of less than 150 m (approximately 70 ms TWTT) and occasional reverse displacements that appear to be related to tight folds within the pre-Permian succession are interpreted from seismic data. The spacing and quality of the seismic dataset and the lack of well ties precludes a detailed model of the Carboniferous structural evolution in this area where the offshore extension of the Northumberland Trough, representative of the extension-dominated domain of De Paolo et al. (2005), passes eastward towards the NW-SE inherited Tornquist trend dominant within the mapped fault pattern in Quadrant 35 and 36 (Fig. 6).

4.5 Forth Approaches Basin

The Forth Approaches Basin is the eastern continuation offshore of the Palaeozoic basins of the Midland Valley of Scotland (MVS). It is bounded to the north and to the south by the seaward extensions of the Highland Boundary and Southern Upland faults respectively (Fig. 9). In this area, Early Devonian extension followed the Caledonian compressive regime and led to the establishment of small basins infilled with continental sediments (Marshall & Hewett 2003). There is no evidence of a Middle Devonian sedimentary succession in the Forth Approaches Basin area, which is interpreted as forming a relative high during this time. However, from latest mid- to late Devonian times, fluvial coarse-grained clastic sediments spread south of the Highland Boundary Fault into the area. Onshore, and in the Firth of Forth (Quadrant 25), a series of N to NNE-trending syn-sedimentary Carboniferous synclines, that are highly oblique to the regional faults, are interpreted to have developed in a predominantly dextral strike-slip regime during the mid to the late Carboniferous (Read*et al.* 2002; Ritchie *et al.* 2003; Underhill *et al.* 2008). late Carboniferous tightening of the folds (Cartwright *et* *al.* 2001; Underhill *et al.* 2008) in the offshore, may indicate Variscan, pre-Permian inversion.

Seismic ties from two key wells (26/07-1, 26/08-1; Fig. 1b) within the south-western part of the Forth Approaches Basin prove a thick coal-, mudstone- and sandstone-bearing Visean-Namurian succession (Firth Coal Formation = Scremerston Formation equivalent) within a half-graben geometry (Fig. 6, Fig. 9 & Fig. 11). South-easterly deepening is shown on the Top Cementstone Formation depth map (Fig. 9) against the fault system defining the northern edge of the Mid North Sea High. Significant south-easterly thickening of Rotliegend sandstones is also observed interpreted as syn-rift deposition during Early Permian extensional reactivation (Cartwright *et al.* 2001; Underhill *et al.* 2008). The southern boundary of the basin is represented by the offshore extension of a northward stepping en-echelon system of faults that onshore include the Dunbar-Gifford and Lammermuir faults; the latter onshore faults form part of the Southern Upland Fault system (British Geological Survey (BGS) 1996); Fig. 6 & Fig. 9). Offshore, faulting is interpreted to be offset northwards into Quadrant 25, adjacent to a NNE-trending syncline, before veering to a NE-SW trend and extending across Quadrants 26 and 20 (Fig. 9). Seismic interpretation between the Upper Devonian footwall succession proven in 26/12-1 (Fig. 9) and an interpreted Top Cementstone Formation succession in the hanging wall to the north-west indicates a throw across the basin bounding structures of over 3000 m (Fig. 9 & Fig. 11).

Towards the NE extremity of the basin (Quadrants 19 and 20), a gravity low (Fig. 5a) has been mapped that could be interpreted as a thick Permo-Carboniferous basin similar to that present to the SW. However, seismic reflections beneath the Base Permian Unconformity at this location are lower amplitude and less continuous and do not image any obvious thickening Carboniferous succession as observed to the south-west; here a relatively thin

Carboniferous succession of approximately 400 m is interpreted and the gravity low may be in response to a thick Devonian succession.

The Midland Valley of Scotland contains oil and gas fields (Midlothian, D'Arcy-Cousland) and a proven working petroleum system (Underhill *et al.* 2008). The lower Carboniferous strata act simultaneously as the main source rock and a trap (Hallett *et al.* 1986; Underhill *et al.* 2008). Its offshore extension, represented by the Forth Approaches Basin, would need to constrain two main critical factors in order to prove that it can be a viable play: a) the maturity and b) the volumes of the source rock. The main source rock, the Firth Coal Formation (Scremerston equivalent), is gas-prone, but according to the basin analysis model conducted by Vincent (2015) the gas window was not reached in the modelled well 26/08-1. However, selected wells from confidential industrial geochemistry reports describe oil and gas shows from a Carboniferous source rock in the Forth Approaches Basin depocentre which could have been deeply buried and, thus, producing hydrocarbons.

4.6 Northern Outer Moray Firth

The Outer Moray Firth – Witch Ground Graben (Figs. 5, 6 & 17) area and the edge of the East Shetland Platform area are two other frontier areas where the Palaeozoic strata could play a significant role in new plays.

The Witch Ground Graben is characterised by extensional faulting during Jurassic and Cretaceous (Beach 1984). However, while the main focus of previous studies has been the Mesozoic structural evolution and petroleum potential of the graben (Glennie & Underhill 1998; Jones *et al.* 1999; Beach 1984), wells drilled in it (e.g. 14/19-12, 15/19-2) prove that it also contains Carboniferous strata, which provide insights to the Palaeozoic petroleum system and the deeper structural styles. The uppermost Devonian/lower Carboniferous intervals are represented by the Tayport Formation. The early Carboniferous (Tournaisian – Visean) is characterised by the Firth Coal Formation. These two formations can act both as potential source rock (Firth Coal/coal-rich sequences) and reservoir (parts of Tayport and Firth Coal/sand-rich facies)

As a regional observation, gravity and magnetic data indicate that the basement deepens towards the north-eastern corner of the modelled area (Fig. 5b). In Quadrant 14, thick Middle Devonian sequences have been proven in wells (Marshall & Hewett 2003; Whitbread & Kearsey 2016) and are seismically interpreted as reaching over 700 meters thick in depocenters such as the Halibut Basin (see Top Orcadia map in Fig. 14). Moving to the east and basinwards of the Caithness Ridge and the West Fladen High, the major ENE-trending bounding faults offset the Devonian strata to depths of over 3 seconds TWTT. Patruno & Reid (2015, 2016) interpreted Devonian strata as present across Quadrant 14 and farther north towards Quadrants 7 – 9. The interpretation of Devonian strata in modern 3D volumes suggests that what has been considered as acoustic basement across some of the highs (such as the Halibut Horst), consists of tilted, deformed and truncated Devonian reflectors (Fig. 12). These deformed reflectors are penetrated by well 14/19-11, proving more than 700 m of Middle Devonian lacustrine sediments (Whitbread & Kearsey 2016). The top of the Devonian sequence is a characterised by a large hiatus between Devonian and Cretaceous strata.

4.7 Inner Moray Firth Basin

Situated in Quadrants 11-13, the Inner Moray Firth Basin is characterised by the presence of Devonian lacustrine source rocks present within confined basins between fault-bounded highs. The area has been subjected to major tectonic episodes during the Devono-Carboniferous, Permo-Triassic, Jurassic to Early Cretaceous and Late Cretaceous to Cenozoic (Andrews *et al.* 1990). Regional Cenozoic erosion played a major role in the area, with estimates of approximately 1 km of sediments being removed across the entire basin with more erosion to the west than to the east (Hillis *et al.* 1994).

The seismic profile in the background of Fig. 4 is a representative example of the horst-graben geometry of the area and its complex tectonic history. At the SSE-end of the profile, a thick Devonian sequence rests on top of the West Bank High (proven in well 12/29-2). The same sequence is interpreted on the hanging wall of the West Bank Fault in depths > 3s TWTT (approximately 4 km) in the Smith Bank Graben area (the top of the Middle Devonian is penetrated in well 12/28-1). On top of the Smith Bank High, Devonian strata are present but thinner (proven in well 12/23-1), suggesting that the area was probably already an elevated (intra-basinal?) high at this time. In the NNW end of the profile, the Wick sub-basin shows a very complex geometry and Palaeozoic strata reaching depths of 3s TWTT. The complex structures are related to the proximity of the basin to the major Great Glen Fault, its Palaeozoic strike-slip activity (Roberts *et al.* 1990) and the subsequent Mesozoic normal faulting of the adjacent Wick and Helmsdale faults (Underhill 1991). Seismic evidence also confirms the presence of contractional features as previously observed (Roberts *et al.* 1990; Underhill & Brodie 1993).

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 and references therein), interpretation of offshore seismic data and onshore field observations show that during the Mesozoic the development of the Inner Moray Firth Basin was the result of normal faulting in an extensional regime with a minimal strike-slip component (Underhill 1991; Thomson & Underhill 1993; Glennie & Underhill 1998). During the Mesozoic in the Inner Moray Firth Basin, the controlling fault was the Helmsdale Fault (situated west of the Great Glen Fault along the Scottish coast) while the Great Glen Fault played a minor strike-slip role (Andrews *et al.* 1990; Underhill 1991).

There are a significant number of publications on the Palaeozoic intervals present in the Orcadian study area. However the majority discuss the onshore stratigraphy, facies analysis and the depositional environments of the study area and the adjacent domains (e.g. Astin 1985, Duncan & Buxton 1995, Clarke & Parnell 1999, Marshall & Hewett 2003, Marshall *et al.* 2011).

Interpretation of the basement provided the first order structure of the basins in Quadrants 12-20. The Top Basement reflector has been defined as the metamorphosed Lower Devonian or older Lower Palaeozoic and Precambrian rocks or granite (e.g. wells 12/29-2, 11/30a-10). The near Top Basement pick can be located above a more transparent and featureless seismic package (i.e. acoustic basement) immediately beneath Devonian, Carboniferous or younger successions. It may also be represented by an angular unconformity.

The Top Basement mapping depicts the remnants of the pre-Permian basin geometry (Fig. 13), however this geometry has been overprinted by Mesozoic and Cenozoic events and the present-day configuration is the combination of reactivated, inverted and eroded features across the Inner Moray Firth Basin.

The mapping has been aided by the use of gravity and magnetic modelling. Fig. 5b shows the stripped gravity grid. It is important to highlight that there are multiple sources for a stripped gravity low over the Inner Moray Firth Basin. In addition to Devonian sedimentary rocks, contributions are likely from low-density Dalradian (Grampian Group) sediments and from granites, possibly including the source of the Lossiemouth magnetic anomaly (Dimitropoulis and Donato 1981; Pilkington et al. 1995). Stripped gravity lows are evident over the Smith Bank Graben and the eastern end of the Caithness Graben, and the Caithness High is characterised by a stripped gravity high and shallow magnetic sources (Kimbell & Williamson 2016)..

The most extensive remnant of the Devonian depocentre is located across the south of Quadrant 12 in the Smith Bank Graben area (Fig. 13 & Fig. 14).

South of the Caithness Ridge (Quadrant 13; Fig. 6 & Fig. 13), a buried depocentre termed the Caithness Graben is infilled with Devonian, Permian and Early Mesozoic sediments that underpins the Halibut Platform (Fig. 15). The broadly ENE-WSW trending depocentre is along strike from the Wick Sub-basin (Fig. 13).

The Top Basement mapping , and the subsequent Devonian thickness map in Fig. 13b shows that apart from the dominant ENE-WSW trend of the basin, there are other less obvious trends. Interpreting in a more regional tectonic model context, the en-echelon configuration of the Central Ridge – West Bank High and Peterhead Ridge on the Top Basement and thickness maps (Fig. 13a & Fig. 13b) indicates that N(NW)-S(SE) and NNE-SSW trending discontinuities could be anticipated in the Moray Firth area, but they are less obvious due to Mesozoic structural overprinting. These structures may relate to Late Devonian- early Carboniferous intracontinental extensional stress. Such structures are similar to the faulting pattern associated to onshore Devonian outliers in the Moray – Buchan area (e.g. Turriff outlier; Stephenson *et al.* 1995, Trewin 2002) and also described in the Helmsdale region (Underhill & Brodie 1993; Leslie *et al.* 2016).

Apart from the Top Basement pick, the Top Orcadia Formation (Middle Devonian) is an indicative event of the Devonian basin configuration across the majority of the Orcadian study area. The interval is regionally extensive, it reaches thicknesses of more than 750 m in Quadrant 12, and at least 700 m in well 14/19-11. Present-day depths are in the order of more than 4 - 4.5 km deep in the Smith Bank Graben (Fig. 14). Onshore, the formation is equally present as the equivalent Caithness Flagstone and Stromness Flagstone in Caithness and Orkney, with thicknesses of at least several hundreds of meters (900 m suggested by Astin 1990) .

Finally, as part of the Inner Moray Firth Basin, the Caithness Graben remains a completely unexplored area, containing deeply buried pre-Permian strata underneath a thick Mesozoic pile. The presence (or absence) of the Devonian Struie Formation and Orcadia Formation source rocks will be primarily controlled by the extent of the intra-basinal Smith Bank High and its role during Devonian times. Poor seismic imaging related to significant depths has reduced interpretation confidence but their presence in the Caithness Graben has been indirectly proven in wells on highs in the proximity, such as 12/18-1, 12/13-1, 13/19-1 and 13/22-1.

4.8 East Orkney Basin

Bounded to the north by the West Fladen High and the south by the Caithness Ridge, the East Orkney Basin is an E-W to WNW-ESE fault-controlled half-graben located in Quadrants 6 and 13 (e.g. Andrews *et al.* 1990, Marshall *et al.* 1996 ; Fig. 6).

