New plays on the Greater East Shetland Platform (UKCS Quadrants 3, 8-9, 14-16) – part 2: newly reported Permo-Triassic intra-platform basins and their influence on the Devonian-Paleogene prospectivity of the area

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Abstract

Despite significant discoveries within Palaeogene-age reservoirs (e.g., Mariner) the East Shetland Platform (ESP) is underexplored, with only ten wells per 1000 km^2. Mesozoic units are thin or absent whilst Paleozoic reflectors resemble acoustic basement on legacy seismic. Recent 3D dual-sensor broadband surveys (GeoStreamer) covering 17,200 km^2 over parts of Quadrants 3, 8-9, 14-16 have allowed for clearer imaging. Here, this dataset is interpreted, leading to new insights into this large frontier region.

The ESP petroleum system comprises multiple proven reservoir and source intervals, with viable play fairways. Up to four regional unconformities are interpreted, merging into fewer erosional surfaces on persistent highs. Elsewhere on the ESP, predominantly subsiding Permo-Triassic depocentres contain a nearly continuous Paleozoic-Mesozoic succession. The most prominent of these, to the south and south-west of the Beryl Embayment, is here referred to as the 'Crawford-Skipper Basin'.

Existing hydrocarbon discoveries on the ESP are in the vicinities (<7 km) of intra-platform Permo-Triassic basin margins. Exploration close to such basins is inherently less risky due to possible positive influences of deep-seated structures on the petroleum system. These include: (1) formation of Meso-Cenozoic closures; (2) Devonian source maturity and presence of simple fault-related migration pathways; (3) viability of sub-Cretaceous reservoir-trap-seal configurations.

Introduction

Owing to the limitations of legacy seismic, much of the Greater East Shetland Platform (ESP) (Figure 1A in Part 1, published in *First Break* December 2016) has been historically conceived as a broad, flat high (Zanella and Coward, 2003) with a shallow acoustic basement and few visible structures (e.g., Ziegler, 1992; Johnson et al., 2005). With the acquisition of several 3D dual-sensor broadband GeoStreamer surveys by PGS covering 17,200 km^2 over parts of UKCS Quadrants 3, 8-9, 14-16 (Figure 1A in Part 1; Figure 1A in Part 2), there is now a unique opportunity to view key stratigraphic intervals with more clarity.

In part 1 of this paper, the source-reservoir-seal system on the Greater ESP was outlined. The Greater ESP area comprises the Piper Shelf, East Shetland Platform (ESP) and adjoining structural terraces, as well as the structural highs located between the 'central basins' and the ESP (see Part 1). In part 2, we are going to show and discuss the results of the interpretation of the new seismic dataset, aiming to dispel some of the long-lasting preconceptions surrounding this vast under-explored frontier region and to improve the understanding of its complex history. The novel elements will be outlined, including newly described intra-platform Permo-Triassic basins.

Tectono-stratigraphic elements

Pre-Tertiary horizons have been mapped over the entire dataset. A history of repeated tectonic inversions is identified, including:

1) High-level of Devonian subsidence, reflecting the extensional collapse of the Caledonian orogen (Seranne, 1992; Ziegler, 1992);
2) Late Carboniferous to Middle Permian Variscan uplifting (Seranne, 1992; Corfield et al., 1996; Zanella and Coward, 2003);
3) Late Permian to Triassic rifting (Ziegler, 1992; Glennie, 1995; Coward et al., 2003);
4) Aalenian uplifting associated with the Mid North Sea doming event (Underhill and Partington, 1993; Davies et al., 1999);
5) Late Jurassic to Early Cretaceous rifting (Ziegler, 1992; Fraser et al., 2003);
6) Cretaceous-Cenozoic thermal subsidence, punctuated by Alpine-age compressional events (e.g. Figure 4) and by enhanced Paleogene subsidence triggered by the uplift of the Shetlands-Orkney islands (Pegrum and Spencer, 1990).

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Thick Devonian successions (up to 4.5 km) occur on present-day prominent highs (Fladen Ground Spur, Kraken High, Figures 1, 5). Sporadic Devonian syn-rift wedges have also been interpreted (Figure 2A, Figure 3B-C, Fault 1 in Figure 4).

At least four different extensional fault trends are revealed (Figures 6-8). Generally, Jurassic faults tend to be oriented parallel to the direction of the closest main Jurassic rift basin: north-south (Viking Graben) and east-west (Witch Ground Graben) (Figure 7). Fault systems oriented transverse to these Jurassic trends are predominantly Permo-Triassic in age.

Different areas on the Greater ESP are characterized by very different fault densities: faults can form dense networks (e.g., Quadrant 14-15; area around Crawford-Skipper) or be extremely rare (e.g., Kraken High, Fladen Ground Spur) (Figure 7). The Devonian depocentres on the Fladen Ground Spur and Kraken High were probably subject to both Variscan and Aalenian uplift and erosion and inverted into subaerial highs (Figure 5C). Marine conditions were brought again over these highs only during the Kimmeridgian Eudoxus marine flooding (Freer et al., 1996).

The complex tectonic history created several regional unconformities: the Saalian, Mid Cimmerian, Base Cretaceous (BCU), and, in the northernmost part of the study area, a Base Tertiary one (Figures 2A-B, 3). On persistent platform highs (e.g., Fladen Ground Spur, Kraken High), these unconformities merge into fewer, composite erosional surfaces, where Devonian deposits are in direct contact with a thin veneer of upper Jurassic or Cretaceous strata, or even directly with Paleocene sediments (Figures 2-3, 5). Elsewhere on the Greater ESP, subsiding mini-basins contain a nearly complete Devonian-Mesozoic succession. The most prominent of these intra-platform basins is discussed below.

The Crawford-Skipper Basin

Mesozoic-age reservoir units contain >85% of the hydrocarbons discovered in the North Sea (Eriksen et al., 2003; Johnson et al., 2005; Figure 1A; Table 2 in Part 1). On the Greater ESP, however, these units have historically been elusive, generally being thin and localized within intra-platform depocentres that were difficult to image with conventional seismic technology (Figure 3). The BCU itself is a prominently 'near-flat' surface (Figure 1A).

As a consequence of the poor sub-BCU seismic imaging of the legacy seismic, regional well-correlation panels were the main tool available to reconstruct the extent of pre-Cretaceous strata (e.g., Glennie et al., 2003; Figure 6). These panels indicated the aforementioned long-lasting hiatuses spanning the top Devonian to Jurassic/Cretaceous interval over the Fladen Ground Spur and Kraken High (Figures 5-6). Between these two regions, wells on the platform to the south and south-west of the Beryl Embayment reported the presence of Permo-Triassic deposits, the sporadic preservation of Jurassic strata and a thick Cretaceous-Tertiary succession (Figure 6B). Within the Jurassic, upper Jurassic strata are more often present, with the lower-middle Jurassic often removed by Aalenian and Callovian-Oxfordian hiatuses (Figure 6A; Davies et al., 1999).

The area of greater Mesozoic preservation between the Kraken High and the Fladen Ground Spur is herein termed the 'Crawford-Skipper Basin' (Figures 5-8). This is clearly imaged by the GeoStreamer seismic (Figures 2B-C, 3-8), which reveal it to be an intra-platform Permo-Triassic Basin with Triassic-age syn-rift wedges (Figure 2C and faults 1-7 in Figure 4). Carboniferous strata have also been identified in a few nearby wells (e.g., 9/16-3) and may extend over at least part of the area (Figures 2B-3, 7). This means that the Crawford-Skipper Basin hosts a nearly continuous stratigraphic succession from the Devonian to the present, including Carboniferous-lower Permian and middle Jurassic strata, which are normally absent elsewhere on the Greater ESP (Figures 6-7; Figure 2 in Part 1).

The Triassic syn-rift fill to the hanging wall of faults 1-2 and 7 in the Crawford-Skipper Basin (Figure 4) represents the majority of the total Mesozoic sediment thickness preserved along this section of the ESP. The Jurassic extension on the basin is minor, with faults of small offset formed or reactivated (Figure 4). This suggests that the Late Jurassic extensional strain became more focused on the incipient Viking Graben depocentre. Triassic syn-rift wedges are usually inverted by later compression (Figures 4-5, with Jurassic-Paleocene horizons all subject to antiformal folding). This compression is of early Alpine age, as constrained by: (1) sub-horizontal Paleocene reflectors onlapping the antiformal structure; and (2) Cretaceous strata becoming anomalously thin towards the antiformal culmination. Within the Crawford-Skipper Basin, several discrete depocentres of variable size can be distinguished (Figure 8), with maximum Triassic-Jurassic TWT-thicknesses of 0.8 seconds. Outside of the basin, the Triassic is generally absent or below seismic resolution.

Other Permo-Triassic basins have been mapped throughout the Greater ESP, for example of the Piper Shelf (e.g., Figure 2D; Patruno and Reid, in press), but are not detailed here. The age of the main syn-rift wedges is Triassic in the Crawford-Skipper Basin and Permian on the Piper Shelf, where half-grabens are filled by Rotliegend sediments (Figure 2D), and Carboniferous marginal-marine deposits are normally preserved (Figure 2 in Part 1; Leeder and Boldy, 1990; Bruce and Stemmerik, 2003).

