New plays on the Greater East Shetland Platform (UKCS Quadrants 3, 8-9, 14-16) – part 1: Regional setting and a working petroleum system

Stefano Patruno[1*], William Reid[1]

Abstract

Despite significant discoveries within Palaeogene-age reservoirs (e.g., Mariner) the East Shetland Platform (ESP) is under-explored, with only ten wells per 1000 km². 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 km² 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

The Greater East Shetland Platform (Greater 'ESP') is the vast region (c. 62,000 km²) lying to the footwall of the border faults of the Viking Graben, Beryl Embayment, East Shetland Basin and Witch Ground Graben (here referred to collectively as 'central basins', Figure 1). 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. (Figure 1A). The Greater ESP, as defined here, is characterized by relatively uniform tectono-stratigraphic elements (Figure 2).

The 'central basin' depocentres are generally characterized by a thick Meso-Cenozoic succession and active Mesozoic extensional structures (Figures 1B-2). The regional stratigraphy of the Greater ESP is instead dominated by thick (≥1.5 km each) Tertiary and Devonian clastic units, occasionally separated by a thin Carboniferous-Mesozoic succession (Figures 2-4; Table 1). Furthermore, in contrast to the 'central basins', the Greater ESP was tectonically less active or even quiescent during the Late Jurassic main rifting event, which shaped the present-day structural grain of the North Sea (Pegrum and Spencer, 1990; Ziegler, 1992; Coward et al., 2003; Fraser et al., 2003). It was instead subject to at least three main phases of uplift and erosion (Figure 2): (1) during the Carboniferous to Middle Permian Variscan orogeny (Seranne, 1992; Zanella and Coward, 2003); (2) during the Aalenian North Sea thermal doming (Ziegler, 1992; Underhill and Partington, 1993; Davies et al., 1999; Coward et al., 2003; Husmo et al., 2003; Johnson et al., 2005; Graversen, 2006); and (3) in the Late Jurassic to earliest Cretaceous period owing to the footwall uplift associated with the activity of the 'central basin' bounding-faults (Davies et al., 1999; Kyrkjebø et al., 2004). These three erosional events lead to the formation of three region-wide erosional unconformities which, in some places, coalesce into composite, long-lasting hiatuses (Figure 2): (1) the Variscan-age 'Saalian Unconformity'; (2) the Aalenian-age 'Mid Cimmerian Unconformity'; and (3) the 'Base Cretaceous Unconformity' (BCU).

The Greater ESP has been underexplored. About ten wells in average per 1000 km² have been drilled to date (c.f., c.

[1] *PGS Reservoir Limited, Weybridge, United Kingdom.*
[*] *Corresponding author, E-mail: stefano.patruno@pgs.com*

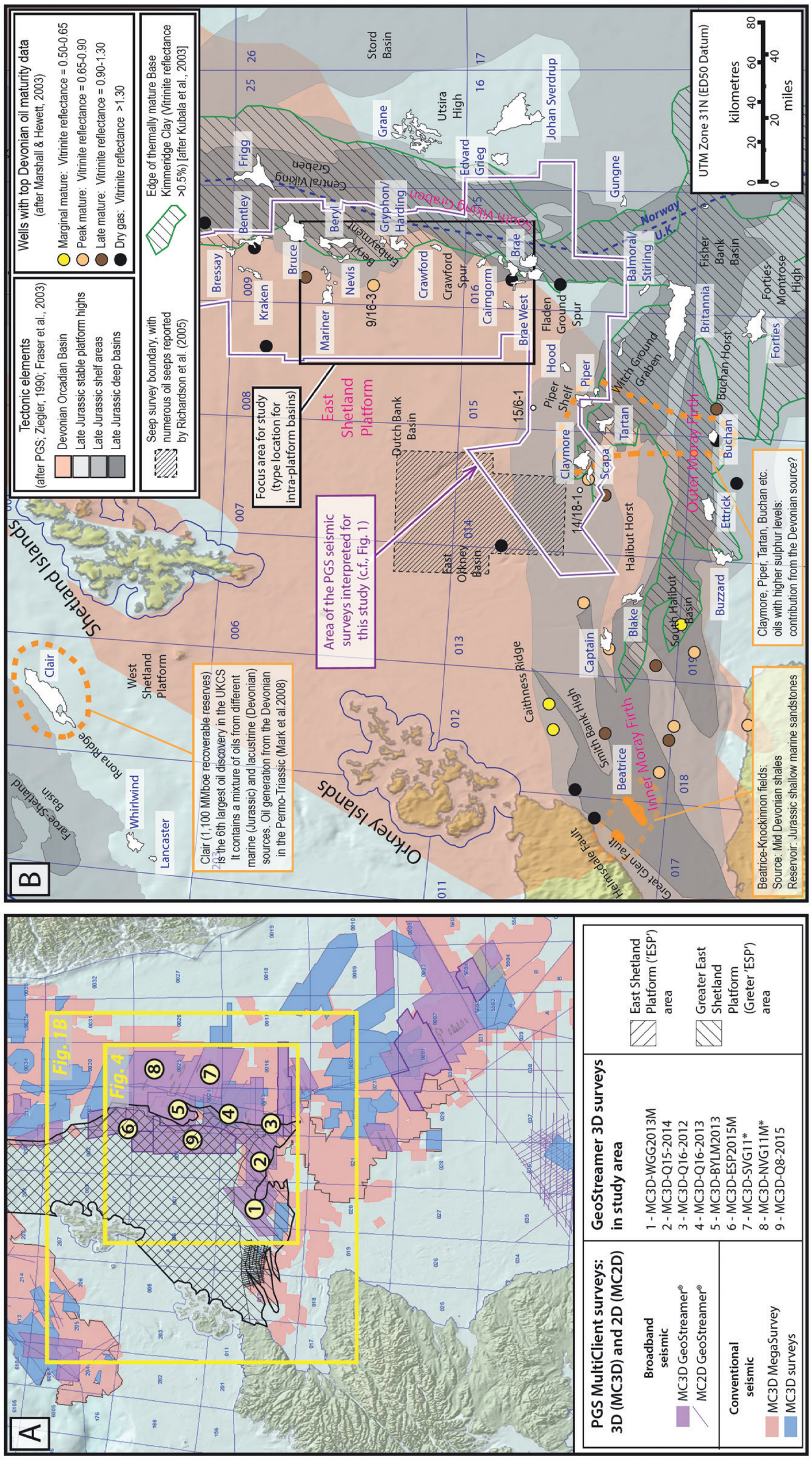

Figure 1 (A) Location map showing the PGS MultiClient data library in the Central North Sea and West of Shetlands. PGS GeoStreamer is a broadband dual-sensor towed streamer system with co-located hydrophones and motion sensors (c.f., Day et al., 2013). (*) The SVG-NVG surveys were acquired in co-operation with TGS. The boundaries of ESP and Greater ESP are drawn according to Fraser et al. (2003). The Greater ESP area comprises the Piper Shelf, East Shetland Platform (ESP) and adjoining structural terraces as well as the transitional zones between the 'central basins' and ESP. The 'Greater ESP' encompasses both ESP and adjoining structural terraces (e.g., Piper Shelf). (B) Regional structural framework of the northern part of the Central North Sea and the West of Shetland region. The location of selected fields is also shown.

55 wells per 1000 km^2 in the 'central basins'). Approximately 83% of these 616 wells were drilled on a narrow 7 km-wide belt straddling the 'central basin' edges. On the remaining 47.000 km^2 wide platform, only 102 wells have been drilled (c. 2 wells per 1000 km^2), mostly on and around existing discoveries. Furthermore, about 76% of wells in the Greater ESP were drilled in the 1970 and 1980s at a time when the conventional 2D seismic data available struggled to image key intervals (e.g., Figures 3-4).