No wells have been drilled in this basin. However, a conspicuous stripped gravity low over the area (Fig. 5b), abundant outcrops on the Orkney Islands and well penetrations further northeast (8/04-1, 9/07-1 and 9/16-3), together with characteristic well-stratified reflectors correlated to probable Early to Mid-Devonian aged sedimentary sequences proven farther south (inset in Fig. 15) strengthen the interpretation that thick fluvio-lacustrine sequences of the Eday Marl, Eday Flagstone and Orcadia formations are also present in the East Orkney Basin. Seismic data (Fig. 15) suggest that the Palaeozoic strata in the basin are deeply buried, thus providing a potentially mature source rock in the area. Richardson *et al.* (2005) have conducted a seep survey in the area near the basin and mapped oil seeps on the seabed. This observation, combined with the suggestion that the Jurassic source rock is immature to early mature in the East Orkney Basin area (Kubala *et al.* 2003) leads to the hypothesis that the oil seeps observed come from a different source rock. The lacustrine Orcadia Formation would be the best candidate for such a hypothesis, and even though no wells have proven it inside the East Orkney Basin, there are wells around the area and outcrops in proximity which prove its presence (Marshall & Hewett 2003; Whitbread & Kearsey 2016).

5 Discussion

5.1 Regional context and basin geometries

The geometrical variability of the described deep basins is largely controlled by the inherited Caledonian structural grain (Iapetan versus Tornquist-related), which affects the accommodation space and the basin evolution. The regional tectonic framework is a broadly NW-SE trending system south of the general Iapetus suture zone (Mid North Sea High area) and a broadly (E)NE - (W)SW trending system farther north due to Caledonian inheritance (Fig. 6).

Regional tectonic models (Coward 1993; Coward *et al.* 2003; Fossen 2010) suggest that during Late Devonian to early Carboniferous times the lateral expulsion of Baltica relative to Laurentia and Avalonia would result in a NE-SW oriented stretch and regional transport direction across the CNS study area (e.g. Mid North Sea High) and strike slip faulting along E(NE) – W(SW) trends (cf. De Paola *et al.* 2005). In the Orcadian study area an E(SE)-W(NW) directed stretching would have been anticipated in the Inner Moray Firth Basin along the Great Glen – Helmsdale Faults. By late Carboniferous times, although plate-scale motion of the Baltica microplate would have been reversed from a north-eastward to a westward or south-westward motion, the overall regional transport directions across large-scale fault structures would have remained similar to that in Late Devonian-early Carboniferous times, i.e. broadly aligned on a NE-SW axis (cf. De Paola *et al.* 2005). To the south of the Central North Sea study area, inversion related to the Variscan orogeny would have been recorded in the early Carboniferous and younger strata. The observations from the major basins of the study, such as the North Dogger Basin, the southern margin of the Mid North Sea High, the Silverpit Basin and the Inner Moray Firth Basin are in agreement with these regional models superimposed upon the inherited structural framework. Observing the complexity of the basin geometries mapped across the study area, one can conclude that in order to better constrain the exact timing and direction of the faulting it is essential to work in a local basin-by-basin basis, whilst keeping in mind the regional overview.

For these mapped Palaeozoic basins, the source rock paleogeography, burial and uplift history, erosion and potential fault breach are all controlling factors of a functioning Palaeozoic petroleum system. The combination of the proximity to the main kitchen areas, with efficient migration routes and non-breached faults could potentially lead to prospects and successful plays.

Concerning the Mid North Sea High area, basin mapping suggests that the southern margin consists of a series of basins and blocks, and not a simple regional high as it is for the Permian and post-Permian succession.

The granitic intrusions are interpreted to have played a crucial role in strain-partitioning, superimposed upon the Devono-Carboniferous structural trends. The Dogger Granite is a representative example. NE and SW of the granite margins, the fault trends are NW-SE and there is a Devono-Carboniferous sequence onlapping on the margins of the high. However north of the Granite, the E-W trends are mapped and in places the faults are interpreted to follow the edge of igneous intrusive bodies (e.g. Western Arcuate Fault).

Onshore, similar observations have led to the hypothesis of time-equivalent, spatially differentiated fault trends, such as the Northumberland Trough-Cheviot Pluton (De Paola *et al.* 2005).

Thickness maps derived from the depth-converted surfaces (see Arsenikos *et al.* 2015) show that the lower-mid Carboniferous succession reaches thicknesses up to 2 km in the North Dogger Basin and 1.5 km in the offshore part of the Northumberland Trough (Quadrant 34) and Quadrant 42. These values are comparable to those in the literature for onshore Carboniferous basins (Fraser & Gawthorpe 1990, Fraser & Gawthorpe 2003, Waters & Davies 2006; thicknesses of the Carboniferous range from 1.5-3 km).

5.2 Implications for source rock extents

Seismic and well interpretation has constrained four major source rock intervals in the CNS and Orcadian study areas: the coal-bearing Scremerston Formation (Visean) in the CNS study area, the lacustrine source rocks of Struie (Lower Devonian) and Orcadia (Middle Devonian) formations, as well as the coal-bearing Firth Coal Formation (Visean-Namurian) in the Orcadian study area.

The Scremerston Formation (CNS study area) has been interpreted as present and mapped more extensively than previously recognised in reports (e.g. Hay *et al.* 2005 ; Fig. 16). The

Formation has been penetrated both south of the Mid North Sea High (e.g. well 38/18-1) and north in the Forth Approaches Basin (e.g. 26/07- 1) indicating its regional deposition. Based on its characteristic reflectivity (high frequency/high amplitude, well-stratified reflectors) it was interpreted in the North Dogger Basin (at depths in the order of 3-3.5 km) and in the area adjacent to the southern margin of the Dogger Granite High and the Silverpit Basin (2.5-3 km depth). It is a good to excellent quality source rock and basin modelling indicates that in southern Quadrants 41 - 43 it could be a viable source rock (Vincent 2015).

Farther north, in the Orcadian study area, the Firth Coal Formation has been proven in more than 15 wells across Quadrants 14-15 and more than 10 in Quadrants 20-21 (Kearsey *et al.* 2015, Whitbread & Kearsey 2016). The potential coal-, mudstone- and oil-shale-bearing source rocks are commonly intercalated with potential reservoir sand bodies. These wells provided a good constraint and led to a confident interpretation of the Firth Coal Formation in the structurally complex depocentres such as the westernmost end of the Witch Ground Graben, adjacent to the Halibut Horst (Fig. 12 & Fig. 17). In this area the formation has been interpreted as reaching depths in the order of 3.5-4 km.

The Orcadia Formation has been extensively mapped on seismic data for the first time in the Inner Moray Firth Basin and the Outer Moray Firth (Fig. 14), and it has also been interpreted in wells as far north as Quadrants 7, 8 and 9 (Patruno & Reid 2015, 2016). The interval is interpreted in the major Palaeozoic depocentres in Quadrants 12 – 14, such as the Smith Bank Graben, the Caithness Graben, the Halibut Basin and Witch Ground Graben. The formation is also proven in wells on some highs such as the Halibut Horst (>700 m in well 14/19-11).

Seismic interpretation suggests that the distribution of the Struie Formation lacustrine source rocks is probably restricted in Quadrant 12 south of the Smith Bank intrabasinal high.

6 Conclusions

A series of Devonian and Carboniferous basins have been mapped from the margins of the East Shetland Platform, southwards to the northern margins of the Southern North Sea. The interpretation was based on 85000 line-km of seismic data, tied to more than 180 wells and a regional gravity/magnetic study. An inherited Caledonian, Iapetan and Tornquist structural fabric emerges. The partitioned stress is related to transtensional and transpressional tectonic regimes, resulting in a variety of Devono-Carboniferous age, NW-SE and NE-SW oriented basins.

The granite-cored blocks have been long-lived highs, playing a significant role on the distribution of the basins and the extent of the sedimentary rocks they contain.

It is notable that, although some parts of the Mid North Sea High are underpinned by elevated domains and platforms, there are a series of potentially prospective Devono-Carboniferous basins over and around the 'high'. The deepest of these basins is the NW-trending North Dogger Basin across Quadrant 38.

Using the best released and unreleased seismic data, source rocks intervals such as the Scremerston, Firth Coal and Orcadia formations have been extensively mapped to depths of more than 4 km (Scremerston Formation).

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9 Figure captions

Fig. 1a) The 21CXRM Palaeozoic Project study areas. The Central North Sea study area includes Quadrants 25 to 44 and the Orcadian Basin study area Quadrants 7 to 22. Thin grey lines represent the 2D seismic profiles interpreted for the study. **1b)** Key wells discussed in this paper and wells penetrating pre-Permian strata (see also Kearsey et al. (2015) and Whitbread & Kearsey (2016)). Orange polygons are the 3D seismic volumes partially interpreted for the study.

Fig. 2 Simplified stratigraphic chart of the Central North Sea and Orcadian study areas. The ages and stratigraphic relationships are based on Kearsey et al. (2015) and Whitbread &

Kearsey (2016). See also Kearsey et al. (this volume). The thick black lines indicate the seismic events interpreted during the study (not all the events are shown in this paper). For the full grid dataset in TWTT and depth see Arsenikos et al. (2015) and Arsenikos et al. (2016)

Fig. 3 Correlation between the Zechstein layer thickness (x-axis in seconds) and the interval velocity in the wells penetrating it (y-axis metres/second). The model is based on the Velmod-1 and Velmod-2 projects from Van Dalfsen et al. (2006)

Fig. 4 Seismic profile (in the background) and velocity model (coloured, in foreground) across the Inner Moray Firth Basin illustrating the very good correlation between the structures and the velocity model applied during depth conversion.

Fig. 5. a) Apparent thickness between the base of the Zechstein and the gravity inversion surface across the Central North Sea study area (after Kimbell & Williamson 2015); **b)** Residual stripped (to top Zechstein) gravity anomalies across the Orcadian study area (after Kimbell & Williamson 2016). For details and comments on the various basins see text and the reports cited above

Fig. 6 Regional structural synthesis resulting from the mapping of the structures across the study areas. Illustrated here are the major basin bounding faults. The Mid North Sea High area is significantly smaller than in previously published maps and a series of basins and highs surround it to the north and to the south-southeast (e.g. Western Arcuate Fault Basin, Q29 Basin).

Fig. 7 Depth to the Middle Devonian Top Kyle Group (5 km resolution) and major faults in the North Dogger Basin and the Silverpit Basin. The most prominent feature is the deep Middle Devonian basin in Quadrant 38 (North Dogger Basin) as well as its extension further NE (the Q29 basin). The green line shows the approximate location of the seismic profile shown in Fig. 8. The Western Arcuate Fault System is also illustrated. A discontinuity with a similar trend exists in depth in the Q29 Basin but it is unclear whether it is the extension of the Western Arcuate Fault System or a separate feature.

Fig. 8 Seismic section across the North Dogger Basin. The basin margins are the Dogger Granite High to the SW and the Auk-Flora Ridge to the NE. At the north-eastern extremity of Quadrant 37, the basin is partitioned in two sub-basins separated by the North Dogger Horst, on the top of which well 37/10-1 penetrated Upper Devonian strata (Tayport and Buchan formations). The Top Kyle Group reflector is strong and easily recognisable on the highs and becomes gradually less evident at deeper levels. This could be related both to imaging issues and a change of facies (becoming more distal basinwards).

Fig. 9 Depth to lower Carboniferous (Tournaisian) Cementstone Formation (5 km resolution). The formation has been regionally mapped in the Central North Sea study area and is present in the offshore extension of the Northumberland Trough (Quadrants 34-35) and the Forth Approaches Basin (Quadrants 25-26). In the offshore Northumberland area, there are two major fault trends mapped: NE and NW, in agreement with De Paola et al. (2005) onshore.

Fig. 10 Composite interpreted seismic section running SW-NE and SE-NW across the offshore Northumberland Trough. The Top Cementstone Formation (Tournaisian) is illustrated in green and the Top Scremerston (Visean) in dotted black. The faults (red lines) were active (or reactivated?) until Upper Permian times, creating the Carboniferous Northumberland Trough.

Fig. 11 Interpreted seismic section across the Forth Approaches Basin. The highly asymmetrical, half-graben geometry is controlled by the major fault to the SE The Top Cementstone pick has been mapped across the area, whereas the Top Scremerston event, although present in well 26/07-1, proved challenging to map in detail. Both formations dip to greater depths to SE and gradually shallow up to NW.

Fig. 12 Interpreted 3D seismic line across the Halibut Horst and the NW segment of the Witch Ground Graben. The Top Firth Coal Formation is penetrated on the highs by wells 14/19-1 and 14/19-2 and is interpreted as present in the hanging walls at depth. The Devonian strata are also present (proven in well 14/19-11) and they are interpreted as deformed and truncated on top of the Halibut Horst.

Fig. 13 a) Depth to Top Basement pick across the Orcadian study area (5 km resolution). The regional trend is the well-known (E)NE – (W)SW direction in the Moray Firth area, resulting from Mesozoic faulting. **b)** Thickness map between the Base of the Zechstein and the Top Basement (Base Devonian) pick. The most prominent depocentre is in Quadrant 12. It is possible in places to distinguish NNE-SSW and NNW-SSE trends which have been heavily overprinted by the NE-SW Permo-Carboniferous and reactivated Mesozoic trends.