Most of the hydrocarbon shows and discoveries to date on the ESP (e.g., Mariner-Bluebeard, Harding-Gryphon-Maclure, Crawford, Skipper, Cairngorm, Brae West) cluster around the Crawford-Skipper Basin, within a maximum distance from the basin edge of 7 km (Figure 9). The reservoirs are mainly Eocene sandstones (Horda, Balder, Beauly formations) and Paleocene sandstones (Dornoch, Sele, Heimdal, Maureen formations) (Figure 2 and Tables 1-2 in Part 1; Figures 6-7). Moreover, in and around the Crawford-Skipper Basin, other oil discoveries and shows are within deeper reservoirs, including: (1) upper Jurassic and lower Cretaceous sandstones; (2) Bajocian-Bathonian and Triassic sandstones (Hugin/Pentland and Skagerrak/Cormorant formations) (e.g., Crawford discovery); and (3) fractured crystalline basement and Devonian sandstones (e.g., Cairngorm, Brae West and Well 9/16-2) (Figures 3-4, 7, 9). Similarly, in Quadrant 15, the Hood oil discovery (upper Jurassic Piper Formation reservoir) is situated over the crest of a tilted fault block bounding a Permian mini-basin (Figure 2 and Tables 1-2 in Part 1; Figure 2D).

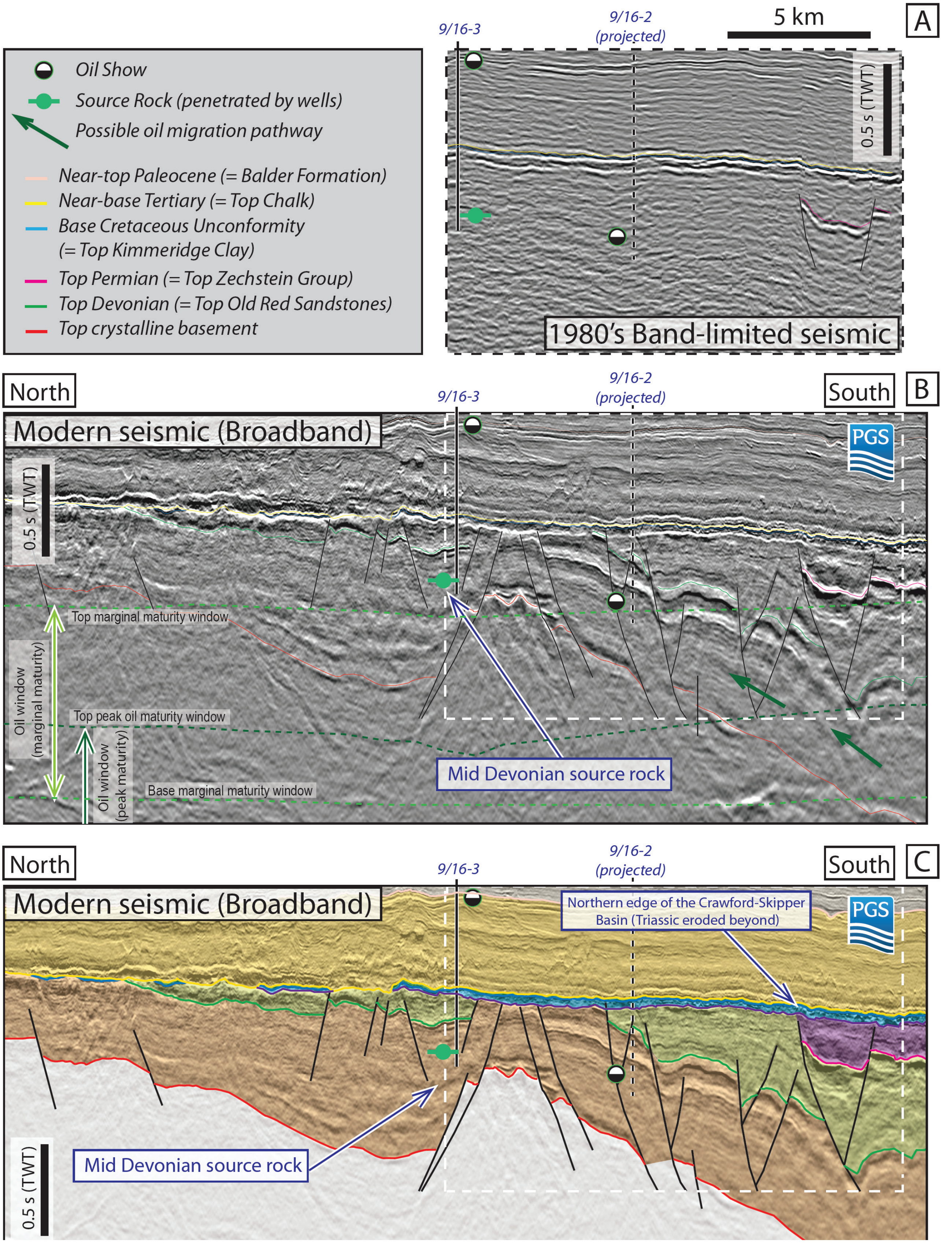

Figure 3 A conventional seismic line (1986 acquisition) (A) compared with a GeoStreamer line (MC3D-BYLM2013 survey) (B-C). Surface and package colours are the same as in Figures 2-3. The eastern half of the GeoStreamer line (highlighted by a white dashed polygon) follows the same north-to-south transect as the conventional line. The main horizons and the computed depths of the present-day oil window are shown. See Figures 1A, 7-8 for line location. The 1986 line does not show interpretable reflectors below the Top Permian; however two wells penetrated thick Devonian strata, containing oil shows (Well 9/16-2) and a middle Devonian lacustrine source rock (Well 9/16-3, see Duncan and Buxton, 1995). These 1980s-90s well results are better understood thanks to the 2013 GeoStreamer seismic (B-C). This clearly shows intra-Devonian reflectors and fault blocks, including an undrilled horst between the two wells.

