Paleozoic plays of NW Europe: an introduction

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Abstract: Despite successful production from Carboniferous and Permian reservoirs in the Southern North Sea and onshore Netherlands and Germany, Paleozoic hydrocarbon plays across parts of NW Europe remain relatively under-explored onshore and offshore. This volume brings together new and previously unpublished knowledge about the Paleozoic plays of NW Europe. Improvements in seismic data quality and availability tied to previously unpublished well datasets form the basis for improved understanding of local to regional structural interpretations, depositional environments and basin history. New interpretations move significantly away from generalized basin development models, with improved definition of structural traps and source rock basins feeding to better constrained, locally variable burial, uplift, maturation and migration models. Particularly notable are the significant mapped extents and thickness of Paleozoic source, reservoir and seal rocks. Areas previously dismissed as regional highs and platforms are dissected by Paleozoic basins with evidence for mature source rocks into basin centres. Numerous potential Paleozoic plays or play elements result within thick organic-rich and variably mature successions. Outside or below existing Jurassic and Southern North Sea to onshore Netherlands and German Permian-Carboniferous plays, Paleozoic plays in frontier areas offer significant additional exploration opportunities.

In the 2010s, Government-level policy in countries with North Sea oil and gas fields increased the focus on extending the life of mature basins and opening up new plays, before ageing infrastructure is decommissioned. The aim has been to maximize economic recovery and maintain the energy security of individual countries. In the mature North Sea petroleum province and surrounding onshore plays of NW Europe, Paleozoic petroleum plays offer new exploration targets in frontier areas in shallow waters, either below or close to producing fields.

Carboniferous source rocks and Carboniferous, Permian and Triassic reservoirs and seals have formed a highly productive gas province in the East Irish Sea, the Southern North Sea (SNS) and onshore into the Netherlands and Germany since the 1960s (e.g. Meadows *et al.* 1997; Glennie & Underhill 1998; Fraser & Gawthorpe 2003; Underhill 2003; Cameron *et al.* 2005; Breunese *et al.* 2010; Gast *et al.* 2010; Kombrink *et al.* 2010; Pletsch *et al.* 2010; **Pharaoh *et al.* 2018**; Figs 1 & 2). Substantial quantities of gas have been produced, e.g. *c.* 3400 bcm at 2005 from fields within the Anglo-Dutch and North German basins (Breunese *et al.* 2010), or are estimated, e.g. estimated recoverable volume of 102 bcm (3.6 tcf[1]) of gas in Carboniferous SNS gas fields in the UK sector at 2015 (**Besly 2018**). The discovery and development of fields such as Breagh with its lower Carboniferous reservoir and the Cygnus (Catto *et al.* 2017) Rotliegend Group, Leman Sandstone reservoir have extended beyond the margins of the established plays (Fig. 1) and within a wider stratigraphical range (Fig. 2). The exploration and development success at these fields exemplifies significant remaining Paleozoic play opportunities in adjacent 'frontier' areas. In addition, unconventional and tight gas resources are known and/or under active exploration within Carboniferous rocks across

[1]bcm = billion cubic metres, tcf = trillion cubic feet.

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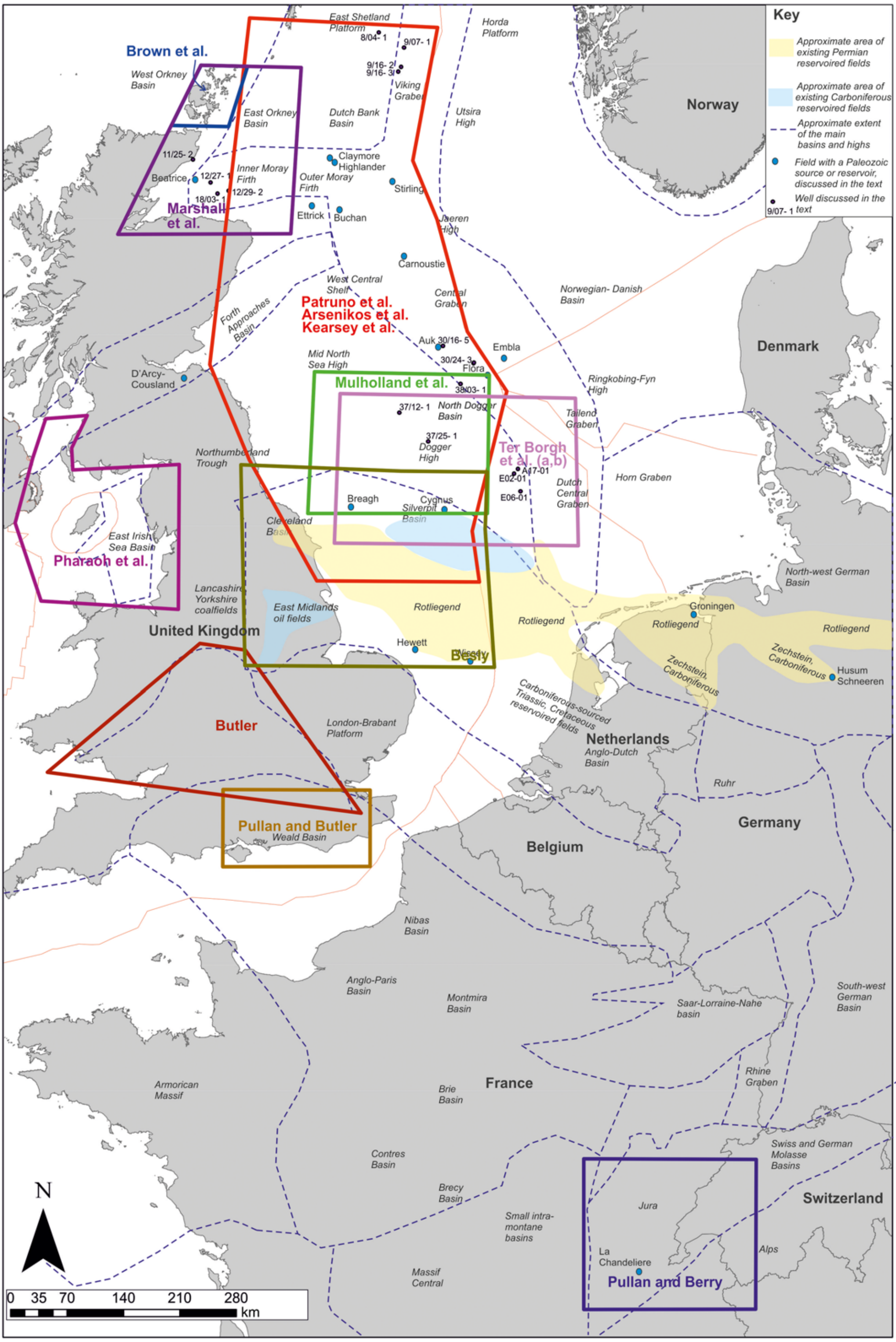
Key
Approximate area of existing Permian reservoired fields
Approximate area of existing Carboniferous reservoired fields
Approximate extent of the main basins and highs
Field with a Paleozoic source or reservoir, discussed in the text
Well discussed in the text
9/07- 1 text
Brown et al.
Marshall et al.
Patruno et al.
Arsenikos et al.
Kearsey et al.
Mulholland et al.
Ter Borgh et al. (a,b)
Pharaoh et al.
Besly
Butler
Pullan and Butler
Pullan and Berry
East Shetland Platform
Horda Platform
8/04- 1
9/07- 1
9/16- 2
9/16- 3
Viking Graben
West Orkney Basin
East Orkney Basin
Dutch Bank Basin
Utsira High
Norway
11/25- 2
Beatrice
12/27- 1
12/29- 2
18/03- 1
Inner Moray Firth
Outer Moray Firth
Claymore
Highlander
Stirling
Ettrick
Buchan
Jaeren High
Carnoustie
West Central Shelf
Central Graben
Norwegian- Danish Basin
Forth Approaches Basin
Auk
30/16- 5
30/24- 3
Embla
Flora
Mid North Sea High
Denmark
D'Arcy-Cousland
38/03- 1
Ringkobing-Fyn High
37/12- 1
North Dogger Basin
Tailend Graben
37/25- 1
Dogger High
Northumberland Trough
A17-01
E02-01
E06-01
Dutch Central Graben
Horn Graben
Breagh
Cygnus
Silverpit Basin
Cleveland Basin
East Irish Sea Basin
North-west German Basin
Lancashire
Yorkshire coalfields
East Midlands oil fields
Rotliegend
Groningen
United Kingdom
Hewett
Wissey
Zechstein, Carboniferous
Husum
Schneeren
Carboniferous-sourced Triassic, Cretaceous reservoired fields
Netherlands
Anglo-Dutch Basin
London-Brabant Platform
Ruhr
Germany
Weald Basin
Belgium
Nibas Basin
Anglo-Paris Basin
Montmira Basin
Saar-Lorraine-Nahe basin
South-west German Basin
Rhine Graben
Armorican Massif
Brie Basin
France
Swiss and German Molasse Basins
Contres Basin
Brecy Basin
Switzerland
Jura
Small intra-montane basins
La Chandeliere
Alps
Massif Central
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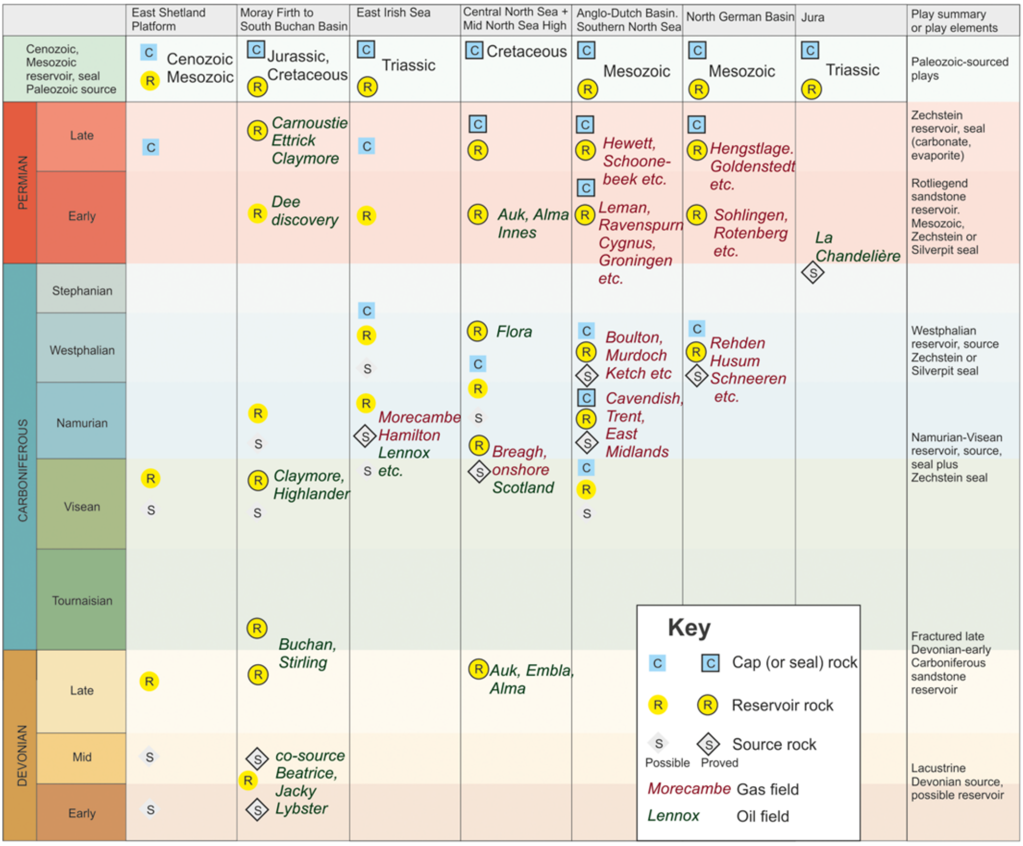