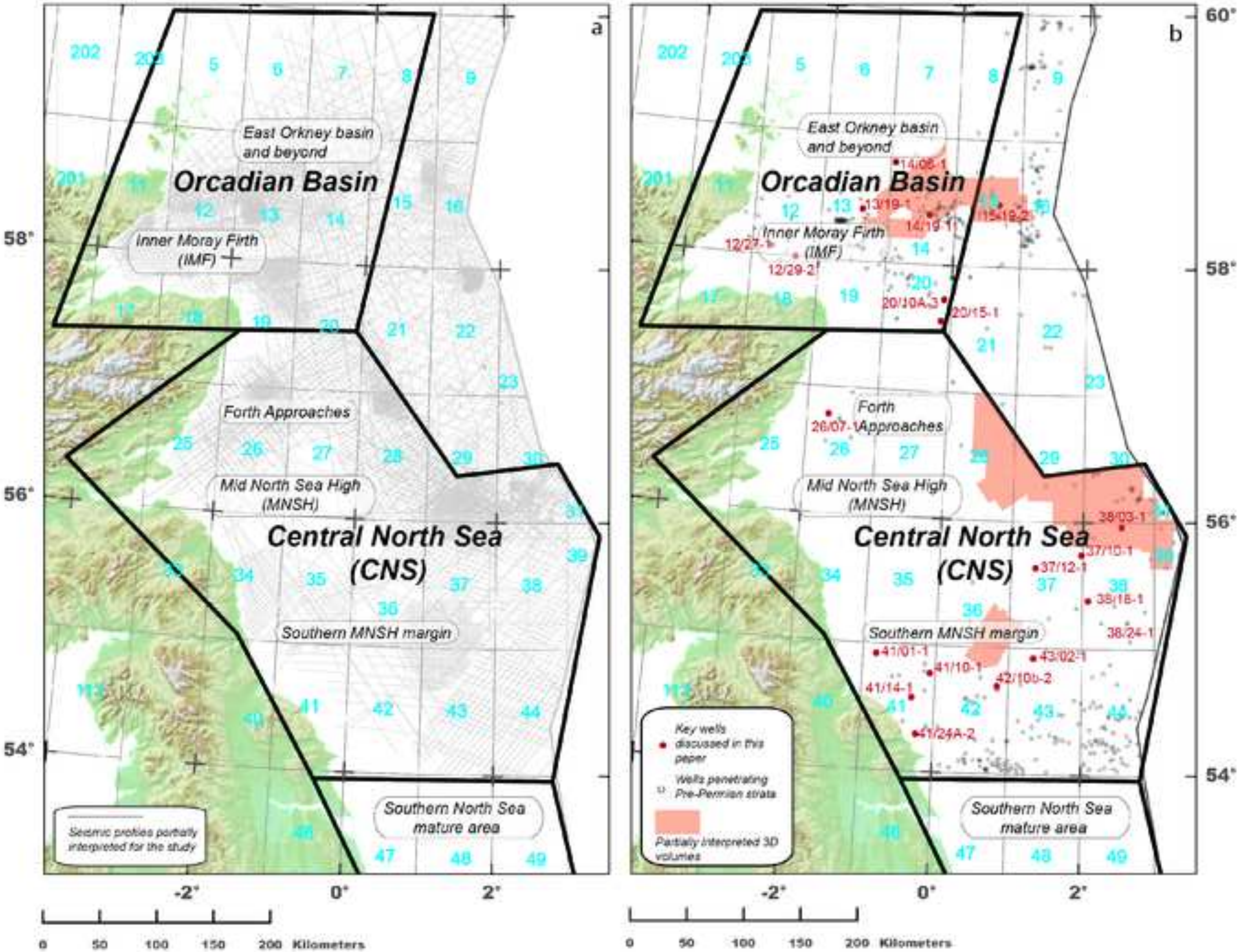
Fig. 14 Depth to the Mid-Devonian Top Orcadia Formation (5 km resolution) showing the regional extent of the current interpretation. The formation is probably also present in the East Orkney Basin (see inset in Fig. 15).

Fig. 15 Interpreted seismic section across the East Orkney Basin (NNE) and the Caithness Graben (SSW). The two depocentres are characterised by deeply buried Devonian strata. The inset illustrates a detail from the profile compared to a correlation polygon from the Wick Sub-basin area, a few km southwest of the Caithness Graben. It illustrates the almost identical seismic character between a seismic sample from the East Orkney Basin (far right square) and one from the Wick Sub-basin (left and middle rectangles). The stars indicate comparable stratified sequences, suggesting that buried Devonian sediments in the East Orkney Basin are similar to the ones in the Wick Sub-basin (i.e. Lower?/ Middle Devonian lacustrine sediments proven in wells; Arsenikos *et al.* 2016, Whitbread & Kearsey 2016).

Fig. 16 Depth to Top Scremerston Formation in meters (5 km resolution). The formation is interpreted across the North Dogger Basin, the Q29 Basin, on the southern part of the Mid North Sea High, in the Silverpit Basin and the Offshore Northumberland Trough. Wells indicate the depth in meters below mean sea level as it has been interpreted from (Kearsey *et al.* 2015)

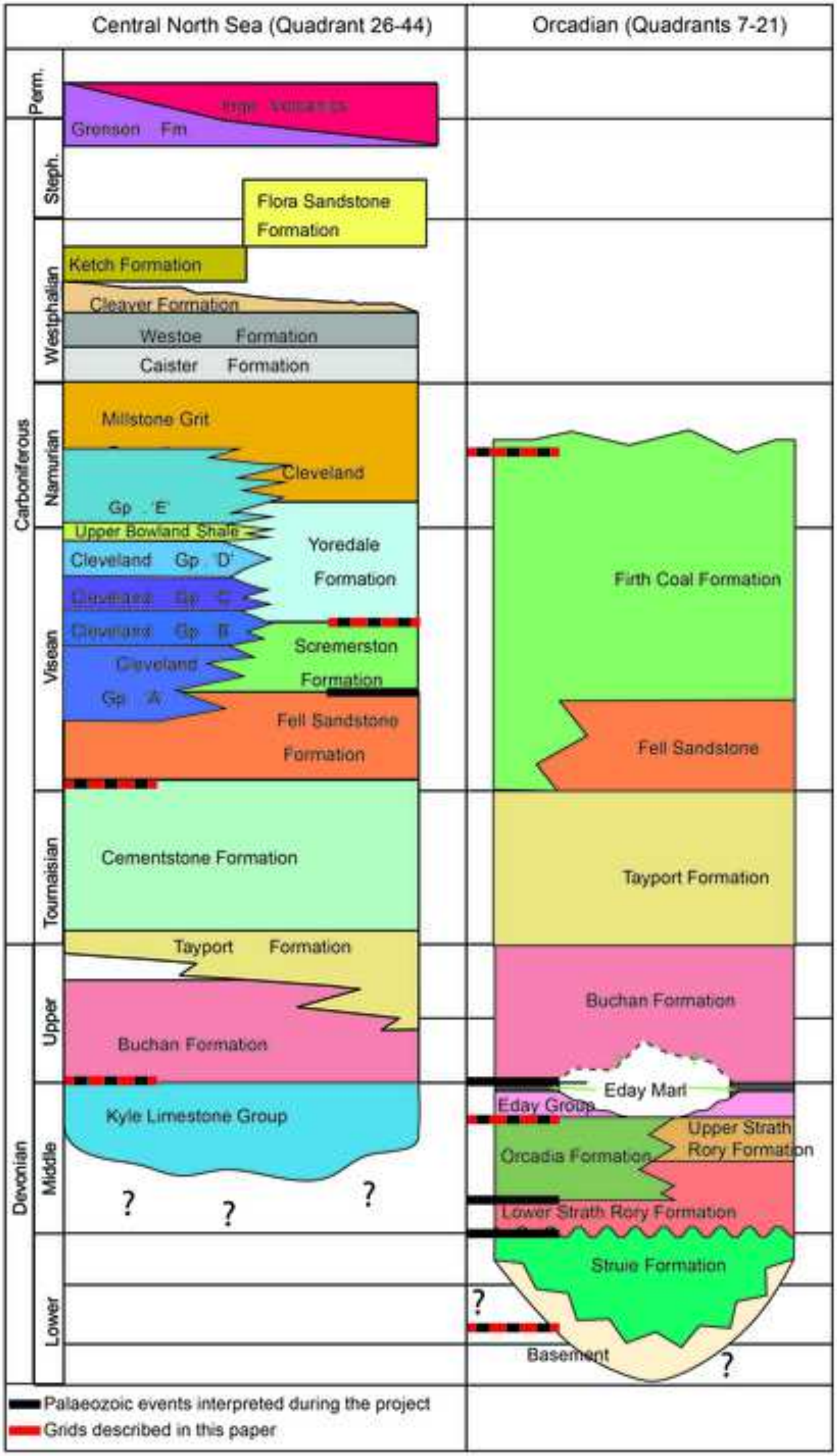
Fig. 17 Depth to Top Firth Coal Formation in meters (5 km resolution). The formation has been proven by wells (red dots) on elevated domains and has been interpreted in deeper grabens (e.g. Witch Ground Graben; see Fig. 12) and in a significant part of the Dutch Bank Basin. Depth-converted time values suggest that the Firth Coal Formation is present at depths of 3.5-4 km.

Figure 1a-1b



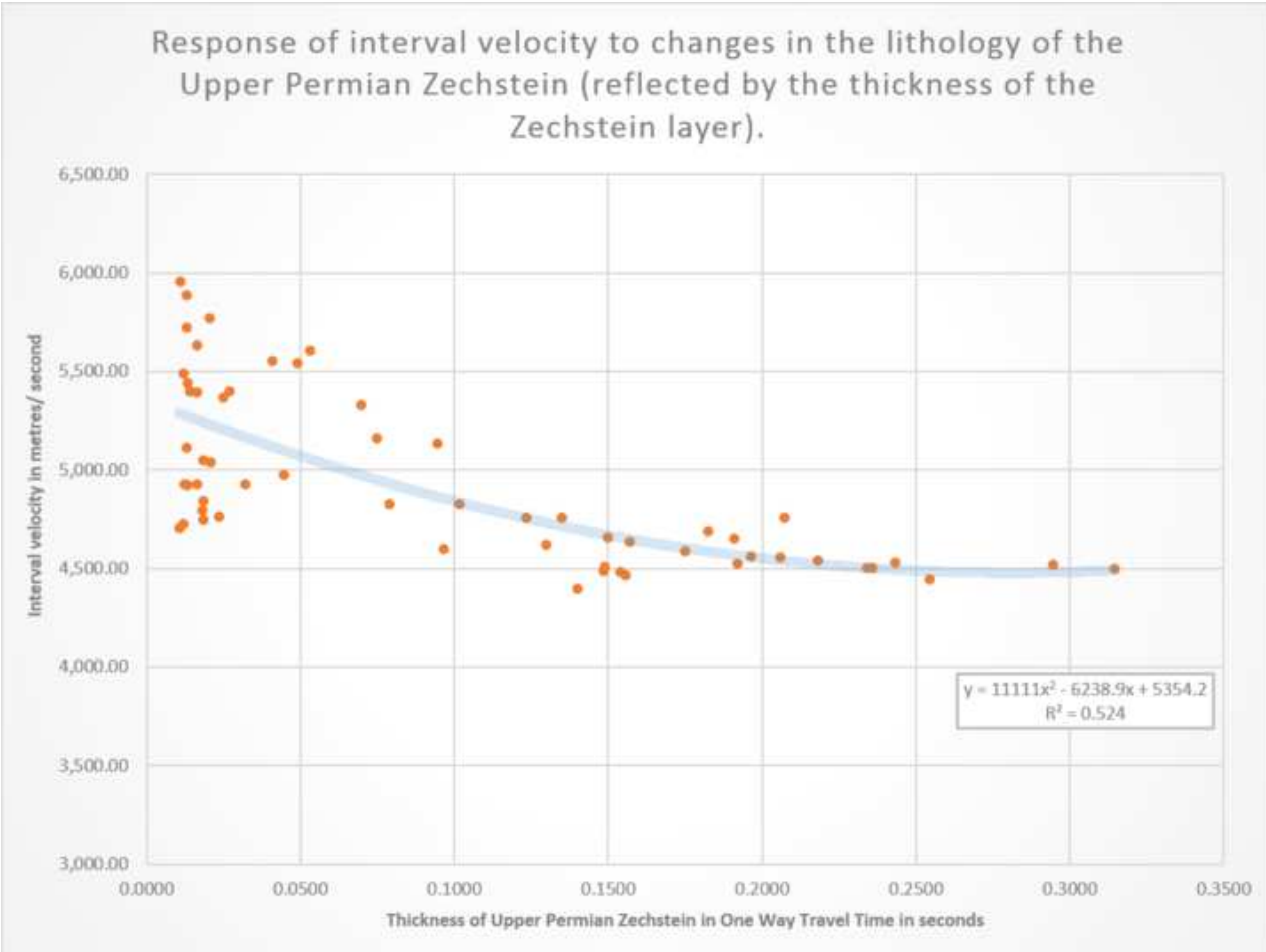
a
b
East Orkney basin and beyond
Orcadian Basin
Inner Moray Firth (IMF)
Forth Approaches
Mid North Sea High (MNSH)
Central North Sea (CNS)
Southern MNSH margin
Southern North Sea mature area
Seismic profiles partially interpreted for the study
Key wells discussed in this paper
Wells penetrating Pre-Permian strata
Partially interpreted 3D volumes
14/06-1
13/19-1
14/19-1
15/19-2
12/27-1
12/29-2
20/10A-3
20/15-1
26/07-1
38/03-1
37/10-1
37/12-1
38/16-1
38/24-1
41/01-1
41/10-1
42/10b-2
43/02-1
41/14-1
41/24A-2
60°
58°
56°
54°
-2°
0°
2°
0
50
100
150
200
Kilometers