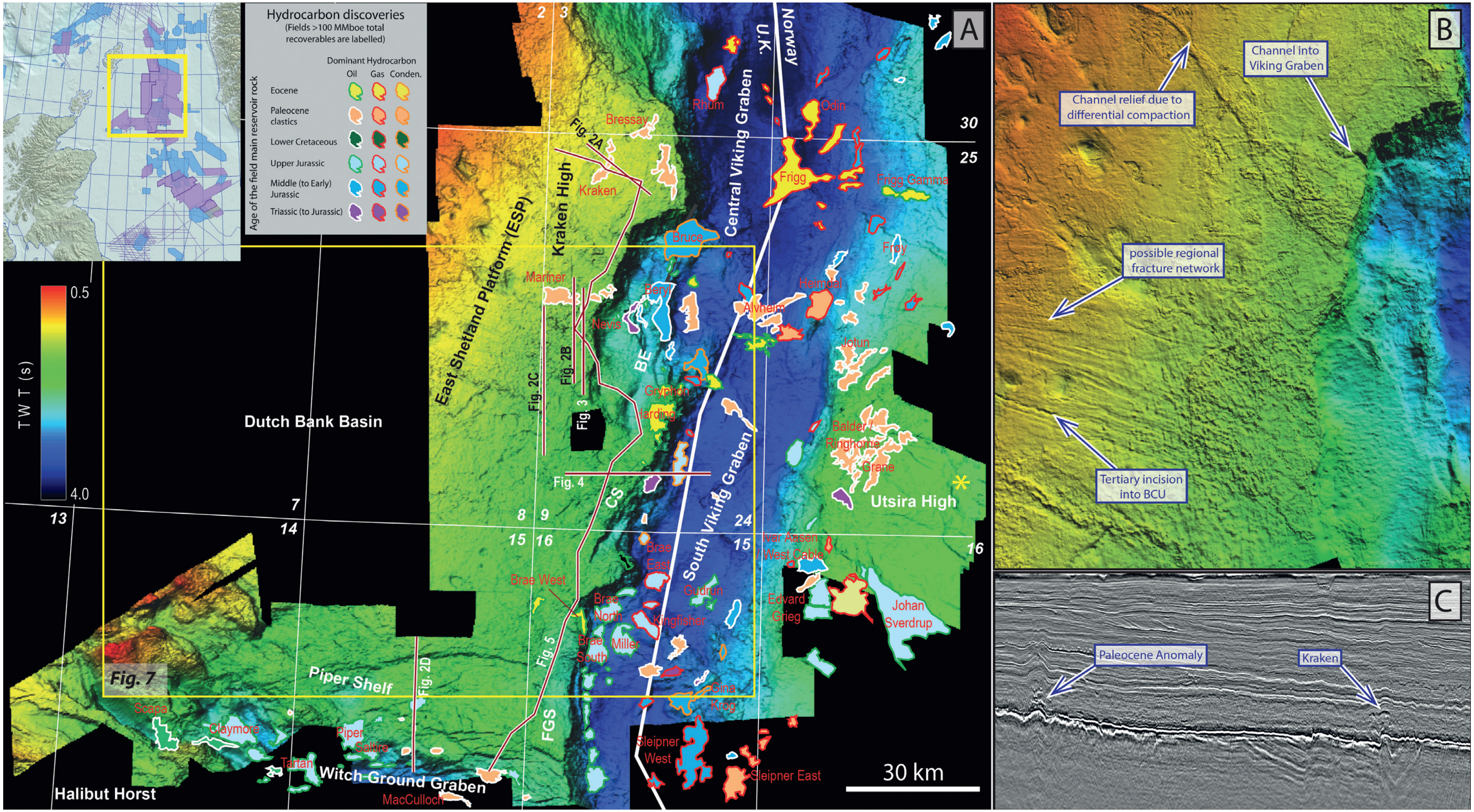

Figure 1 A) Base Cretaceous Unconformity (BCU) TWT-structure map (see Figure 1A in Part 1 for a larger location map and Figure 5 in Part 1 for 3 detailed caption). The largest discoveries on the ESP target Paleocene deltaic-turbiditic sandstones (e.g., Bressay, Kraken, Mariner). Upper Jurassic deltaic-marine sandstones are the main reservoir on the southern platform margins (e.g., Claymore, Piper in Quadrants 14-15) and in the Viking Graben (Brae province in Quadrant 16). In the Beryl Embayment (Quadrant 9), large fields are in Triassic-Jurassic fluvio-deltaic sandstones (e.g., Beryl, Bruce, Nevis) and Eocene injectites (Gryphon-Harding). B) Identifies lineaments and channels observable on the BCU, further discussed in the text. C) An East-West section with amplitude anomalies in the Paleocene section to the west of the Kraken discovery. FGS = Fladen Ground Spur; CS = Crawford Spur; BE = Beryl Embayment.

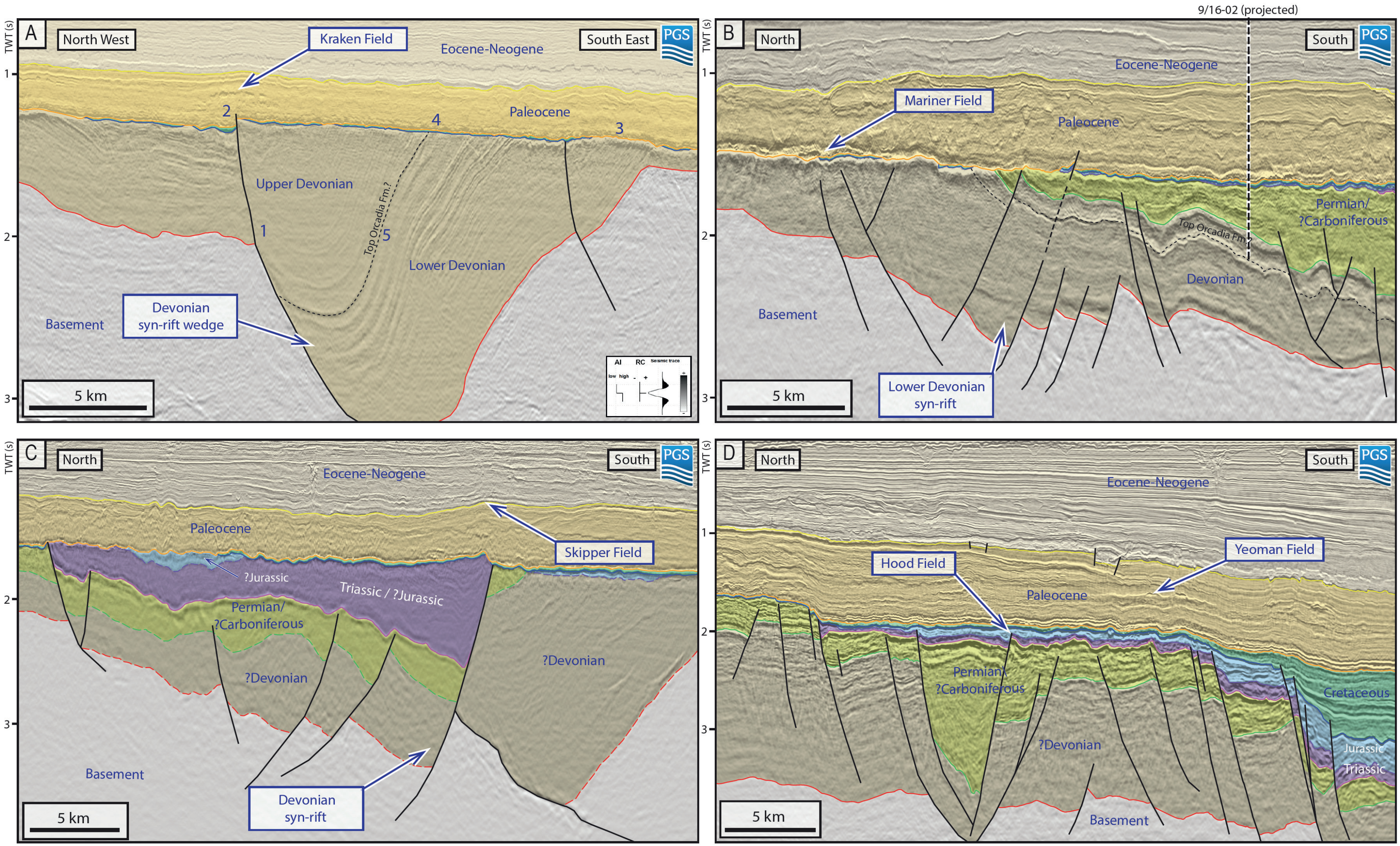

Figure 2 Examples of the relationships between deep-seated Paleozoic structures and existing Meso-Cenozoic discoveries (see Figure 1A for line locations), located in anticlines formed by the partial inversion of Devonian master faults. Surface and package colours are the same as in Figures 3-4A) Kraken Field (upper Paleocene Heimdal Sandstone reservoir; MC3D-BBK2011 survey). B) Mariner Field (lower Paleocene Maureen Sandstone and upper Paleocene Heimdal Sandstone), just beyond the northern edge of the Permo-Triassic Crawford-Skipper Basin (Figure 7) (MC3D-BYLM2013 survey). C) Skipper discovery (lower Eocene Beauly Sandstone) at the western edge of the Crawford-Skipper Basin (MC3D-Q8-2015 Fast-track survey). D) Hood and Yeoman discoveries (upper Jurassic Piper Formation; Paleocene Balmoral Sandstone) (Piper Shelf, MC3D-Q15-2014 survey).

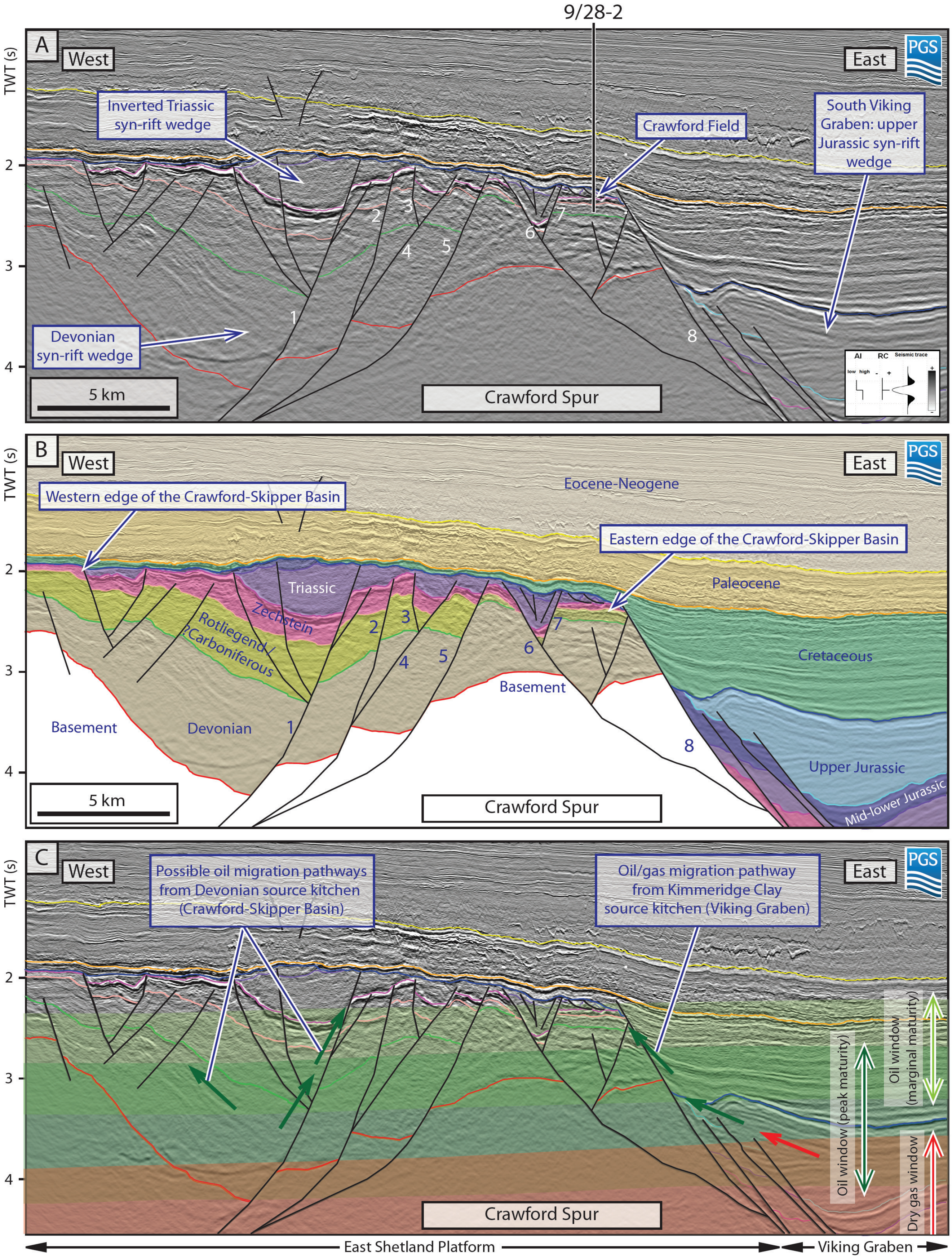

Figure 4 E-W line across the partly inverted Crawford-Skipper Basin and the western edge of the Viking Graben (MC3D-Q16-2013 survey; see Figures 1A, 7-8 for location). A) Interpreted seismic line; B) geo-seismic section; C) section with computed TWT-depths for the present-day hydrocarbon maturation windows. Surface colours are the same as in Figures 2-3. Several deep-seated extensional structures are visible.

