Petroleum prospectivity of the principal sedimentary basins on the United Kingdom Continental Shelf

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Statistics and licences
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Introduction

This account provides a summary of the remaining and future petroleum potential of the offshore United Kingdom Continental Shelf (UKCS), and is largely based on a previous review by Brooks *et al*. (2001). The UKCS contains a plethora of mature, lightly explored and frontier sedimentary basins. The distribution of these basins, together with that of the oil, gas and condensate fields that they contain, is illustrated in Figure 1.

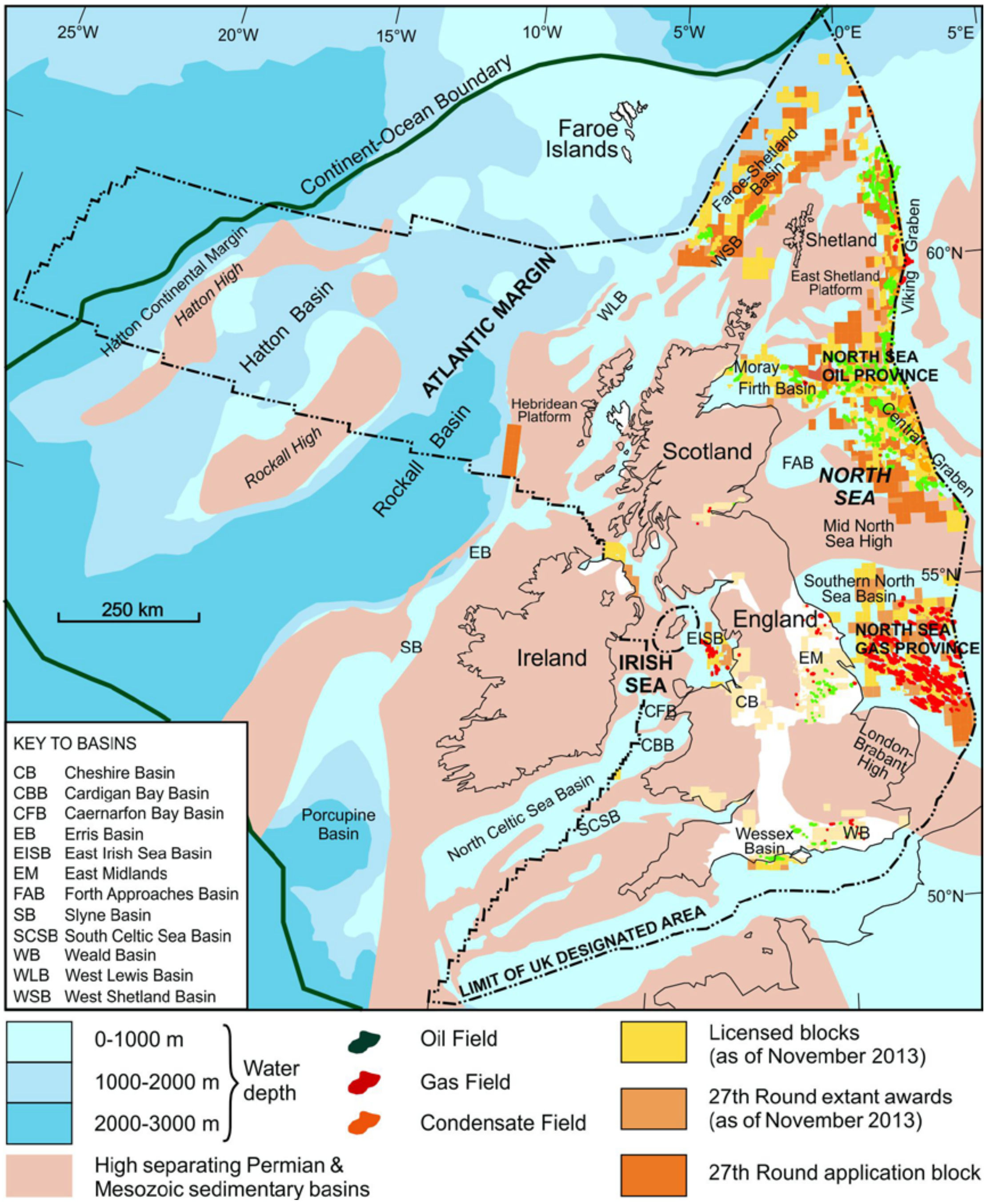

Fig. 1 Location of the hydrocarbon-producing basins and frontier basins of the UK and its designated waters

Up to end 2012, 4272 exploration and appraisal wells (including sidetracks) had been drilled on the UKCS over 48 years. In January 2013, these wells had resulted in 373 producing fields, 33 fields which have ceased production and another 57 significant discoveries (27 of which were under development) (DECC, 2013). The peak of exploration and appraisal activity occurred in 1990 when 159 exploration wells were drilled. The success rate over the last 47 years averages out at 32.3%. Amongst several significant finds made since 2000, the Buzzard discovery has estimated in-place reserves of 800–1100 x 10^6 barrels of oil (Doré and Robbins 2005), making it the largest discovery on the UKCS since Schiehallion in 1993. Significant discoveries made during 2010 include the 28/9-1 Catcher well, which encountered an estimated in