Fig. 2. Summary of proved and possible upper Paleozoic petroleum play elements across NW Europe. Information synthesized and modified from wide range of sources including Bruce & Stemmerik (2003), Marshall & Hewett (2003), Breunese *et al.* (2010), Gast *et al.* (2010), Kombrink *et al.* (2010), Pletsch *et al.* (2010), BGS (2016) and reports therein; Monaghan *et al.* (2016), Patruno & Reid (2016, 2017), BGS (2017), IGI Ltd (2017) and Pullan & Berry (2018).

NW Europe (e.g. USEIA 2013; Clarke *et al.* 2014; Hennissen *et al.* 2017; OGA 2017*a*, *b*).

In the Central–Northern North Sea, lacustrine Devonian source rocks have long been recognized (Andrews *et al.* 1990; Hillier & Marshall 1992; Duncan & Buxton 1995; Marshall 1998; Marshall & Hewett 2003) with renewed exploration interest in their charge to Mesozoic- and Cenozoic-hosted fields and prospects (e.g. Richardson *et al.* 2005; Patruno & Reid 2016, 2017). More widely across NW Europe, Paleozoic source rocks have been documented in the Northern Permian Basin (Pedersen *et al.* 2006; Ohm *et al.* 2012); Permo-Carboniferous source and reservoir intervals are proved in the developing Barents Sea plays (e.g. Van Koeverden *et al.* 2010), as well as forming reservoirs and providing source rock contributions to fields west of Shetland (e.g. Coney *et al.* 1993; Mark *et al.* 2008).

However, in comparison with the well-characterized Jurassic-sourced petroleum systems of the North Sea a number of challenges exist in Paleozoic plays:

- data quality – e.g. seismic below Zechstein evaporites, quality of old well logs; biostratigraphic control for accurate subsurface calibration;

Fig. 1. Approximate areas of interest of the papers in this volume with extent of main basins and highs, selected fields with a Paleozoic involvement and extent of established, producing Paleozoic play systems. Information synthesized and modified from wide range of sources including USGS (1997), Bruce & Stemmerik (2003), Marshall & Hewett (2003), Breunese *et al.* (2010), Gast *et al.* (2010), Kombrink *et al.* (2010), Pletsch *et al.* (2010), BGS (2016) and BGS (2017).

- data availability – e.g. limited well penetrations owing to burial depth, limited sample analyses;
- variable source, reservoir and seal quality over large geological time spans and widespread geographical areas;
- complex structural and maturation/migration history.

As a result, Paleozoic plays can be perceived as complex and risky, with expert knowledge built up through years of experience, and collaboration being particularly important. Historically, the loss of knowledge from company reorganizations related to fluctuations in the oil price has significantly hampered wider understanding of the plays (**Besly 2018**).

Various leading explorationists from industry and academia have suggested that a paradigm shift is required in knowledge and play concepts to open up major new Paleozoic plays and reduce perceived risk. In this volume, **Besly (2018)** discusses the history of Carboniferous gas exploration and production in the UK sector of the SNS and the challenges faced. Five areas of Carboniferous petroleum geology in which the currently accepted status quo is open to question, named the 'founding myths', are described; (1) Westphalian coals as the dominant source rock; (2) lack of reservoir intervals; (3) pessimistic view of intra-formational seals; (4) sub-basin depocentre distribution and migration pathways; and (5) oversimplified tectonic models and burial histories. **Besly (2018)** provides a summary of evidence to question these 'founding myths', which provide new positive insight. Together with papers in this volume and other recently published papers, reports and datasets, evidence is growing of potentially prospective Paleozoic plays.

In the Netherlands, EBN and TNO have been active in understanding Paleozoic plays in the northern offshore Dutch sector (Schroot *et al.* 2006; de Bruin *et al.* 2015; EBN 2015*a*, *b*; **Ter Borgh *et al.* 2018*a*, *b***). Despite the challenge of limited well datasets and a complex structural and burial history, evidence is growing for Rotliegend and Carboniferous (Visean–Namurian) plays (de Bruin *et al.* 2015; **Ter Borgh *et al.* 2018*a*, *b***).

In the UK, following a major review of the oil and gas industry (Wood 2014), the UK Government (the then Department for Energy and Climate Change), Oil and Gas UK and the British Geological Survey (BGS) consulted with industry as to their priorities for future maximizing economic recovery on the UK continental shelf. The 'frontier' plays of the Paleozoic were ranked as top priority for new datasets, regional interpretations and collaborative working. A joint industry project, the 21st Century Exploration Roadmap (21CXRM) Paleozoic Project, was initiated, undertaken by BGS in 2014–16, which included a focus on collaboration, data sharing and release (products at BGS 2016). In tandem, the newly formed Oil and Gas Authority (OGA) acquired and released the results of a £20 million Government-funded seismic survey across the Paleozoic frontier area of the Mid North Sea High, and initiated a number of innovation projects and university research studies to further stimulate exploration, culminating in the 29th Offshore Licensing Round in 2016/17. The 2018 31st Offshore Licensing Round also includes frontier Paleozoic plays of the East Shetland Platform and to the west of Britain, with an additional set of seismic data release, background datasets and interpretative reports released in 2017 (BGS 2017; Frogtech Geoscience 2017; Getech 2017; IGI Ltd 2017; OGA 2017*c*).

Paleozoic Plays of NW Europe conference and aim of this volume

The renewed interest in Paleozoic prospectivity led to a Geological Society of London 'Paleozoic Plays of NW Europe' conference convened by industry, academic, BGS and OGA representatives in May 2016.

This volume contains some of the key papers presented at that conference and aims to bring new insights to Paleozoic petroleum play systems and fill a gap between academic and industry studies. It aims to bring previously unpublished literature into the public domain. Most of the papers presented fall within a scale intermediate between that of Millennium Atlas (Bruce & Stemmerik 2003; Glennie *et al.* 2003; Marshall & Hewett 2003)/Southern Permian Basin Atlas (Breunese *et al.* 2010; Gast *et al.* 2010; Kombrink *et al.* 2010; Peryt *et al.* 2010; Pletsch *et al.* 2010) and field-scale studies and provide a regional overview, forming a data-evidenced framework for future exploration. Several papers are focused on Paleozoic plays outside the extent of mature Jurassic (Kimmeridge) North Sea source rocks (e.g. **Besly 2018**; **Mulholland *et al.* 2018**; **Pullan & Butler 2018**; **Ter Borgh *et al.* 2018*a*, *b***). In some areas, Paleozoic play elements such as those described in papers by **Marshall *et al.* (2018)**, **Patruno *et al.* (2018)** and others provide an additional source beneath existing Jurassic and younger plays (e.g. Moray Firth) or act as a reservoir for migrated Jurassic oil (e.g. Auk-Flora Ridge, Buchan Field). The focus of prospective play systems described in this volume is dominantly upper Paleozoic (Devonian, Carboniferous, Permian). Western European substage timescale names are commonly used (e.g. Heckel & Clayton 2006; Holliday & Molyneux 2006) throughout this volume owing to their basis in biostratigraphical subdivision.

This introductory paper begins with a summary of exploration history of Paleozoic plays. Particular detail has been included on Devonian exploration as this is not documented elsewhere. The increasing knowledge of the structure, stratigraphy, petroleum systems and basin and migration histories of Paleozoic plays across NW Europe is then discussed, placing the new papers in this volume into context. The paper concludes with a summary of current and future exploration opportunities.

Exploration history: Devonian

It is worth taking the opportunity at this time to review the thinking that lay behind the exploration of the Devonian, as both a source and a reservoir. The generation of geologists who led much of this exploration is now passing into retirement and much of the information is anecdotal oral information with the relevant company files long shredded.