Figure 2



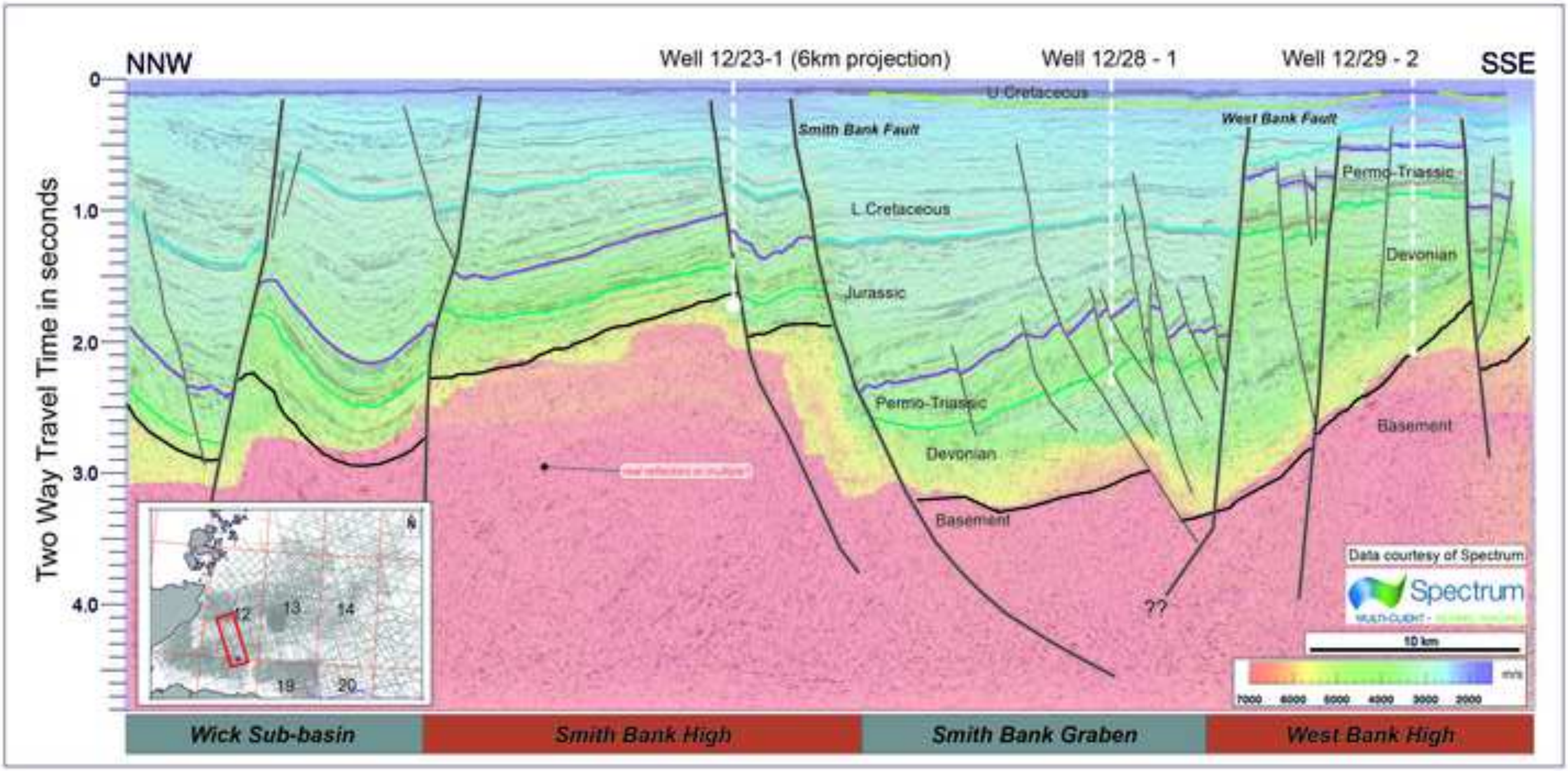
Central North Sea (Quadrant 26-44)
Orcadian (Quadrants 7-21)
Perm.
Carboniferous
Steph.
Westphalian
Namurian
Visean
Tournaisian
Devonian
Upper
Middle
Lower
Grenson Fm
Flora Sandstone Formation
Ketch Formation
Cleaver Formation
Westoe Formation
Caister Formation
Millstone Grit
Cleveland
Gp 'E'
Upper Bowland Shale
Cleveland Gp 'D'
Yoredale Formation
Scremerston Formation
Cleveland
Gp 'A'
Fell Sandstone Formation
Cementstone Formation
Tayport Formation
Buchan Formation
Kyle Limestone Group
?
?
?
Firth Coal Formation
Fell Sandstone
Tayport Formation
Buchan Formation
Eday Marl
Eday Group
Upper Strath Rory Formation
Orcadia Formation
Lower Strath Rory Formation
Struie Formation
?
Basement
?
Palaeozoic events interpreted during the project
Grids described in this paper

Figure 3



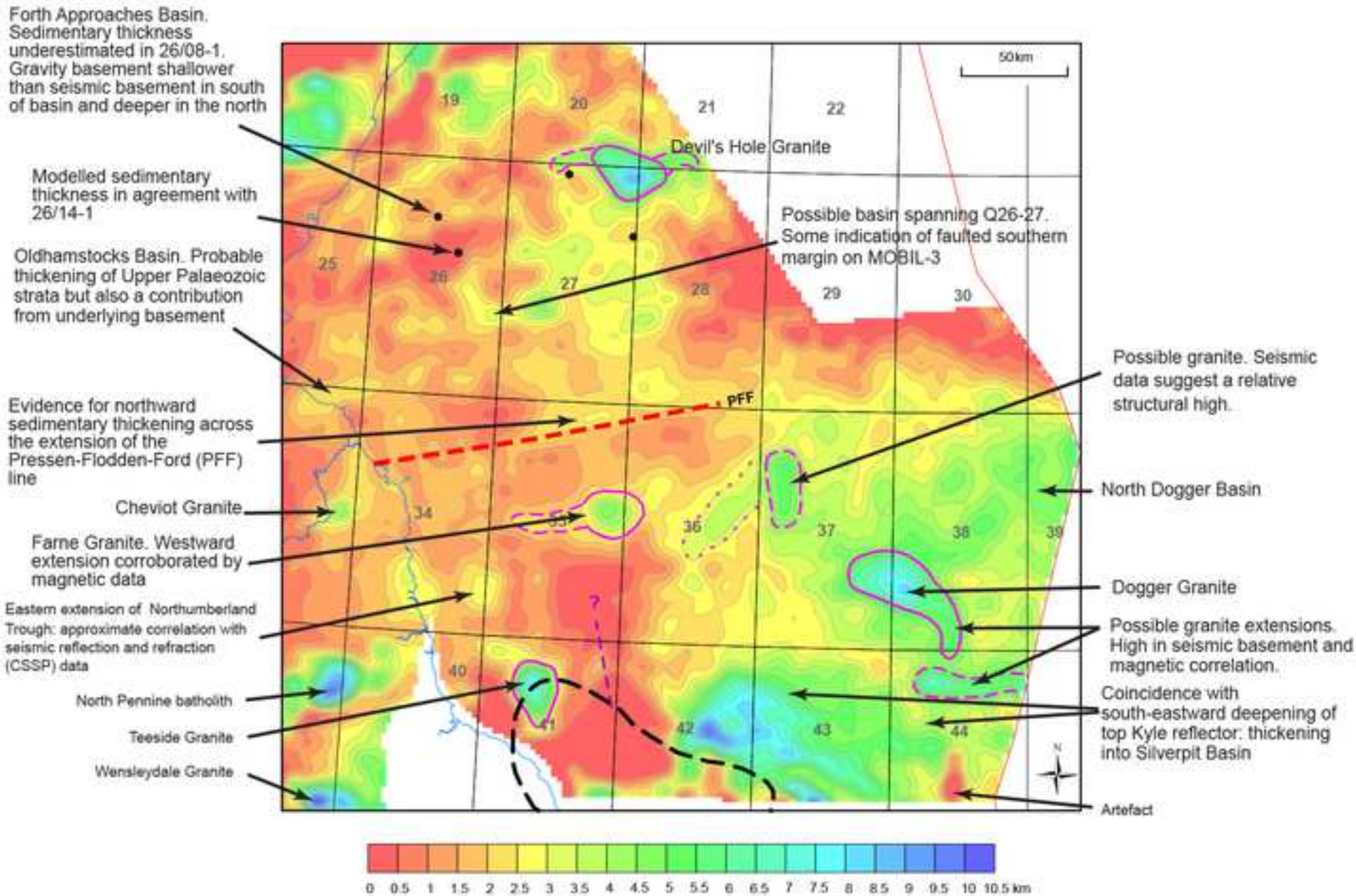
Response of interval velocity to changes in the lithology of the Upper Permian Zechstein (reflected by the thickness of the Zechstein layer).
6,500.00
6,000.00
5,500.00
5,000.00
4,500.00
4,000.00
3,500.00
3,000.00
Interval velocity in metres/ second
0.0000
0.0500
0.1000
0.1500
0.2000
0.2500
0.3000
0.3500
Thickness of Upper Permian Zechstein in One Way Travel Time in seconds
y = 11111x² - 6238.9x + 5354.2
R² = 0.524

Figure 4



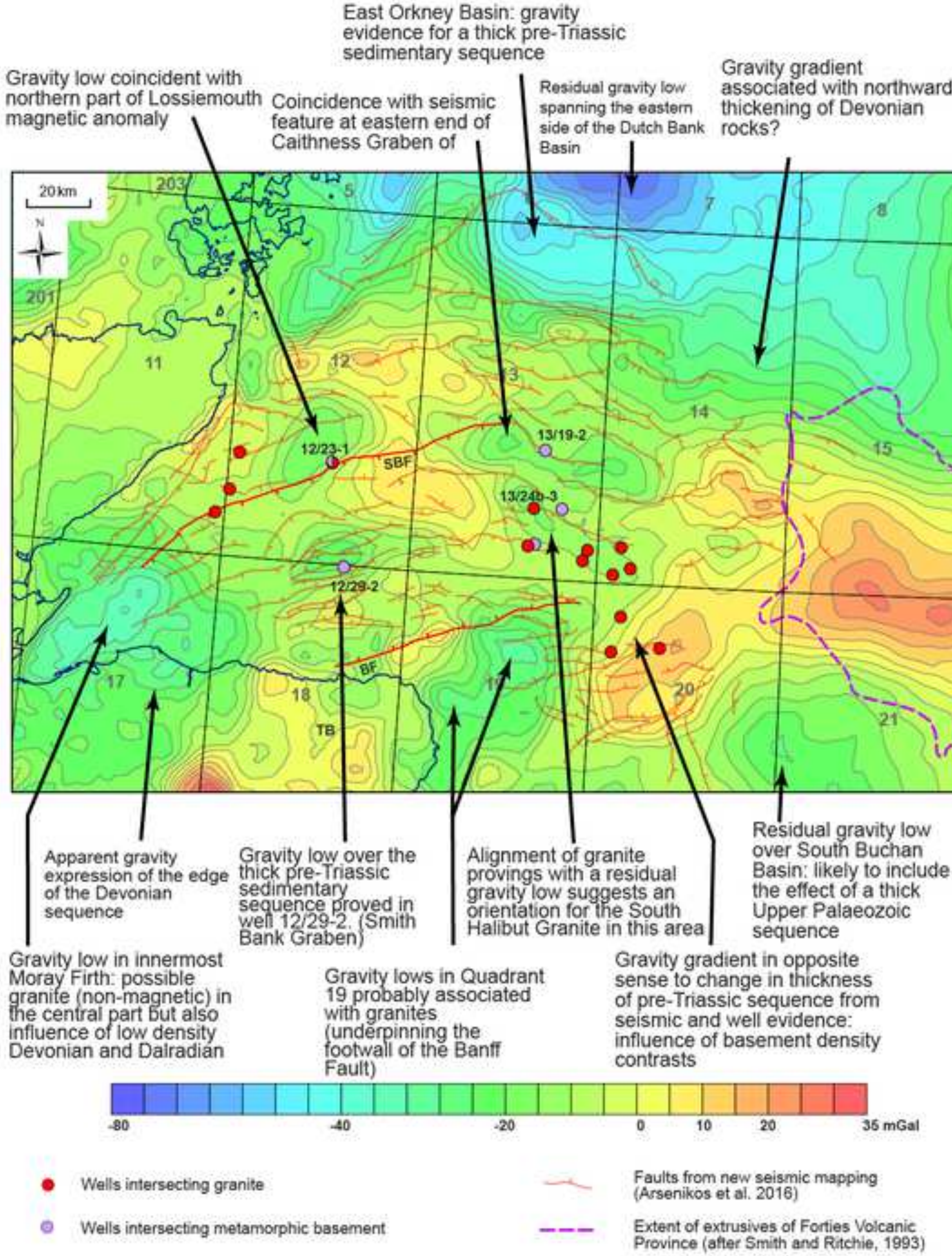
NNW
Well 12/23-1 (6km projection)
Well 12/28 - 1
Well 12/29 - 2
SSE
Two Way Travel Time in seconds
0
1.0
2.0
3.0
4.0
U Cretaceous
Smith Bank Fault
West Bank Fault
Permo-Triassic
L Cretaceous
Devonian
Jurassic
Permo-Triassic
Devonian
Basement
Basement
??
Data courtesy of Spectrum
Spectrum
10 km
m/s
7000
6000
5000
4000
3000
2000
12
13
14
19
20
Wick Sub-basin
Smith Bank High
Smith Bank Graben
West Bank High