Part 1 of this paper aims to highlight the existing petroleum system on the Greater ESP and its outstanding potential. Part 2 of this paper (*First Break* January, 2017) combines

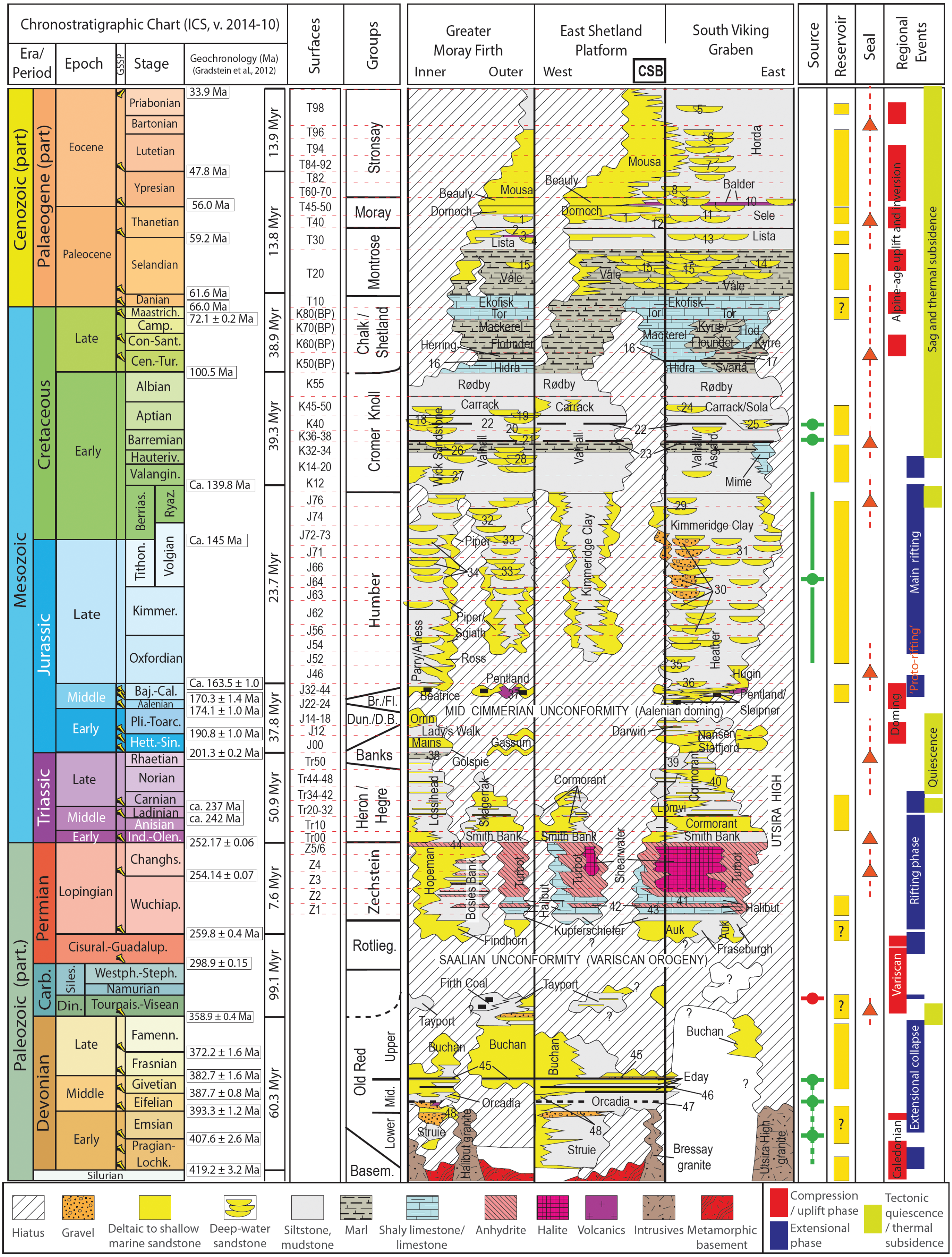

Figure 2 Stratigraphic framework of the ESP and adjacent basinal depocentres (Outer Moray Firth-Witch Ground Graben and South Viking Graben). CSB = Crawford-Skipper Basin. Rotlieg. = Rotliegend Group; Dun./D.B. = Dunlin Group/Dunrobin Bay Group; Br./Fl. = Brent Group / Fladen Group. See Table 1 for key to the minor stratigraphic units, here numbered from 1 to 48.

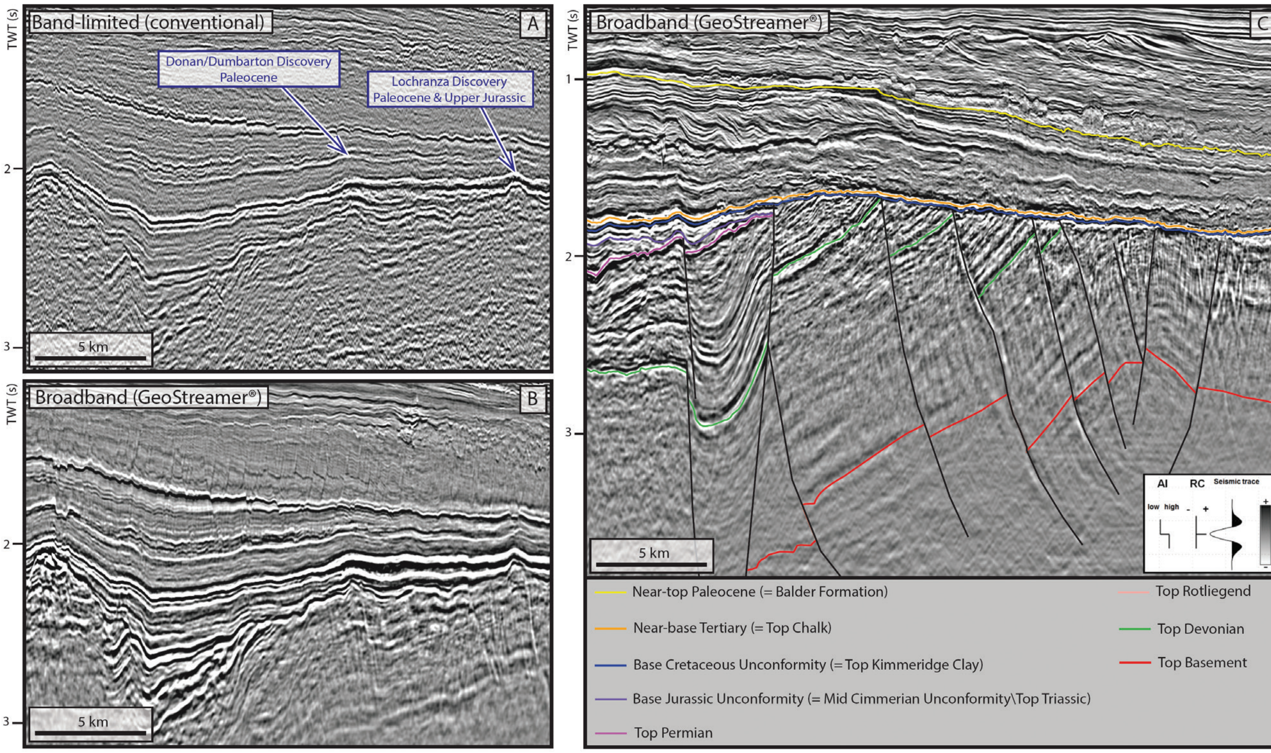

Figure 3 (A-B) Comparison between a line from a conventional 3D seismic dataset (A) and a line from the same location from a 3D GeoStreamer dataset (B) (MC3D-Q15-2014, see Figure 5 for location). Due to the richer frequency content of GeoStreamer, improved imaging is visible at every stratigraphic level, including: (1) less noisy, sharper Meso-Cenozoic reflectors; and (2) pre-rift Paleozoic strata, which might have previously mistaken for acoustic basement (C) Clearly imaged, yet undrilled, large Devonian tilted fault blocks, together with a faulted anticline and a Permian mini-basin (GeoStreamer MC3D-Q15-2014 3D survey, see). An undrilled amplitude anomaly is visible in an upper Paleocene anticline (possibly representing Forties or Mey Sandstones), immediately below the prograding shelf-edge clinoforms of the base Eocene Dornoch Formation. Paleocene sandstones with similar seismic geometries were successfully targeted farther south, towards the Witch Ground Graben (c.f., Figure 5).

seismic interpretation of a 3D GeoStreamer with well data, aiming to dispel some of the long-lasting preconceptions surrounding the Greater ESP and to improve the understanding of the complex tectono-stratigraphic and thermal history of this vast under-explored frontier region.

Despite being underexplored, several oil and gas discoveries were made in the Greater ESP, some of which contain sizeable ultimate recoverable reserves (URR). For example, each of the Mariner, Bressay and Bentley Paleocene discoveries (Quadrant 9) contains 200-300 million barrels of oil equivalent (MMboe) (Table 2, Figures 1B, 5, 6A). With a respective hydrocarbon content of 1147 and 709 MMboe (URR), the upper Jurassic Claymore and Piper fields, at the south-western edge of the Piper Shelf, represent the fifth and the tenth largest oil discoveries on the entire UK Continental Shelf (UKCS) (Table 2, Figures 1B, 5, 6A).