As regards Devonian source rocks, it was long known to the onshore geological community that the lacustrine sediments of the Orcadian Basin were rich in organic matter. There had been an abandoned attempt in the 17th or 18th centuries to mine for 'coal' (Miller 1841) at a Cromarty Fish Bed locality (Coal Heugh) based on the assumption that these black shales were related to coals. This was a prediction that was not entirely unwarranted given the existence of the Jurassic Brora Coal further north along the coast and other isolated 'Highland' occurrences of Carboniferous coals (e.g. Inninmore, Morvern). Following the primary survey of Caithness (Crampton & Carruthers 1914), a bituminous shale known locally as the 'black man' was reported. In addition, there have been many records of solid bitumens from onshore Orkney (**Brown *et al.* 2018**) that were numerous enough to be named the mineral Cloustonite. Beds that 'resemble impure oil shales' were also described in Orkney (Wilson *et al.* 1935). Many of these records have been reviewed by Parnell (1983), including a recent account (Parnell *et al.* 2017) of the extensive networks of basement-hosted bitumen veins from the Inverness area that were economically mined from at least the 18th century. These fractures represent a reservoir analogue for the Jurassic sourced hydrocarbons found within 'basement' reservoirs of both the Clair and Lancaster fields and related discoveries/prospects under development by Hurricane Energy. Despite this long record of occurrences of Orcadian bitumens, it proved very difficult for some groups to accept that there could be any source rock other than the Jurassic Kimmeridge Clay. For example, J.G.C.M. Fuller – a senior industry figure in the 1970s development of the North Sea – was an arch proponent of this single Kimmeridge source rock model (see review in Jones & Scott 1980) and regarded it as the only source rock capable of generating significant volumes of North Sea oil. He had a lecture party piece of setting fire to a piece of Kimmeridge Clay to show its richness as a source rock. Whilst very entertaining, this did nothing to disprove the existence of other source rock systems. This was at a time when the Devonian was often regarded as economic basement within the North Sea area. However, there was increasing knowledge from the industry of the source potential of the onshore Devonian which was incorporated in the widely attended fieldtrips to the Moray Firth run by Robertson Research. In addition, there was continuing research from UK universities that was showcased at the Orcadian Basin meeting in Cambridge in September 1984 that was attended by many industrial participants and published as an Orcadian Basin thematic set in the *Scottish Journal of Geology* (Trewin 1985), including three source rock papers.

As documented by **Marshall *et al.* (2018)**, there was a significant inability to recognize top Devonian beneath the Rotliegend Group and this resulted in many long Devonian sections being drilled. Top Devonian was often only recognized when obvious dark-coloured lacustrine mudstones were finally penetrated. However, the offshore section that drew the most attention from exploration geologists was in well 12/27-1. Here in 1982 Burmah Oil were drilling a Jurassic play on a fault block in the Inner Moray Firth. The well was drilled to basement as the agreed target and in doing so revealed (Richards 1985) a kilometre of Early Devonian lacustrine mudstones rich in organic matter. These were the equivalents of the rather poorly exposed and presumed much thinner onshore equivalents around the Strathpeffer area in Easter Ross. This discovery subsequently made the Devonian both a primary and a secondary target. For example, in 1985 Kerr-McGee drilled 12/29-2, which penetrated both a Lower Devonian source rock section and overlying alluvial fan deposits that included a thick interval (*c.* 200 m) of high-porosity (15–21%) sandstone. This was followed by similar wells such as 18/3-1 (1992) and 11/25-2ST1 (1986), the latter being drilled into the Great Glen Fault Zone. The Eday Group equivalent sandstones were tested in Quadrant 13, largely in the 1980s and generally identified at that time as Rotliegend sandstone.

A key Devonian well in the southern part of the North Sea was 30/24-3, drilled in 1972 on what was to become the Argyll Field with its combined Jurassic, Zechstein, Rotliegend and Devonian reservoir section. Well 30/24-3 penetrated an interval of what proved to be a Mid Devonian marine limestone (Pennington 1975) that was considerably distant from any known marine margin and in what was generally believed to be well within the Old Red Sandstone continent. This discovery caused considerable discussion with various counter claims, including that the Devonian stromatoporoid was not truly restricted to marine environments or that it was merely a thick calcrete. Subsequent wells with much better cuttings recovery (Marshall *et al.* 1996), together with core, proved the existence of what was to become known as the Kyle Limestone. This Kyle Limestone has been the target for subsequent exploration, including well 37/25-1 drilled on the Corbenic Prospect in 2009.

The thickest Central North Sea Devonian section was drilled by Mobil in 1975 in well 38/03-1, which penetrated over 1500 m of sandstone before terminating in the Kyle Limestone. In part, this could be palynologically dated as Frasnian to Givetian in age. It was equally unusual in that Devonian 'coal seams' were apparently identified. However, investigation of wireline and mud logs together with analyses (atomic H/C ratio, vitrinite reflectivity, palynology) of hand-picked coal fragments from cuttings shows them to be a drilling mud additive. This additive was found to be coincident with hole rugosities that were of sufficient size to cause cycle skipping on the sonic log and give the appearance of interbedded coals. We can only speculate that the operator continued drilling such a long section based on the presumption that it was drilling through Carboniferous Coal Measures.

There have been rare longer Devonian penetrations on the East Shetland Platform and particularly towards the graben margins. These include wells 9/7-1 (1974), 9/16-2 (1987), 9/16-3 (1991) and 8/4-1 (1994). These are particularly important in that they reveal a stratigraphy and sediment infill that is common to other parts on the Orcadian Basin, including that of SE Shetland. The key stratigraphic markers can be recognized and the infill includes organic matter rich lacustrine sediment. They provide the essential information for focused sub-Permian exploration (**Patruno *et al.* 2018**) on the East Shetland Platform.

Throughout this exploration of the Devonian, there was a continuing debate about the origin of oil from the Beatrice Field (1976; Stevens 1991). This was the considerable oilfield that lies close inshore in the Inner Moray Firth and contained nearly 500 mmboe (millions of barrels of oil equivalent) of heavy degraded oil within a Jurassic reservoir. There has been a continuing history of biomarker analysis of this oil that has paralleled technological advances in organic geochemistry. This has seen the Beatrice oil go from a Jurassic source to a mixed Devonian–Jurassic source (e.g. Stevens 1991) to a wholly Devonian source (Bailey *et al.* 1990), with the final argument based on δ^{13}C values (Marshall & Hewett 2003). This has been paralleled by changes in our understanding of its geological context with claims for long-distance migration (from what proved to be a thermally immature Jurassic section) to more direct evidence of bitumen being sourced from Devonian intervals as in 12/27-1 (Marshall 1998).

As regards the Devonian as a reservoir interval, there were initial early discoveries of Devonian sections within tilted fault blocks and charged from the Mesozoic. For example, the Buchan Field (Quadrants 20/21, fractured Upper Devonian–lower Carboniferous reservoir) was discovered in 1974 (Edwards 1991) and the Stirling Field (Block 16/21) produces from an Upper Devonian reservoir (Gambaro & Currie 2003).

Devonian play elements have been tested by a handful of wells further south, for example penetrations of the Kyle Limestone Group and Buchan Formation (Mid-Upper Devonian) in the Auk–Flora Ridge area (UK Quadrant 30, e.g. wells 30/16-5, 30/24-3, 30/25a-2). The Auk and Argyll (renamed Alma) fields (UK sector blocks 30/16, 30/24 and 30/25) and Embla Field (Norwegian sector, block 2/7) contain proved Devonian fluvial sandstone reservoirs, in fault blocks updip of a Jurassic source (Marshall & Hewett 2003; Ohm *et al.* 2012).

In central-southern parts of the North Sea, a Mid Devonian play system comprising karstified carbonate reef and platform reservoirs fringed by mudstone source rocks and a mudstone seal has been advocated by analogy to Mid Devonian strata in Belgium and the West Canadian Basin (Bełka *et al.* 2010; De Jong *et al.* 2016). However, limited numbers of tests of the Kyle Limestone Group on structural highs either were dry (37/12-1, in 1985) or the target strata were absent (37/25-1, in 2009; ExxonMobil 2010).

In the northern Dutch offshore sector, three wells (A17-1, E06-1 and E02-1) penetrate the Middle–Upper Devonian (Bełka *et al.* 2010). The hydrocarbon potential of the Devonian onshore NW Europe is limited by sparse data and high thermal maturation of source rock intervals, with Bełka *et al.* (2010) stating that there was no hydrocarbon production in onshore areas.

Exploration history: Carboniferous

Onshore UK oil and gas exploration of the Carboniferous sequence in the UK began as early as 1919, with small fields producing in the East Midlands and Yorkshire (1940s to present day; Pharaoh *et al.* 2011) and Midland Valley of Scotland (1960s, Hallett *et al.* 1985). In the early days of North Sea exploration, 1965–70, wells were drilled across the Central North Sea/Mid North Sea High, with many of these wells remaining the only penetrations of the Carboniferous. Bruce & Stemmerik (2003) summarize fields with a Carboniferous component in the Central-Northern North Sea, with details given by Edwards (1991; Buchan) and Harker *et al.* (1991; Claymore).

In the East Irish Sea, the Carboniferous-sourced, Triassic-reservoir Morecambe fields were first drilled in 1969 and discovered in the 1970s (Cowan 1996). Renewed drilling activity in the East Irish Sea from 1989 resulted in the discovery of oil and gas fields such as Hamilton, Douglas and Lennox (e.g. Haig *et al.* 1997; Yaliz 1997).

Many significant gas discoveries in the Carboniferous Southern North Sea play were made between 1984 and 2000 (Cameron *et al.* 2005). The exploration history within the UK Southern North Sea gas basin is further summarized by **Besly (2018)** and references therein. Outside of the Westphalian and Namurian play, the Visean–Namurian Breagh gas field came onstream in 2013, following re-appraisal of gas shows in well 42/13- 2 first identified in 1997.

Kombrink *et al.* (2010), Breunese *et al.* (2010) and Pletsch *et al.* (2010) give details of Carboniferous exploration from onshore UK to the Netherlands–North German Basin, with Schroot *et al.* (2006) and De Bruin *et al.* (2015) giving additional detail on the northern Dutch offshore. Exploration of the first onshore Carboniferous fields (e.g. Coevorden gas field 1951) was followed by discoveries in the gas province of the Cleaver Bank High area, e.g. the 1974 K4-FA field of the Netherlands sector, with discoveries such as Husum Schneeren gas field in Germany from the 1980s (Van Buggenum & Den Hartog Jager 2007; Kombrink *et al.* 2010).

Exploration success based on Westphalian–Stephanian Coal Measures to Autunian (Permian) bituminous shales source rocks within the Variscan basins of France, Switzerland and Germany has been limited (literature summary in BGS 2017) with a case history given by **Pullan & Berry (2018)**.

Exploration history: Permian

Exploration of Permian reservoirs was ignited by the discovery of the major Groningen Field in the northern Netherlands in the late 1950s. Recognition that similar aeolian sandstones were exposed in NE England led to speculation that the Rotliegend Group reservoir may extend beneath the North Sea (Glennie 1998). Exploration drilling during the late 1960s and early 1970s not only confirmed the continuous nature of the sandstone play fairway, but also opened up a major gas province throughout the Southern Permian Basin in which the aeolian and fluvial sandstones ascribed to the Schlochteren or Leman Sandstone Formation were charged by Carboniferous source rocks beneath and sealed by evaporites belonging to the Zechstein Supergroup (Glennie 1998; Glennie & Underhill 1998; Underhill 2003; Gast *et al.* 2010).