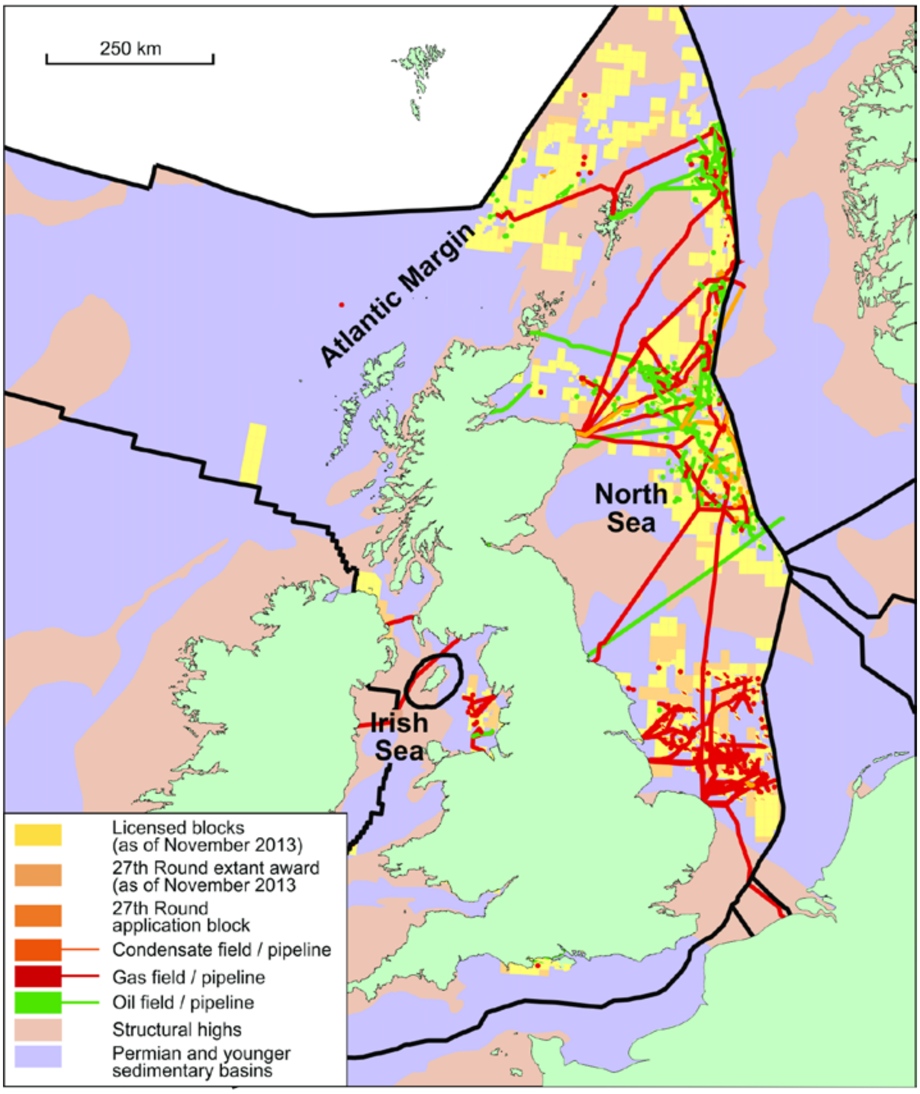

Fig. 2 Infrastructure on the UK Continental Shelf

place 300 x 10^6 barrels of oil within an early Eocene (Cromarty Sandstone Member) reservoir in a shallowly-buried basin-marginal play that had been considered previously to be only marginally prospective.

Reserves contained within established fields and those for which development is planned are designated Discovered Recoverable Reserves by the UK Department of Energy and Climate Change (DECC). Those reserves contained within other discoveries for which no development plans have yet been made are designated Potential Additional Resources (DECC 2013). The UK's maximum remaining discovered reserves are estimated to be 10.08 x 10^9 barrels of oil and 35.7 x 10^{12} cubic feet [tcf] of gas (DECC 2013). In addition, the UK also contains a wealth of undrilled exploration prospects. Published estimates of undiscovered recoverable resources within these prospects range between 3.4 – 10.1 x 10^9 barrels of oil and 13.0 – 35.7 tcf of gas (DECC 2013). The vast majority of these remaining undiscovered resources and undrilled exploration prospects lie in the offshore area.

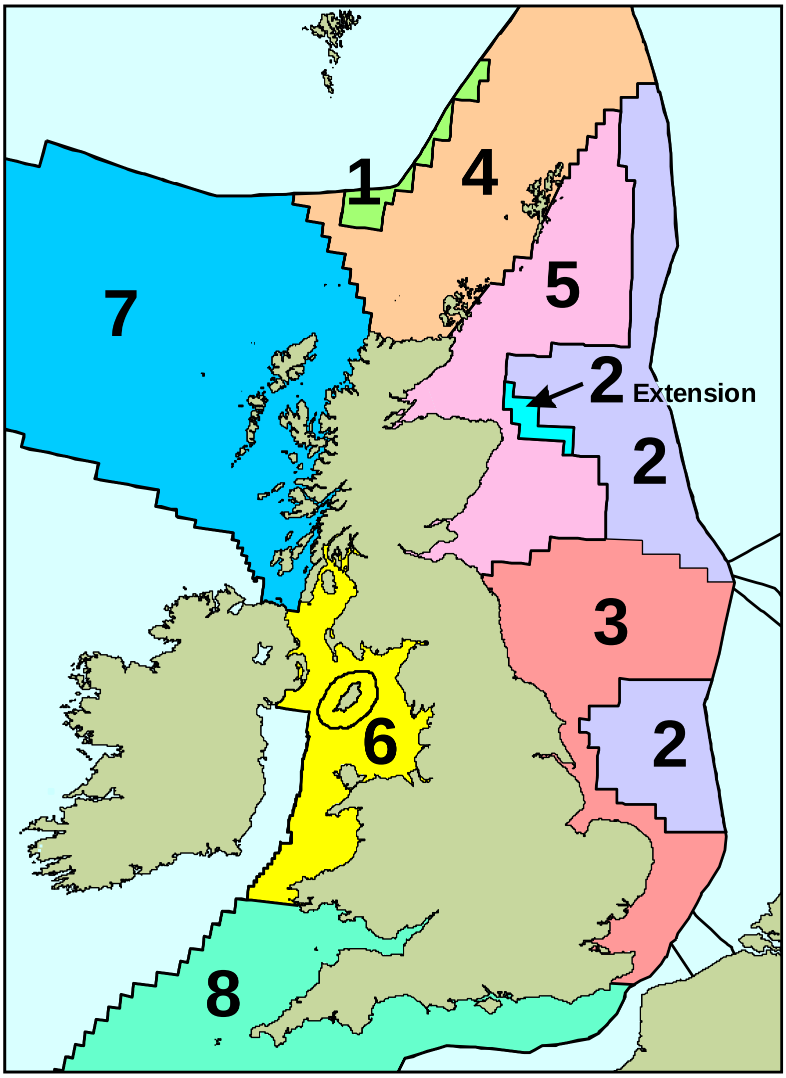

Fig. 3 Location of Strategic Environmental Assessment (SEA) areas 1-8

The British Geological Survey (BGS), on behalf of the DECC, has compiled information on selected undeveloped discoveries and selected undrilled prospects or leads on the UK Continental Shelf that all currently (November 2012) lie within unlicensed acreage. The estimated recoverable resources for some of these are relatively small, but they lie close to existing infrastructure

(Figure 2). Others farther from infrastructure are estimated to contain more than 100 x 10^6 barrels of oil equivalent. The majority of the undiscovered recoverable resources of oil and gas on the UKCS lie in currently licensed acreage, providing farm-in opportunities to existing exploration projects.

Exploration of the UKCS has proceeded at a rapid rate, stimulated and controlled to a significant extent by the frequency and regularity of licensing rounds. Since 1999, the DECC has conducted Strategic Environmental Assessments (SEAs) prior to offshore licensing rounds. Eight SEA areas were defined (Figure 3), and the assessments are now completed for all of these, allowing all areas of the UKCS to be made available in the 27th and all future Licensing Rounds.