Hydrocarbon discoveries relying on older reservoirs also exist on both the ESP (e.g., Crawford, Stirling, Cairngorm) and nearby areas in the Central North Sea and West of Shetlands (e.g., the Buchan Field in the Outer Moray Firth and Clair Field on the Rona Ridge) (Table 1 in Part 2; Table 2 in Part 1, Figures 1B, 5, 6B). These reservoirs can host sizeable hydrocarbon volumes and thus should not be disregarded as exploration targets. Buchan and Clair, for example, contain 227 and 1100 MMboe (URR) respectively, within fractured Devonian sandstone reservoirs. Clair, in particular, represents the sixth largest oil discovery on the whole UKCS.

Both Jurassic and Devonian source rocks are known to exist on the Greater ESP (Figure 1B). Previous studies have highlighted positive source- and migration-related elements on the platform (e.g., Duncan and Buxton, 1995; Marshall and Hewett, 2003; Mark et al., 2008; Cornford, 2009). These include: (1) oil seeps in the middle of the ESP, highlighting a working source; (2) a mixed Jurassic-Devonian provenance for the oils of large fields around the ESP; (3) mature Devonian source rock intervals penetrated by several wells in the Moray Firth and the ESP (Figures 1B, 4).

Because of the limitations of legacy seismic, much of the ESP has been for a long time conceived as a broad, flat high (Zanella and Coward, 2003) with a shallow acoustic basement and very few visible structures (e.g., Figure 7 of Ziegler, 1992; Platt and Cartwright, 1998; Figures 4.10C-D of Zanella and Coward, 2003; Figure 5 of Johnson et al., 2005). With the recent 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), clearly mappable Paleozoic reflectors are now visible on the Greater ESP, highlighting large, mostly yet undrilled, fault blocks and

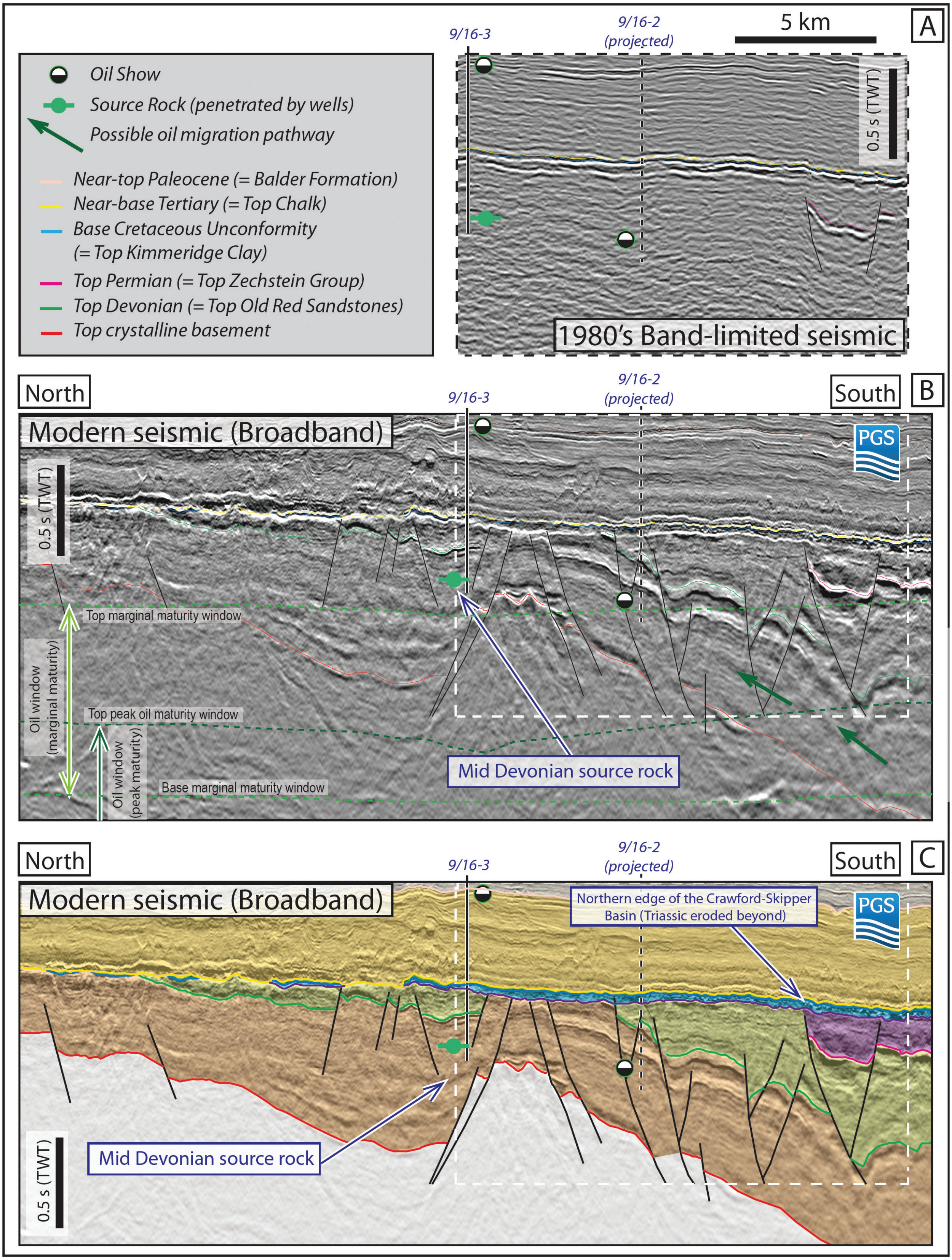

Figure 4 A conventional band-limited seismic line with a shallow tow (1986 acquisition) (A) compared with a GeoStreamer (MC3D-BYLM2013 survey) (B-C). The eastern half of the GeoStreamer line (highlighted by a white dashed polygon) has been extracted along the same north-to-south transect as the conventional line (Figure 5 for location), on the northern ESP (Quadrant 9). The main horizons and the computed depths of the present-day oil window are shown. See Figure 5 for line location; see text for figure discussion.

anticlines (Figures 3-4). A major improvement in the imaging of 'traditional' Meso-Cenozoic targets is also apparent (e.g., Figures 3-4).

Petroleum system of the Greater ESP

A total of 45 hydrocarbon discoveries are situated on the Greater ESP (Table 2, Figures 1B, 5-6). These discoveries, together with the further insights revealed by the new GeoStreamer seismic data, prove the presence of a working or feasible petroleum system. Such a petroleum system is here subdivided into its constituent components and discussed.

Reservoir

The 45 existing hydrocarbon discoveries are characterized by reservoirs corresponding to 25 individual stratigraphic units, including multi-reservoir fields (Table 2; Figure 6A-B). The diverse range of ages, lithologies and depositional environments (Figure 6A-B) demonstrates the presence of numerous working reservoirs on the Greater ESP.

About 48% of the 65 reservoir components of all the existing discoveries are Early Eocene to Late Paleocene in age, and an additional 5% are Early Paleocene (Figure 5A-B). The reason behind this predominance is that large volumes of deep-marine and shelfal clinoform sediments (c.f., Patruno et al., 2015) were deposited on the Greater ESP owing to the tectonically-induced rejuvenation of the Orkney-Shetland hinterland (Pegrum and Spencer, 1990). All Palaeogene discoveries and stratigraphic units are detailed in Figures 2, 5-6 and Tables 1-2.

About 9% of all the reservoirs on the Greater ESP are Cretaceous in age. The lower Cretaceous deep-marine Scapa Member (Valhall Formation) forms the main reservoir for several discoveries at the north-westernmost transitional zone of the Witch Ground Graben (e.g., Athena, Scapa, Scapa West, Claymore, Highlander; Figures 2, 5-6; Tables 1-2).