By the 1980s, it was clear that the northern limit of the Rotliegend play fairway was defined by the deposits of a large, intracontinental saline Silverpit Lake, the southern margin of which comprised a continental sandy sabkha forming a ‘waste zone’ (i.e. an area that was neither the high-quality reservoir of the Rotliegend or a complete Silverpit seal; Alberts & Underhill 1991; Glennie 1998; Glennie & Underhill 1998; Underhill 2003). Recognition that the Silverpit Claystone Formation could act as a seal for erosionally truncated Carboniferous sequences lying beneath the Base Permian (Variscan) Unconformity led to an exploration campaign for Westphalian and Namurian reservoirs described in the previous section. The recent development of the Cygnus field (Catto *et al.* 2017) has extended the Rotliegend play to the northern edge of the Silverpit Lake.

Some notable, but more limited, exploration success in the Permian Rotliegend Group also occurred in the Northern Permian Basin, most notably at Auk, where oil derived from the Kimmeridge Clay Formation migrated from its kitchen in the Central Graben to fill traps on the rift flanks (e.g. Glennie *et al.* 2003).

The depositional extent of the Zechstein evaporites forms an effective limit to the regional seal. However, whilst that is detrimental for the underlying Rotliegend Group reservoir plays, it has led to gas migrating into Zechstein carbonates (e.g. Hewett field, Cooke-Yarborough & Smith 2003; Underhill & Hunter 2008; Wissey field, Duguid & Underhill 2010; Peryt *et al.* 2010) and Triassic reservoirs belonging to the Hewett and Bunter Sandstone formations (Underhill 2003). The Zechstein and Triassic play continues into the Netherlands sector (e.g. P6 gas field) and onshore into the Netherlands and northern Germany (e.g. Schoonebeek gas field; see Peryt *et al.* 2010). The Zechstein carbonate play has proved to be successful in onshore areas of the Cleveland Basin, UK and the acquisition of new seismic data over the Mid North Sea High has suggested that some similar opportunities may exist there too (Patruno *et al.* 2017; **Mulholland *et al.* 2018**). Farther north, the Zechstein is a reservoir in the Carnoustie, Ettrick and Claymore fields (Glennie *et al.* 2003).

Structural complexity of the Paleozoic

As a result of syn- and post-depositional tectonism, Paleozoic plays are generally faulted, folded and bound by unconformities. Structural traps are common. For example:

- Late Carboniferous–early Permian Variscan inversion, uplift and folding along with NW–SE/WNW–ESE and NE–SW faults formed the many structural traps of the Westphalian UK SNS play (e.g. Cameron *et al.* 2005). Dip and fault closures adjacent to the base Permian unconformity (Variscan) and Permian seal rocks form a major trap type (Pletsch *et al.* 2010).

- The Groningen field onshore the Netherlands, a large structural high, is dissected by east–west- and NNW–SSE-trending faults (Gast *et al.* 2010).
- In the Moray Firth, Mesozoic rifting and Cenozoic uplift control trapping geometries, and in areas lacking Zechstein evaporite seal, faults and tilted saline aquifers that rise to subcrop the seabed may act as key migration pathways (Marshall 1998; Underhill 1991; Hillis *et al.* 1994; Richardson *et al.* 2005; Guariguata-Rojas & Underhill 2017).

High-quality seismic data of kilometres-deep, faulted and folded Paleozoic strata are essential to unravel the structural evolution and its impact on hydrocarbon prospectivity. Seismic data quality can be challenging, especially beneath Zechstein evaporites. Taken together with the cost and availability of seismic data, many studies had, until recently, tended to be localized to block- or field-scale interpretations, lacking semi-regional context. Prior exploration had focussed on significant regional highs observed in two-way travel time, with little widespread mapping of Paleozoic structures or detailed depth conversion.

Significant improvements in seismic data quality and image fidelity of Paleozoic successions have been made in recent years along with a more widespread acquisition of 3D surveys (e.g. Rodriguez *et al.* 2014; Patruno & Reid 2016, 2017; **Patruno *et al.* 2018**; **Ter Borgh *et al.* 2018*b***). Together with the acquisition and release of Government-funded seismic data in the UK sector and regional studies (e.g. De Bruin *et al.* 2015; BGS 2016; **Arsenikos *et al.* 2018**), recent studies greatly improve our understanding of the extent of play fairways along the northern margin of the Southern Permian Basin, the structural complexity of the basin's Paleozoic succession and their combined influence on hydrocarbon prospectivity.

In this volume, **Arsenikos *et al.* (2018)** present regional structure maps of Devonian and lower Carboniferous seismic reflectors based on released and unreleased seismic datasets, re-interpreted well ties and gravity and magnetic studies from the East Orkney Basin and Central North Sea (Fig. 1). Basement inheritance, stress partitioning and the presence of granite-cored blocks are believed to influence the variety of observed fault trends, with sub-basin depocentres cutting across 'platform' areas, and relative highs. Extensive lower Carboniferous and Lower-Middle Devonian source rock intervals are interpreted at depths of around 4–5 km.

Patruno *et al.* (2018) present seismic interpretations from the East Shetland Platform to the Greater Mid North Sea High, highlighting Paleozoic to recent polyphase subsidence and inversion on a variety of trends and linked to variable prospectivity. The lack of a Permo-Triassic rifting phase in the Mid North Sea High platform area and its influence on maturation and migration is contrasted with interpretations of a deep, mature middle Devonian source rock across the East Shetland Platform.

The continuation of Devono-Carboniferous basins and highs (e.g. Elbow Spit High, North Elbow Basin/Outer Rough Basin) and of WNW–ESE and Carboniferous-Permian NE–SW faults from the UK sector of the Southern-Central North Sea (e.g. Cameron *et al.* 2005; Milton-Worssell *et al.* 2010; **Arsenikos *et al.* 2018**) into the Dutch sector is mapped by **Ter Borgh *et al.* (2018*b*)**. Faults with a NE–SW trend are known to cause reservoir compartmentalization (Oudmayer & De Jager 1993; Van Hulten 2010) and both fault sets have potential to generate intra-Carboniferous closures (**Ter Borgh *et al.* 2018*b***).

Paleozoic-sourced potential trapped within inversion structures is highlighted by a number of papers. In the Irish Sea, **Pharaoh *et al.* (2018)** document Variscan inversion structures superimposed on Carboniferous fault blocks and highlight potential prospectivity within the deeply buried Carboniferous–Permian succession and around the margins of the oil- and gas-producing East Irish Sea Basin. **Butler (2018)** documents a regional seismostratigraphic framework of central-southern England that also includes a significant history of inversion and unconformity development within deeply buried sequences, including Variscan inversion over the Midlands Microcraton. Paleozoic to Cenozoic inversion structures also play a role in likely Paleozoic source rock distribution, maturity and migration for a proposed gas source in the Weald Basin of southern England (**Pullan & Butler 2018**). Finally, **Pullan & Berry (2018)** describe a Permo-Carboniferous source and Triassic reservoir proven in a number of small discoveries in thrust-bound structural highs in the Jura fold belt of France and Switzerland.

In summary, high-quality 2D and 3D seismic datasets have allowed detailed mapping of structurally complex Paleozoic successions. Prospective faulted and folded Paleozoic basins and highs are evident across wide areas of the North Sea and onshore. A range of structural orientations, styles and timings evidence polyphase and partitioned extension, strike-slip and inversion applied to an inherited structural fabric and dissected by younger events. Areas previously considered as regional highs (Mid North Sea High, East Shetland Platform) are dissected by Paleozoic basins. New interpretations move significantly away from generalized and simplified basin development models, to better pinpoint structural traps, source rock kitchens and their implications for maturation and migration.

Stratigraphical and facies complexity

High-level summaries of basin and national stratigraphical nomenclature are given in the Millennium Atlas and Southern Permian Basin Atlas (e.g. Bruce & Stemmerik 2003; Marshall & Hewett 2003; Gast *et al.* 2010; Kombrink *et al.* 2010; Pletsch *et al.* 2010) drawing together formal stratigraphic treatise such as the UKOOA volumes (e.g. Cameron *et al.* 1992*a*, *b*; Cameron 1993*a*, *b*), Waters *et al.* (2011), Van Adrichem Boogaert & Kouwe (1993–97) and updated interpretations. However, challenges in Paleozoic stratigraphic correlation and interpretation exist where large, laterally variable volumes of rock are poorly constrained by well and biostratigraphic datasets, and where stratigraphical nomenclature changes onshore to offshore and across basin or country borders. This can hinder facies interpretation and create confusion for prospectivity assessments.

Kearsey *et al.* (2018) present a simplified stratigraphy for the pre-Westphalian Carboniferous rocks of the UK sector from the Outer Moray Firth to Southern North Sea based on revised well and seismic interpretations. Biostratigraphically and lithostratigraphically constrained time slices highlight lateral facies variability within a regionally extensive delta system, mapping more specifically a regional understanding on the distribution of stacked source and reservoir intervals (e.g. Collinson 2005; Kombrink *et al.* 2010) to that farther north (Leeder & Boldy 1990).

Many challenges remain in the detailed understanding of correlation and distribution of Paleozoic strata, based on sparse data and in sequences where facies distribution, extent and thickness exert a strong control on the petroleum system. The impact of facies variations in Zechstein carbonates and anhydrites over the Mid North Sea High to reservoir and seal intervals is described by **Mulholland *et al.* (2018)**. The importance of Rotliegend-age sandstones preserved in areas of low palaeorelief is also highlighted and the predicted extent of each play type is discussed. This adds to a growing interest in the prospectivity of Rotliegend and Zechstein reservoirs to the north of the Silverpit and Southern Permian Basin and above or updip of Visean–Namurian source rocks (see also De Bruin *et al.* 2015; Patruno *et al.* 2017).

The challenges of stratigraphical correlation with largely barren sandstone reservoir intervals have been studied previously in the Westphalian D and Rotliegend of the Southern Permian Basin (e.g. Besly 2005; Rotliegend summary in Gast *et al.* 2010). **Marshall *et al.* (2018)** present revised stratigraphical interpretations of Devonian and Permian Rotliegend sandstones in the Moray Firth that significantly change the understanding of their thickness and distribution. A field analogue in Greenland provides further insight into the nature of the unconformable contact and interpretation of the sandstone units.