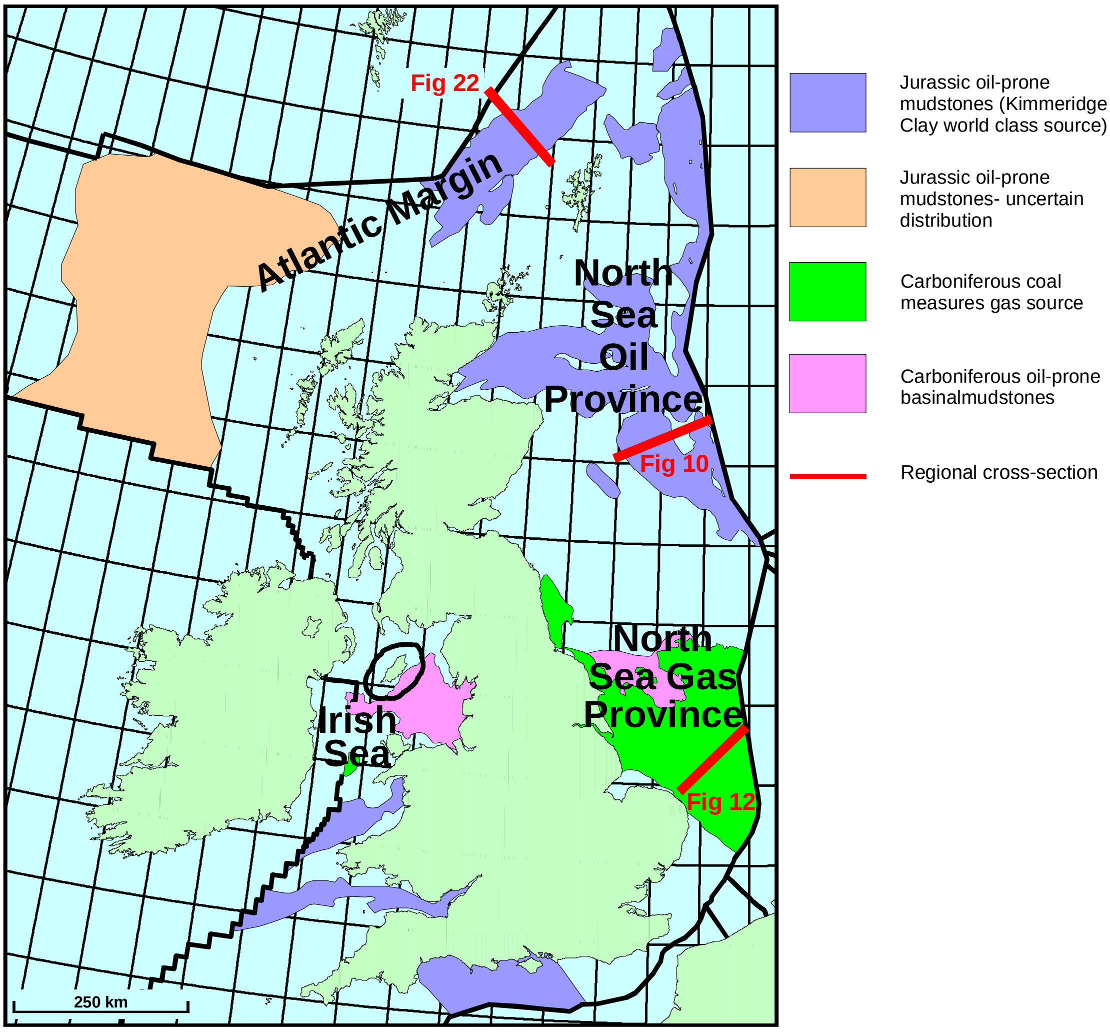

Fig. 4 Distribution of oil and gas provinces and petroleum source rocks on the UK Continental Shelf

The main sedimentary basins within the UKCS can be broadly divided into a number of separate provinces, on the basis of petroleum geology and location. These provinces comprise the North Sea Oil Province, the North Sea Gas Province, the Irish Sea and the Atlantic Margin (Figure 4). The remaining and future petroleum potential of these provinces is summarised below. The North Sea oil and gas provinces contain the majority of the UK's fields and discoveries, and their stratigraphic range is summarised in Figure 5. The following six exploration plays, in particular are anticipated to offer significant hydrocarbon potential (Munns *et al*., 2005):

- Upper Jurassic syn-rift deep-water play
- Upper Jurassic shallow-marine ‘inter-pod’ play
- Lower Cretaceous deep-water play
- Paleogene deep-water play
- Upper Cretaceous Chalk play
- Lower Permian basin-margin play

To provide additional stimulus to exploration and development, recent UK government and oil industry initiatives include the establishment of Internet-based mechanisms for data capture. One such development is the Internet-based Digital Energy Atlas and Library (DEAL) data catalogue for the UK offshore oil and gas industry (web site address - www.ukdeal.co.uk). This and future initiatives are designed to maintain the UK’s position as a world-class operating environment. The DECC is committed to ensuring that the regulatory regime remains flexible and responsive to the changing needs of the hydrocarbon industry and of the UK.

North Sea Oil Province

The North Sea Oil Province is one of the world’s major oil-producing regions. The geological history of the oil province was dominated by an episode of late Jurassic to earliest Cretaceous crustal extension, which developed the Viking Graben, Moray Firth and Central Graben rift systems (Figure 6). Syn-rift, organic-rich marine mudstones (Kimmeridge Clay Formation) are the source rocks for virtually all of the region’s hydrocarbons. Post-rift thermal subsidence enabled these source rocks to become mature for hydrocarbon generation along the rift axes from Paleogene times onwards (Johnson and Fisher, 1998). Hydrocarbon migration has been mainly vertical. Consequently, most of the producing oil and gas fields lie within the geographical boundary of the mature source rocks (Figure 6).

Hydrocarbons occur in a wide range of pre-rift, syn-rift and post-rift reservoirs (Figure 5). Although extensional rifting generally ceased during the earliest Cretaceous (Ryazanian), fault-controlled subsidence persisted in parts of the Moray Firth Basin (Figure 6), throughout much of Early Cretaceous times. This localised tectonism was considered by Oakman and Partington (1998) to have been controlled by strike-slip faulting.

Pre-rift

Pre-rift producing fields can be subdivided into three categories: Palaeozoic, Triassic to Lower Jurassic, and Middle Jurassic. Those fields having reservoirs of Palaeozoic (Devonian, Carboniferous or Permian) age (Figure 6) are concentrated on tilted footwall blocks, are adjacent to the major graben-bounding faults, or are on intrabasinal highs (e.g. Buchan, Auk and Argyll fields). Reservoir quality in these areas is difficult to predict, but may be enhanced by syn-rift fracturing, or by leaching beneath a base Cretaceous unconformity (Johnson and Fisher, 1998).