Upper Jurassic sandstones constitute another major reservoir (≈19%) for the discoveries on the Greater ESP. Particularly, two upper Jurassic reservoir units dominate the area between

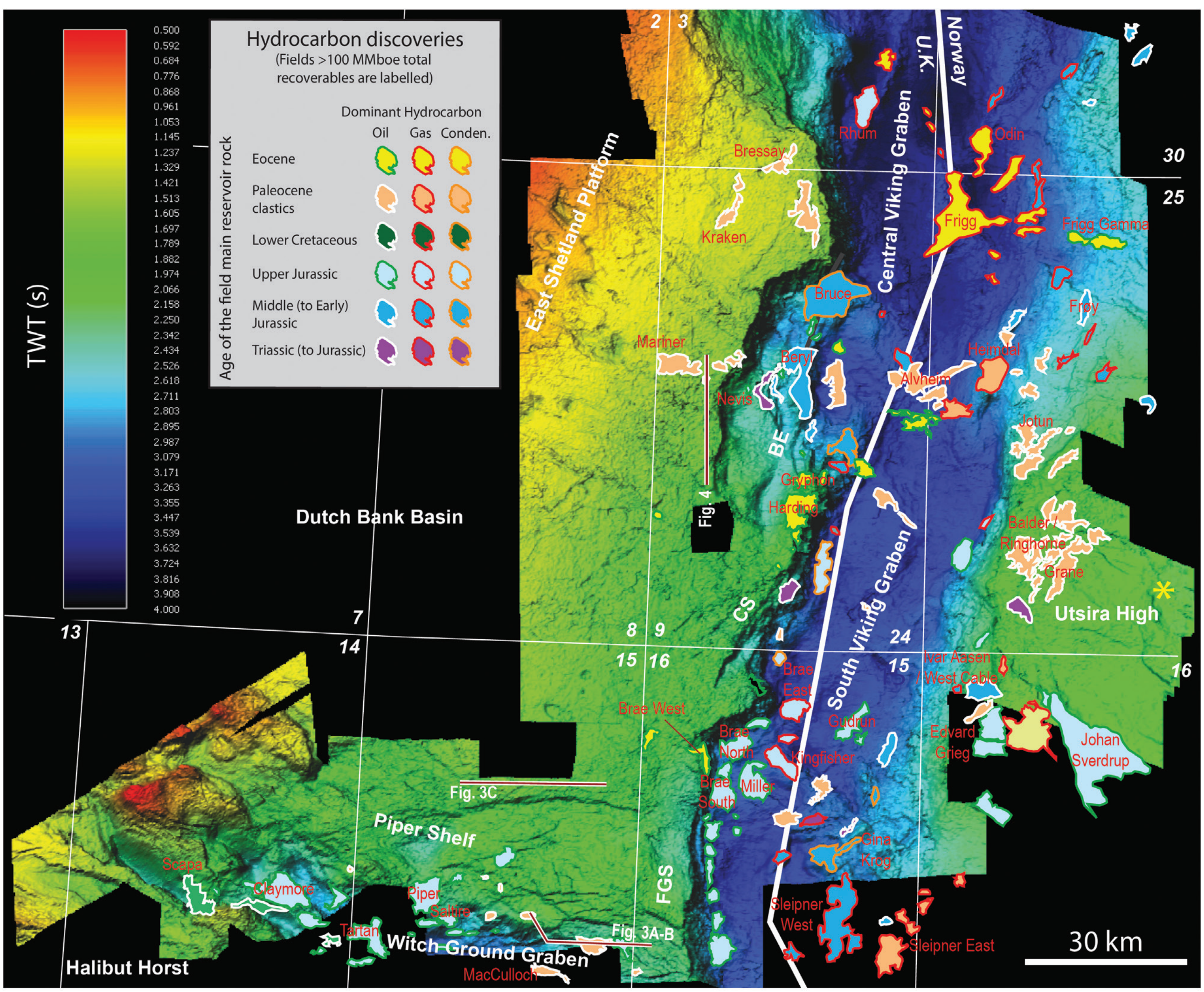

Figure 5 Base Cretaceous Unconformity (BCU) TWT structure map, interpreted on the 9 GeoStreamer 3D surveys highlighted in Figure 1A. The fields and discoveries are also shown, with colours reflecting both the dominant hydrocarbon content and the age of the main reservoir interval. CS = Crawford Spur; FGS = Fladen Ground Spur.

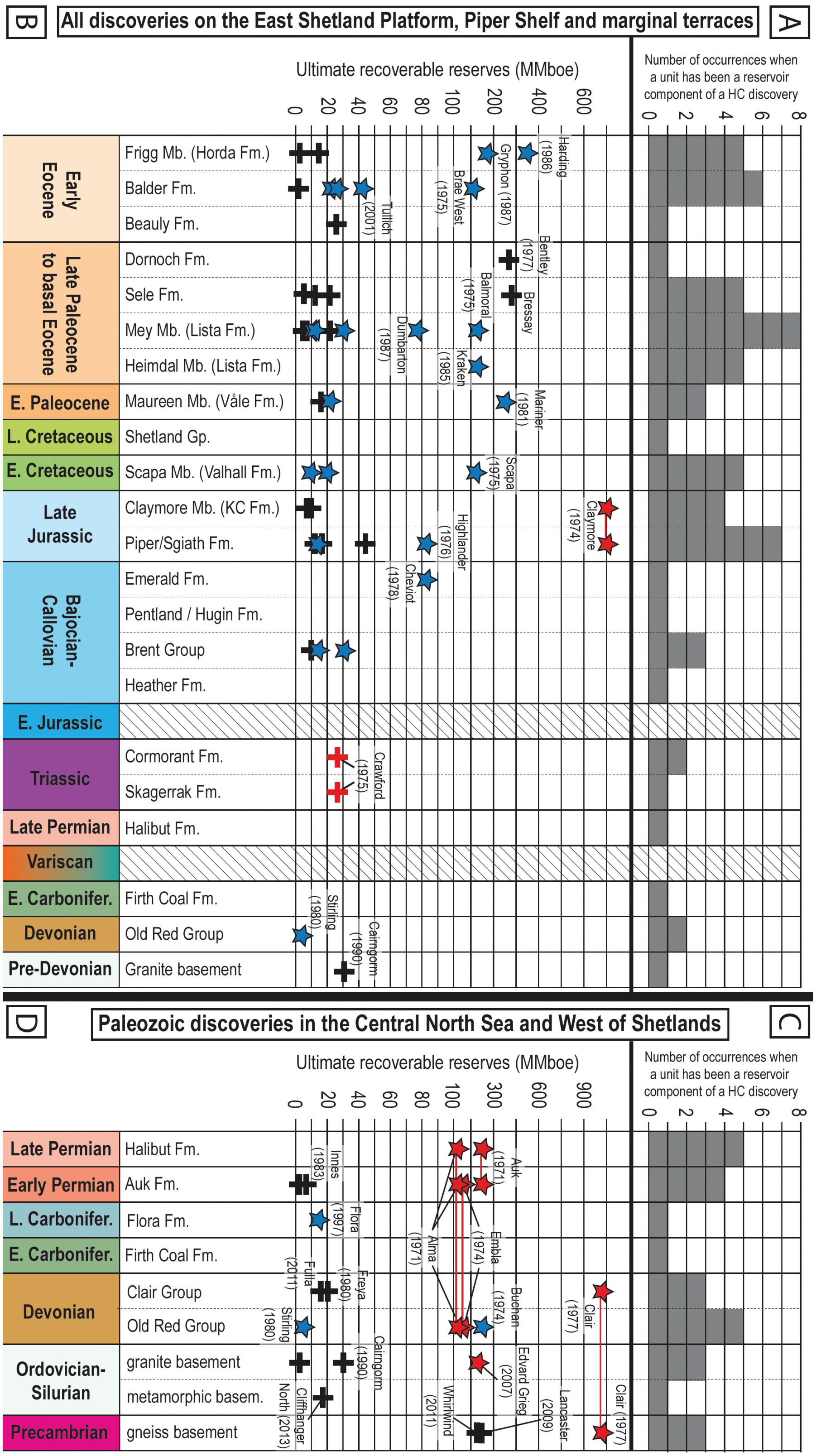

Figure 6 *(A-B) Statistical distribution of the existing hydrocarbon discoveries on the East Shetland Platform, Piper Shelf and adjoining tectonic terraces (see Figures 1-2, 5 and Tables 1-2 for details). (C-D) Statistical distribution of the hydrocarbon discoveries with at least a Paleozoic reservoir component throughout the Central North Sea and West of Shetlands area (see Figure 2 in Part 1 and Figure 9 in Part 2 and Tables 1-2 in Part 1 and Table 1 in Part 2 for details). Parts A and C show all the reservoir components encountered in the study areas (including minor components of discoveries characterized by multiple reservoir configurations); parts B and D only take into account one reservoir component (i.e., the dominant one) for each hydrocarbon discovery. Crosses in A and B indicate hydrocarbon discoveries (yet to be developed); stars represent fields that have been developed or in production (Table 2 in Part 1; Table 1 in Part 2). Red crosses or stars in B and D indicate discoveries with more than one main reservoir interval; the years in brackets indicate when some of the most significant hydrocarbon discoveries were first drilled (Table 2 in Part 1; Table 1 in Part 2).*

the Witch Ground Graben and Piper Shelf (Quadrants 14-15). These include the Kimmeridgian-Volgian deep-marine Claymore Sandstone Member (Claymore, Claymore West, Highlander, Bordeaux discoveries) and the Oxfordian-Kimmeridgian shallow-marine Piper Formation (Claymore, Highlander, Hood, Kildrummy, Balloch, Lochranza) (Figures 2, 5-6; Tables 1-2). Furthermore, a thin upper Jurassic veneer, occasionally with good reservoir qualities, can be found over the Fladen Ground Spur and elsewhere over the ESP, where it represents a frontier exploration target (Figures 2-5).