New insights into source (distribution, quality, maturity), reservoir and seal

A number of entirely Paleozoic plays are documented across NW Europe, such as the Westphalian-sourced, Rotliegend-reservoired gas play (e.g. Leman, Groningen fields), the Visean–Namurian play (e.g. Breagh) and the Carboniferous-sourced, Zechstein-reservoired play (e.g. Hewett, Schoonebeek fields; Fig. 2). Many more fields and plays have a Paleozoic source rock (e.g. Triassic-reservoired fields of the East Irish Sea and Anglo-Dutch Basin, Devonian co-sourced, Jurassic-reservoired fields in the Moray Firth) with migration into Mesozoic and Cenozoic reservoirs. Given the thickness and diversity of organic-rich successions, it is unsurprising that Paleozoic plays of NW Europe comprise a diverse range of petroleum system elements in a variety of play fairways. New work presented in this volume increases understanding of stratigraphical, facies, structural, thermal and burial history variability within the Paleozoic successions, which highlights some of the future opportunities and plays.

In a detailed examination of the Visean–Namurian play proved by the Breagh field, changes in fluvio-deltaic to basinal shale depositional facies, NE to SW across the southern part of the Central North Sea, are shown by **Ter Borgh *et al.* (2018*a*)** and **Kearsey *et al.* (2018)** to influence reservoir and source rock prospectivity. Post-well analysis in the Dutch sector by **Ter Borgh *et al.* (2018*a*)** demonstrates invalid tests, drilled off-structure by the majority of existing wells, leading to the suggestion of significant hydrocarbon potential remaining untested within this play.

Brown *et al.* (2018) summarize the evidence for an exhumed Devonian petroleum system on Orkney, sourced by lacustrine laminites. Oil seeps are associated with faults and bitumen-bearing sandstones crop out within a broad anticlinal structure. Onshore observations provide insight to Devonian-sourced hydrocarbons, potential Devonian reservoir intervals and migration histories in the Moray Firth to East Shetland Platform offshore to the east.

Possibilities for further Paleozoic prospectivity onshore related to relatively structurally complex settings include a marine Devonian shale source for dry gas in Mesozoic reservoirs of the Weald Basin of southern UK advocated by **Pullan & Butler (2018)** based on isotopic, gas composition and maturity data. The distribution of Paleozoic rocks beneath the Variscan and Acadian unconformities is poorly defined by data and affected by compressional deformation, but this deeper gas source could open up Paleozoic and Triassic plays beneath the traditional Jurassic play of the Weald Basin.

The small gas fields and oil and gas shows in the Jura documented by **Pullan & Berry (2018)** are typical of late and post-orogenic piedmont and intramontane basins of the internal Variscides in containing coals, high-quality algal-rich lacustrine Autunian and bituminous Stephanian shales, in this case sourcing a Triassic reservoir and seal system. Many other similar, small basins exist across France and Germany, with thick coal seams common in Westphalian and Stephanian sequences (e.g. Saar-Lorraine-Nahe basin and coalfield; references summarized in BGS 2017).

Burial and uplift history linked to prospectivity

Increased understanding of structural evolution, source rock distribution and maturity highlighted by regional studies has led to an appreciation of the variability in timing and amount of thermal maturation, source rock productivity and resultant oil and gas migration and accumulation. **Besly (2018)** documents variability in basin modelling studies and that simple rift and sag models of basin evolution are oversimplified for the Carboniferous of the Southern North Sea and onshore UK. Variability in basin evolution, maturation and migration from the Outer Moray Firth, Forth Approaches and to south of the Mid North Sea High has been documented by Monaghan *et al.* (2015, 2016, 2017), Vincent (2015, 2016), IGI Ltd (2017) and **Patruno *et al.* (2018)**. Ter Borgh *et al.* (2018*a*, *b*), De Bruin *et al.* (2015) and Schroot *et al.* (2006) give basin modelling examples from the Dutch sector.

Onshore, **Pullan & Butler (2018)** report on basin modelling that indicates gas-mature Paleozoic source rocks in the centre of the Weald Basin from Jurassic times. **Pullan & Berry (2018)** incorporated fold and thrust models in their basin modelling of a Jura petroleum system that is mature for gas from the Jurassic–Cretaceous with maturity progressively decreasing to the west and SW.

The papers and reports summarized in this section above illustrate how detailed local studies constrained by observations of semi-regional basin history allow improved understanding of Paleozoic or Paleozoic-sourced oil and gas accumulations.

Current exploration of Paleozoic plays

In the 18 months of 2016–17 since this volume was initiated, and despite company reorganizations owing to a sustained low oil price, research, exploration and development of Paleozoic plays of NW Europe have returned some successes. For example, in the UK sector the Cygnus gas field came onstream and the Ruby discovery (Rotliegend sandstone) was announced straddling the Dutch/German sectors. Exploration drilling was active in the Barents Sea, including successful appraisal of the Permian–Triassic reservoir in the Alta discovery.

In the UK sector, the OGA has actively promoted a Southern North Sea tight gas strategy that applies to Carboniferous and Permian sandstones (OGA 2017*a*, *b*). An exploration/appraisal well to test the deep Namurian tight gas play has been drilled by BP at Ravenspurn, Block 43/26, and the Grove Deep prospect by Spirit Energy. The UK 29th offshore licensing round in 2016/17 focussed on frontier areas and, of the licences awarded, the focus for Paleozoic plays was on the southern side of the Mid North Sea High (the north of Quadrants 41–44, the south of Quadrants 35–38). Onshore UK, permissions have been granted for testing of unconventional Namurian shale gas prospects in central England (e.g. Yorkshire, Kirby Misperton; Lancashire, Preston New Road).

Future opportunities

Recently published papers, reports and datasets show progress towards a greater understanding and de-risking of Paleozoic plays in NW Europe. The variety of play fairways through thick successions offering numerous source, reservoir and seal intervals and with variable structural and thermal histories means that a single paradigm shift for Paleozoic exploration is not appropriate. There are, however, a number of emerging, promising plays for which there is now greater data availability and semi-regional knowledge to stimulate and de-risk exploration. Promising plays include:

- The Visean–Namurian play on the southern side of the Mid North Sea High and northern side of the Anglo-Dutch basin in the UK and Netherlands sectors, extending southwards to tight gas plays beneath existing gas fields.
- The Rotliegend play on the northern side of the Silverpit Basin, i.e. extending the Cygnus reservoir interval.
- The Zechstein plays both north and south of the Southern North Sea to onshore gas fields.
- Devonian and Carboniferous sourced plays around the Orcadian Basin, from the south Buchan Basin to the East Shetland Platform, in Paleozoic and younger reservoirs.
- Smaller onshore and structurally complex plays, for example the Westphalian–Autunian late- to post-orogenic basins of the internal and northern

external Variscides (France, Germany, Switzerland, southern Britain).
- Basement plays that involve Paleozoic elements or 'basement' reservoirs, e.g. Clair, Johan Sverdrup.

In addition to conventional Paleozoic plays, exploration of tight oil and gas and shale gas plays will probably form a future opportunity. The long-term use of oil and gas fields and possibly co-development of wells and fields for more widespread energy storage, as well as the use of depleted fields for carbon storage (e.g. IEAGHG 2009; Underhill *et al.* 2009; SCCS 2015) and geothermal energy (e.g. Gluyas *et al.* 2016) may also become economically viable and socially desirable.

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References

Alberts, M.A. & Underhill, J.R. 1991. The effect of Tertiary structuration on Permian gas prospectivity, Cleaver bank area, southern North Sea, UK. *In*: Spencer, A.M. (ed.) *Generation, Accumulation and Production of Europe's Hydrocarbons*. Special Publications of the European Association of Petroleum Geoscientists, Memoirs, Oxford University Press, Oxford, **1**, 161–173.

Andrews, I.J., Long, D., Richards, P.C., Thomson, A.R., Brown, S., Chesher, J.A. & Mccormac, M. 1990. *United Kingdom Offshore Regional Report*. The Geology of the Moray Firth, HMSO for the British Geological Survey, London.

Arsenikos, S., Quinn, M., Kimbell, G., Williamson, P., Pharaoh, T. & Monaghan, A. 2018. Structural development of the Devono-Carboniferous plays of the UK North Sea. *In*: Monaghan, A.A., Underhill, J.R., Marshall, J.E.A. & Hewett, A.J. (eds) *Paleozoic Plays of NW Europe*. Geological Society, London, Special Publications, **471**. First published online March 20, 2018, https://doi.org/10.1144/SP471.3.

Bailey, N.J., Burwood, R. & Harriman, G.E. 1990. Application of pyrolysate carbon isotope and biomarker technology to organofacies definition and oil correlation problems in North Sea basins. *Organic Geochemistry*, **16**, 1157–1172.

Bełka, Z., Devleeschouwer, X., Narkiewicz, M., Piecha, M., Reijers, T.J.A., Ribbert, K.-H. & Smith, N.J.P. 2010. Devonian. *In*: Doornenbal, J.C. & Stevenson, A.G. (eds) *Petroleum Geological Atlas of the Southern Permian Basin Area*. EAGE, Houten, 71–79.

Besly, B. 2018. Exploration and development in the Carboniferous of the southern North Sea: a 30year retrospective. *In*: Monaghan, A.A., Underhill, J.R., Marshall, J.E.A. & Hewett, A.J. (eds) *Paleozoic Plays of NW Europe*. Geological Society, London, Special Publications, **471**. First published online May 03, 2018, https://doi.org/10.1144/SP471.10

Besly, B.M. 2005. Late Carboniferous redbeds of the UK southern North Sea, viewed in a regional context. *In*: Collinson, J., Evans, D., Holliday, D. & Jones, N. (eds) *Carboniferous Hydrocarbon Geology: The Southern North Sea and Surrounding Onshore Areas*. Yorkshire Geological Society, Occasional Publications, **7**, 225–226.