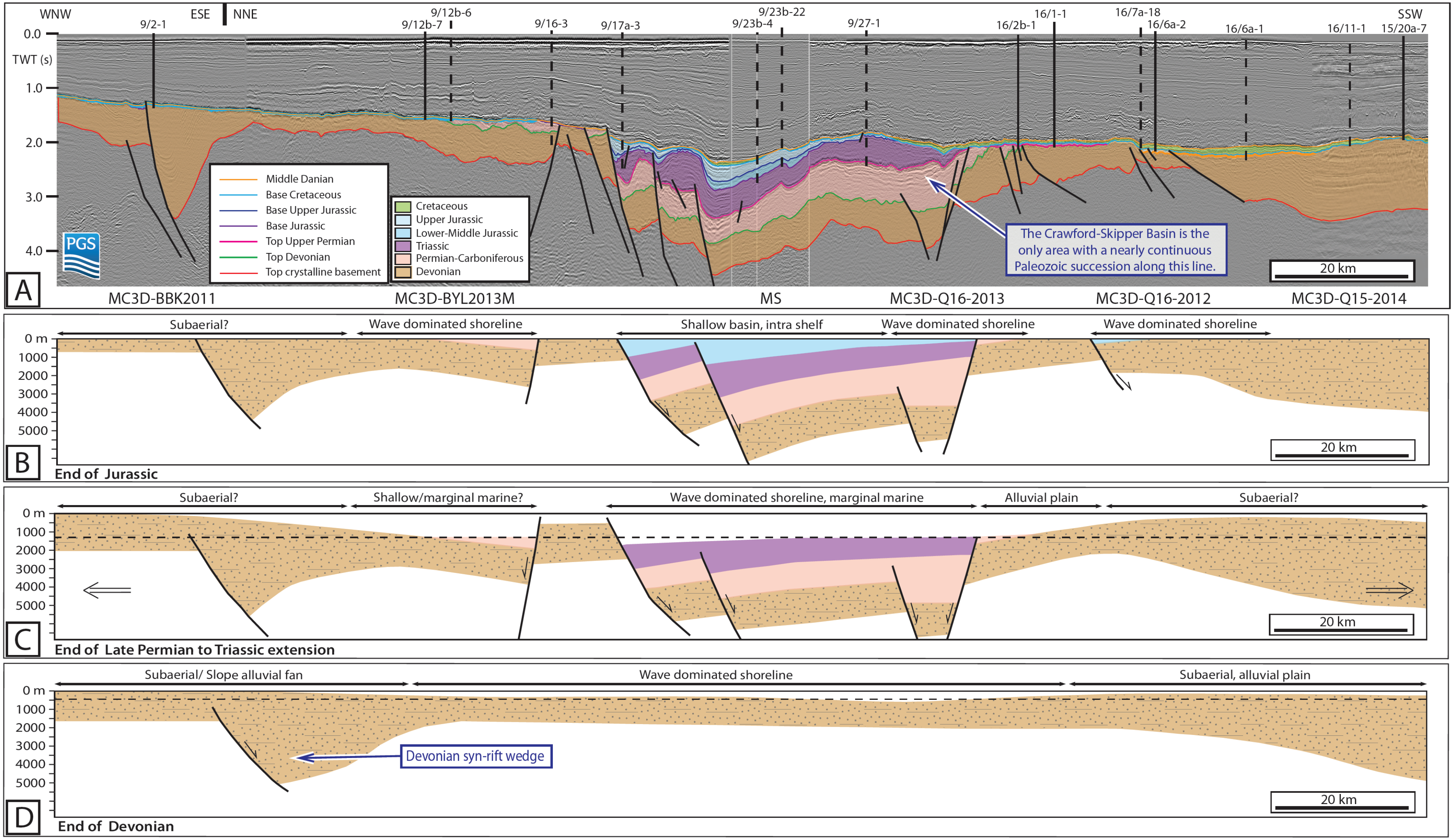

Figure 5 A) Interpreted north-south regional seismic cross-section along Quadrants 9 and 16, showing the transition from the Kraken High into the 'Crawford-Skipper Basin' and to the Fladen Ground Spur High. See Figures 1A, 6-7 for line location. MS = MegaSurvey (conventional streamers). The other surveys are all recent GeoStreamer ones. B-D) A series of cartoons highlighting the structural evolution along the same transect. These were reconstructed based on: stratal geometries (seismic interpretation); inferred depositional thickness trends (seismic interpretation and wells); backstripping analysis of selected wells; facies variations in the wells; knowledge of regional tectonic events.

Discussions: positive implications of intra-platform permo-Triassic basins

Permo-Triassic rifting has been described in several areas throughout the North Sea and northern Europe (Ziegler, 1992; Glennie, 1995; Coward et al., 2003). Examples include the northernmost ESP (e.g., Pobie Fault in Zanella and Coward, 2003) and the Horda Platform to the east of the Viking Graben (e.g., Færseth, 1996). The Crawford-Skipper Basin and the other Permo-Triassic basins that punctuate the outer Greater ESP, however, appear to have been described here for the first time.

The Millennium Atlas, for example, does not mention intra-platform basins on the ESP. The only partial exception therein is represented by maps of Goldsmith et al. (2003) and Glennie et al. (2003), showing preserved Permo-Triassic lobes. The structural map of Zanella and Coward (2003) does not show any fault-related depocentres in the outer ESP, with regional lines that imply a sub-BCU acoustic basement (e.g., their Figures 4.10C-D). Similar inferences were drawn by other authors (e.g., Figure 7 of Ziegler, 1992; Figure 5 of Johnson et al., 2005; Figure 7 of Platt and Cartwright, 1998).

Beyond the academic interest associated with the discovery of new intra-platform basins, there are at least three important implications for the prospectivity of the under-explored Greater ESP. These concern: (1) the formation and geometry of Meso-Cenozoic traps; (2) the Devonian source rock maturity and the related hydrocarbon migration pathways; (3) the presence of deeper, viable, reservoir-trap-seal configurations. The cumulative effect of these positive implications may explain why most discoveries on the Greater ESP are located in close proximity with Permo-Triassic intra-platform basins (e.g., the Crawford-Skipper Basin – Figures 2B-C, 7; Hood in the Piper Shelf – Figure 2D).

Implications on the formation of Meso-Cenozoic traps

Previous authors suggested the presence of inherent zones of weakness that were repeatedly reactivated and inverted during the North Sea polyphase tectonic evolution (Bartholomew et al., 1993). This study highlights tectonic inheritance and repeated inversions in specific zones. For example, the Crawford area evolved from a Devonian high, through a Permo-Triassic rift-related basin (part of the Crawford-Skipper Basin), to the relay ramp of the evolving Viking Graben in the Late Jurassic (Figure 5). Another example is a 20km-long, northeast-southwest-trending Devonian growth fault on the Kraken High, already recognized by Marshall and Hewett (2003). This fault was partially inverted in the Palaeogene (Figure 2A).