Middle Jurassic deltaic sandstones are an important reservoir limited to the northern part of the platform (e.g., Cheviot, Barra, Harris, Heather Southwest discoveries). They are missing elsewhere on the Greater ESP, owing to both the regional Aalenian doming-related erosion (Underhill and Partington, 1993; Zanella and Coward, 2003; Husmo et al., 2003) and rift-marginal footwall uplift in the Callovian-Oxfordian (Davies et al., 1999). The Bajocian-Bathonian Pentland/Hugin formation sandstones are sporadically preserved in the Central North Sea, where they represent the oldest preserved sediments after the Aalenian doming (Davies et al., 1999). On the eastern edge of the ESP, these

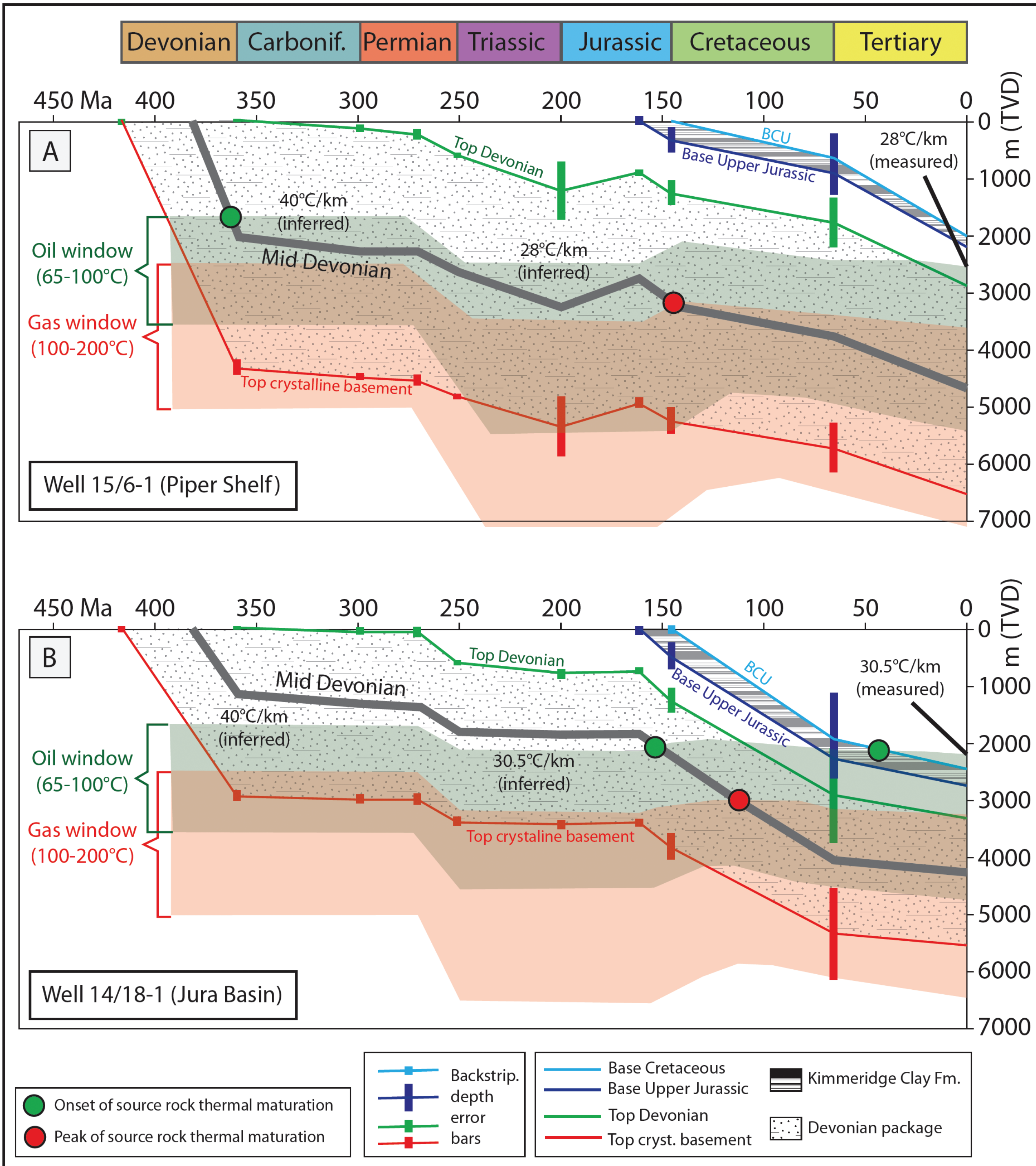

Figure 7 *Total subsidence curves below present-day sea level of backstripped wells 15/6-1 (A) and 14/18-1 (B) (method by Allen and Allen, 2005), versus modelled depths of oil and gas maturation windows.*

units represent a minor reservoir of the Crawford discovery (Figures 2, 5-6; Tables 1-2).

About 12% of the reservoir components for the discoveries on the Greater ESP are Triassic-Paleozoic in age (Figure 6A-B). Triassic fluvio-deltaic sandstones (Cormorant/ Skagerrak formations) represent the key reservoir of the Crawford discovery, as well as a reservoir component for the Heather South-West discovery, at the flank of the East Shetland Basin (Figures 1-2, 5 and Tables 1-2). Minor reservoirs for the chiefly Jurassic Claymore-Highlander fields (Quadrant 14) are represented by upper Permian carbonates (Halibut Formation) and Carboniferous fluvio-deltaic sandstones (Figures 2, 5-6; Tables 1-2). Devonian fractured sandstones (Old Red Group) are the reservoir for the Stirling Field while fractured Silurian granite basement represents the reservoir in the Cairngorm discovery (Figures 2, 5-6; Tables 1-2). Larger Paleozoic producing fields (e.g., Devonian Clair and Buchan fields, with, respectively, 1100 and 228 MMboe URR) are situated just beyond the ESP (Figure 1B and 6B) and demonstrate the regional exploration potential of these older intervals. Clair, particularly, is the sixth-largest oil discovery in the UKCS.

Source

In the 'central basins', Late Jurassic rift-related subsidence allowed for the deposition within fault-bounded depocentres of a thick 'Kimmeridge Clay' Formation, which is prime source rock in the North Sea (e.g., Pegrum and Spencer, 1990). This unit is presently mature in the graben source kitchens, where post-rift subsidence was sufficient to trigger hydrocarbon generation (Figure 1B). The Kimmeridge Clay, however, is absent or, where present, relatively thin (≤10-50 m) and thermally immature over the Greater ESP (Figure 1B). Hydrocarbon discoveries over the platform that are of the Kimmeridge Clay Formation type are situated at up to 30 km away from the edges of the Jurassic source kitchen (Figure 1B), suggesting active lateral migration from the 'central basin' edge to at least 30 km into the Greater ESP area.