BGS 2016. 21CXRM Palaeozoic project reports (9 Central North Sea/Mid North Sea High, 9 Orcadian Basin to Forth Approaches, 6 Greater Irish Sea, 1 overview) and datasets can be downloaded from http://www.bgs.ac.uk/research/energy/petroleumGeoscience/explorationRoadmap.html Also in the open access repository http://nora.nerc.ac.uk/

BGS 2017. *South-West Approaches Study: A Review of Late- and Post- Variscan Basins and Source Potential in Western Europe*. British Geological Survey Commissioned Report, **CR/17/031**. Report produced for the OGA as part of the 21st Century Exploration Road Map (21CXRM), https://www.ogauthority.co.uk/data-centre/interactive-maps-and-tools/

Breunese, J., Anderson, J. et al. 2010. Appendix 3. *In*: *Petroleum Geological Atlas of the Southern Permian Basin Area*. EAGE, Houten, 305–314.

Brown, F.J., Astin, T.R. & Marshall, J.E.A. 2018. The Paleozoic petroleum system in the north of Scotland-outcrop analogues. *In*: Monaghan, A.A., Underhill, J.R., Marshall, J.E.A. & Hewett, A.J. (eds) *Paleozoic Plays of NW Europe*. Geological Society, London, Special Publications, **471**. First published online December 19, 2018, https://doi.org/10.1144/SP471.14.

Bruce, D.R.S. & Stemmerik, L. 2003. Carboniferous. *In*: Evans, D., Graham, C., Armour, A. & Bathurst, P. (eds and co-ordinators) *The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea*. Geological Society, London, 83–89.

Butler, M. 2018. Seismostratigraphic analysis of Paleozoic sequences of the Midlands Microcraton. *In*: Monaghan, A.A., Underhill, J.R., Marshall, J.E.A. & Hewett, A.J. (eds) *Paleozoic Plays of NW Europe*. Geological Society, London, Special Publications, **471**. First published online April 30, 2018, https://doi.org/10.1144/SP471.6

Cameron, T.D.J. 1993*a*. 5. Carboniferous and Devonian of the southern North Sea. *In*: Knox, R. & Cordey, W. (eds) *Lithostratigraphical Nomenclature of the UK North Sea*. HMSO for the British Geological Survey, London, 1–118.

Cameron, T.D.J. 1993*b*. 4. Triassic, Permian and Pre-Permian (Central and Northern North Sea). *In*: Knox, R. & Cordey, W. (eds) *Lithostratigraphical Nomenclature of the UK North Sea*. HMSO for the British Geological Survey, London, 1–196.

Cameron, T.D.J., Crosby, A., Balson, P.S., Jeffery, D.H., Lott, G.K., Bulat, J. & Harrison, D.J. 1992*a*. Upper Permian. *In*: *United Kingdom Offshore Regional Report: The Geology of the Southern North Sea*. HMSO for the British Geological Survey, London, 43–54.

Cameron, T.D.J., Crosby, A., Balson, P.S., Jeffery, D.H., Lott, G.K., Bulat, J. & Harrison, D.J. 1992*b*. Lower Permian. *In*: *United Kingdom Offshore Regional Report: The Geology of the Southern North Sea*. HMSO for the British Geological Survey, London, 38–42.

Cameron, T.D.J., Munns, J. & Stoker, S. 2005. Remaining hydrocarbon exploration potential of the Carboniferous fairway. *In*: Collinson, J., Evans, D., Holliday, D. & Jones, N. (eds) *Carboniferous Hydrocarbon Geology: The Southern North Sea and Surrounding Onshore Areas*. Yorkshire Geological Society, Occasional Publications, **7**, 209–224.

Catto, R., Taggart, S. & Poole, G. 2017. Petroleum geology of the Cygnus gas field, UK North Sea: from discovery to development. *In*: Bowman, M. & Levell, B. (eds) *Petroleum Geology of NW Europe: 50 Years of Learning – Proceedings of the 8th Petroleum Geology Conference*. Geological Society, London, Petroleum Geology Conference Series, **8**, 307–318, 23 March 2017, https://doi.org/10.1144/PGC8.39

Clarke, H., Eisner, L., Styles, P. & Turner, P. 2014. Felt seismicity associated with shale gas hydraulic fracturing: the first documented example in Europe. *Geophysical Research Letters*, **41**, 8308–8314.

Collinson, J. 2005. Dinantian and Namurian depositional systems in the southern North Sea. *In*: Collinson, J., Evans, D., Holliday, D. & Jones, N. (eds) *Carboniferous Hydrocarbon Geology: The Southern North Sea and Surrounding Onshore Areas*. Yorkshire Geological Society, Occasional Publications, **7**, 35–56.

Coney, D., Fyfe, T.B., Retail, P. & Smith, P.J. 1993. Clair appraisal: the benefits of a co-operative approach. *In*: Parker, J.R. (ed.) *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*. Geological Society, London, Petroleum Geology Conference Series, **4**, 1409–1420, https://doi.org/10.1144/0041409

Cooke-Yarborough, P. & Smith, E. 2003. The Hewett Fields: Blocks 48/28a, 48/29, 48/30, 52/4a, 52/5a, UK North Sea: Hewett, Deborah, Big Dotty, Little Dotty, Della, Dawn and Delilah Fields. *In*: Gluyas, J.G. & Hichens, H.M. (eds) *United Kingdom Oil and Gas Fields, Commemorative Millennium Volume*. Geological Society, London, Memoirs, **20**, 731–739, https://doi.org/10.1144/GSL.MEM.2003.020.01.60

Cowan, G. 1996. The development of the North Morecambe gas field, East Irish Sea Basin, UK. *Petroleum Geoscience*, **2**, 43–52, https://doi.org/10.1144/petgeo.2.1.43

Crampton, C.B. & Carruthers, R.G. 1914. *The Geology of Caithness (sheets 110 and 116 with parts of 109, 115 and 117)*. Memoirs of the Geological Survey, Scotland, HMSO, Edinburgh.

de Bruin, G., Bouroullec, R. *et al.* 2015. *New Petroleum Plays in the Dutch Northern Offshore*. TNO Report, **R10920**.

de Jong, K., Jaarsma, B., Reijmer, J. & Ter Borgh, M. 2016. *Assessing the petroleum potential of Devonian Carbonates in the Mid North Sea area*. Presentation from Msc thesis, https://www.ebn.nl/wp-content/uploads/2016/12/Conference-K.-de-Jong-et-al.-2016.pdf

Duguid, C. & Underhill, J.R. 2010. Geological Controls on Upper Permian Plattendolomite Formation reservoir propsectivity, Wissey Field, UK Southern North Sea. *Petroleum Geoscience*, **16**, 331–348, https://doi.org/10.1144/1354-0793/10-021

Duncan, A.D. & Buxton, N.W.K. 1995. New evidence for evaporitic Middle Devonian lacustrine sediments with hydrocarbon source potential on the East Shetland Platform, North Sea. *Journal of the Geological Society, London*, **152**, 251–258, https://doi.org/10.1144/gsjgs.152.2.0251

EBN 2015*a*. Poster from EAGE downloaded from the website, https://www.ebn.nl/wp-content/uploads/2014/11/Poster4_EBN_EAGE2015_Dinant.pdf [last accessed 14 December 2015].

EBN 2015*b*. Poster from EAGE downloaded from the website, https://www.ebn.nl/wp-content/uploads/2014/11/Poster6_EBN_EAGE2015_TectD.pdf [last accessed 14 December 2015].

Edwards, C.W. 1991. The Buchan Field, Blocks 20/5a and 21/1a, UK North Sea. *In*: Abbotts, I.L. (ed.) *United Kingdom Oil and Gas Fields, 25 Years Commemorative Volume*. Geological Society, London, Memoirs, **14**, 253–259.

ExxonMobil 2010. Relinquishment Report for Licence P1259 Blocks: 36/15, 36/20, 36/25, 37/11, 37/16, 37/17, 37/18, 37/19, 37/20, 37/21, 37/22, 37/23, 37/24, 37/25, 38/16, 38/21, 38/22, 38/26, 38/27 and 38/28. https://itportal.decc.gov.uk/web_files/relinqs/p1259.pdf

Fraser, A.J. & Gawthorpe, R.L. 2003. *An Atlas of Carboniferous Basin Evolution in Northern England*. Geological Society, London, Memoirs, **28**, https://doi.org/10.1144/GSL.MEM.2003.028.01.01

Frogtech Geoscience 2017. 21XCRM East Shetland Platform Project Phase 1 – SEEBASE Study. Report produced for the OGA as part of the 21st Century Exploration Road Map (21CXRM), https://www.ogauthority.co.uk/data-centre/interactive-maps-and-tools/

Gambaro, M. & Currie, M. 2003. The Balmoral, Glamis and Stirling Fields, Block 16/21, UK Central North Sea. *In*: Gluyas, J.G. & Hichens, H.M. (eds). *United Kingdom Oil and Gas Fields Commemorative Millennium Volume*. Geological Society, London, Memoirs, **20**, 395–413.

Gast, R.E., Dusar, M. *et al.* 2010. Rotliegend. *In*: Doornenbal, J.C. & Stevenson, A.G. (eds) *Petroleum Geological Atlas of the Southern Permian Basin Area*. EAGE, Houten, 101–121.

Getech 2017. *Gravity and Magnetic Data: SW Approaches and Western Europe*. Report produced for the OGA as part of the 21st Century Exploration Road Map (21CXRM), https://www.ogauthority.co.uk/data-centre/interactive-maps-and-tools/

Glennie, K., Highman, J. & Stemmerik, L. 2003. Permian. *In*: Evans, D., Graham, C., Armour, A. & Bathurst,

P. (eds and co-ordinators) *The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea*. Geological Society, London, 8–1, 8–44.

Glennie, K.W. 1998. Permian. *In*: Glennie, K. (ed.) *Introduction to the Petroleum Geology of the North Sea*. Blackwell Science, Oxford, 42–84.

Glennie, K.W. & Underhill, J.R. 1998. The development and evolution of structural styles in the North Sea. *In*: Glennie, K. (ed.) *Introduction to the Petroleum Geology of the North Sea*. Blackwell Science, Oxford, 42–84.

Gluyas, J., Mathias, S. & Goudarzi, S. 2016. North Sea – next life: extending the commercial life of producing North Sea fields. *In*: Bowman, M. & Levell, B. (eds) *Petroleum Geology of NW Europe: 50 Years of Learning*. Geological Society, London, Petroleum Geology Conference Series, **8**, 27 October 2016, https://doi.org/10.1144/PGC8.30

Guariguata-Rojas, G.J. & Underhill, J.R. 2017. Implications of Early Cenozoic uplift and fault reactivation for carbon storage in the Moray Firth Basin. *Interpretation*, **5**, 1–21.