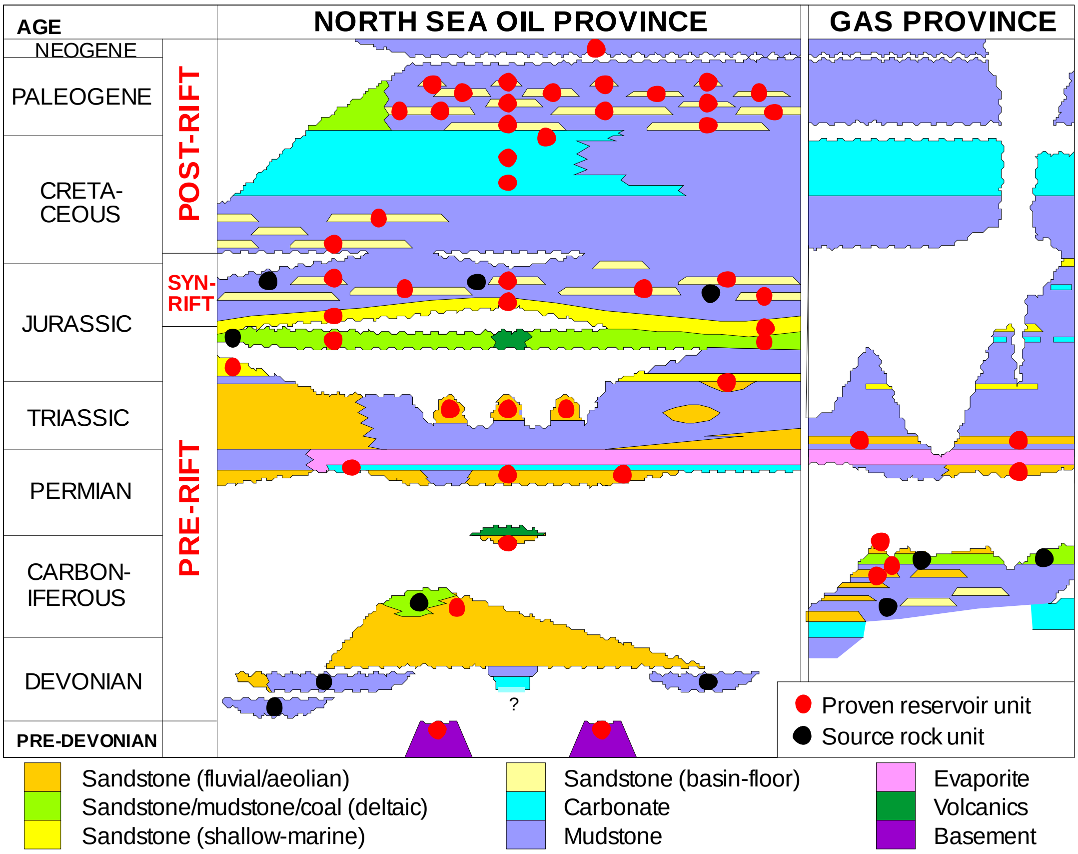

Fig. 5 Simplified stratigraphy and lithofacies in the North Sea oil and gas provinces

Pre-rift producing fields with reservoirs of Triassic to Lower Jurassic age have traps either in tilted footwall blocks adjacent to the major graben, as subcrop closures beneath syn-rift or post-rift strata, (e.g. Marnock-Skua Field) or in stacked plays beneath producing Middle or Upper Jurassic sandstones (e.g. Statfjord Field) (Johnson and Fisher 1998). These reservoirs are typically thick, highly feldspathic, fluvial channel and sheetflood sandstones.

The pre-rift, Middle Jurassic tilted fault-block play is one of the most productive in the North Sea (e.g. Brent and Ninian fields) (Figure 6). The Middle Jurassic reservoirs were deposited within a diachronous clastic wedge, mainly in coastal or delta-plain environments in the south, and as coastal barrier and wave-dominated deltaic facies in the north.

Pre-rift, Middle Devonian lacustrine sediments, a partial source for oil in the Beatrice Field in the Inner Moray Firth (Figure 6), are now thought to be widespread beneath the northern half of the oil province (Duncan and Buxton, 1995). This distribution provides a possibility that the geographic range of Palaeozoic hydrocarbon resources may extend far beyond the graben margins.

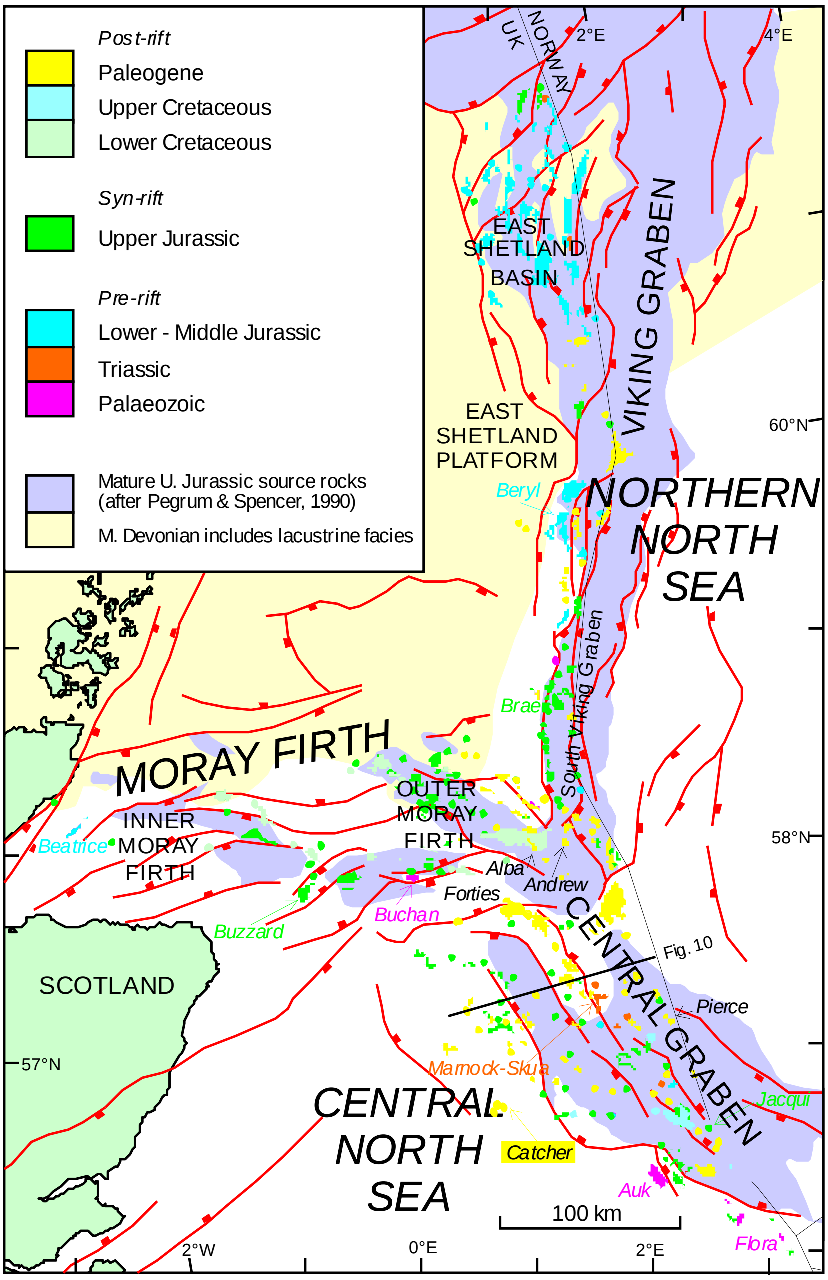

Fig. 6 Age of principle reservoirs in oil and gas fields and distribution of mature Upper Jurassic and potential Middle Devonian source rocks in the North Sea Oil Province

Syn-rift

The Upper Jurassic syn-rift play is currently, and will continue to be, one of the most active in the North Sea. The play is mainly confined to the syn-rift graben, and owes its success to the widespread occurrence within these rifts of high-quality sandstone reservoirs, and closely associated mature source rocks. Interest in the play has been very high since the discovery of the Buzzard Field in 2001, where oil is reservoired within Upper Jurassic deep-water sandstones in a stratigraphic pinch-out trap at the basin margin (Doré and Robbins, 2005).

The producing syn-rift reservoirs include both shallow-marine and deep-marine sandstones. As relative sea level rose rapidly during the early stages of rifting, retrogradational packages of shallow-marine shelf and coastal sands were deposited around the basin margins of the Outer Moray Firth and Central Graben in particular. As rifting continued, footwall uplift along major graben-bounding faults locally exceeded the continuing relative rise in sea level. This led to footwall erosion and mass transfer of coarse clastic debris into the adjacent deep-water basins.