Oil seep data in sectors of Quadrants 6, 7 and 14 (Richardson et al., 2005) suggest a working source and/or viable migration pathways at the very centre of the ESP, at up to 80 km away from the closest Kimmeridge Clay source kitchen (Figure 1B). An alternative source rock is hosted by the Devonian Orcadian Basin, encompassing the Greater ESP and Moray Firth areas (Ziegler, 1990; Figures 1B, 4). This source rock comprises organic-rich lacustrine intervals within the lower Devonian Struie Formation and middle Devonian Orcadia and Eday Flagstone formations (Figure 2; Marshall and Hewett, 2003; Pedersen et al., 2006). The lower Devonian source rock is generally localized in fault-related depocentres, and has been encountered only in the Inner Moray Firth (Marshall and Hewett, 2003). The middle Devonian source rock was deposited in laterally extensive lacustrine basins, and has been penetrated by numerous wells in the Moray Firth (Marshall and Hewett, 2003), the West of Shetlands (Mark et al., 2008) and the ESP (Figures 1B, 4; Duncan and Buxton, 1995). The Devonian sourced the majority of the oil in large Inner Moray Firth fields such as Beatrice (Figure 1B; Marshall and Hewett, 2003) and is likely to have at least partially contributed to the oils in very large fields in the Witch Ground Graben (Figure 1B; Cornford, 2009) and the West of Shetlands (e.g., Clair, Mark et al., 2008).

The key risks associated with the Devonian source rock are its distribution and maturity timing. Vitrinite reflectance data indicate that this source rock varies from marginal- to post-mature (Figure 1B; Marshall and Hewett, 2003). If generation occurred early on, initial accumulations might have been breached owing to the complex pre-Cretaceous tectonics (Duncan and Buxton, 1995; Figure 2). There are nevertheless exceptions to this rule in cases of more stable traps. For example, the oil of the Clair Field (Figure 1B) is partly sourced from the Devonian, even though the thermal history suggests a Permian expulsion time (Mark et al., 2008). Examples of stable, potentially unbreached, reservoir-trap-seal structural configurations have now been better imaged on the ESP with recent broadband seismic data (e.g., large fault blocks in Figures 3-4 and Part 2).

1D subsidence and thermal modelling was undertaken at key well locations for this study, with well data integrated with seismic interpretation for the deeper tops (Figure 7). The thermal model has been calibrated with temperature data derived from wells and present-day geothermal gradients from geological analogues. The modelling results show that the Kimmeridge Clay is at best marginally mature away from the 'central basins' (c.f., Figures 1B, 4, 7).

The middle Devonian interval is currently mature for oil expulsion over most of the Greater ESP, particularly where the Devonian package is buried at greater depths beneath preserved Permo-Triassic basins (Figure 4). As such the timing of maturation of the middle Devonian source rock varies, but there are places (e.g., parts of Q14-15, Crawford area) where thermal maturation is reached post-Jurassic, thus post-dating the uplift events which could have breached earlier traps (Figure 7B).

Burial history modelling of a well close to Claymore (Figure 7B), suggests that peak maturation of the mid-Devonian was reached from the Cretaceous, which is compatible with migration into Jurassic structural traps, such as Claymore itself. This is consistent with the geochemical analysis of Cornford (2009), which points out that higher sulphur oil is found in major Witch Ground Graben fields (e.g., Piper, Claymore, Tartan, Buchan), and may represent a contribution from the Devonian.

Other potential source rocks are represented by oil-prone lower Jurassic shales and gas-prone lower Carboniferous shales and coals (Pedersen et al., 2006). The Carboniferous interval is generally situated above the top of the gas window in the few areas of the Greater ESP where it is preserved (e.g., on the Piper Shelf – Figures 2-3, Figure 6 in Part 2) and is unlikely to be mature

Traps and seal

On the Greater ESP, most of the Cretaceous-Cenozoic section is muddy to marly, with interspersed sandstone-prone units (Figure 2). For pre-Cretaceous targets, structural/combination traps are often truncated by the BCU and sealed by overlying mudstones and marlstones, or by Carboniferous-Jurassic intra-formational mudstones (Figures 3-4). The BCU two-way-time structure map (Figure 5) shows a Cretaceous to Tertiary overburden of 1-2 seconds (TWT) over most of the Greater ESP. Even the Palaeogene targets are normally buried at time-depths exceeding 1 second (TWT) (Figures 3-4, Figures 2-5 in Part 2), which is likely to guarantee a sufficient seal integrity and lithostatic pressure for Paleozoic to Paleocene reservoirs. The thick Tertiary overburden over much of the area was caused by the Paleogene thermal uplift of the Orkney-Shetland islands (e.g., Pegrum and Spencer, 1990).

The majority of the discoveries on the platform rely on Palaeogene-age traps, ranging from stratigraphic (e.g., Brae West, Bluebeard) to structural (e.g., Balmoral, Beauly, Yeoman, Skipper, c.f., Figure 2C in Part 2) to mixed stratigraphic-structural (e.g., Gryphon, Kraken, Mariner, c.f., Figures 2A-B, 3 in Part 2) (e.g., Gray and Haile, 2011). Upper Jurassic plays between the Piper Shelf and the Witch Ground Graben are structural (e.g., Claymore) or mixed stratigraphic-structural (e.g., Highlander, Hood, c.f. Figure 2D in Part 2). Older fields rely on predominantly structural, fault-block- and unconformity-related traps (e.g., Crawford, Stirling, Cairngorm; c.f., Figures 3-4). As with existing multi-reservoir discoveries in the study area (e.g., Claymore and Crawford fields – Table 2), some leads on the platform comprise multiple stacked reservoirs/targets that may be drilled by a single well (e.g., Eocene clinoforms, Paleocene amplitude anomalies and Devonian fault blocks, Figure 3C).

Both large anticlines and fault-blocks within the Devonian section are visible as a result of the recent broadband seismic data (e.g., Figures 3-4, Figures 2-5 in Part 2; Patruno and Reid, in press). The majority of these features are undrilled and represent new exploration potential in the area. A clear example is shown in Figure 4, where the sub-Tertiary reflectors visible on the GeoStreamer line are absent using conventional seismic data and the Tertiary reflectivity is better defined. A Devonian horst and syn-rift wedge are now visible and old wells, drilled in 1987 (9/16-2) and 1991 (9/16-3) targeting Paleocene prospects, can be better understood. These wells reported mid-Devonian source rock (9/16-3) (c.f., Duncan and Buxton, 1995) and oil shows in the Devonian reservoir (9/16-2), but both clearly missed penetrating the top of the horst structure. A new deep potential play is therefore opened up in this frontier region as a result of the added clarity from modern seismic acquisition and processing.

Multiple sources are known, in the Jurassic and Devonian-Carboniferous. Lateral migrations of 30 km occurred from the Jurassic source kitchens of the Viking Graben and Witch Ground Graben (c.f., Mariner Field). Additional charge may be provided both within and beyond this 30 km 'margin' by vertical/lateral migration from oil-prone Devonian source intervals (c.f., Beatrice and Clair fields). Burial history modelling suggests that the best-case scenario (late generation/expulsion from the Devonian) occurred in parts of this region and is supported by previous geochemical analyses, which postulated Devonian contributions for the oils of major fields near the ESP (e.g., Claymore, Piper, Tartan, Buchan). Oil seep data from Quadrants 6-7 suggest a working source and viable migration pathways at the very centre of the ESP at up to 80 km away from the closest Jurassic source kitchen.

Large Devonian to Eocene traps, an extensive Tertiary seal (>1 s TWT thickness) and a total of 45 hydrocarbon discoveries have been identified on the Greater ESP. These 45 discoveries highlight the presence of 25 proven reservoir units, including: (1) lower Eocene (e.g., Skipper, Brae West fields); (2) Paleocene (e.g., Mariner, Kraken, Bressay, Bentley fields); (3) Jurassic-Triassic (e.g., Crawford, Claymore, Hood fields); (4) Paleozoic sandstones and carbonates (e.g., Cairngorm, Stirling, components in Claymore). About 48% of the reservoirs of the existing discoveries on the Greater ESP are Late Paleocene to Early Eocene in age, while 12% are Triassic and Paleozoic.

Although large Paleozoic hydrocarbon fields exist in nearby areas (e.g., the Clair Field, with Devonian reservoir sandstones, represents the 6th largest oil discovery in the entire UKCS), the Paleozoic-Triassic interval is still the least explored in the ESP. Modern seismic reveals significant structures beneath the Base Cretaceous Unconformity, which were not reliably imaged by legacy data. These include large anticlines and fault-blocks within the Devonian section. As nearly all of these features are undrilled, a more rewarding exploration play may be opened up in this frontier region than the Palaeogene targets.

In Part 2 of this paper (*First Break* January, 2017), the results of the interpretation of the 3D GeoStreamer acquired by PGS over this frontier region will be shown and discussed. The novel elements will be outlined and their significance explained, including newly observed intra-platform Permo-Triassic basins.