Haig, D.B., Pickering, S.C. & Probert, R. 1997. The Lennox oil and gas Field. *In*: Meadows, N.S., Trueblood, S.P., Hardman, M. & Cowan, G. (eds) *Petroleum Geology of the Irish Sea and Adjacent Areas*. Geological Society, London, Special Publications, **124**, 417–436, https://doi.org/10.1144/GSL.SP.1997.124.01.25

Hallett, D., Durant, G.P. & Farrow, G.E. 1985. Oil exploration and production in Scotland. *Scottish Journal of Geology*, **21**, 547–570.

Harker, S.D., Green, S.C.H. & Romani, R.S. 1991. The Claymore Field, Block 14/19, UK North Sea. *In*: Abbotts, I.L. (ed.). *United Kingdom Oil and Gas Fields, 25 Years Commemorative Volume*. Geological Society, London, Memoirs, **14**, 269–278, https://doi.org/10.1144/GSL.MEM.1991.014.01.33

Heckel, P.H. & Clayton, G. 2006. The Carboniferous System. Use of the new official names for the subsystems, series and stages. *Geologica Acta*, **4**, 403–407.

Hennissen, J.A.I., Hough, E., Vane, C.H., Leng, M.J., Kemp, S.J., & Stephenson, M.H. 2017. The prospectivity of a potential shale gas play: an example from the southern Pennine Basin (central England, UK). *Marine and Petroleum Geology*, **86**, 1047–1066, https://doi.org/10.1016/j.marpetgeo.2017.06.033

Hillier, S. & Marshall, J.E.A. 1992. Organic maturation, thermal history and hydrocarbon generation in the Orcadian Basin, Scotland. *Journal of the Geological Society, London*, **149**, 491–502, https://doi.org/10.1144/gsjgs.149.4.0491

Hillis, R.R., Thomson, K. & Underhill, J.R. 1994. Quantification of Tertiary Erosion in the Inner Moray Firth using sonic velocity data from the Chalk and the Kimmeridge Clay. *Marine and Petroleum Geology*, **11**, 283–293.

Holliday, D.W. & Molyneux, S.G. 2006. Editorial statement: new official names for the subsystems, series and stages of the Carboniferous System – some guidance for contributors to the Proceedings. *Proceedings of the Yorkshire Geological Society*, **56**, 57–58, https://doi.org/10.1144/pygs.56.1.57

IEAGHG 2009. *CO_2 Storage in Depleted Gas Fields*. Report number **2009/01**, http://hub.globalccsinstitute.com/sites/default/files/publications/95786/co2-storage-depleted-gas-fields.pdf

IGI Ltd 2017. Source rock potential of the East Shetland Platform Area. Report produced for the OGA as part of the 21st Century Exploration Road Map (21CXRM), https://www.ogauthority.co.uk/data-centre/interactive-maps-and-tools/

Jones, J.M. & Scott, P.W. 1980. Progress report on fossil fuels – exploration and exploitation. *Proceedings of the Yorkshire Geological and Polytechnic Society*, **42**, 581–593.

Kearsey, T.I., Millward, D., Ellen, R., Whitbread, K. & Monaghan, A.A. 2018. Revised stratigraphic framework of pre-Westphalian Carboniferous petroleum system elements from the Outer Moray Firth to the Silverpit Basin, North Sea, UK. *In*: Monaghan, A.A., Underhill, J.R., Marshall, J.E.A. & Hewett, A.J. (eds) *Paleozoic Plays of NW Europe*. Geological Society, London, Special Publications, **471**. First published online May 03, 2018, https://doi.org/10.1144/SP471.11.

Kombrink, H., Besly, B.M. et al. 2010. Carboniferous. *In*: Doornenbal, J.C. & Stevenson, A.G. (eds) *Petroleum Geological Atlas of the Southern Permian Basin Area*. EAGE, Houten, 81–99.

Leeder, M.R. & Boldy, S.A.R. 1990. The Carboniferous of the Outer Moray Firth Basin, quadrants 14 and 15, Central North Sea. *Marine and Petroleum Geology*, **7**, 29–37.

Mark, D.F., Green, P.F., Parnell, J., Kelley, S.P., Lee, M.R. & Sherlock, S.C. 2008. Late Palaeozoic hydrocarbon migration through the Clair field, West of Shetland, UK Atlantic margin. *Geochimica et Cosmochimica Acta*, **72**, 2510–2533, https://doi.org/10.1016/j.gca.2007.11.037

Marshall, J.E.A. 1998. The recognition of multiple hydrocarbon generation episodes: an example from Devonian lacustrine sedimentary rocks in the Inner Moray Firth, Scotland. *Journal of the Geological Society, London*, **155**, 335–352, https://doi.org/10.1144/gsjgs.155.2.0335

Marshall, J.E.A. & Hewett, A.J. 2003. Devonian. *In*: Evans, D., Graham, C., Armour, A. & Bathurst, P. (eds and co-ordinators) *The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea*. Geological Society, London, 65–81.

Marshall, J.E.A., Rogers, D.A. & Whiteley, M.J. 1996. Devonian marine incursions into the Orcadian Basin, Scotland. *Journal of the Geological Society, London*, **153**, 451–466.

Marshall, J.E.A., Glennie, K.W., Astin, T.R. & Hewett, A.J. 2018. The Old Red Group (Devonian) – Rotliegend (Permian) unconformity in the Inner Moray Firth. *In*: Monaghan, A.A., Underhill, J.R., Marshall, J.E.A. & Hewett, A.J. (eds) *Paleozoic Plays of NW Europe*. Geological Society, London, Special Publications, **471**. First published online June 22, 2018, https://doi.org/10.1144/SP471.12.

Meadows, N.S., Trueblood, S., Hardman, M. & Cowan, G. 1997. *Petroleum Geology of the Irish Sea and Adjacent Areas*. Geological Society, London, Special Publications, **124**, https://doi.org/10.1144/GSL.SP.1997.124.01.26

Miller, H. 1841. *The Old Red Sandstone, or New Walks in an Old Field*. Johnstone, Edinburgh.

Milton-Worssell, R., Smith, K., McGrandle, A., Watson, J. & Cameron, D. 2010. The search for a Carboniferous petroleum system beneath the Central North Sea. *In*: Vining, B.A. & Pickering, S.C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference*, The Geological Society, London, 57–75, https://doi.org/10.1144/0070057

Monaghan, A.A., Arsenikos, S. *et al.* 2015. *Palaeozoic Petroleum Systems of the Central North Sea/Mid North Sea High*. British Geological Survey Commissioned Report, **CR/15/124**, http://nora.nerc.ac.uk/516766/

Monaghan, A.A., Johnson, K. *et al.* 2016. *Palaeozoic Petroleum Systems of the Orcadian Basin to Forth Approaches, Quadrants 6–21, UK*. British Geological Survey Commissioned Report, **CR/16/038**, http://nora.nerc.ac.uk/id/eprint/516781/

Monaghan, A.A., Arsenikos, S. *et al.* 2017. Carboniferous petroleum systems around the Mid North Sea High. *Journal of Marine and Petroleum Geology*, **88C**, 282–302, https://doi.org/10.1016/j.marpetgeo.2017.08.019

Mulholland, P., Esestime, P., Rodriguez, K. & Hargreaves, P.J. 2018. The role of paleo-relief in the control of Permian facies distribution over the Mid North Sea High, UKCS. *In*: Monaghan, A.A., Underhill, J.R., Marshall, J.E.A. & Hewett, A.J. (eds) *Paleozoic Plays of NW Europe*. Geological Society, London, Special Publications, **471**. First published online May 03, 2018, https://doi.org/10.1144/SP471.8

OGA 2017*a*. https://www.ogauthority.co.uk/media/3770/oil-gas-southern-north-sea-tight-gas-strategy.pdf

OGA 2017*b*. https://www.ogauthority.co.uk/media/4521/oga-sns-tight-gas-stimulation-december-2017.pdf

OGA 2017*c*. OGA Regional Geological Mapping Project - Southern North Sea, Central North Sea and Moray Firth, 2017. Maps produced by Lloyds Register under contract to the OGA, https://www.ogauthority.co.uk/data-centre/interactive-maps-and-tools/

Ohm, S.E., Karlsen, D.A., Phan, N.T., Strand, T. & Iversen, G. 2012. Present Jurassic petroleum charge facing Paleozoic biodegraded oil: geochemical challenges and potential upsides, Embla field, North Sea. *AAPG Bulletin*, **96**, 1523–1552.

Oudmayer, B.C. & De Jager, J. 1993. Fault reactivation and oblique-slip in the Southern North Sea. Geological Society, London, Petroleum Geology Conference Series, **4**, 281–1290, 1 January 1993, https://doi.org/10.1144/0041281

Parnell, J. 1983. The distribution of hydrocarbon minerals in the Orcadian Basin. *Scottish Journal of Geology*, **19**, 205–213, https://doi.org/10.1144/sjg19020205

Parnell, J., Baba, M. & Bowden, S. 2017. Emplacement and biodegradation of oil in fractured basement: the ‘coal’ deposit in Moinian gneiss at Castle Leod, Ross-shire. *Transactions of the Royal Society of Edinburgh, Earth and Environmental Science*, **107**, 23–32.

Patruno, S. & Reid, W. 2016. New plays on the Greater East Shetland Platform (UKCS Quadrants 3, 8–9, 14–16) – part 1: regional setting and a working petroleum system. *First Break*, **34**, 33–45.

Patruno, S. & Reid, W. 2017. 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. *First Break*, **35**, 59–69.

Patruno, S., Reid, W., Jackson, C.A.-L. & Davies, C. 2017. New insights into the unexploited reservoir potential of the Mid North Sea High (UKCS quadrants 35–38 and 41–43): a newly described intra-Zechstein sulphate–carbonate platform complex. *In*: Bowman, M. & Levell, B. (eds) *Petroleum Geology of NW Europe: 50 Years of Learning*. Geological Society, London, Petroleum Geology Conference Series, **8**, 87–124, 13 June 2017, https://doi.org/10.1144/PGC8.9

Patruno, S., Reid, W., Berndt, C., Feuilleaubois, L. 2018. Polyphase tectonic inversions and hydrocarbon prospectivity: a comparative synopsis for the under-explored platforms of the eastern UK Continental Shelf (Greater East Shetland Platform and Mid North Sea High). *In*: Monaghan, A.A., Underhill, J.R., Marshall, J.E.A. & Hewett, A.J. (eds) *Paleozoic Plays of NW Europe*. Geological Society, London, Special Publications, **471**. First published online May 04, 2018, https://doi.org/10.1144/SP471.9.

