

Paleozoic plays of NW Europe: an introduction

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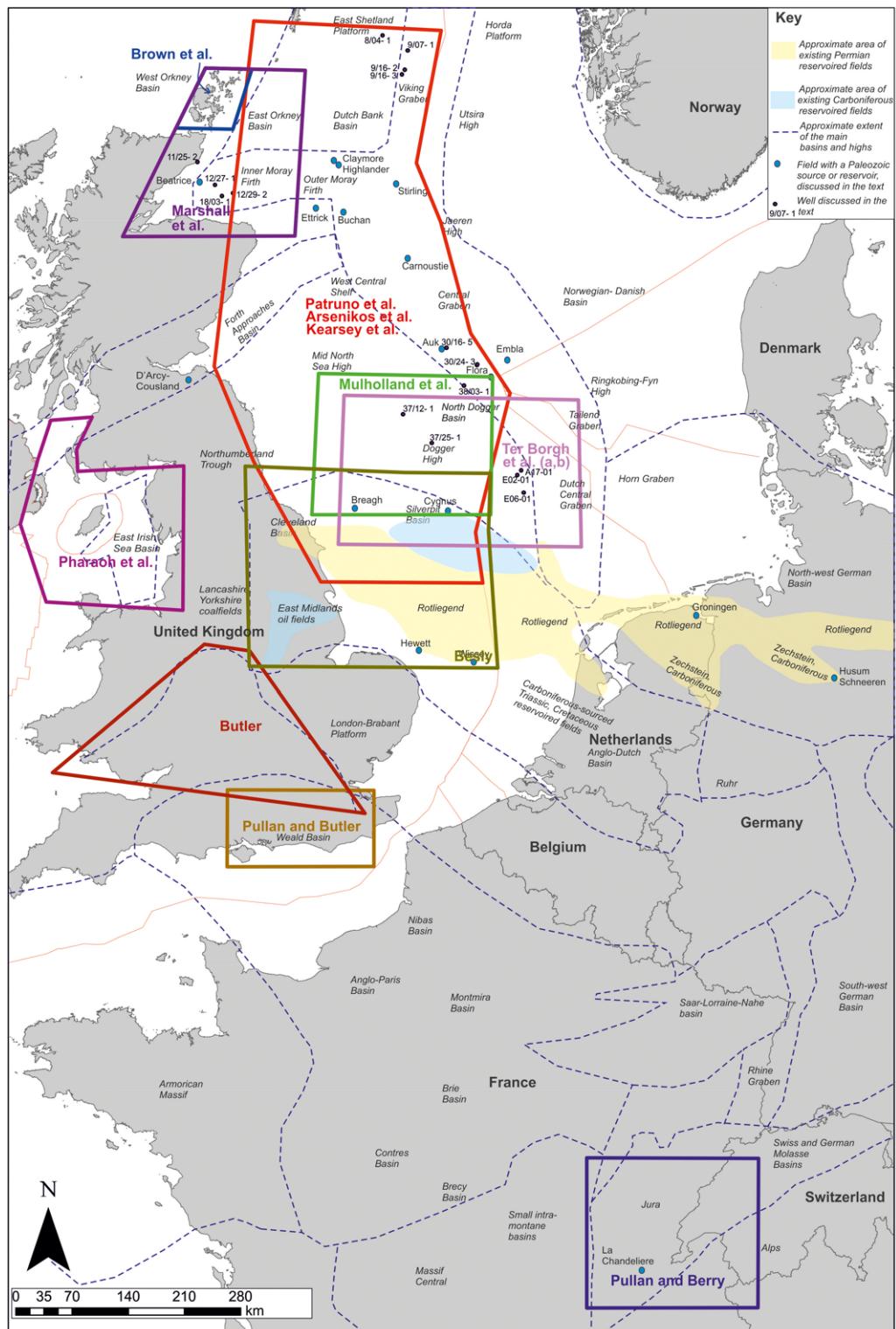
Abstract: Despite successful production from Carboniferous and Permian reservoirs in the Southern North Sea and onshore Netherlands and Germany, Paleozoic hydrocarbon plays across parts of NW Europe remain relatively under-explored onshore and offshore. This volume brings together new and previously unpublished knowledge about the Paleozoic plays of NW Europe. Improvements in seismic data quality and availability tied to previously unpublished well datasets form the basis for improved understanding of local to regional structural interpretations, depositional environments and basin history.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 tcf¹) 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