Figure 5a



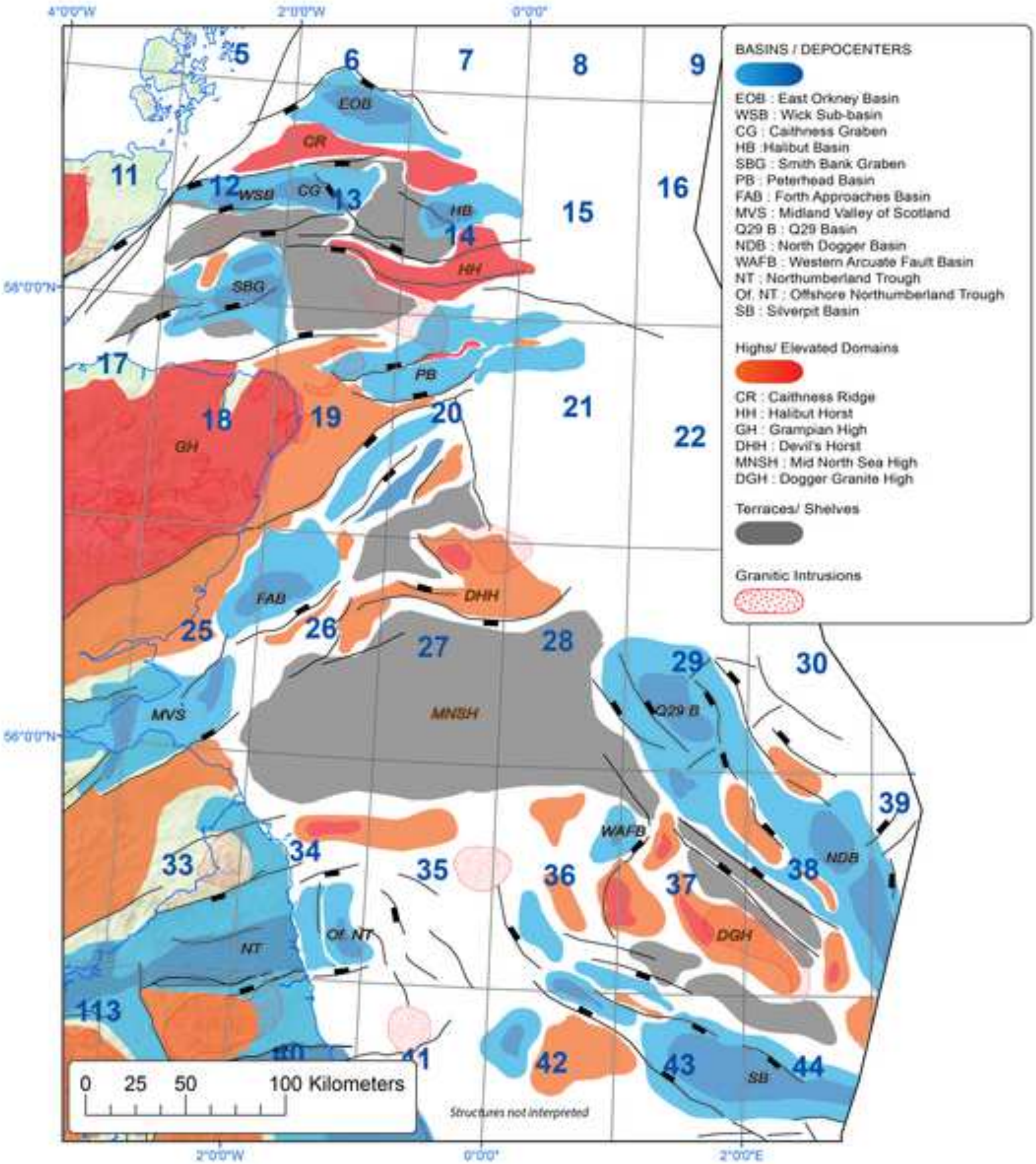
Forth Approaches Basin. Sedimentary thickness underestimated in 26/08-1. Gravity basement shallower than seismic basement in south of basin and deeper in the north
Modelled sedimentary thickness in agreement with 26/14-1
Oldhamstocks Basin. Probable thickening of Upper Palaeozoic strata but also a contribution from underlying basement
Evidence for northward sedimentary thickening across the extension of the Pressen-Flodden-Ford (PFF) line
Cheviot Granite
Farne Granite. Westward extension corroborated by magnetic data
Eastern extension of Northumberland Trough: approximate correlation with seismic reflection and refraction (CSSP) data
North Pennine batholith
Teeside Granite
Wensleydale Granite
Devil's Hole Granite
Possible basin spanning Q26-27. Some indication of faulted southern margin on MOBIL-3
PFF
Possible granite. Seismic data suggest a relative structural high.
North Dogger Basin
Dogger Granite
Possible granite extensions. High in seismic basement and magnetic correlation.
Coincidence with south-eastward deepening of top Kyle reflector: thickening into Silverpit Basin
Artefact
50 km
19
20
21
22
25
26
27
28
29
30
34
35
36
37
38
39
40
41
42
43
44
?
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10 10.5 km

Figure 5b



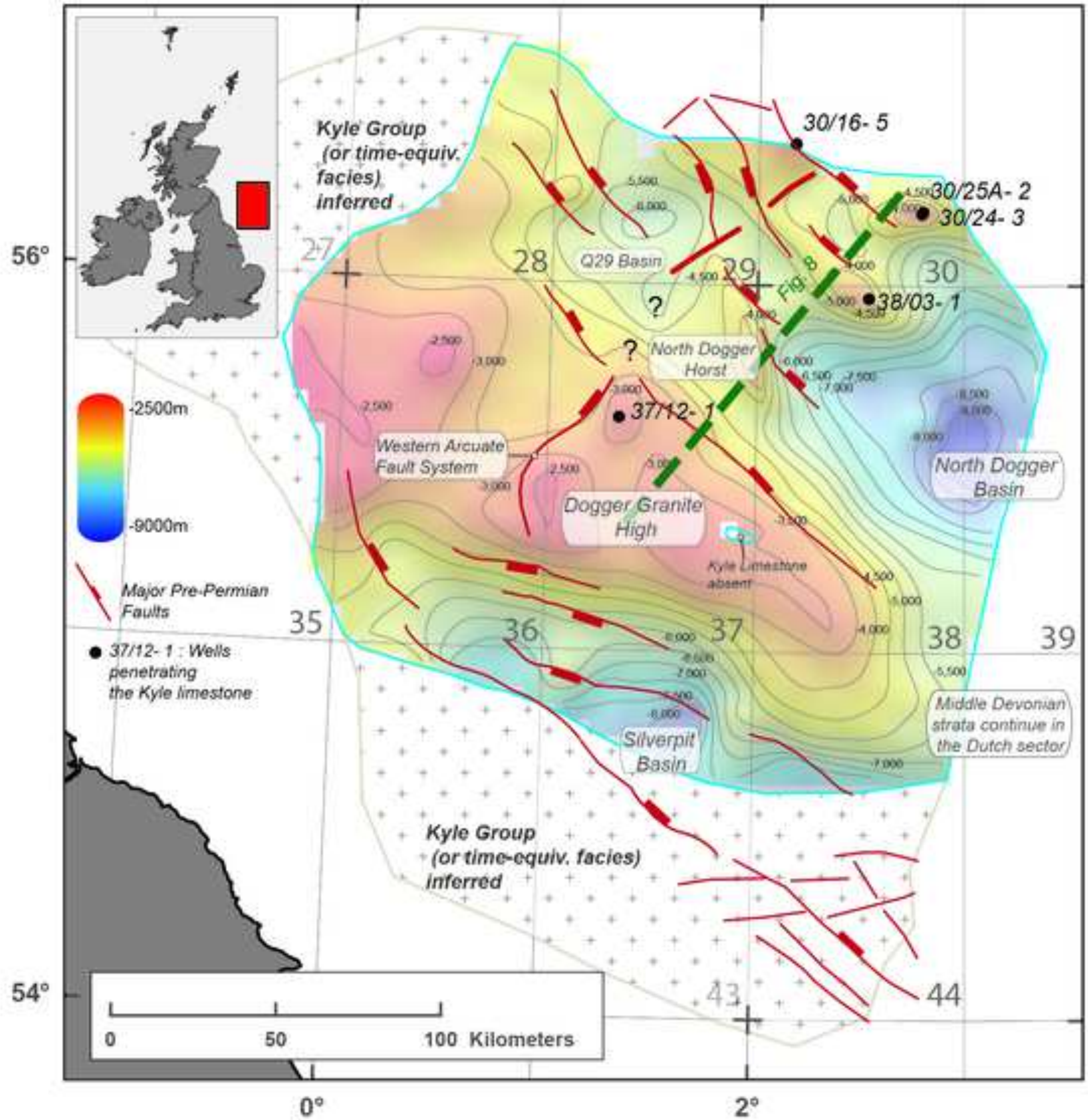
East Orkney Basin: gravity evidence for a thick pre-Triassic sedimentary sequence
Gravity low coincident with northern part of Lossiemouth magnetic anomaly
Coincidence with seismic feature at eastern end of Caithness Graben of
Residual gravity low spanning the eastern side of the Dutch Bank Basin
Gravity gradient associated with northward thickening of Devonian rocks?
20 km
N
203
5
7
8
201
11
12
13
14
15
12/23-1
SBF
13/19-2
13/24b-3
12/29-2
BF
17
18
19
20
21
TB
Apparent gravity expression of the edge of the Devonian sequence
Gravity low over the thick pre-Triassic sedimentary sequence proved in well 12/29-2. (Smith Bank Graben)
Alignment of granite provings with a residual gravity low suggests an orientation for the South Halibut Granite in this area
Residual gravity low over South Buchan Basin: likely to include the effect of a thick Upper Palaeozoic sequence
Gravity low in innermost Moray Firth: possible granite (non-magnetic) in the central part but also influence of low density Devonian and Dalradian
Gravity lows in Quadrant 19 probably associated with granites (underpinning the footwall of the Banff Fault)
Gravity gradient in opposite sense to change in thickness of pre-Triassic sequence from seismic and well evidence: influence of basement density contrasts
-80
-40
-20
0
10
20
35 mGal
Wells intersecting granite
Wells intersecting metamorphic basement
Faults from new seismic mapping (Arsenikos et al. 2016)
Extent of extrusives of Forties Volcanic Province (after Smith and Ritchie, 1993)

Figure 6



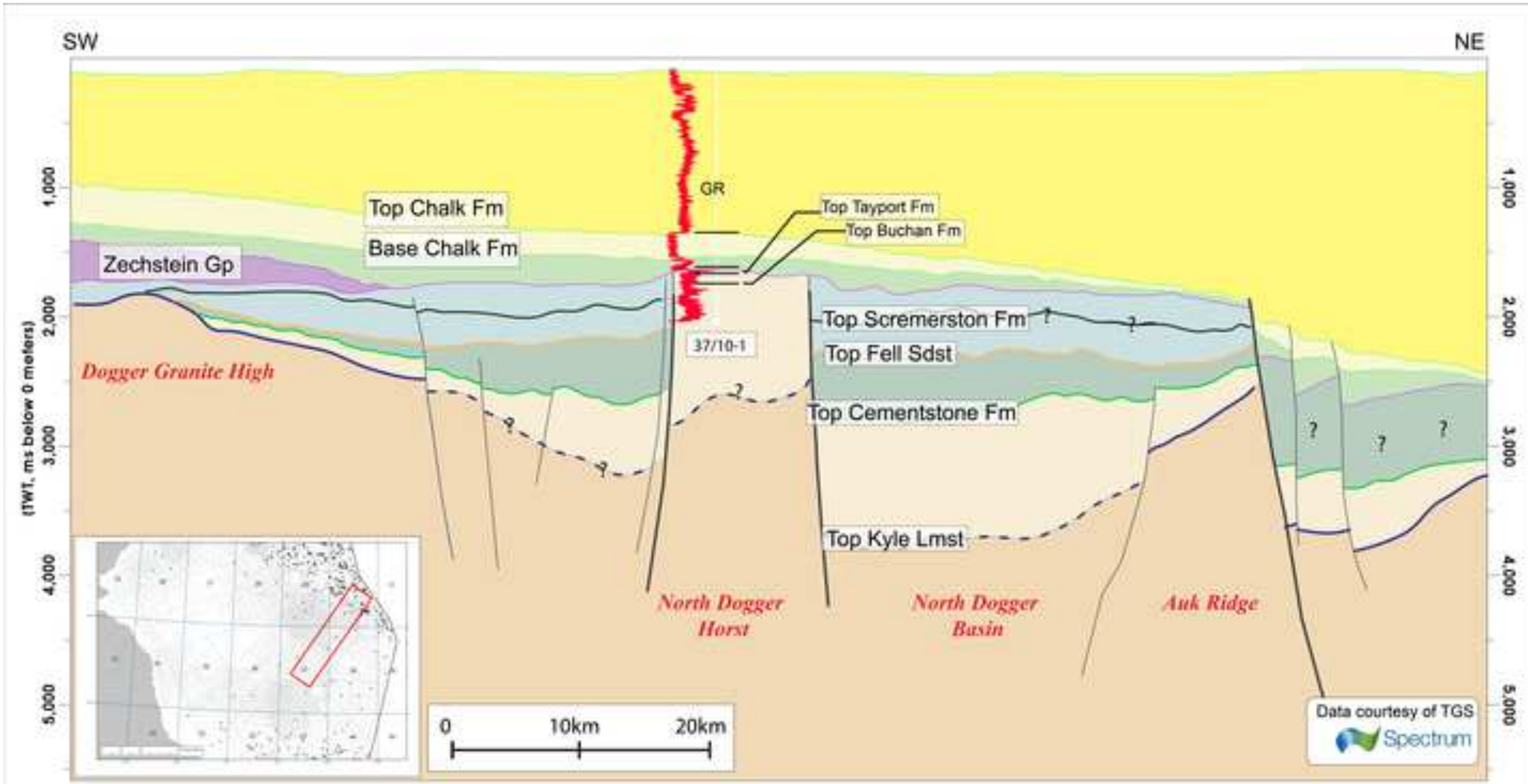
BASINS / DEPOCENTERS
EOB : East Orkney Basin
WSB : Wick Sub-basin
CG : Caithness Graben
HB :Halibut Basin
SBG : Smith Bank Graben
PB : Peterhead Basin
FAB : Forth Approaches Basin
MVS : Midland Valley of Scotland
Q29 B : Q29 Basin
NDB : North Dogger Basin
WAFB : Western Arcuate Fault Basin
NT : Northumberland Trough
Of. NT : Offshore Northumberland Trough
SB : Silverpit Basin
Highs/ Elevated Domains
CR : Caithness Ridge
HH : Halibut Horst
GH : Grampian High
DHH : Devil's Horst
MNSH : Mid North Sea High
DGH : Dogger Granite High
Terraces/ Shelves
Granitic Intrusions
0 25 50 100 Kilometers
Structures not interpreted