Conclusions

A viable petroleum system exists over the Greater East Shetland Platform (ESP).

Please note Table 2 was too large to fit our page format and can be viewed in the PDF online at www.firstbreak.org/patruno-2016. 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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Appendix

Numbers (in Figure 2)	Unit	Parent unit
1	Forties Sandstone Member	(Sele Formation)
2	Balmoral Sandstone (Mey) Member	(Lista Formation)
3	Balmoral Tuffite or Glamis (Mey) Member	(Lista Formation)
4	Andrew Sandstone (Mey) Member	(Lista Formation)
5	Brioc Sandstone Member	(Horda Formation)
6	Grid Sandstone Member	(Horda Formation)
7	Caran Equivalent Sandstone Member	(Horda Formation)
8	Frigg / Skroo Sandstone Member	(Horda Formation)
9	Odin (Beauly) Sandstone Member	(Balder Formation)
10	Balder Tuff Member and overlying Balder Claystone Member	(Balder Formation)
11	Flugga/Hermod Sandstone Member	(Sele Formation)
12	Teal/Skadan Sandstone Member	(Sele Formation)
13	Heimdal Sandstone Member	(Lista Formation)
14	Ty Sandstone Member	(Våle Formation)
15	Maureen Sandstone Member	(Våle Formation)
16	Black Band Bed Member (= Plenus Marl Member)	(Herring Formation)
17	Blodøcks and Tryggvason Formation	(Chalk/Shetland Group)
18	Captain Sandstone Member	(Wick Sandstone Formation)
19	Britannia Sandstone Member	(Carrack Formation)
20	Sloop Sandstone Member	(Valhall Formation)
21	Yawl Sandstone Member	(Valhall Formation)
22	Fischschiefer Bed Member	(Valhall Formation)
23	Munk Marl Bed Member	(Valhall Formation)
24	Skiff Sandstone Member	(Carrack Formation)
25	Ran Sandstone Member	(Carrack/Sola Formation)
26	Coracle Sandstone Member	(Wick Sandstone Formation)
27	Punt Sandstone Member	(Wick Sandstone Formation)
28	Scapa Sandstone Member	(Valhall Formation)
29	Birch Sandstone Member	(Kimmeridge Clay Formation)
30	Brae Formation	(Humber Group)
31	Miller Sandstone Member	(Brae Formation)
32	Dirk Sandstone Member	(Kimmeridge Clay Formation)
33	Claymore/Galley Sandstone Member	(Kimmeridge Clay Formation)
34	Ettrick and Burns Sandstone members	(Kimmeridge Clay Formation)
35	Bruce Sandstone Member	(Heather Formation)
36	Ling Sandstone Member	(Heather Formation)
37	Rattray Volcanic Member	(Pentland Formation)
38	Stotfield Calcrete Member	(Lossihead Formation)
39	Harris Member	(Cormorant Formation)
40	Lewis Sandstone Member	(Cormorant Formation)
41	Argyll Limestone Member	(Halibut Formation)
42	Iris Anhydrite Member	(Halibut Formation)
43	Innes Limestone Member	(Halibut Formation)
44	Morag Anhydrite Member	(Turbot Formation)
45	Eday Marl	(Eday Formation)
46	John O'Groats Fish Bed	(Eday Formation)
47	Achanarras Fish Bed	(Orcadia Formation)
48	Strath Rory Formation	Old Red Group

***Table 1** List of minor ranking stratigraphic units (usually members) in the East Shetland Platform, South Viking Graben and Greater Moray Firth regions. The numbers in the first column of the table refer to those in the stratigraphic column of Figure 2.*