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



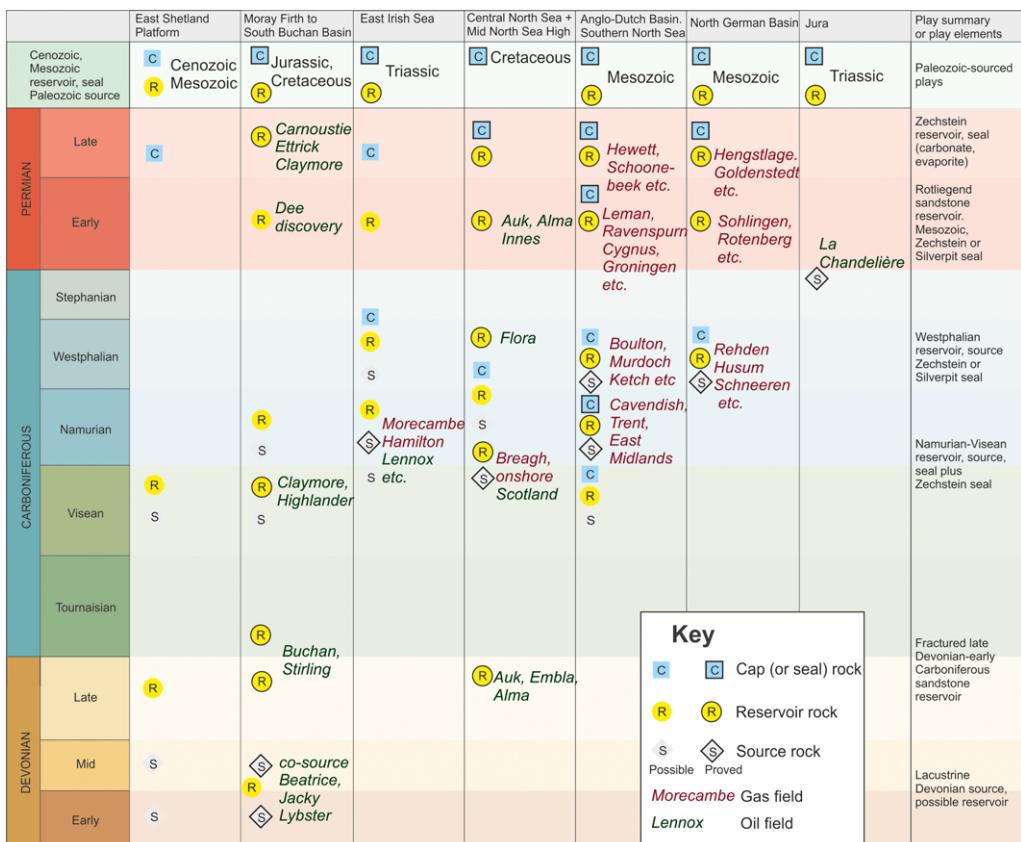


Fig. 2. Summary of proved and possible upper Paleozoic petroleum play elements across NW Europe. Information synthesized and modified from wide range of sources including Bruce & Stemmerik (2003), Marshall & Hewett (2003), Breunese *et al.* (2010), Gast *et al.* (2010), Kombrink *et al.* (2010), Pletsch *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 2017a, 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 2015a, b; Ter Borgh *et al.* 2018a, 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.* 2018a, 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 2017c).

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; Perty *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.* 2018a, 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 & Molynieux 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. Innnomore, Morvern). Following the primary survey of Caithness (Crampston & 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 $\delta^{13}\text{C}$ 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 (Belka *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 (Belka *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 Belka *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.* 2018b). 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.* (2018b). Faults with a NE–SW trend are known to cause reservoir compartmentalization (Oudmayer & De Jager 1993; Van Hulsen 2010) and both fault sets have potential to generate intra-Carboniferous closures (Ter Borgh *et al.* 2018b).

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.* 1992a, b; Cameron 1993a, 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.* (2018a) and Kearsey *et al.* (2018) to influence reservoir and source rock prospectivity. Post-well analysis in the Dutch sector by Ter Borgh *et al.* (2018a) 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 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. (2018a, 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 2017a, 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.

Acknowledgements The conference from which this volume originated was run by the Geological Society of London and the Petroleum Group and sponsored by Origo Exploration, EBN, Cairn Energy, Draupner Energy and Nexen. The original additional conference convenors were Hugh Dennis, Henry Allen, Andrea James, Ian Roche, Nick Richardson and Paul Herrington. The Geological Society Publishing House staff are thanked for dealing with numerous queries, particularly Angharad Hills, Tamzin Anderson and Samuel Lickiss. Nick Richardson and Teresa Sabato Ceraldi are thanked as Society Book Editors for this volume.

Numerous industry, academic and retired paper reviewers are thanked for their time and constructive input to the papers within this volume. A. Monaghan publishes this introductory paper with the permission of the Executive Director, British Geological Survey (NERC).

Funding The authors acknowledge financial support from the Natural Environment Research Council (NERC).

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