Figure 7



Kyle Group (or time-equiv. facies) inferred
30/16- 5
30/25A- 2
30/24- 3
38/03- 1
37/12- 1
Q29 Basin
North Dogger Horst
Western Arcuate Fault System
Dogger Granite High
North Dogger Basin
Kyle Limestone absent
Silverpit Basin
Middle Devonian strata continue in the Dutch sector
Fig. 8
27
28
29
30
35
36
37
38
39
43
44
56°
54°
0°
2°
-2500m
-9000m
Major Pre-Permian Faults
37/12- 1 : Wells penetrating the Kyle limestone
0
50
100 Kilometers

Figure 8



SW
NE
GR
Top Chalk Fm
Base Chalk Fm
Zechstein Gp
Top Tayport Fm
Top Buchan Fm
Top Scremerston Fm
Top Fell Sdst
Top Cementstone Fm
Top Kyle Lmst
37/10-1
Dogger Granite High
North Dogger Horst
North Dogger Basin
Auk Ridge
(TWT, ms below 0 meters)
1,000
2,000
3,000
4,000
5,000
0
10km
20km
Data courtesy of TGS
Spectrum

Figure 9

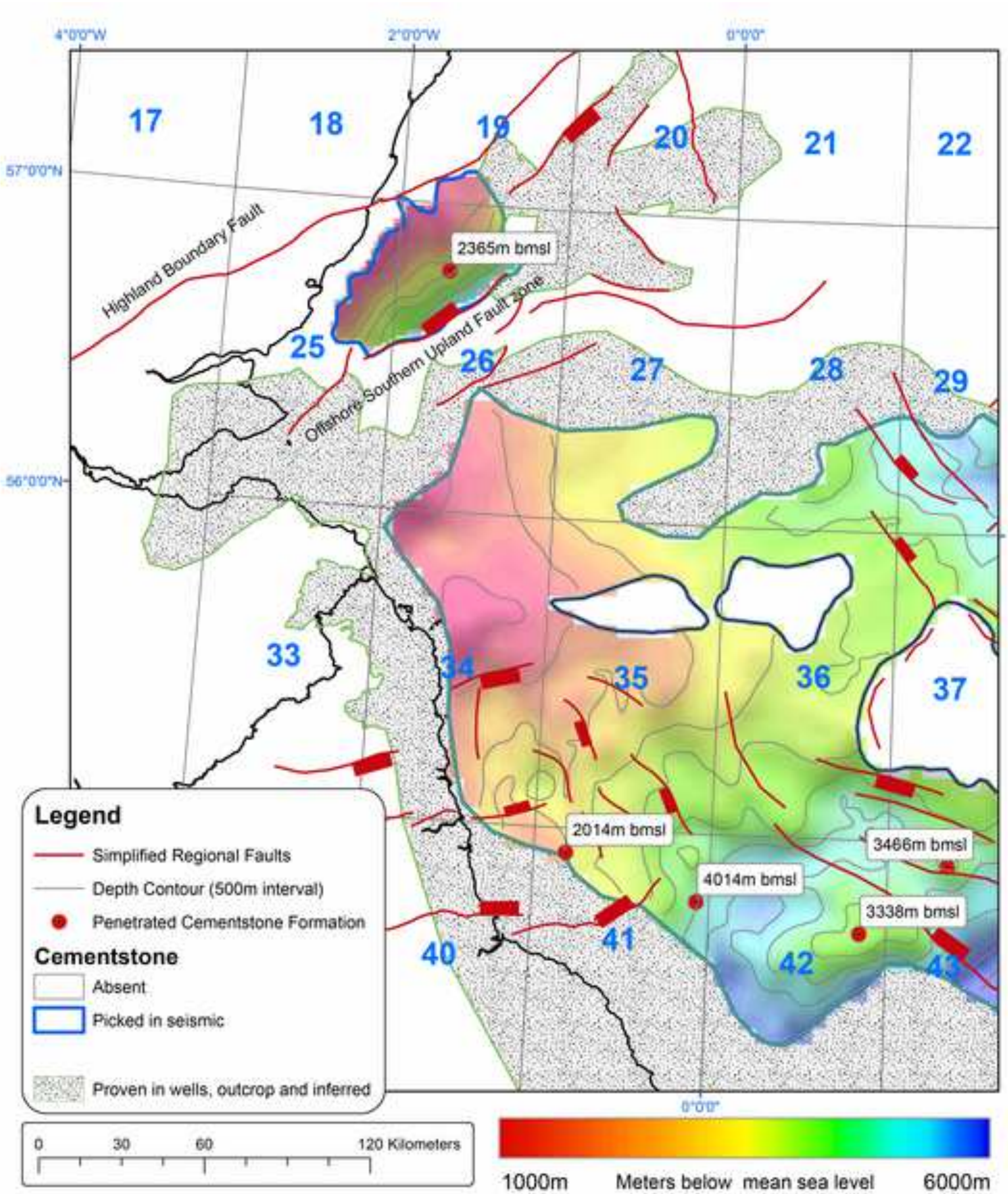

4°0'0"W
2°0'0"W
0°0'0"
57°0'0"N
56°0'0"N
17
18
19
20
21
22
25
26
27
28
29
33
34
35
36
37
40
41
42
43
Highland Boundary Fault
Offshore Southern Upland Fault zone
2365m bmsl
2014m bmsl
4014m bmsl
3466m bmsl
3338m bmsl
Legend
Simplified Regional Faults
Depth Contour (500m interval)
Penetrated Cementstone Formation
Cementstone
Absent
Picked in seismic
Proven in wells, outcrop and inferred
0
30
60
120 Kilometers
1000m
Meters below mean sea level
6000m

Figure 10

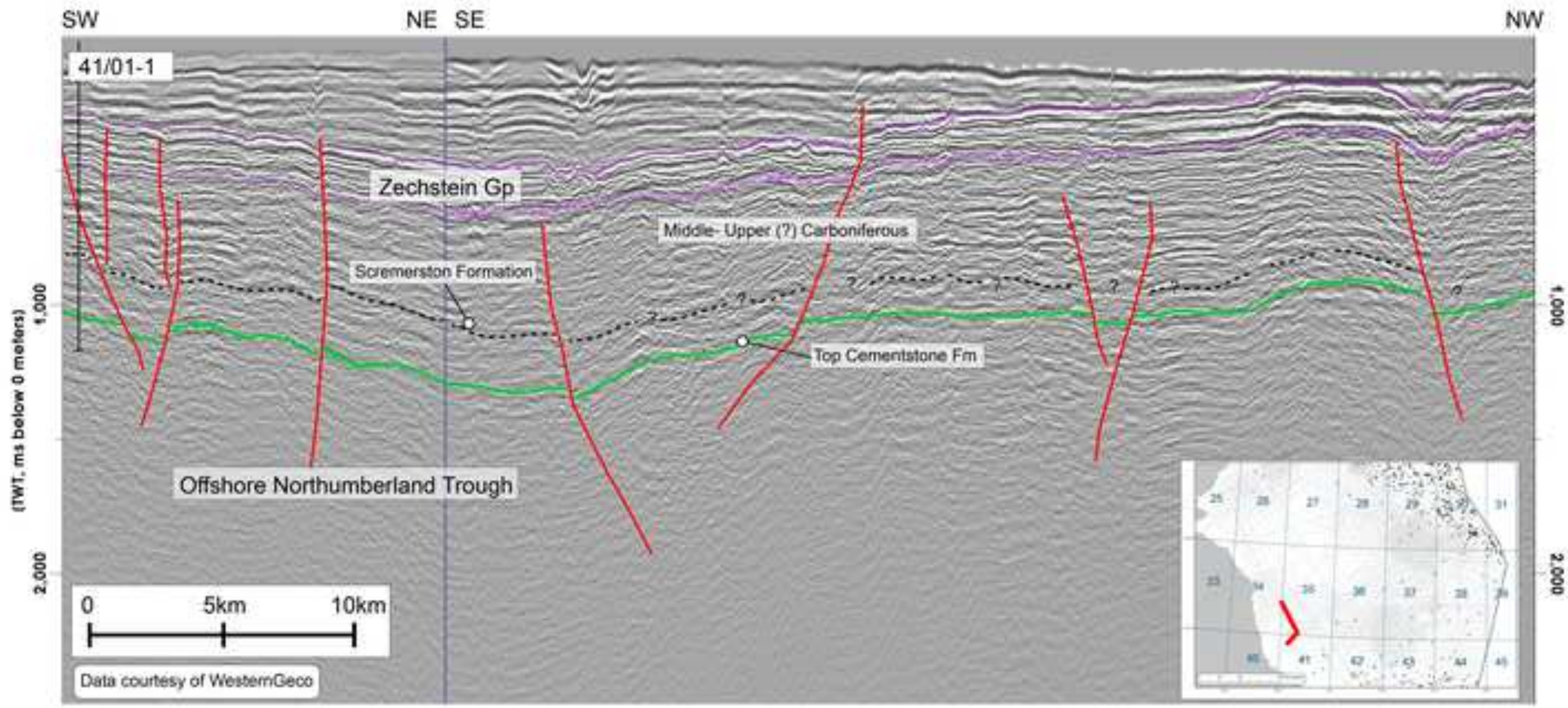
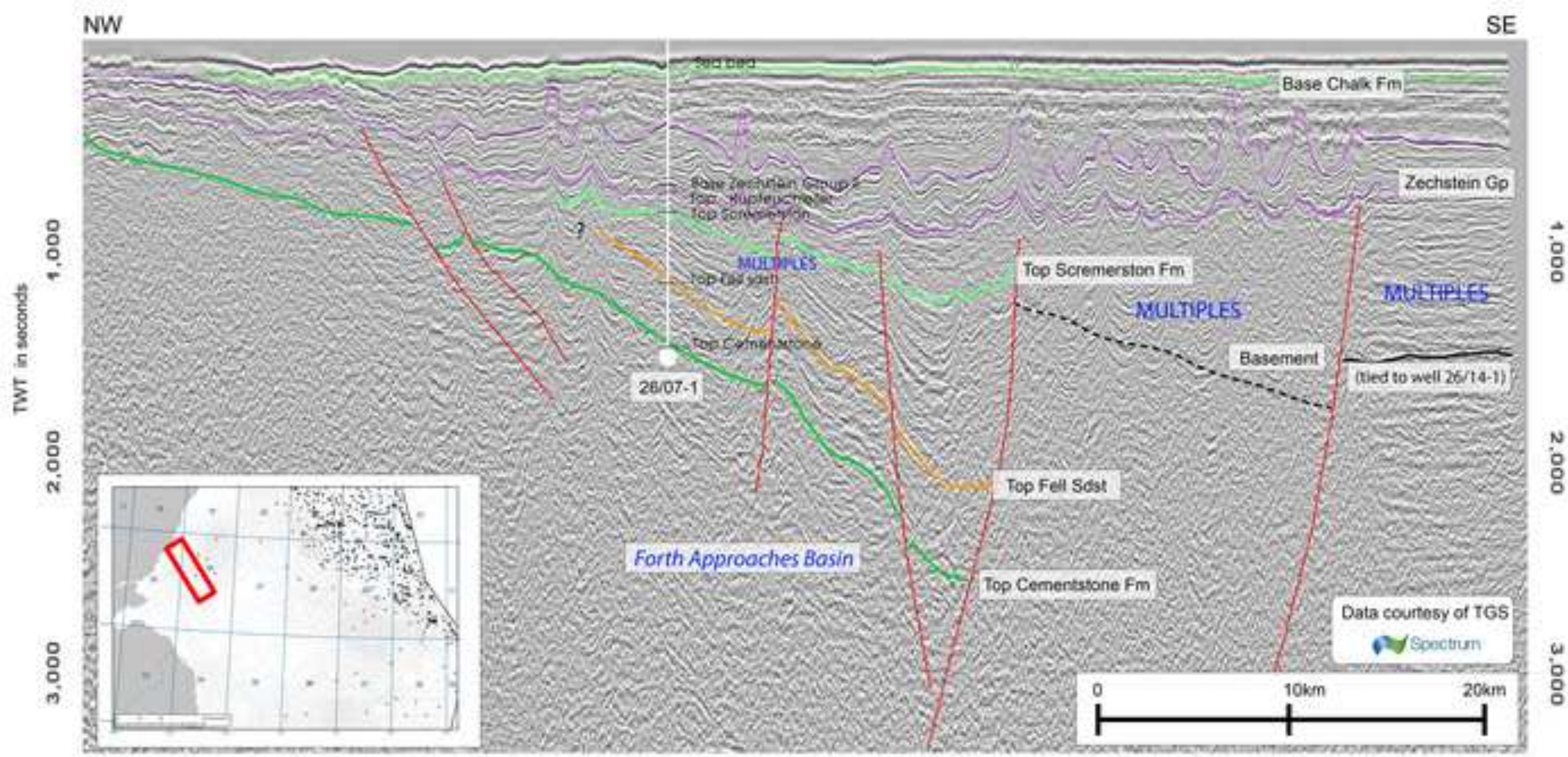
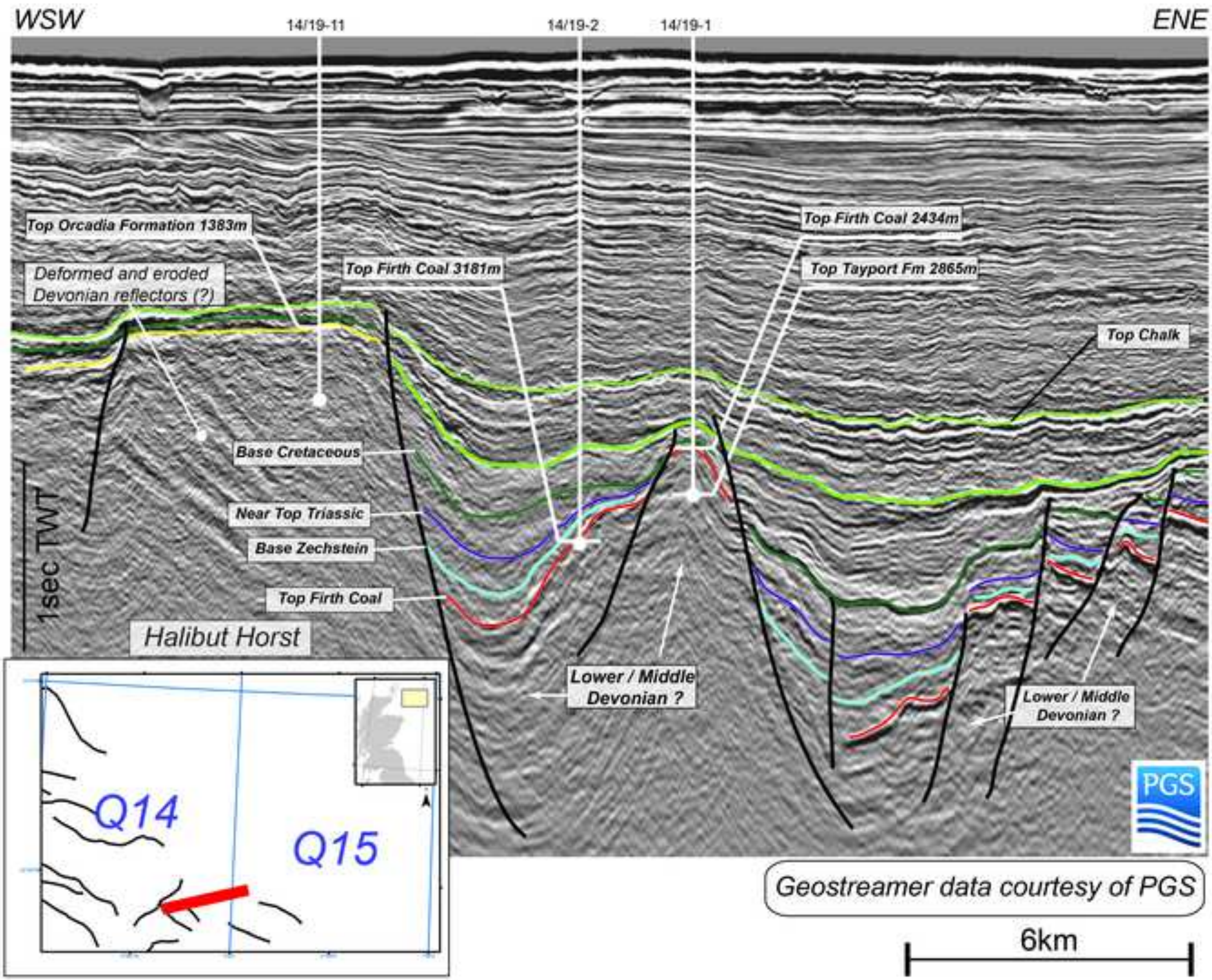