Discovery name	Discovery well	Location	Year	Current prod. status	Main reservoir component	Minor reservoir component(s)	Fluid type	Total recoverable reserves	ESP reserve ranking*	UKCS reserve ranking*
009/23a-06	009/23a-06	CVG Margin	1987	Discovery	Lower Eocene (Frigg Sandstone Member, Horda Fm.)	-	Gas Fields	1.7 MMboe	45/45	581/802 (gas discoveries, UKCS)
009/23b-19	009/23b-19	CVG Margin	1990	Appraising	Upper Paleocene to lower Eocene transition (Sele Fm. sandstones)	-	Gas Fields	11.7 MMboe	35/45	307/802 (gas discoveries, UKCS)
Athena	014/18b-07Z	WGG Margin	1991	Producing, improved recovery	Lower Cretaceous (Scapa Sandstone Member, Valhall Fm.)	-	Oil	10.5 MMboe	36/45	275/453 (oil discoveries, UKCS)
Balloch	015/20b-18Z	FGS (ESP)	2010	Producing	Upper Jurassic (Piper Formation sandstones)	-	Oil & Gas	14.2 MMboe	31/45	239/453 (oil discoveries, UKCS)
Balmoral	016/21-01	FGS (ESP)	1975	Producing, improved recovery	Upper Paleocene (Mey Sandstone Member, Lista Fm.)	-	Oil & Gas	127.0 MMboe	8/45	58/453 (oil discoveries, UKCS)
Barra (Western Isles)	210/24a-08	ESB Margin	1996	Developing	Middle Jurassic (Brent Gp. sandstones)	-	Oil	15.6 MMboe	29/45	226/453 (oil discoveries, UKCS)
Beauly	016/21c-32	WGG Margin	1998	Temporarily shut-in	Upper Paleocene (Mey Sandstone Member, Lista Fm.)	-	Oil & Gas	12.7 MMboe	32/45	249/453 (oil discoveries, UKCS)
Bentley	009/03-01	ESP	1977	Appraising	Upper Paleocene to lower Eocene transition (Upper Dornoch Fm. sandstones)	-	Oil	270.9 MMboe	4/45	27/453 (oil discoveries, UKCS)
Bladon	016/21d-31	FGS (ESP)	1996	Abandoned	Upper Paleocene (Mey Sandstone Member, Lista Fm.)	-	Oil & Gas	4.8 MMboe	43/45	365/453 (oil discoveries, UKCS)
Blenheim	016/21b-21 (P01)	FGS (ESP)	1990	Abandoned	Upper Paleocene (Mey Sandstone Member, Lista Fm.)	-	Oil & Gas	21.9 MMboe	24/45	173/453 (oil discoveries, UKCS)
Blue Sky	009/23a-30	CVG Margin	2001	Appraising	Upper Paleocene to lower Eocene transition (Sele Fm. sandstones)	-	Oil & Gas	21.4 MMboe	26/45	181/453 (oil discoveries, UKCS)
Bluebeard	009/12-03	ESP	1975	Discovery	Lower Paleocene (Maureen Sandstones Mb., Våle Formation)	Eocene (Stronsay Gp. sandstones)	Oil	17.2 MMboe	28/45	202/453 (oil discoveries, UKCS)
Bordeaux	014/18-01	WGG Margin	1978	Discovery	Upper Jurassic (Claymore Sandstone Member, Kimmeridge Clay Fm.)	-	Oil & Gas	10.2 MMboe	38/45	281/453 (oil discoveries, UKCS)
Brae West	016/07-02	FGS (ESP)	1975	Producing, improved recov	Lower Eocene (Balder Formation sandstones)	1) Devonian (Buchan Formation sandstones) 2) Lowermost Eocene to Uppermost Paleocene (Flugga Sandstone Member, Sele Formation)	Oil & Gas	108.0 MMboe	10/45	65/453 (oil discoveries, UKCS)
Bressay	003/28-01	ESP	1976	Await development approval	Upper Paleocene to lower Eocene transition (Teal Sandstone Member, Sele Fm.)	-	Oil & Gas	291.7 MMboe	3/45	26/453 (oil discoveries, UKCS)
Burghley	016/22-07	FGS (ESP)	2005	Producing	Upper Paleocene (Mey Sandstone Member, Lista Fm.)	-	Oil	12.4 MMboe	34/45	248/453 (oil discoveries, UKCS)
Cairngorm	016/03a-11Z	FGS (ESP)	1990	Appraising	Silurian granite basement	-	Oil	30.5 MMboe	17/45	136/453 (oil discoveries, UKCS)
Cheviot	002/10a-04	ESB Margin	1978	Redeveloping	Callovian (Emerald Formation sandstones)	Paleocene (Montrose Gp. sandstones)	Oil & Gas	82.5 MMboe	12/45	95/453 (oil discoveries, UKCS)
Claymore	014/19-02	WGG Margin	1974	Temporarily shut-in	Oxfordian-Kimmeridgian (Sgiath Fm. and Piper Fm. sandstones) Kimmeridgian-Volgian (Claymore Sandstone Member, Kimmeridge Clay Fm.)	Carboniferous (Firth Coal Fm. sandstones) Upper Permian (Halibut Fm. carbonate) Lower Cretaceous (Scapa Sandstone Mb., Valhall Formation)	Oil & Gas	708.5 MMboe	1/45	10/453 (oil discoveries, UKCS)
Claymore West	014/19b-23	WGG Margin	1989	Discovery	Kimmeridgian-Volgian Claymore Sandstone Member (Kimmeridge Clay Formation)	-	Oil	7.8 MMboe	39/45	313/453 (oil discoveries, UKCS)
Crawford	009/28-02	SVG Margin	1975	Abandoned	Mid-Upper Triassic (Skagerrak Fm. sandstones) Upper Triassic (Cormorant Fm. sandstones)	3) Bajocian-Bathonian (Pentland Fm. and Hugin Fm. sandstones) 4) Campanian (Shetland Gp. limestone) 5) Upper Paleocene (Heimdal Sandstone Member, Lista Formation)	Oil & Gas	27.6 MMboe	21/45	172/453 (oil discoveries, UKCS)
Dalmore	016/06b-06	FGS (ESP)	1997	Discovery	Lower Eocene (Skroo Sandstone Member, Horda Formation)	-	Oil	15.3 MMboe	30/45	229/453 (oil discoveries, UKCS)
Deep Gryphon	009/18b-31	CVG Margin	1998	Discovery	Lower Eocene (Balder Formation)	-	Oil	2.2 MMboe	44/45	408/453 (oil discoveries, UKCS)
Dumbarton	015/20a-04	FGS (ESP)	1987	Producing, improved recovery	Upper Paleocene (Balmoral Sandstone Member, Mey Mb., Lista Formation)	-	Oil & Gas	78.3 MMboe	13/45	82/453 (oil discoveries, UKCS)
Gryphon	009/18b-07	CVG Margin	1987	Producing, improved recovery	Lower Eocene (Frigg Sandstone Member, Horda Formation)	Lower Eocene (Balder Formation)	Oil & Gas	187.7 MMboe	6/45	49/453 (oil discoveries, UKCS)
Harding	009/23b-05	CVG Margin	1986	Producing, improved recovery	Lower Eocene (Frigg Sandstone Member, Horda Formation)	-	Oil & Gas	350.0 MMboe	2/45	28/453 (oil discoveries, UKCS)
Harding Southeast	009/23b-24	CVG Margin	1990	Producing	Lower Eocene (Balder Formation)	-	Oil	23.3 MMboe	23/45	179/453 (oil discoveries, UKCS)
Harris (Western Isles)	210/24a-11	ESB Margin	2008	Developing	Middle Jurassic (Brent Group sandstones)	-	Oil	31.3 MMboe	16/45	135/453 (oil discoveries, UKCS)
Heather Southwest	002/05-10	ESB Margin	1979	Discovery	Middle Jurassic (Brent Group sandstones)	1) Oxfordian-Callovian Heather Formation sandstones 2) Triassic Cormorant Formation sandstones	Oil & Gas	10.5 MMboe	37/45	274/453 (oil discoveries, UKCS)
Highlander	014/20-05	WGG Margin	1976	Temporarily shut-in	Oxfordian-Kimmeridgian (Piper Formation sandstones)	1) Kimmeridgian (Claymore Sandstone Member, Kimmeridge Clay Formation) 2) Lower Cretaceous (Scapa Sandstone Member, Valhall Formation)	Oil & Gas	83.1 MMboe	11/45	78/453 (oil discoveries, UKCS)
Hood	015/13-02	PS Terrace	1975	Appraising	Oxfordian-Kimmeridgian (Piper Formation sandstones)	-	Oil	12.5 MMboe	33/45	246/453 (oil discoveries, UKCS)
Kildrummy	015/12b-04	PS Terrace	2001	Appraising	Oxfordian-Kimmeridgian (Piper Formation sandstones)	-	Oil & Gas	42.9 MMboe	14/45	114/453 (oil discoveries, UKCS)
Kraken	009/02-01	ESP	1985	Developing	Upper Paleocene (Heimdal Sandstone Member, Lista Fm.)	-	Oil	139.3 MMboe	7/45	50/453 (oil discoveries, UKCS)
Lochranza	015/20a-09	FGS (ESP)	1990	Producing	Upper Paleocene (Balmoral Sandstone Member, Mey Mb., Lista Formation)	Oxfordian-Kimmeridgian (Piper Formation sandstones)	Oil & Gas	30.0 MMboe	18/45	142/453 (oil discoveries, UKCS)
Lowlander	014/20-06Z	WGG Margin	1976	Appraising	Oxfordian-Kimmeridgian (Piper Formation sandstones)	-	Oil & Gas	28.3 MMboe	19/45	165/453 (oil discoveries, UKCS)
Maria	015/18a-12	PS Terrace	2008	Appraising	Uppermost Paleocene (Forties Sandstone Member, Sele Fm.)	-	Oil & Gas	5.5 MMboe	41/45	352/453 (oil discoveries, UKCS)
Mariner	009/11-01	ESP	1981	Developing	Lower Paleocene (Maureen Sandstones Member, Våle Formation)	Upper Paleocene (Heimdal Sandstone Member, Lista Formation)	Oil	258.5 MMboe	5/45	29/453 (oil discoveries, UKCS)
Mariner East	009/11b-11	ESP	1997	Developing	Lower Paleocene (Maureen Sandstones Member, Våle Formation)	Upper Paleocene (Heimdal Sandstone Member, Lista Formation)	Oil	21.8 MMboe	25/45	169/453 (oil discoveries, UKCS)
Morrone	009/23b-21	CVG Margin	1990	Developing	Lower Eocene (Balder Formation sandstones)	-	Oil & Gas	28.3 MMboe	20/45	155/453 (oil discoveries, UKCS)
Scapa	014/19-09	WGG Margin	1975	Intermittent production	Lower Cretaceous (Scapa Sandstone Member, Valhall Fm.)	-	Oil & Gas	119.2 MMboe	9/45	62/453 (oil discoveries, UKCS)
Scapa West	014/19b-E06	WGG Margin	1988	Intermittent production	Lower Cretaceous (Scapa Sandstone Member, Valhall Fm.)	-	Oil & Gas	20.0 MMboe	27/45	192/453 (oil discoveries, UKCS)
Skipper	009/21-02	FGS (ESP)	1990	Appraising	Lower Eocene (Beauly Formation sandstones)	-	Oil	26.8 MMboe	22/45	148/453 (oil discoveries, UKCS)
Stirling	016/21a-02	FGS (ESP)	1980	Producing	Devonian (Old Red sandstone)	-	Oil	5.2 MMboe	42/45	355/453 (oil discoveries, UKCS)
Tullich	009/23a-29A	CVG Margin	2001	Producing	Lower Eocene (Balder Formation sandstones)	-	Oil & Gas	42.5 MMboe	15/45	126/453 (oil discoveries, UKCS)
Yeoman	015/18b-11	PS Terrace	2005	Discovery	Upper Paleocene (Balmoral Sandstone Member, Mey Mb., Lista Formation)	-	Oil & Gas	6.3 MMboe	40/45	329/453 (oil discoveries, UKCS)

Table 2 *List of all the hydrocarbon discoveries to date in the the Greater ESP area including terraces and 'central basin' margins. (see Figures 1B and 5 for location).*

(*) This ranking of the discoveries and fields reflects the relative size in terms of ultimate recoverable reserves in the Piper Shelf and East Shetland Platform (ESP) area (IHS Edin, 2016).

(**) This ranking of the discoveries and fields reflects the relative size in terms of ultimate recoverable reserves (MMbbl oil or MMboe gas) in the UK Continental Shelf (UKCS) (IHS Edin, 2016). Gp. = Group; Fm. = Formation; Mb. = Member, ESP = East Shetland Platform; FGS = Fladen Ground Spur (part of the East Shetland Platform); CVG = Central Viking Graben; SVG = South Viking Graben; PS = Piper Shelf; WGG = Witch Ground Graben; ESB = East Shetland Basin. The ESP and FGS, together with the transitional terraces and highs in the surrounding central basin margins (CVG, SVG, PS, WGG, ESB), comprise the Greater East Shetland Platform. This is characterized by relatively uniform structural-stratigraphic elements.