The syn-rift producing fields (e.g. Piper, Brae and Fulmar fields) display a wide variety of trapping mechanisms, including tilted fault blocks, four-way dip closures, hanging-wall closures, stratigraphic closures and combined structural-stratigraphic closures. Widespread Upper Jurassic and Lower Cretaceous mudstones provide a regional top seal for many syn-rift traps. Wells in the deepest parts of the graben areas have extended the play fairway for Upper Jurassic syn-rift shallow-marine and basin-floor sandstones. This deep basin-axis high temperature/high pressure gas condensate play is developed through overpressure that has preserved good reservoir quality at anomalous depths relative to present depth (Figure 7).

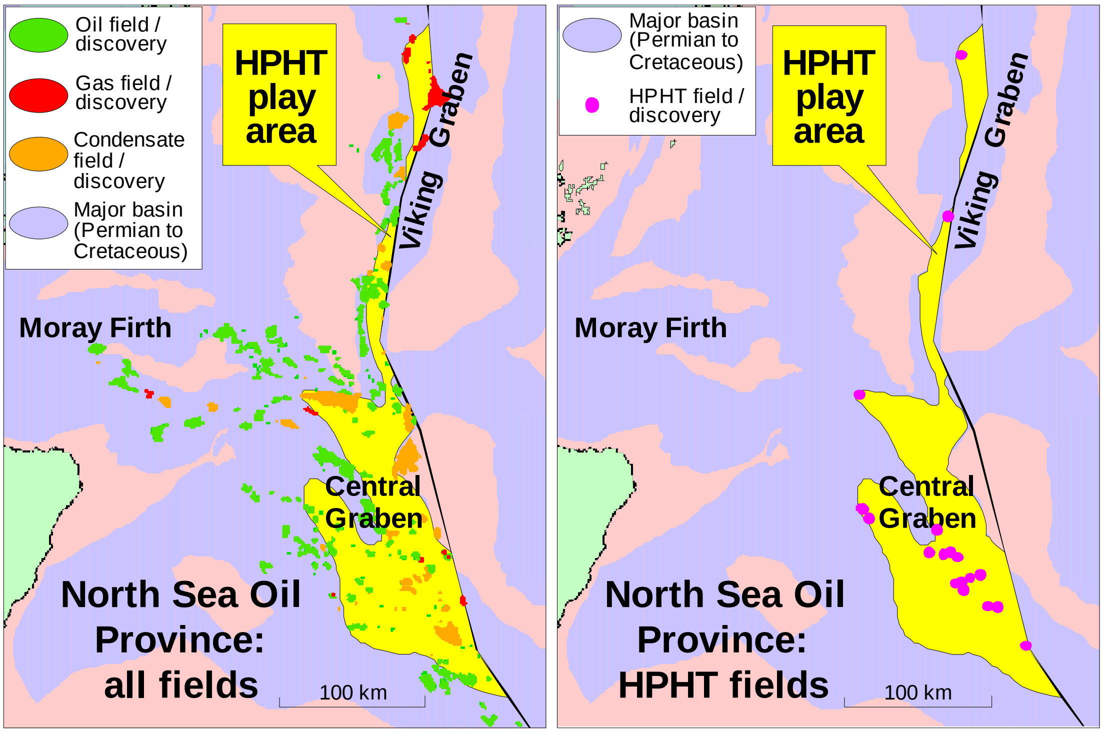

Fig. 7 Extent of the high pressure/high temperature (HPHT) gas condensate exploration play in the North Sea Oil Province

Post-rift

Post-rift thermal subsidence has continued from the cessation of rifting to the present day. Over most of the North Sea, the post-rift Lower Cretaceous succession comprises argillaceous rocks. In the Moray Firth, however, Lower Cretaceous deep-water mass flow deposits include sandstones that form reservoirs in a number of fields (e.g. Captain and Britannia fields) (Figure 6). There is a growing realization that equivalent sandstones may also occur farther south within the depocentres of the Central Graben, where their potential as hydrocarbon reservoirs remains largely unexplored (Milton-Worssell *et al.,* 2006).

The Upper Cretaceous chalk across much of the Central Graben and Moray Firth has generally poor reservoir properties. However, stratigraphic, dynamic and constriction traps offer significant future exploration potential in the southeastern part of the Central Graben (Megson and Tygesen, 2005). Upper Cretaceous sediments in the Viking Graben are dominantly composed of non-reservoir mudstones.

Regional patterns of sedimentation changed dramatically in the early Paleocene with the influx into basinal areas of huge volumes of coarse clastic detritus as mass flows. This detritus was shed from the uplands of northern Scotland and from the Orkney-Shetland Platform that were undergoing uplift in response to development of the Iceland plume and opening of the North Atlantic Ocean (White, 1989).

The Paleogene reservoirs occur in a succession of up to fifteen gently eastward dipping, overlapping depositional sequences bounded by erosional unconformities. The distribution of reservoir sandstones and potentially sealing mudstones within an individual sequence reflects the gross depositional setting of that sequence. Consequently, each sequence requires a separate play evaluation (Johnson and Fisher, 1998). Virtually all of the sand systems become progressively more distal towards the east or south-east.

In 1998 Johnson and Fisher predicted that the Paleogene play could potentially yield around 45% of future oil and 30% of future gas discoveries in the North Sea's oil province. They predicted that future exploration would focus on locating subtle stratigraphic traps, and on extending the geographic range of discoveries into basin-marginal areas. For example, a palaeogeomorphic exploration play is associated with deep incision and subsequent infill of Paleogene deltaic sediments along the western margin of the South Viking Graben (Figure 1), and possibly also within the Atlantic Margin Province (Underhill, 2001). Depth of burial is relatively shallow in these areas, leading to a preponderance of heavy, biodegraded oils. Nevertheless, experience gained in maximizing production from similar existing fields is continuing to improve the economic potential of the many untested prospects in such areas.

To summarise, the undiscovered recoverable resources in the North Sea oil province may be as much as 8.08 x 10^9 barrels of oil equivalent (BBOE) (Figure 8). Most of these resources are likely to be found in syn-rift Upper Jurassic shallow-marine and basin-floor sandstone plays and in post-rift Lower Cretaceous and Paleogene basin-floor sandstone plays. However, a significant component of discoveries will continue to be made from pre-rift Palaeozoic, Triassic to Lower Jurassic and Middle Jurassic plays.