SW
NE
SE
NW
41/01-1
Zechstein Gp
Middle- Upper (?) Carboniferous
Scremerston Formation
Top Cementstone Fm
Offshore Northumberland Trough
(TWT, ms below 0 meters)
1,000
2,000
0
5km
10km
Data courtesy of WesternGeco

Figure 11



NW
SE
Base Chalk Fm
Zechstein Gp
MULTIPLES
Top Scremerston Fm
MULTIPLES
MULTIPLES
Basement
(tied to well 26/14-1)
28/07-1
Top Fell Sdst
Forth Approaches Basin
Top Cementstone Fm
Data courtesy of TGS
0
10km
20km
TWT in seconds
1,000
2,000
3,000
1,000
2,000
3,000

Figure 12



WSW
ENE
14/19-11
14/19-2
14/19-1
Top Orcadia Formation 1383m
Deformed and eroded
Devonian reflectors (?)
Top Firth Coal 3181m
Top Firth Coal 2434m
Top Tayport Fm 2865m
Top Chalk
Base Cretaceous
Near Top Triassic
Base Zechstein
Top Firth Coal
1sec TWT
Halibut Horst
Lower / Middle
Devonian ?
Lower / Middle
Devonian ?
PGS
Q14
Q15
Geostreamer data courtesy of PGS
6km

Figure 13

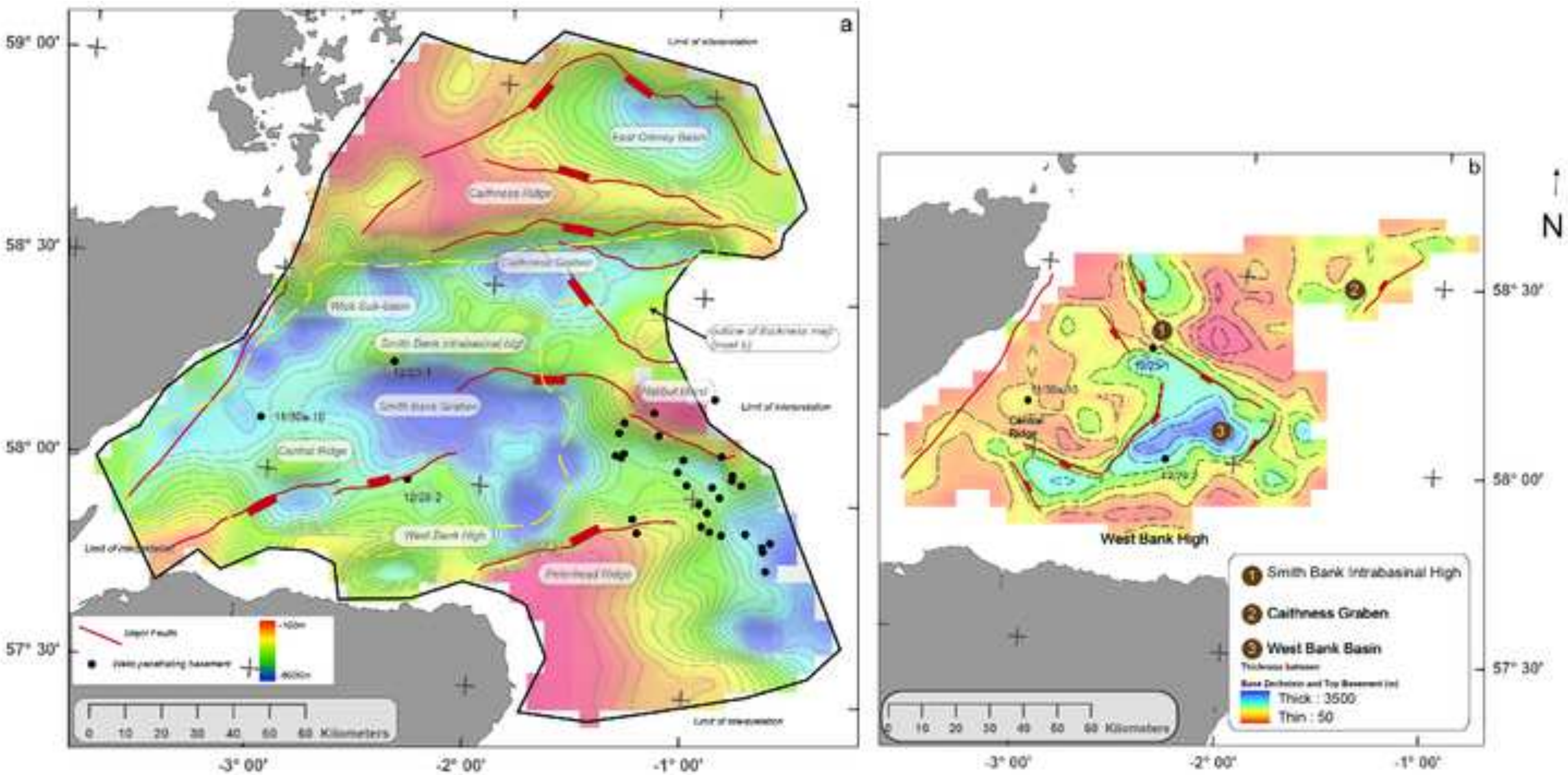
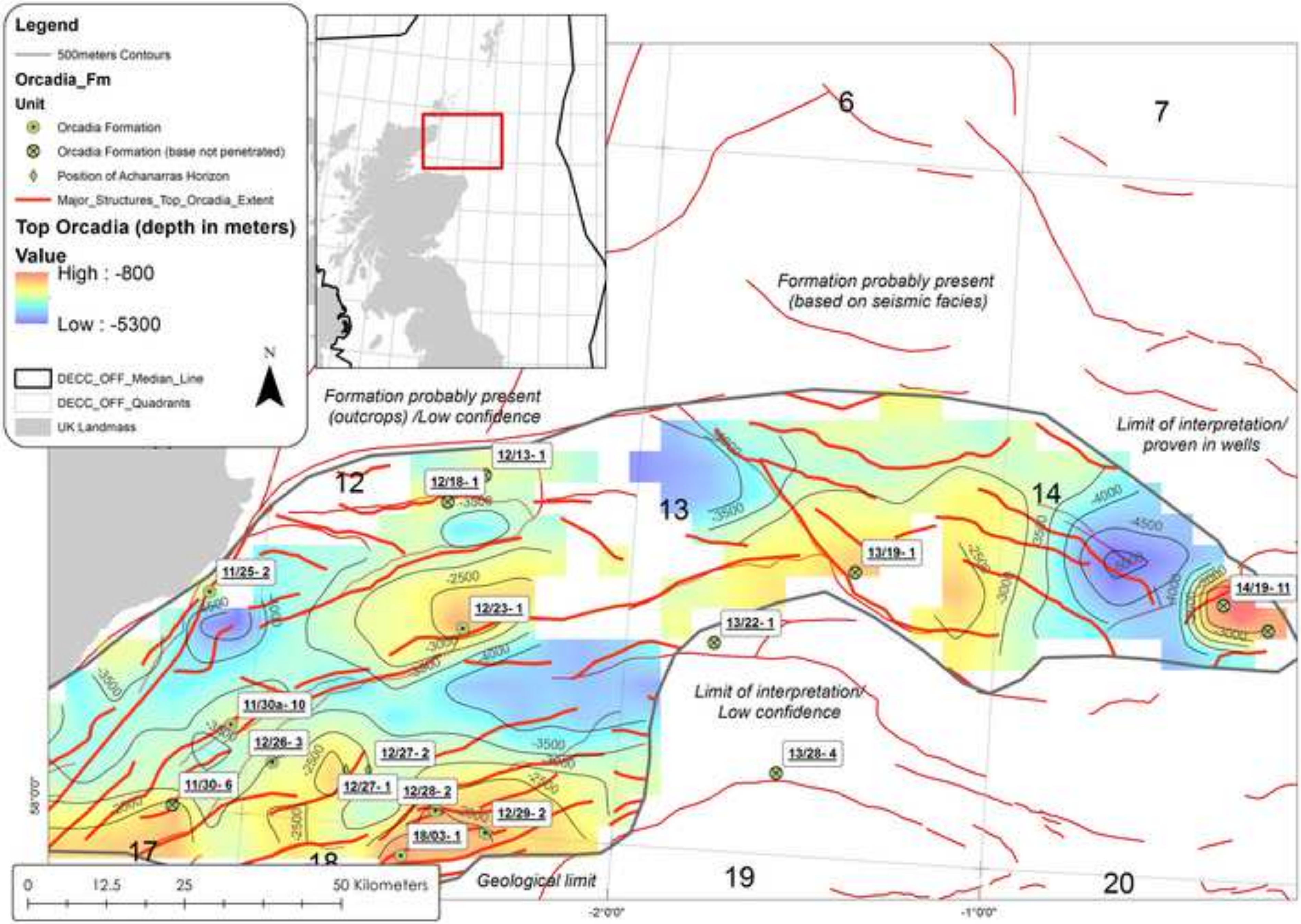
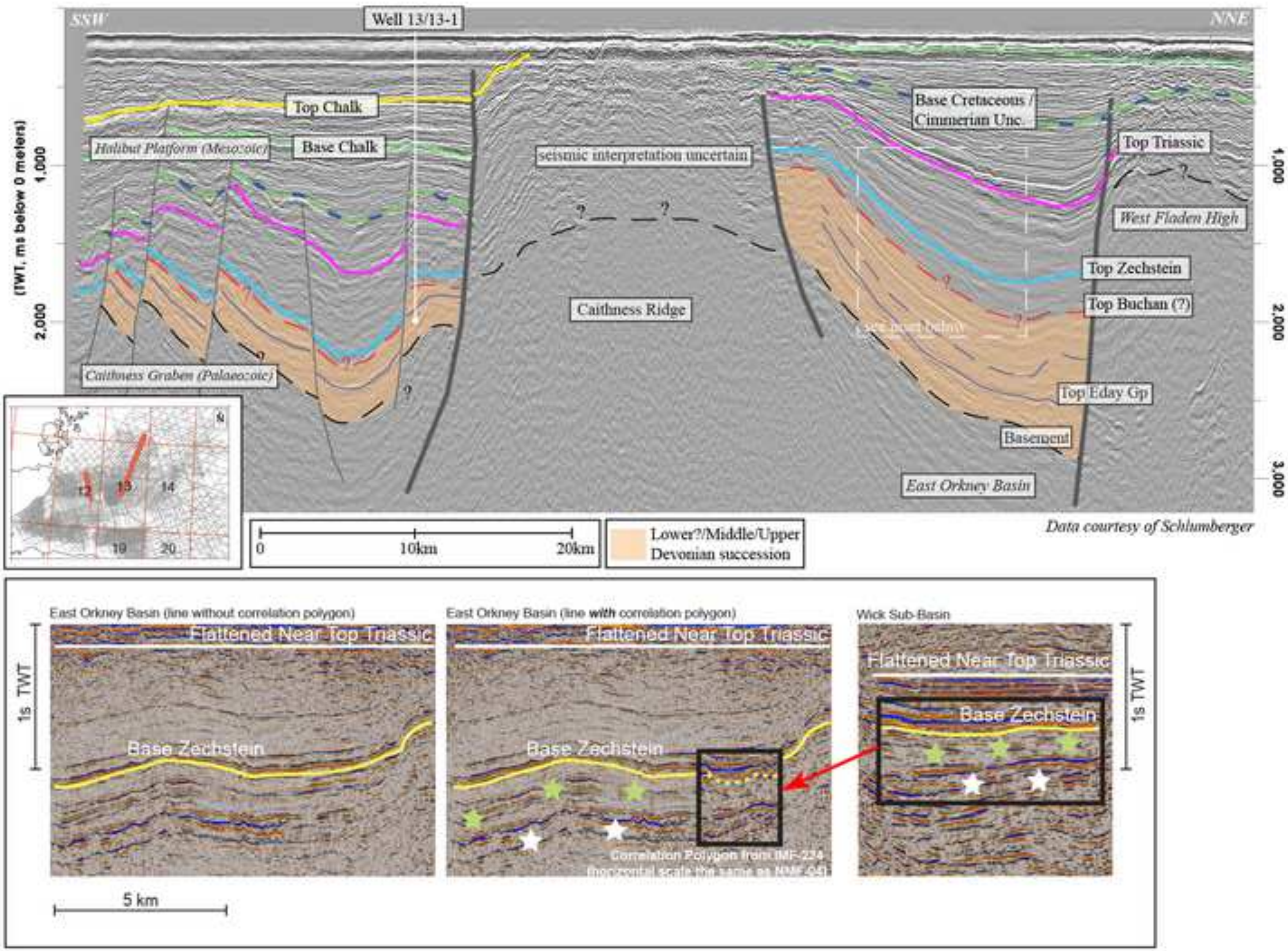