Most traps for the existing discoveries on the Greater ESP (e.g., Kraken, Mariner, Skipper, Hood) reveal a connection with deep-seated structures (Figure 2), (c.f., Bartholomew et al., 1993). These Meso-Cenozoic anticlinal and draped traps were formed either due to pre-existing structural-related topographic relief, or caused by the Alpine-age inversion of older extensional features (e.g., Figure 2A). Other examples concern Eocene-age injectite fields (Gryphon-Harding-Maclure; Figure 7), which are situated above the Crawford Spur fault-related basement high (north-east-

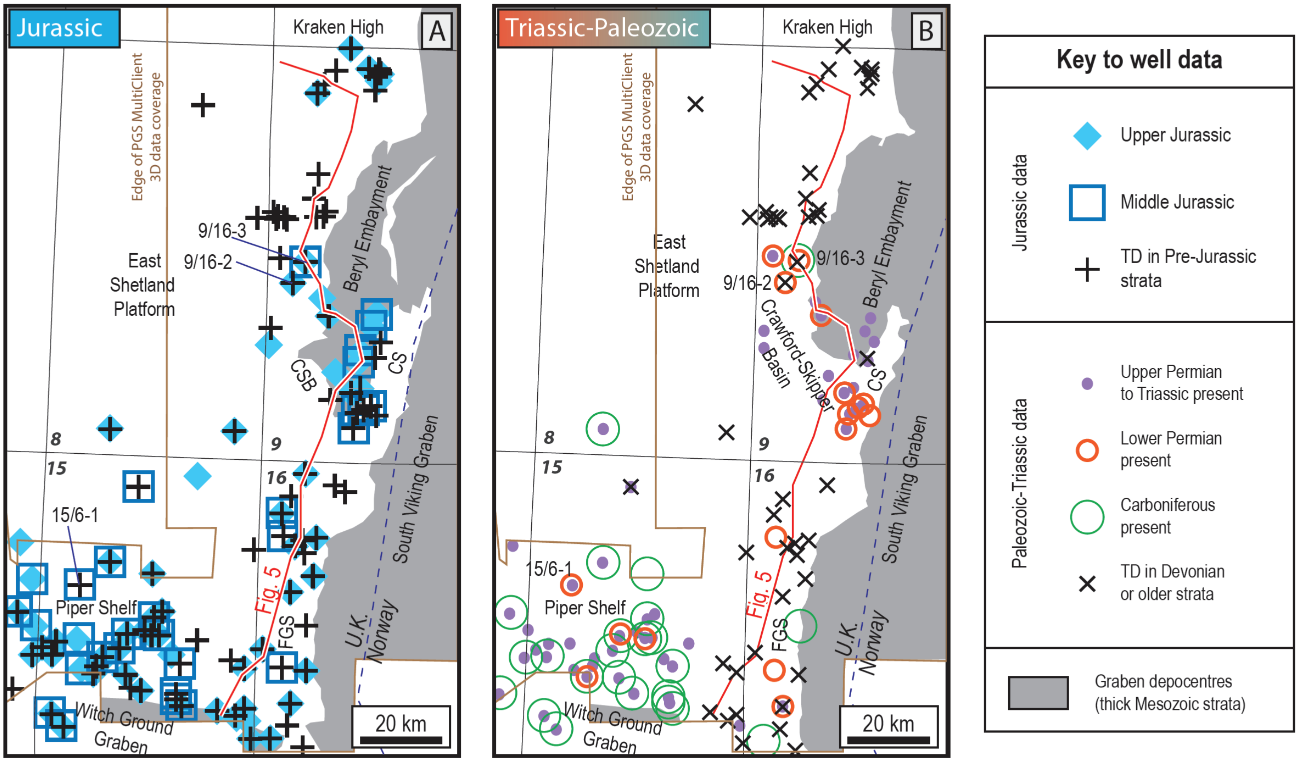

Figure 6 Well result map, showing trends of presence and absence of strata of different age, which in turns reflect regional patterns of erosions. CSB = Crawford-Skipper Basin; CS = Crawford Spur; FGS = Fladen Ground Spur. A) Wells with bottom-hole age older than Top Jurassic that encountered upper Jurassic strata, middle Jurassic strata, both or neither. Lower Jurassic strata are generally absent. B) Wells with bottom-hole age older than Top Triassic that encountered upper Permian-Triassic strata and/or various combinations of strata of different Paleozoic age (lower Permian; Carboniferous; Devonian and older).

ern edge of the Crawford-Skipper Basin). A possible connection between sand overpressuring and buried lineaments is reminiscent of the link suggested by Huuse and Mickelson (2004).

Implications on source maturity and hydrocarbon migration

The highest risk associated with the play models on the Greater ESP utilizing an intra-platform Devonian source rock is related to its maturity timing, with the worst case scenario being of pre-Jurassic hydrocarbon expulsion (see Part 1). In areas hosting very thick Devonian successions, oil maturation for the middle Devonian interval starts as early as the latest Devonian (Figure 7A in Part 1). Therefore, high vitrinite reflectance values for Devonian sediments penetrated in Devonian depocentres (e.g., Fladen Ground Spur, Kraken High) are likely to have been attained pre-Variscan uplift (Figure 9). Geochemical analyses on the maturity of the mid Devonian source rock in Well 9/16-3 (Figure 2), about 11 km to the north of the Crawford-Skipper Basin towards the Kraken High, similarly suggests maximum burial/temperature prior to the Variscan orogeny, with the maturation process 'switched off' at this location as a result of the Variscan uplift (Duncan and Buxton, 1995).

Conversely, areas hosting a thinner Devonian section but a thicker Carboniferous-Jurassic overburden might have caused the middle Devonian rocks to have entered the oil-window post-Middle Jurassic, following most of the regional uplift events that could enhance seal breaching risks (Figure 7A in Part 1). The Crawford-Skipper Basin is characterized by a similar regional stratigraphy to that of such best-case scenarios. In particular, the Devonian package is thinner than 3 km, and is currently buried at a greater depth owing to the presence of a thicker Carboniferous-Jurassic overburden. This implies that the middle Devonian interval is currently mature for oil generation throughout most of the basin depocentre (Figures 3B, 4C) and, simultaneously, this maturity was likely to have been achieved in the post-Carboniferous age. A practical example of this concept is illustrated by Figure 3B. Here, moving away from Well 9/16-3 (where the middle Devonian is currently immature, see Duncan and Buxton, 1995) towards the Crawford-Skipper Basin, the Devonian becomes buried at greater depths under the preserved Triassic-Carboniferous wedge, until it is 'pushed' into the oil window.

Another consequence associated with the presence of deep-seated faults penetrating the Meso-Cenozoic package and stemming from the Devonian units, is that to form pathways for the vertical migration of hydrocarbons from the Devonian source kitchen towards the Meso-Cenozoic traps (Figures 2-4). Similarly, at the edge of the Crawford-Skipper Basin, outwardly tilted Paleozoic monoclinal strata might represent another conduit

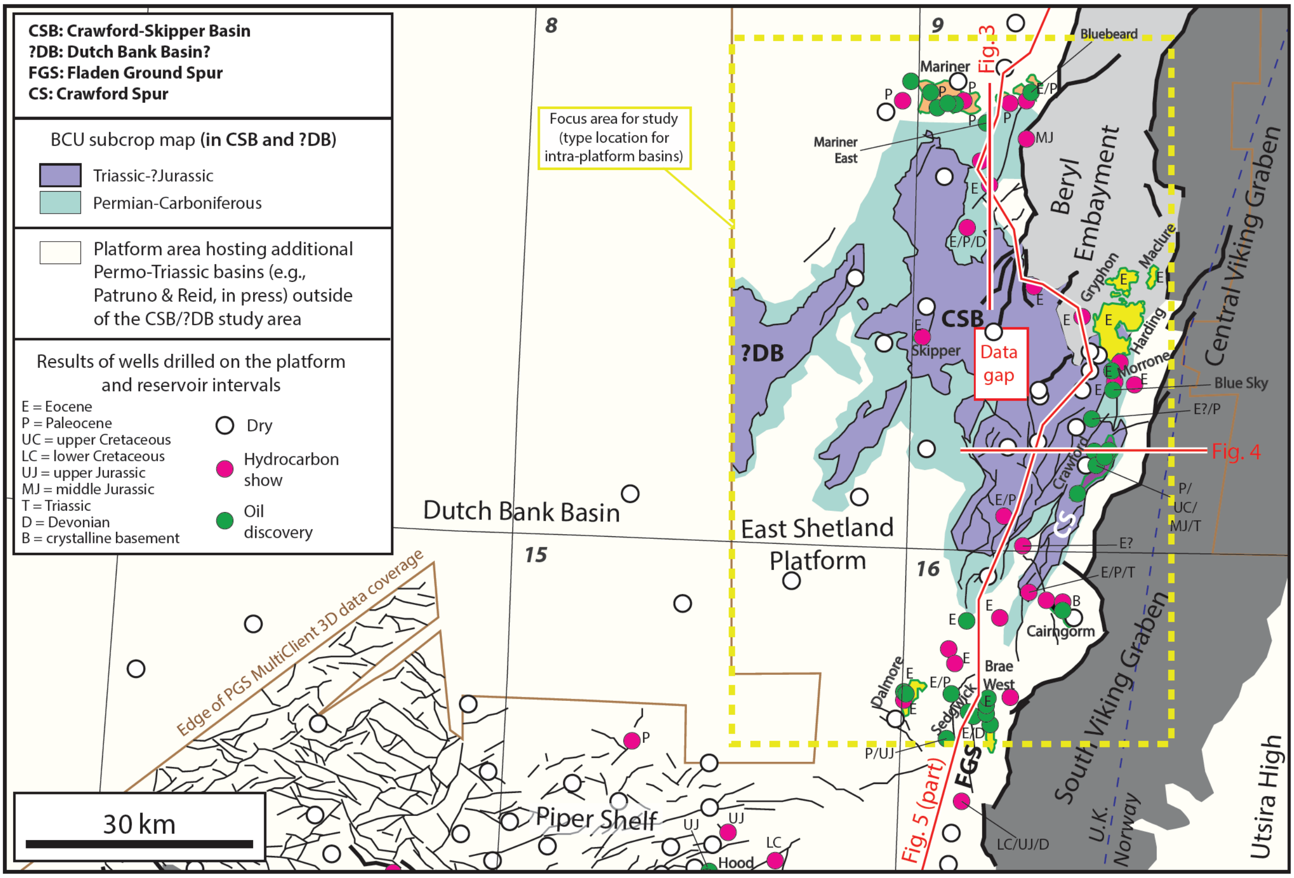

Figure 7 Structural elements in the study area. See Figure 1A for location. In Quadrants 9 and 14-16, intra-platform fault traces are shown, representing the intersections between the fault surfaces and a BCU+0.7 s (TWT) horizon. Intra-platform discoveries and wells are also shown, together with the main reservoirs of 'discovery' and 'hydrocarbon show' wells. The field colours reflect the age of the main reservoir interval (see Figure 1A for key). Several other Permo-Triassic basins are present throughout the rest of the Greater ESP (e.g., Quadrant 15, see Patruno and Reid, in press), but are not shown on this map and are not detailed in this article (which focuses on the Crawford-Skipper Basin).