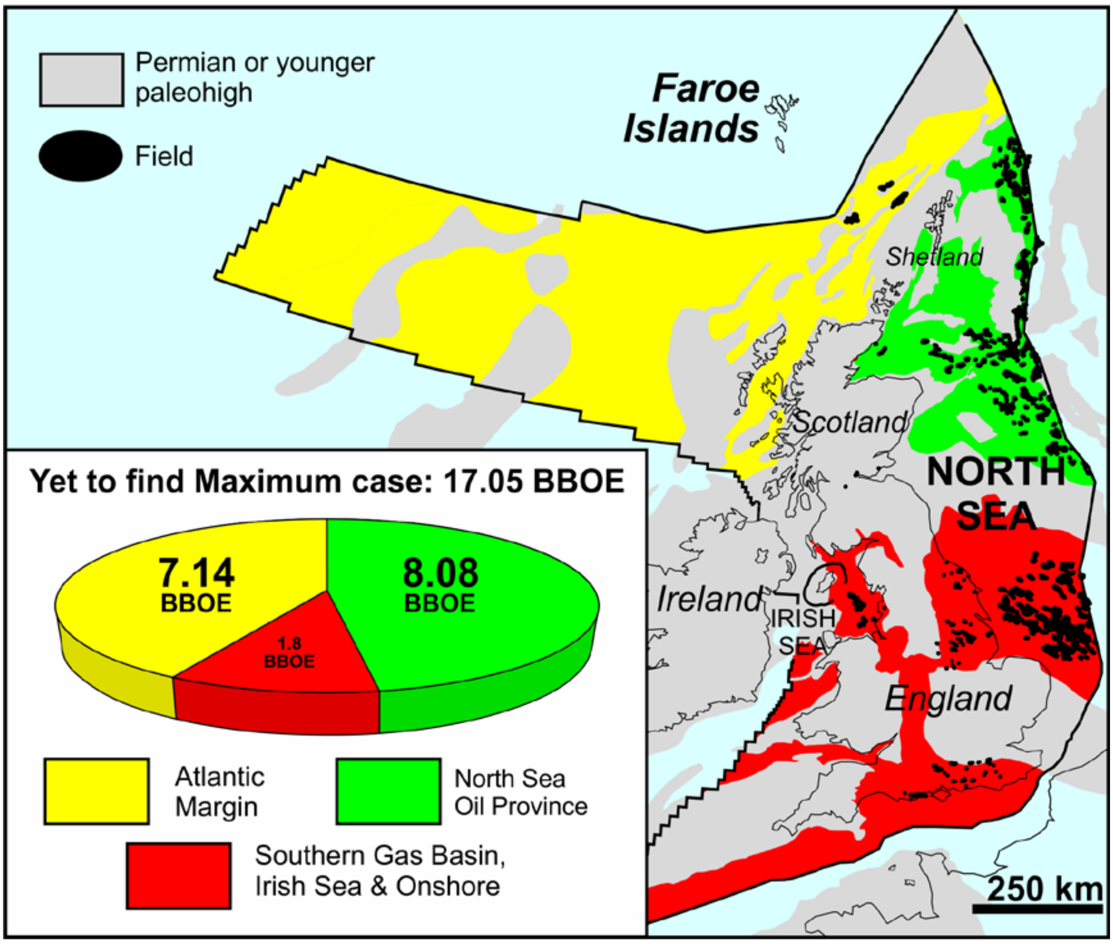

Fig. 8 UK undiscovered reserves - maximum case scenario (Date source: DECC 2013a)

Northern North Sea

The Northern North Sea includes the East Shetland Basin, Beryl Embayment, Viking Graben and East Shetland Platform (Figure 6). Producing fields in the East Shetland Basin and Beryl Embayment dominantly contain pre-rift reservoirs, although post-rift fields also occur in the south. In contrast, producing fields in the South Viking Graben dominantly have syn-rift reservoirs, although post-rift reservoirs are also present. The East Shetland Platform contains hydrocarbon-bearing post-rift reservoirs (e.g. Bressay area) (Underhill, 2001).

Pre-rift producing fields in the East Shetland Basin and the Beryl Embayment have reservoirs of Lower-Middle Jurassic age (e.g. Statfjord Field) (Figure 6). The traps are mostly tilted fault blocks that are topsealed by Upper Jurassic and Cretaceous mudstones. Virtually all of the large footwall closures north of 58°N have already been tested, but the potential for economic resources in hanging-wall closures is under-explored.

In the South Viking Graben, the producing **syn-rift** reservoirs are dominantly deep-marine sandstones. This southern area may offer an opportunity for discovering untapped resources in pre-rift and syn-rift reservoirs near the

UK/Norway median line, due to the development of a high pressure and high temperature play (Figure 7). In this area, overpressure, caused mainly by high sedimentation rates in the overburden, is likely to have preserved economic porosity and permeability to anomalous depths in the graben. Farther north, the 2008 Cladhan 210/29a-4 discovery was made in a syn-rift Upper Jurassic basin-floor fan adjacent to the East Shetland Basin's boundary fault, suggesting that significant syn-rift reserves may still await discovery from this play.

Post-rift Paleogene reservoirs are also developed in the East Shetland Basin, Beryl Embayment and South Viking Graben (Figure 6). The Paleogene play remains highly prospective and also extends into basin-marginal areas such as the East Shetland Platform, where pre-rift, Middle Devonian lacustrine sediments may provide an additional source for oil.

Moray Firth Basin

Within the Moray Firth Basin (Figure 6), the majority of fields produce hydrocarbons from syn-rift and post-rift reservoirs. A number of pre-rift producing fields also occur on tilted footwall blocks (e.g. Beatrice Field), or on intrabasinal highs (e.g. Buchan Field).

The pinch-out of **syn-rift**, Upper Jurassic shallow marine sandstones at the margins of the Outer Moray Firth will continue to provide an attractive exploration target. In this Mesozoic basin margin exploration play, the principal challenge is to develop a sequence stratigraphic framework that utilises all the eustatic and local tectonic influences as a means of determining the preservation potential for the reservoir sandstones (Johnson and Fisher, 1998).

Within basinal parts of the Moray Firth, the Upper Jurassic syn-rift exploration play remains prospective. In the Inner Moray Firth, for instance, there has been only limited exploration to date of Upper Jurassic basin-floor sandstones. This may be because it is not widely appreciated that the Upper Jurassic source rocks (Kimmeridge Clay Formation) are fully mature for oil generation in the deepest parts of the asymmetrical graben that characterize this area (Oakman and Partington, 1998). Middle Devonian lacustrine sediments in the footwalls of these graben are also likely to be mature for hydrocarbon generation. The most attractive play comprises up-dip, distal pinch-out of sandstone reservoirs, with encasing basinal mudstones providing lateral seal (Figure 9). It is not known yet whether the reservoir sandstones are widespread along the axes of the graben, or whether they are relatively localized, comprising separate accumulations derived from point sources.

Recent wells in the deepest parts of the Outer Moray Firth have extended the play fairway for thick, Upper Jurassic syn-rift basin-floor sandstones. This deep basin-axis play will continue to be a focus for future exploration. Furthermore, recent drilling successes have proven that substantial hydrocarbon resources still remain to be discovered on the hanging walls of the major faults of the region.

A basin-floor sandstone fairway (e.g. Kopervik play) within the **post-rift** Lower Cretaceous succession of the Moray Firth is proving to be an attractive exploration target. In this area, localised footwall erosion possibly associated with strike-slip faulting led to the mass transfer of coarse-clastic debris into the adjacent deep-water basins. This play therefore shows similarity with the Upper Jurassic, syn-rift basin-floor sandstone play. Drilling has established that sea-floor bathymetry had a significant impact on depositional processes here too, with the thickest sandstones being encountered in localized basinal areas within under-filled Late Jurassic graben (Oakman and Partington, 1998). Early successes were in structural traps, but recent discoveries have revealed the potential for significant undiscovered hydrocarbons in stratigraphic traps. Increased bandwidth in the seismic data will be necessary to adequately define the limit of this fairway.