a
59° 00'
58° 30'
58° 00'
57° 30'
-3° 00'
-2° 00'
-1° 00'
East Orkney Basin
Caithness Ridge
Caithness Graben
Wick Sub-basin
Smith Bank Graben
Central Ridge
West Bank High
Peterhead Ridge
12/29-2
Limit of interpretation
0 10 20 30 40 50 60 Kilometers
b
N
58° 30'
58° 00'
57° 30'
West Bank High
Smith Bank Intrabasinal High
Caithness Graben
West Bank Basin
Thick : 3500
Thin : 50
0 10 20 30 40 50 60 Kilometers

Figure 14



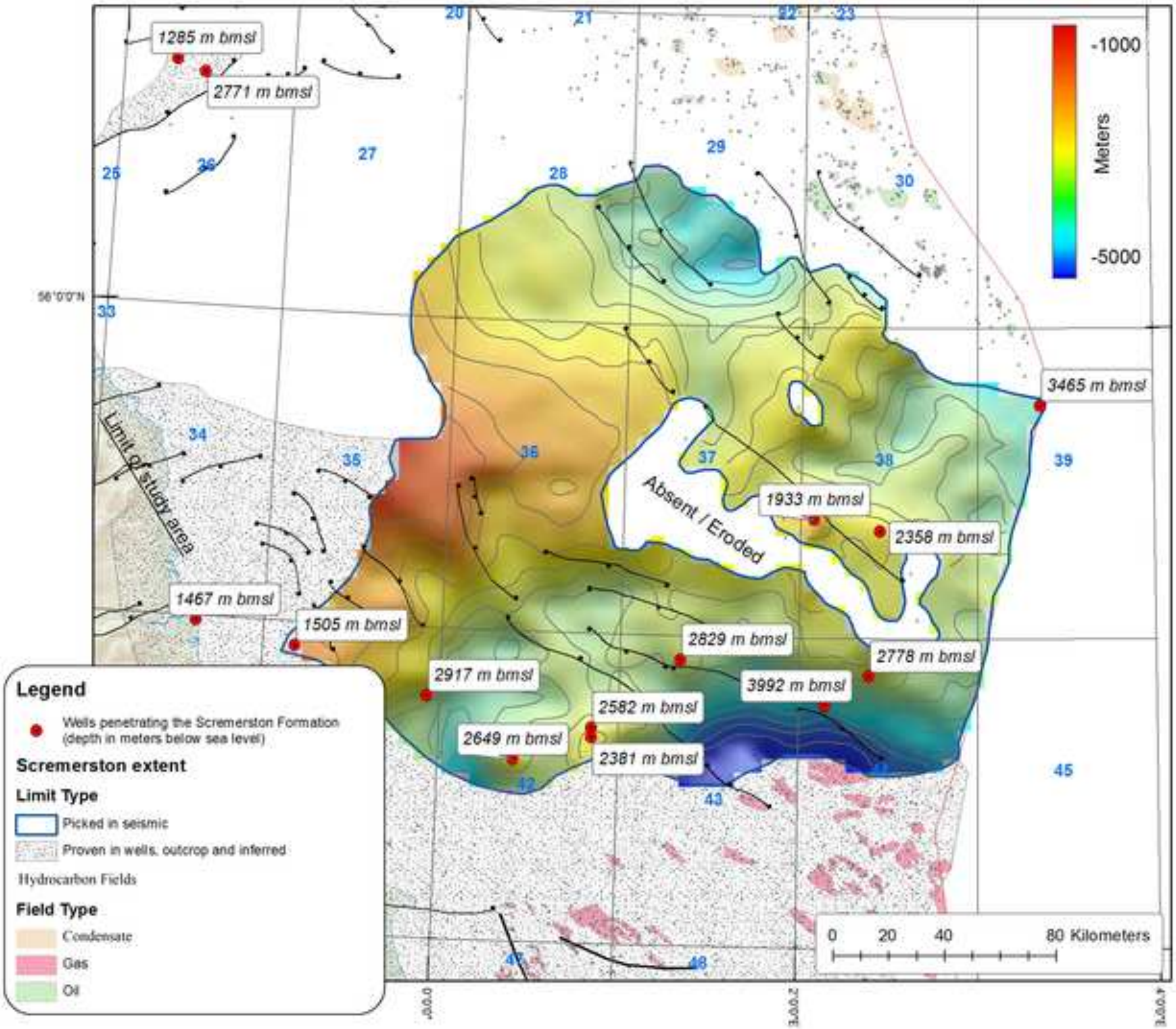
Legend
500meters Contours
Orcadia_Fm
Unit
Orcadia Formation
Orcadia Formation (base not penetrated)
Position of Achanarras Horizon
Major_Structures_Top_Orcadia_Extent
Top Orcadia (depth in meters)
Value
High : -800
Low : -5300
DECC_OFF_Median_Line
DECC_OFF_Quadrants
UK Landmass
N
Formation probably present (outcrops) /Low confidence
Formation probably present (based on seismic facies)
Limit of interpretation/ proven in wells
Limit of interpretation/ Low confidence
Geological limit
6
7
12
13
14
17
18
19
20
12/13- 1
12/18- 1
11/25- 2
12/23- 1
13/19- 1
13/22- 1
14/19- 11
11/30a- 10
12/26- 3
12/27- 2
12/27- 1
12/28- 2
12/29- 2
11/30- 6
18/03- 1
13/28- 4
0
12.5
25
50 Kilometers
-2°0'0"
-1°0'0"
58°0'0"

Figure 15



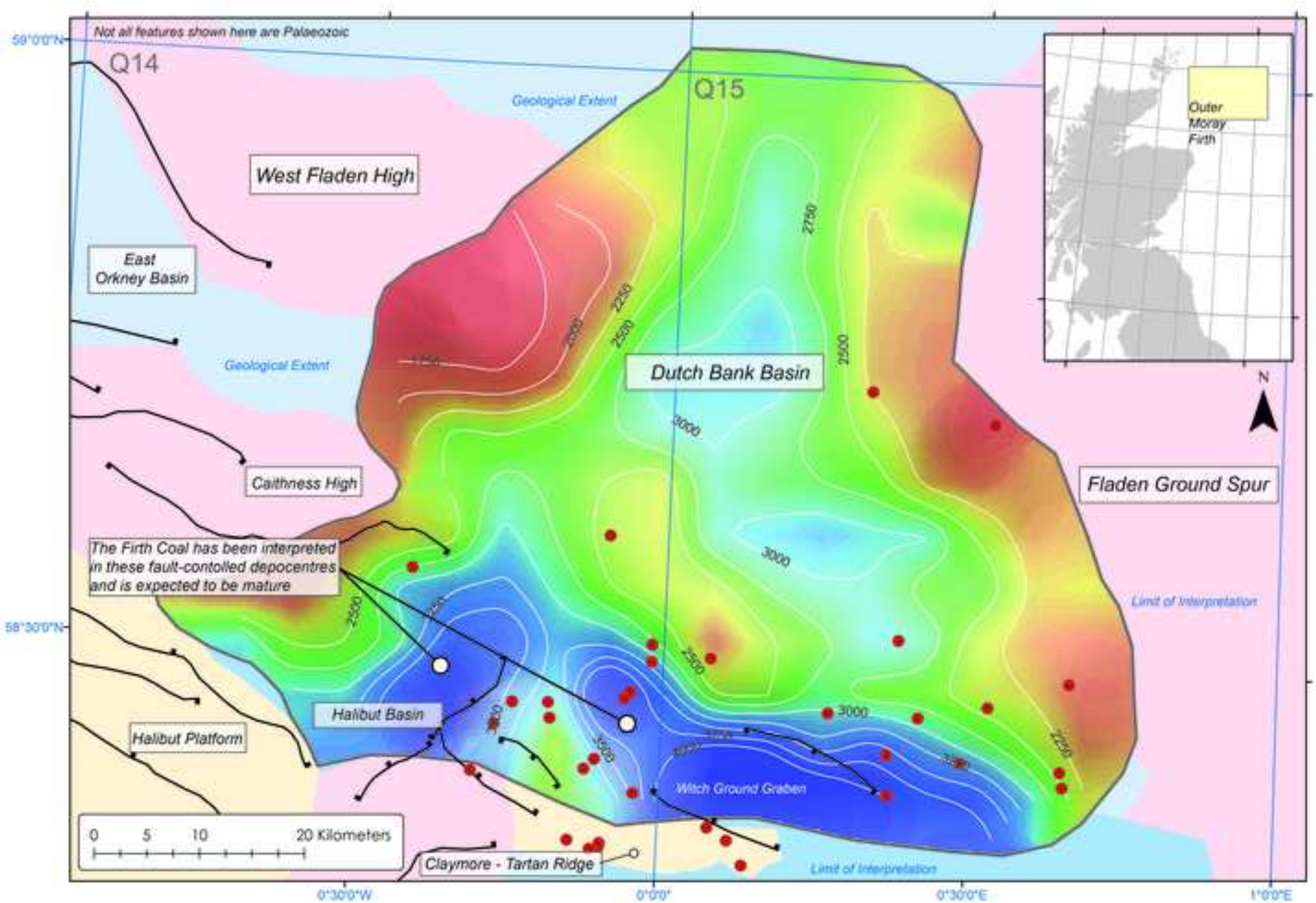
SSW
NNE
Well 13/13-1
Top Chalk
Base Chalk
Halibut Platform (Mesozoic)
seismic interpretation uncertain
Base Cretaceous / Cimmerian Unc.
Top Triassic
West Fladen High
Top Zechstein
Top Buchan (?)
Caithness Ridge
Caithness Graben (Palaeozoic)
Top Eday Gp
Basement
East Orkney Basin
(TWT, ms below 0 meters)
1,000
2,000
3,000
0
10km
20km
Lower?/Middle/Upper Devonian succession
Data courtesy of Schlumberger
East Orkney Basin (line without correlation polygon)
East Orkney Basin (line with correlation polygon)
Wick Sub-Basin
Flattened Near Top Triassic
Base Zechstein
1s TWT
5 km

Figure 16



1285 m bmsl
2771 m bmsl
3465 m bmsl
1933 m bmsl
2358 m bmsl
1467 m bmsl
1505 m bmsl
2829 m bmsl
2778 m bmsl
2917 m bmsl
3992 m bmsl
2582 m bmsl
2649 m bmsl
2381 m bmsl
Absent / Eroded
Limit of study area
-1000
Meters
-5000
56°0'0"N
0°0'0"
2°0'0"E
4°0'0"E
0 20 40 80 Kilometers
20
21
22
23
25
26
27
28
29
30
33
34
35
36
37
38
39
42
43
45
47
48
Legend
Wells penetrating the Scremerston Formation (depth in meters below sea level)
Scremerston extent
Limit Type
Picked in seismic
Proven in wells, outcrop and inferred
Hydrocarbon Fields
Field Type
Condensate
Gas
Oil

Figure 17



Not all features shown here are Palaeozoic
59°0'0"N
Q14
Q15
Geological Extent
West Fladen High
East Orkney Basin
Geological Extent
Dutch Bank Basin
Caithness High
Fladen Ground Spur
The Firth Coal has been interpreted in these fault-contolled depocentres and is expected to be mature
Limit of Interpretation
58°30'0"N
Halibut Basin
Halibut Platform
Witch Ground Graben
0 5 10 20 Kilometers
Claymore - Tartan Ridge
Limit of Interpretation
0°30'0"W
0°0'0"
0°30'0"E
1°0'0"E
Outer Moray Firth
N
2750
2250
2500
3000