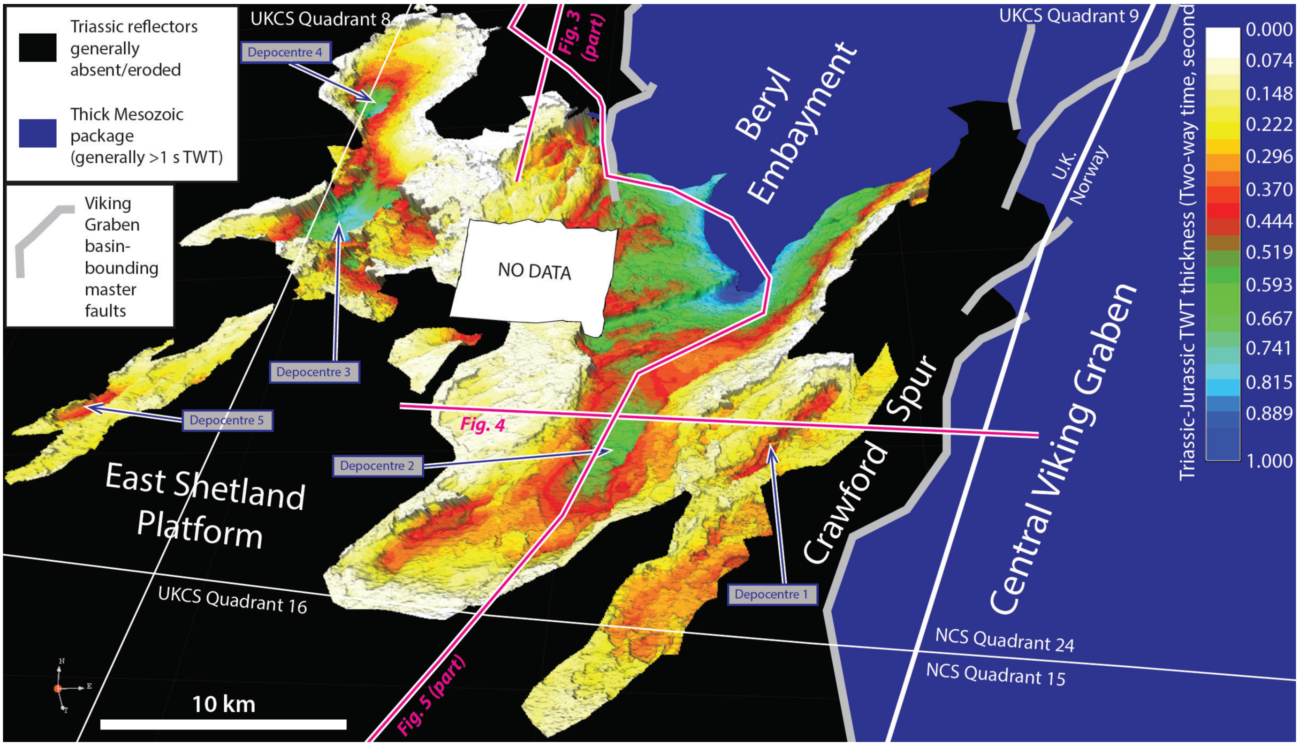

Figure 8 3D view of an isochron map, showing the TWT-thickness of Triassic to Jurassic reflectors in the Crawford-Skipper Basin area. Several discrete depocentres can be distinguished within an area of enhanced Mesozoic-Carboniferous preservation on the platform.

to allow for lateral migration of the hydrocarbon from the source kitchen towards, and beyond, the basin edge (Figures 3B, 4C. This might explain the presence of oil shows in the Devonian sandstones penetrated by well 9/16-2, close to an undrilled horst block (Figure 3B), and might partly clarify why most discoveries on the platform are situated just beyond intra-platform Permo-Triassic basin edges (Figure 7).

Implications on the viability of deeper plays

In the Greater ESP, as well as in many other areas in the Central and Northern North Sea and in the West Shetland Platform, several oil/gas discoveries have a Devonian-Triassic reservoir (Figure 9; Table 1 in Part 2; Figure 6B-C in Part 1). Permian-Carboniferous carbonates and sandstones (Innes, Auk, Argyll/Alma, Claymore, Johan Sverdrup, Ettrick fields), fractured Devonian sandstones (Clair, Buchan, Stirling, Embla, Alma/Argyll fields) and crystalline basement (Edvard Grieg, Lancaster, Whirlwind discoveries) have all been successful in the past. The largest producing fields with Paleozoic reservoirs contain >100 MMboe of ultimate recoverable reserves (e.g., Clair, Buchan, Auk, Lancaster) and up to 1100 MMboe contained by the Devonian reservoir sandstones of the Clair Field, which represents the 6th largest oil discovery in the whole UKCS. (Table 1 in Part 2; Figure 6B-C in Part 1).

Devonian-Triassic rocks can therefore represent good reservoir intervals and legitimate exploration targets. The existing Paleozoic discoveries rely on large structural traps, combined with extensive fracture networks to enhance the reservoir properties. Our analysis has revealed large undrilled Paleozoic structures throughout the Greater ESP (Figures 2-5; Patruno and Reid, in press). There are also areas hosting several large fault blocks and tightly folded anticlines, likely to contain a denser fracture network (Figure 3C in Part 1). These are rare examples, within a mature hydrocarbon basin such as the North Sea, asyet untested, simple, large structures. If successful, this may open up a more rewarding exploration play than the Palaeogene structural-stratigraphic targets.

The additional advantage to target deep structural closures buried beneath Permo-Triassic intra-platform basins (Figures 2B-C, 3-4) is that sub-Cretaceous seal presence, integrity and effectiveness is greater than on regional highs lacking most of the Carboniferous-Jurassic succession (Figures 2A, 3, 5). This interval is in fact largely composed of seal rocks, including mudstones, evaporites and tight carbonates (Figure 2 in Part 1). As discussed in Part 1, more tectonically 'stable' structural configurations may allow traps to hold in place hydrocarbons since Paleozoic times, as demonstrated by the Clair case study (Mark et al., 2005).

The ability to image large structural closures at greater burial depths as a result of the GeoStreamer technology allows for these deep plays to be mapped, explored and potentially exploited.

Conclusions

A working petroleum system with a total of 45 hydrocarbon discoveries exists over the Greater East Shetland Platform (ESP), as detailed in Part 1 of this paper.

The interpretation of new GeoStreamer 3D surveys over the Greater ESP reveals several intra-platform Permo-Triassic depocentres, in areas previously identified as acoustic basement. The most prominent of these is the Crawford-Skipper Basin, between the Kraken High and the Fladen Ground Spur. This basin contains Triassic syn-rift wedges and a relatively continuous Devonian-Quaternary succession. This makes it a good location