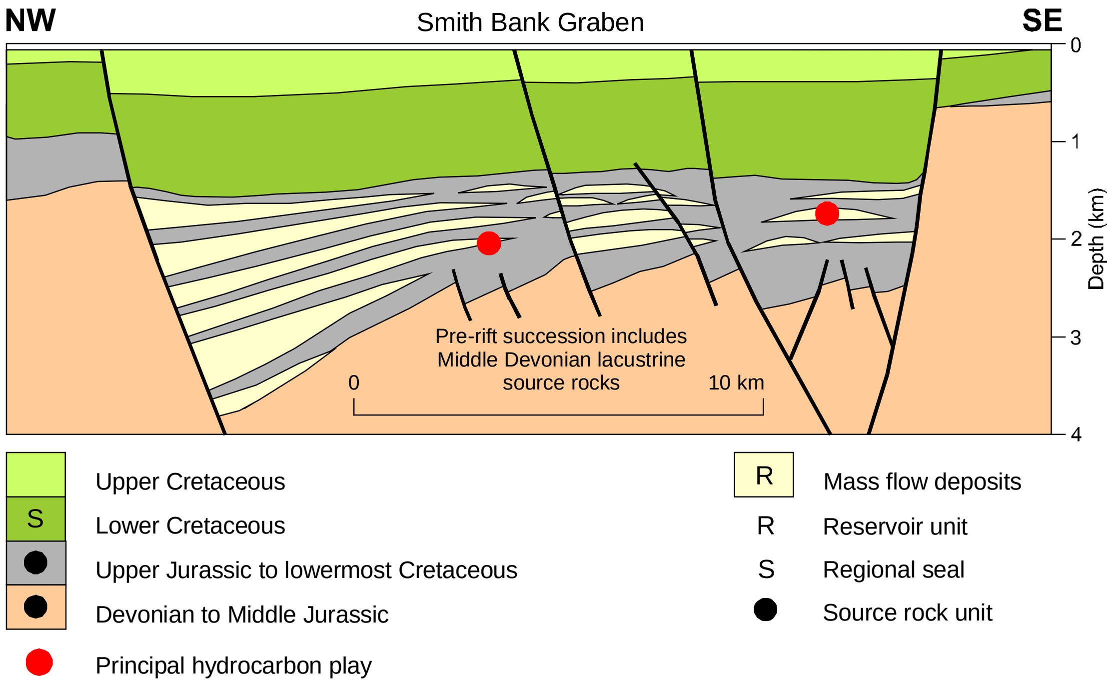

Fig. 9 Schematic play diagram for Upper Jurassic to basal Cretaceous of Inner Moray Firth, North Sea Oil Province

Post-rift Paleogene reservoirs occur in both structural and stratigraphic traps, and within both basin-floor sandstone and deltaic plays. The Paleogene plays are largely confined to the eastern part of the Moray Firth Basin.

Central Graben

The Central Graben contains a wide range of pre-, syn- and post-rift fields. Its pre-rift producing fields have mainly Palaeozoic or Triassic to Lower Jurassic reservoirs. Those having reservoirs of Palaeozoic (Devonian, Carboniferous or Permian) age (Figure 6) are concentrated on tilted footwall blocks (e.g. Auk Field) associated with the major graben-bounding faults. The discovery in

1998 of the Flora Field, with its ?Stephanian[1] reservoir indicates that the Palaeozoic play has not reached maturity yet. Indeed, the reservoir potential of the Carboniferous strata remains underexplored (Milton-Worssell *et al*, 2010)

The traps for **pre-rift** producing fields with reservoirs of Triassic to Lower Jurassic age are subcrop closures beneath syn-rift or post-rift strata (e.g. Marnock Field). The reservoirs are typically thick, highly feldspathic, fluvial channel and sheetflood sandstones. They are fine-grained on the western flank of the Central Graben, where they are partly confined to topographic lows that formed in response to halokinesis of underlying Upper Permian evaporites (Penge *et al*. 1999) (Figure 10). This has led to abrupt reservoir thickness changes, elongate patterns of net sandstone, and poor connectivity between adjacent sand systems. Reservoir properties are highly variable. Not all of the prospective structural or subcrop traps have been drilled as yet, and the potential for traps defined by reservoir pinch-out is under-explored.

Pre-rift Middle Jurassic clastic reservoirs in the Central Graben are associated with volcanic centres, and reservoir prediction is difficult. Nevertheless, there may be an opportunity for discovering untapped resources, because there is a likelihood that overpressure has preserved economic porosity and permeability to anomalous depths in the graben. The most attractive prospects may be those stacked below syn-rift targets.

The pinch-out of **syn-rift**, Upper Jurassic shallow marine and basin-floor sandstones at the margins of the Central Graben will continue to provide an attractive exploration target (e.g. Buzzard Field, Fig. 6). Careful sequence stratigraphic analysis will be required to fully evaluate the distribution of shoreline facies reservoirs in this Mesozoic basin margin play.

Exploration within overpressured parts of the Central Graben has revealed that the basal syn-rift shallow-marine sandstones are more widespread than previously recognized (Cordey, 1993). Identification of drilling targets will be more challenging here than around the basin margins, but careful sequence-stratigraphic interpretation of 3D seismic data should yield further successes in this area. Contemporaneous halokinesis is another factor affecting facies distributions in the Central Graben, and later halokinesis is also important as a trapping mechanism.

Recent wells in the deepest parts of the Central Graben have extended the play fairway for thick, overpressured Jurassic syn-rift basin-floor sandstones into this area too. It is these sandstones that provide the gas reservoir for the recently discovered Jacqui Field (Figure 6). Furthermore, recent drilling successes have demonstrated that substantial hydrocarbon resources still remain to be discovered on the hanging walls of the major faults of the region.

[1] European nomenclature is utilised for subdivision of the Carboniferous throughout this account. The Dinantian and basal part of the Namurian subsystems are equivalent to the Mississippian, and the remainder of the Namurian with the Westphalian and Stephanian are equivalent to the Pennsylvanian of American usage (see Figure. 15).