Pedersen, J.H., Karlsen, D.A., Lie, J.E., Brunstad, H. & Di Primio, R. 2006. Maturity and source-rock potential of Palaeozoic sediments in the NW European Northern Permian Basin. *Petroleum Geoscience*, **12**, 13–28, https://doi.org/10.1144/1354-079305-666

Pennington, J.J. 1975. The geology of the Argyll Field. *In*: Woodland, A.W. (ed.) *Petroleum Geology of the Continental shelf of NW Europe*. Applied Science, Barking, 285–291.

Peryt, T.M., Geluk, M., Mathiesen, A., Paul, J. & Smith, K. 2010. Zechstein. *In*: Doornenbal, J.C. & Stevenson, A.G. (eds) *Petroleum Geological Atlas of the Southern Permian Basin Area*. EAGE, Houten, 123–148.

Pharaoh, T.C., Vincent, C.J., Bentham, M.S., Hulbert, A.G., Waters, C.N. & Smith, N.J. 2011. *Structure and Evolution of the East Midlands Region of the Pennine Basin*. The British Geological Survey, Keyworth, Nottingham, Subsurface Memoir.

Pharaoh, T.C., Gent, C.M.A. *et al.* 2018. An overlooked play? Structure, stratigraphy and hydrocarbon prospectivity of the Carboniferous in the East Irish Sea-North Channel basin complex. *In*: Monaghan, A.A., Underhill, J.R., Marshall, J.E.A. & Hewett, A.J. (eds) *Paleozoic Plays of NW Europe*. Geological Society, London, Special Publications, **471**. First published online March 22, 2018, https://doi.org/10.1144/SP471.7.

Pletsch, T., Appel, J. *et al.* 2010. Petroleum generation and migration. *In*: Doornenbal, J.C. & Stevenson, A.G. (eds) *Petroleum Geological Atlas of the Southern Permian Basin Area*. EAGE, Houten, 225–253.

Pullan, C. & Berry, M. 2018. Paleozoic sourced oil play in the Jura mountains of France and Switzerland. *In*: Monaghan, A.A., Underhill, J.R., Marshall, J.E.A. & Hewett, A.J. (eds) *Paleozoic Plays of NW Europe*. Geological Society, London, Special Publications, **471**. First published online March 20, 2018, https://doi.org/10.1144/SP471.2.

Pullan, C. & Butler, M. 2018. Paleozoic Gas Potential in the Weald Basin of Southern England. *In*: Monaghan, A.A., Underhill, J.R., Marshall, J.E.A. & Hewett, A.J. (eds) *Paleozoic Plays of NW Europe*. Geological Society, London, Special Publications, **471**. First published online March 22, 2018, https://doi.org/10.1144/SP471.1.

RICHARDS, P.C. 1985. A Lower Old Red Sandstone lake in the offshore Orcadian Basin. *Scottish Journal of Geology*, **21**, 381–383, https://doi.org/10.1144/sjg21030381.

RICHARDSON, N.J., ALLEN, M.R. & UNDERHILL, J.R. 2005. Role of Cenozoic fault reactivation in controlling pre-rift plays, and the recognition of Zechstein Group evaporite-carbonate lateral facies transitions in the East Orkney and Dutch Bank basins, East Shetland Platform, UK North Sea. *In*: DORÉ, A.G. & VINING, B.A. (eds) *Petroleum Geology: North-West Europe and Global Perspectives – Proceedings of the 6th Petroleum Geology Conference*. Geological Society, London, 337–348.

RODRIGUEZ, K., WRIGLEY, R., HODGSON, N. & NICOLLS, H. 2014. Southern North Sea: unexplored multi-level exploration potential revealed. *First Break*, **32**, 107–113.

SCCS 2015. CO2-EOR Joint Industry Project Reports. University of Edinburgh, http://www.sccs.org.uk/expertise/reports/co2eor-joint-industry-project

SCHROOT, B.M., v. BERGEN, F., ABBINK, O.A., DAVID, P., v. EIJS, R. & VELD, H. 2006. *Hydrocarbon Potential of the Pre-Westphalian in the Netherlands on- and Offshore – Report of the Petroplay Project*. TNO Report, **NITG 05-155-C**.

STEVENS, V. 1991. The Beatrice Field, Block 11/30a, UK North Sea. *In*: ABBOTTS, I.L. (ed.) *United Kingdom Oil and Gas Fields, 25 Years Commemorative Volume*. Geological Society, London, Memoirs, **14**, 245–252.

TER BORGH, M.M., EIKELENBOOM, W. & JAARSMA, B. 2018*a*. Hydrocarbon potential of the Visean and Namurian in the northern Dutch offshore. *In*: MONAGHAN, A.A., UNDERHILL, J.R., MARSHALL, J.E.A. & HEWETT, A.J. (eds) *Paleozoic Plays of NW Europe*. Geological Society, London, Special Publications, **471**. First published online March 20, 2018, https://doi.org/10.1144/SP471.5.

TER BORGH, M.M., JAARSMA, B. & ROSENDAAL, E.A. 2018*b*. Structural development of the Mid North Sea Area, NL North Sea: paleozoic to present. *In*: MONAGHAN, A.A., UNDERHILL, J.R., MARSHALL, J.E.A. & HEWETT, A.J. (eds) *Paleozoic Plays of NW Europe*. Geological Society, London, Special Publications, **471**. First published online March 20, 2018, https://doi.org/10.1144/SP471.4.

TREWIN, N.H. 1985. Orcadian Basin issue. Editorial introduction. *Scottish Journal of Geology*, **21**, 225–226, https://doi.org/10.1144/sjg21030225

UNDERHILL, J.R. 1991. Implications of Mesozoic–Recent basin development in the western Inner Moray Firth, UK. *Marine and Petroleum Geology*, **8**, 359–369.

UNDERHILL, J.R. 2003. The tectonic and stratigraphic framework of the United Kingdom's oil and gas fields. *In*: GLUYAS, J.G. & HICHENS, H.M. (eds) *United Kingdom Oil and Gas Fields, Commemorative Millennium Volume*. Geological Society, London, Memoirs, **20**, 17–59, https://doi.org/10.1144/GSL.MEM.2003.020.01.04

UNDERHILL, J.R. & HUNTER, K.L. 2008. Effect of Zechstein Supergroup (Z1 Cycle) Werrahalit pods on Prospectivity in the Southern North Sea. *AAPG Bulletin*, **92**, 827–851.

UNDERHILL, J.R., LYKAKIS, N. & SHAFIQUE, S. 2009. Turning exploration risk into a carbon storage opportunity in the UK Southern North Sea. *Petroleum Geoscience*, **15**, 291–304, https://doi.org/10.1144/1354-079309-839

US ENERGY INFORMATION ADMINISTRATION (USEIA) 2013. Technically recoverable shale oil and shale gas resources: an assessment of 137 shale formations in 41 countries outside the United States. Report prepared by Advanced Resources International Inc., https://www.eia.gov/analysis/studies/worldshalegas/ [last accessed October 2016]

USGS 1997. *Map Showing Geology, Oil and Gas Fields, and Geologic Provinces of Europe including Turkey*. Compiled by Mark J. Pawlewicz, Douglas W. Steinshouer and Donald L. Gautier. Open file report **97-470I**, https://pubs.usgs.gov/of/1997/ofr-97-470/OF97-470I/

VAN ADRICHEM BOOGAERT, H.A. & KOUWE, W.F.P. 1993–97. *In*: *Stratigraphic Nomenclature of the Netherlands*, https://www.dinoloket.nl/nomenclature-deep

VAN BUGGENUM, J.M. & DEN HARTOG JAGER, D.G. 2007. Silesian. *In*: WONG, T.E., BATJES, D.A.J. & DE JAGER, J. (eds). *Geology of the Netherlands*. Royal Netherlands Academy of Arts and Sciences, Amsterdam, 43–62.

VAN HULTEN, F.F.N. 2010. Geological factors effecting compartmentalization of Rotliegend gas fields in the Netherlands. *In*: JOLLEY, S.J., FISHER, Q.J., AINSWORTH, R.B., VROLIJK, P.J. & DELISLE, S. (eds). *Reservoir Compartmentalization*. Geological Society, London, Special Publications, **347**, 301–315.

VAN KOEVERDEN, J.H., KARLSEN, D.A., SCHWARK, L., CHPITSGLOUZ, A. & BACKER-OWE, K. 2010. Oil-prone Lower Carboniferous coals in the Norwegian Barents Sea: implications for a Palaeozoic petroleum system. *Journal of Petroleum Geology*, **33**, 155–182, https://doi.org/10.1111/j.1747-5457.2010.00471.x

VINCENT, C.J. 2015. *Maturity Modelling of Selected Wells in the Central North Sea*. British Geological Survey Commissioned Report, **CR/15/122**, http://nora.nerc.ac.uk/516764/

VINCENT, C.J. 2016. *Maturity Modelling of Selected Wells in the Orcadian Basin*. British Geological Survey Commissioned Report, **CR/16/036**, http://nora.nerc.ac.uk/id/eprint/516743/

WATERS, C.N., SOMERVILLE, I.D. *ET AL.* (eds) 2011. *A Revised Correlation of Carboniferous Rocks in the British Isles*. Geological Society, London, Special Report, **26**.

WILSON, G.V., EDWARDS, W., KNOX, J., JONES, R.C.B. & STEPHENS, J.V. 1935. *The Geology of the Orkneys*. Memoirs of the Geological Survey Scotland. HMSO, Edinburgh.

WOOD, I. 2014. UKCS Maximising Economic Recovery Review: Final Report 'The Wood Review', https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/471452/UKCS_Maximising_Recovery_Review_FINAL_72pp_locked.pdf [last accessed December 2016]

YALIZ, A.M. 1997. The Douglas Oil Field. *In*: MEADOWS, N.S., TRUEBLOOD, S.P., HARDMAN, M. & COWAN, G. (eds) *Petroleum Geology of the East Irish Sea and Adjacent Areas*. Geological Society, London, Special Publications, **124**, 399–416, https://doi.org/10.1144/GSL.SP.1997.124.01.24