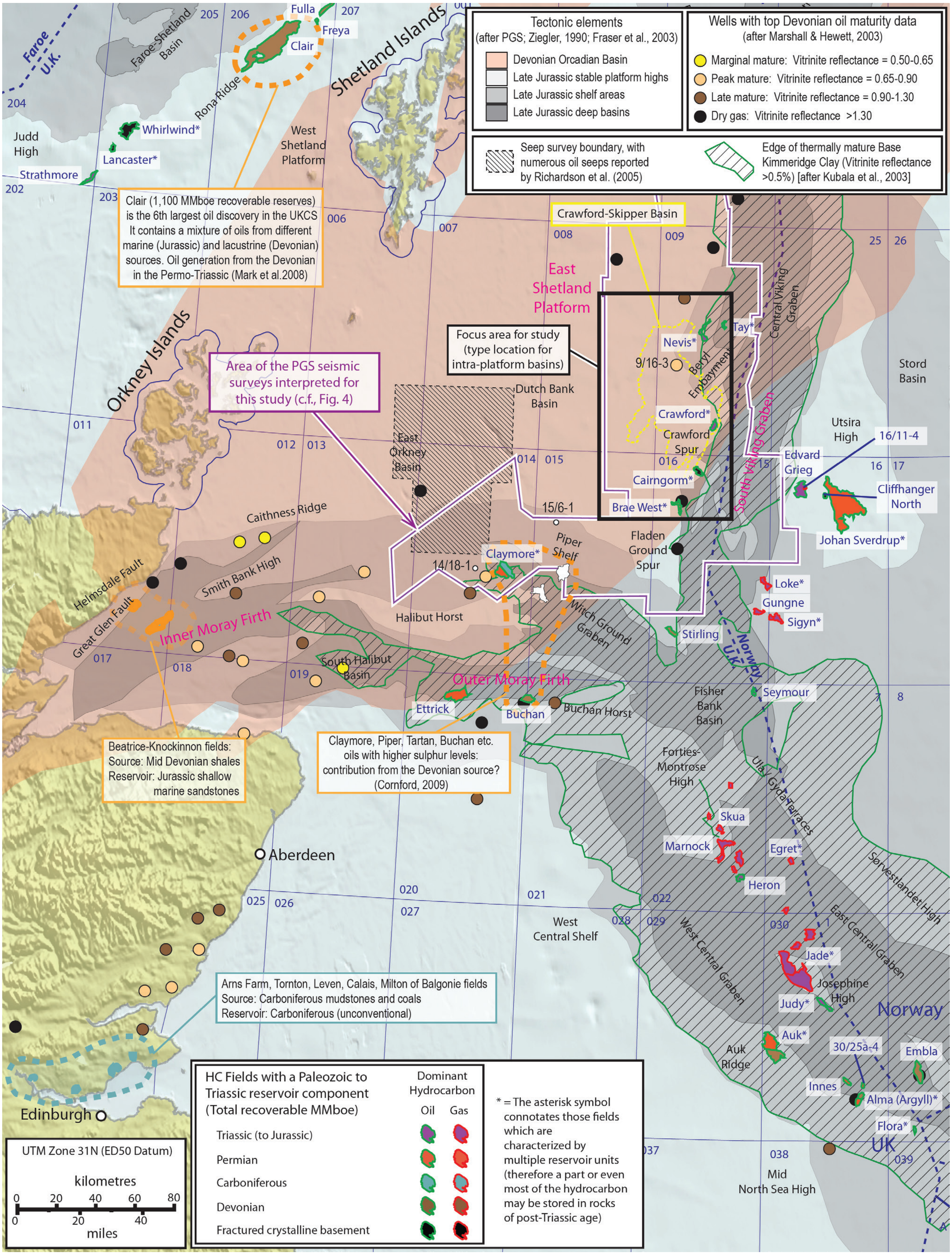

Figure 9 Structural map of the Central North Sea and West of Shetlands region, showing the discoveies with a Paleozoic-Triassic reservoir (see Table 1 for details). Areas of interest for a working pre-Jurassic source rock are also shown (e.g., seep survey, Beatrice Field, high sulphur oils in the Witch Ground Graben; see discussion in Part 1).

for drilling an exploratory well to reconstruct the idealized stratigraphy over this underexplored part of the Orcadian Basin.

Existing hydrocarbon discoveries on the Greater ESP are situated in the immediate vicinities (<7 km) of the Crawford-Skipper Basin and other intra-platform basins. Exploration close to such basins is inherently less risky because of three potential positive influences of deep-seated structures on the overall petroleum system.

Several Meso-Cenozoic structural-stratigraphic closures were formed owing to inherited highs, or to the Alpine-age inversion of deep-seated faults (e.g., Hood, Kraken).

The presence of Permo-Triassic strata pushes the middle Devonian source rock to greater depths, and often places it within present-day oil-windows. Simple fault- and tilting-related pathways are also present within these basins, which could allow for the effective migration of hydrocarbons from the Devonian source kitchen towards the Meso-Cenozoic traps.

Carboniferous to Triassic mudstone-rich basin fills guarantee a more stable and effective sealing of Devonian-Permian targets, allowing for improved trap integrity, even in cases of early hydrocarbon accumulations (c.f., Clair).

In the Central North Sea and West of Shetlands there are several discoveries within fractured basement, Devonian-Permian sandstones and carbonates and Triassic sandstones (e.g., Clair, Buchan, Auk, Alma/Argyll), demonstrating the regional viability of these older reservoirs. Clair, particularly, has 1100 MMboe of recoverable reserves within Devonian-Carboniferous reservoir, which makes it the sixth-largest oil field of the whole UKCS.

Modern seismic reveals significant structures in the Devonian-Triassic section, which were not reliably imaged by conventional legacy data. These include large anticlines and fault-blocks. As nearly all of these features are undrilled, a more rewarding exploration play may be opened up in this frontier region than the smaller Palaeogene targets.

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Please note Table 1 was too large to fit our page format and can be viewed in the PDF online at www.firstbreak.org/patruno-2017. Also some other figures had to be reduced in size for space reasons. They too can be found in the online version at a better resolution.

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Table 1. List of all the Paleozoic discoveries in the UK and Norwegian Central North Sea and West of Shetlands (between latitude 56° and 60.9°), together with the closest Triassic discoveries to our study area (between latitude 58.2° and 60.9°). (*) The named plays refer to pre-Jurassic reservoir components only; however some of these discoveries have multi-component reservoirs. See Figure 9 for location. (**) The ranking of the discoveries and fields in this table reflects the relative size in terms of ultimate recoverable reserves of, respectively, predominantly oil and gas offshore discoveries in either the UK Continental Shelf (UKCS) or the Norwegian Continental Shelf (NCS) (IHS Edin, 2016).

Play*	Discovery name	Discovery well	Location	Year	Current prod. status	Pre-Jurassic* reservoir component(s)	Main reservoir component	Minor reservoir component(s)	Fluid type	Total recoverable reserves	NCS/UKCS reserve ranking**	Density	Tests from pre-Jurassic units
Fractured basement	**16/1-4**	Norway 16/1-4	Utsira High	1993	Discovery	Ordovician granite basement	Ordovician granite basement	-	Gas / cond.	0.56 MMboe	340/375 (gas discoveries, NCS)	-	-
	Cairngorm	UK 16/3a-11Z	Fladen Ground Spur (East Shetland Platform)	1990	Appraising	Silurian granite basement	Silurian granite basement	-	Oil	30.5 MMboe	135/453 (oil discoveries, UKCS)	39 API max	2,016 oil bbl/day; 2.3 gas MMscf/day
	Cliffhanger North	Norway 16/2-18S	Utsira High	2013	Discovery	Paleozoic metamorphic basement	Paleozoic metamorphic basement	-	Oil	18.75 MMboe	130/256 (oil discoveries, NCS)	-	-
	Lancaster	UK 205/21a-4	Rona Ridge (West of Shetlands)	2009	Appraising	Archean granitic gneiss basement	Archean granitic gneiss basement	Lower Cretaceous (Commodore Fm. sandstones and limestones)	Oil	207 MMboe	34/453 (oil discoveries, UKCS)	38 API max	2,350-5,300 oil bbl/day
	Whirlwind	UK 205/21a-5	Flett-Foula Sub-basin (West of Shetlands)	2011	Appraising	Archean granitic gneiss basement	Archean granitic gneiss basement	Lower Cretaceous (Valhall Fm. limestone)	Gas / Cond.	190 MMboe	30/802 (gas discoveries, UKCS)	52 API max	110 oil bbl/day; 6.8 MMscf/day
	Clair	UK 206/8-1A	Rona Ridge (West of Shetlands)	1977	Producing, improved recovery	1) Devonian to Lower Carboniferous (Clair Gp. sandstone and conglomerate) 2) Precambrian (Lewisian Complex gneiss)	1) Devonian to Lower Carboniferous (Clair Gp. sandstone and conglomerate) 2) Precambrian (Lewisian Complex gneiss)	-	Oil / Gas	1,100 MMboe	6/453 (oil discoveries, UKCS)	25 API max	1,502 oil bbl/day from Clair Gp.
Predominantly Devonian (to Lower Carboniferous)	**Brae West**	UK 16/7-2	Fladen Ground Spur (East Shetland Platform)	1975	Producing, improved recovery	Devonian (Buchan Fm. sandstones)	Lower Eocene (Balder Fm. sandstones)	1) Devonian (Buchan Fm. sandstones) 2) Lower Eocene (Flugga Mb. sandstones)	Oil / Gas	108 MMboe	65/453 (oil discoveries, UKCS)	38 API (Devonian); 23 API (Eocene)	In Devonian: 3,700 oil bbl/day
	Buchan	UK 21/1a-1	Buchan Graben (Outer Moray Firth)	1974	Producing	Devonian-Lower Carboniferous (Old Red fluvial sandstones) [porosity 8.9%]	Devonian-Lower Carboniferous (Old Red fluvial sandstones) [porosity 8.9%]	-	Oil / Gas / Cond.	227.7 MMboe	32/453 (oil discoveries, UKCS)	34 API max	2,177 oil bbl/day; 0.35 gas MMscf/day
	Freya	UK 206/10a-1	West of Shetlands	1980	Discovery	Devonian to Lower Carboniferous (Clair Gp. sandstones)	Devonian to Lower Carboniferous (Clair Gp. sandstones)	Upper Cretacoues (Whiting Sands Unit)	Oil	20 MMboe	181/453 (oil discoveries, UKCS)	15 API max	-
	Fulla	UK 206/5a-3	West of Shetlands	2011	Discovery	Devonian to Lower Carboniferous (Clair Gp. sandstones)	Devonian to Lower Carboniferous (Clair Gp. sandstones)	Upper Cretacoues (Whiting Sands Unit)	Oil	16.7 MMboe	206/453 (oil discoveries, UKCS)	19 API max	-
	Stirling	UK 16/21a-2	Fladen Ground Spur (East Shetland Platform)	1980	Producing	Devonian (Old Red fluvial sandstones) [porosity 9.5%; permeability 0.75 mD]	Devonian (Old Red fluvial sandstone) [porosity 9.5%; permeability 0.75 mD]	-	Oil	5.2 MMboe	363/453 (oil discoveries, UKCS)	36 API max	2,100 oil bbl/day; 0.5 gas MMscf/day
	Embla	Norway 2/7-9	Central Graben	1974	Producing	Lower Permian to Upper Devonian sandstones and conglomerates	Lower Permian to Upper Devonian sandstones and conglomerates	-	Oil / Gas / Cond.	118 MMboe	57/256 (oil discoveries, NCS)	-	Only Lower Cretaceous tested
	Alma (Argyll)	UK 30/24-2	Argyll Ridge (Mid North Sea High / Central Graben)	1971	Re-developing	1) Upper Devonian (Buchan Fm. sandstones) 2) Lower Permian (Auk Fm. sandstones) 1) Upper Permian (Zechstein Gp. dolomite)	Kimmeridgian to Upper Devonian sandstones and dolomites	1) Kimmeridgian to Oxfordian (Fulmar Fm. sandstones)	Oil / Gas	107 MMboe	67/453 (oil discoveries, UKCS)	34 API max (Devon.); 38.5 API max (Permian)	In Devonian: 2,440 oil bbl/day; 0.33 gas MMscf/day In Permian: 3,825 oil bbl/day; 0.46 gas MMscf/day
Predominantly Permian (to Carboniferous)	**Auk**	UK 30/16-1	Auk Ridge (Mid North Sea High / Central Graben)	1971	Producing	1) Lower Permian (Auk Fm. sandstones and conglomerates) 2) Upper Permian (Halibut Fm. dolomite)	Campanian to Permian brecciated reservoir comprising: 1) Lower Permian (Auk Fm. sandstones and conglomerates) 2) Upper Permian (Halibut Fm. dolomite) 3) Lower Cretaceous (Cromer Knoll Gp. breccia and dolomite breccia) 4) Upper Cretaceous (Chalk Gp.)	-	Oil / Gas	223.3 MMboe	31/453 (oil discoveries, UKCS)	37.2 API max (Upper Permian Halibut Fm. dolomite)	5,920 oil bbl/day (Upper Permian Halibut Fm. dolomite)
	Claymore	UK 14/19-2	Witch Ground Graben	1974	Temp. shut in	1) Carboniferous (Firth Coal Fm. sandstones) 2) Upper Permian (Halibut Fm. carbonate)	1) Oxfordian-Kimmeridgian (Sgiath Fm. and Piper Fm. sandstones) 2) Kimmeridgian-Volgian (Claymore Mb. sandstones)	1) Carboniferous (Firth Coal Fm. sandstones) 2) Upper Permian (Halibut Fm. carbonate) 3) Volgian-Hauterivian (Scapa Mb. sandstones)	Oil	708.5 MMboe	10/453 (oil discoveries, UKCS)	Only Kimmer. Tested	Only Kimmeridgian tested
	Flora	UK 31/26a-12	Central Graben	1997	Abandoned after improved recovery	Stephanian-Westphalian (Flora Fm. fluvial sandstone)	Stephanian-Westphalian (Flora Fm. fluvial sandstone)	Maastrichtian-Campanian (Tor Fm. chalk)	Oil	15.8 MMboe	208/453 (oil discoveries, UKCS)	34 API max	6,500 oil bbl/day (in Carboniferous)
	30/25a-4	UK 30/25a-4	Central Graben	1990	Discovery	Lower Permian (Auk Fm. sandstones)	Lower Permian (Auk Fm. sandstones)	-	Oil	2.17 MMboe	411/453 (oil discoveries, UKCS)	40 API max	350 oil bbl/day; 0.17 gas MMscf/day
	Innes	UK 30/24-24	Central Graben	1983	Abandoned	Lower Permian (Auk Fm. fluvial sandstones)	Lower Permian (Auk Fm. fluvial sandstones)	-	Oil / Gas	7.3 MMboe	335/453 (oil discoveries, UKCS)	45 API max	6,200 oil bbl/day; 7.4 gas MMscf/day
	Ettrick	UK 20/2-1	Outer Moray Firth	1981	Temp. shut in	Upper Permian (Argyll Mb. and Turbot Mb. dolomite)	Volgian-Berriasian (Burns Mb. sandstones)	Upper Permian (Argyll Mb. and Turbot Mb. dolomite)	Oil / Gas	30 MMboe	138/453 (oil discoveries, UKCS)	37.6 API max	28 oil bbl/day (in Zechstein dolomite)
	Johan Sverdrup	Norway 16/2-6	Utsira High	2010	Developing	Upper Permian (Zechstein Gp. limestone) [Permeability 4000 mD]	1) Middle Jurassic (Vestland Gp. shallow marine sandstones) 2) Kimmeridgian-Volgian (Intra-Draupne Fm. sandstones)	Upper Permian (Zechstein Gp. limestone)	Oil	2,307 MMboe	5/256 (oil discoveries, NCS)	40 API max	Permian untested
Predominantly Triassic	**Edvard Grieg**	Norway 16/1-8	Utsira High	2007	Developing	Ordovician (granite basement) Upper Triassic (Hegre Gp. sandstones/ conglomerates	1) Ordovician (granite basement) 2) Upper Triassic (Hegre Gp. sandstones/ conglomerates 3) Callovian-Oxfordian (Viking Gp. sandstones/ conglomerates) 4) Lower Cretaceous (Cromer Knoll Gp. sandstones)	-	Oil / Gas	183.3 MMboe	35/256 (oil discoveries, NCS)	-	5,700 oil bbl/day
	Crawford	UK 9/28-2	Crawford Spur (East Shetland Platform)	1975	Abandoned	1) Mid-Upper Triassic (Skagerrak Fm. sandstones) 2) Upper Triassic (Cormorant Fm. lacustrine sandstones) [Porosity 14.7%]	1) Mid-Upper Triassic (Skagerrak Fm. sandstones) 2) Upper Triassic (Cormorant Fm. sandstones)	3) Bajocian-Bathonian (Pentland Fm. and Hugin Fm. sandstones) 4) Campanian (Shetland Gp. limestone) 5) Upper Paleocene (Heimdal Mb. sandstones)	Oil / Gas	27.6 MMboe	172/453 (oil discoveries, UKCS)	35 API max	2,525 oil bbl/day; 2.5 gas MMscf/day (Trias Skagerrak Fm.)
	Gungne	Norway 15/9-15	South Viking Graben	1982	Producing	Triassic (Skagerrak Fm. alluvial sandstones)	Triassic (Skagerrak Fm. alluvial sandstones)	-	Gas / Cond.	118.5 MMboe	48/375 (gas discoveries, NCS)	53 API max	18 gas MMscf/day; 1,271 cond. bbl/day
	Loke	Norway 15/9-17	South Viking Graben	1983	Producing	Upper Triassic (Skagerrak Fm. sandstones)	1) Upper Triassic (Skagerrak Fm. sandstones) 2) Middle Jurassic (Vestland Gp. sandstones)	Thanetian (Heimdal Fm. sandstones)	Gas / Cond.	11 MMboe	218/375 (gas discoveries, NCS)	-	20.8 gas MMscf/day (in Trias Skagerrak Fm. sandstones)
	Nevis	UK 9/13-4	Beryl Embayment	1974	Producing, improved recovery	Mid-Upper Triassic (Lewis Mb. sandstones)	Middle Jurassic (Hugin Fm. sandstones)	Mid-Upper Triassic (Lewis Mb. sandstones)	Oil / Gas / Cond.	191.6 MMboe	54/453 (oil discoveries, UKCS)	37 API max	From Lewis Mb.: 3,078 oil bbl/day
	Sigyn	Norway 16/7-4	South Viking Graben	1982	Producing	Upper Triassic (Skagerrak Fm. alluvial sandstones)	Upper Triassic (Skagerrak Fm. alluvial sandstones)	-	Gas / Cond./ Oil	78.4 MMboe	91/375 (gas discoveries, NCS)	60 API max.	16.7 gas MMscf/day; 1,730 cond. bbl/day (in Upper Triassic)
	Strathmore	UK 205/26a-3	Solan Basin (West of Shetlands)	1990	Discovery	Lower Triassic (Otter Bank Fm. fluvial sandstones)	Lower Triassic (Otter Bank Fm. fluvial sandstones)	-	Oil / Gas	32 MMboe	131/453 (oil discoveries, UKCS)	-	3,650 Psi pressure (ITPF)
	Tay	UK 9/13b-26	Central Viking Graben (Beryl)	1986	Producing	Upper Triassic (Heron Gp. lacustrine sandstones) [Porosity 14.7%; Permeability 109 mD]	Upper Triassic (Heron Gp. lacustrine sandstones) [Porosity 14.7%; Permeability 109 mD]	1) Rhaetian-Hettangian (Banks Gp. sandstones) 2) Bajocian-Bathonian (Hugin Fm. sandstones)	Oil / Gas	16 MMboe	230/453 (oil discoveries, UKCS)	37.6 API max	7,616 oil bbl/day; 14.3 gas MMscf/day (Triassic Lewis Mb.)