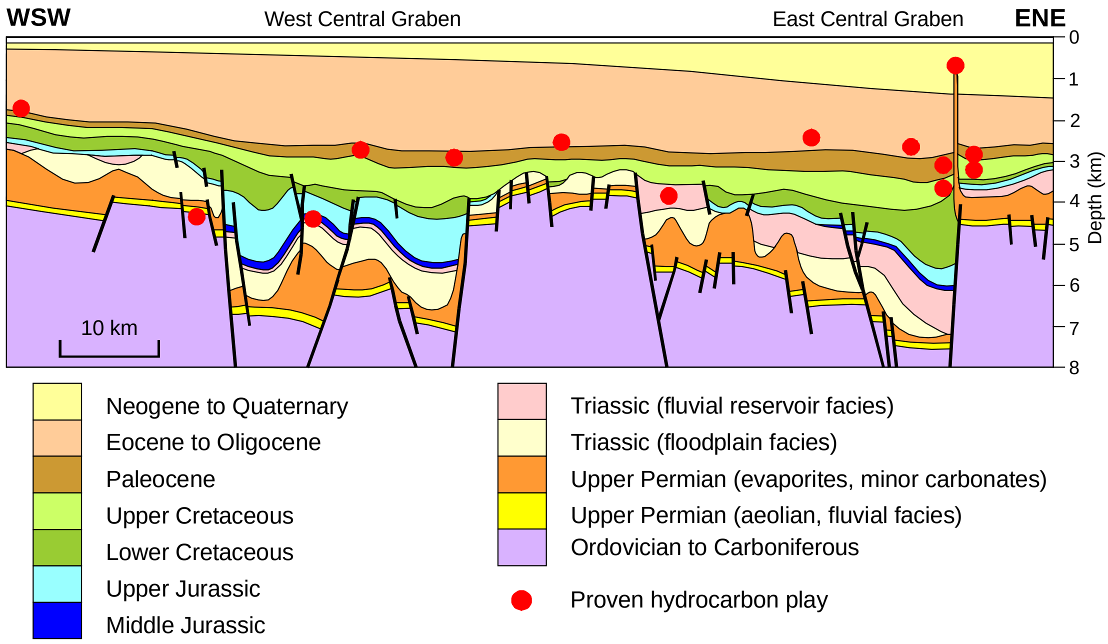

Fig. 10 Schematic section illustrating principal under-explored plays in the Central North Sea. See Fig. 4 for locations

Up to 1,000 m of **post-rift** Upper Cretaceous chalk accumulated in the Central Graben. The chalk has generally poor reservoir properties in the UK sector. Exceptions include chalk that has been redeposited by gravity flow processes at the base of oversteepened slopes, for instance around rising salt diapirs and around the graben margins. The potential for stratigraphic entrapment within porous redeposited chalk encased in non-porous sediment remains under-explored in basinal areas, but requires an effective migration conduit from underlying source rocks. There is also a possibility that chalk porosity has remained anomalously high relative to depth of burial in overpressured areas of the Central Graben. Even where relatively porous, however, it has yet to be proven that significant resources remain to be discovered from chalk reservoirs in the UK sector of the North Sea. All of the existing fields (e.g. Joanne and Kyle fields) are in the south-east of the oil province. They are small and only marginally economic.

The Paleogene reservoirs in the Central Graben occur in both structural and stratigraphic traps. Structural traps are located mainly over pre-Tertiary structural highs (e.g. Forties Field), or are either flanking or overlying Permian salt diapirs (e.g. Andrew Field, Pierce Field). Top seal is provided by regionally extensive mudstone intervals. Stratigraphic traps include mounded closures and sand pinch-outs, which can occur in a wide range of depositional settings. The pinch-out traps have a higher exploration risk of seal failure, although they have not always been tested in optimal drilling locations (Bain, 1993).

North Sea Gas Province

The Southern North Sea had produced around 45.8 tcf of gas from 140 gas fields by the end of 2012 (DECC 2013) Around 80.4% of this production has been from Lower Permian (Rotliegend) aeolian dune sandstones, and 12.6%

from Triassic fluvial sandstones (Figures 11 and 12). Upper Permian carbonates have contributed minor production from three fields. Remaining 7.0 % of production has been from Carboniferous fluvial sandstones.

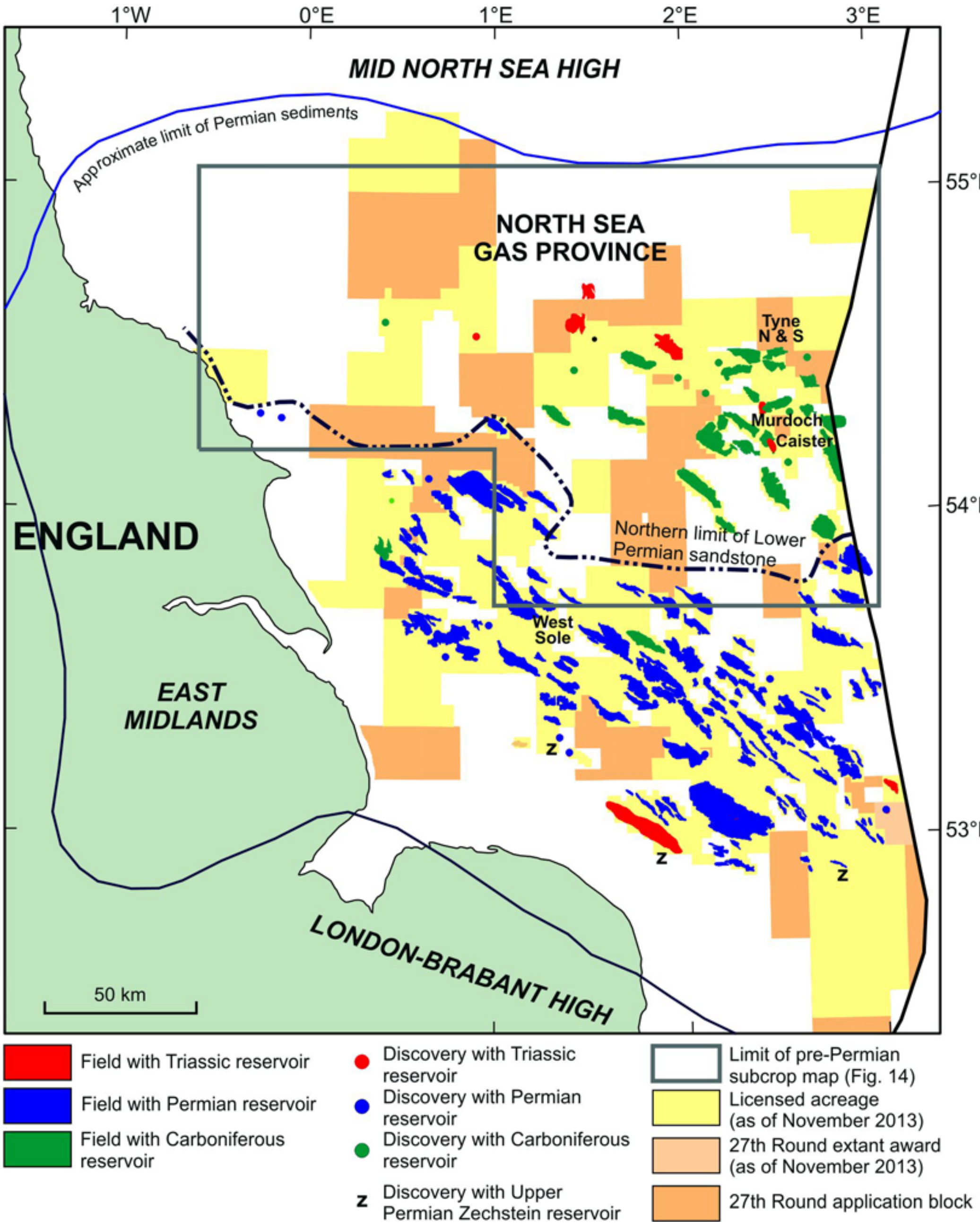

Fig. 11 Fields and discoveries in the UK North Sea Gas Province

The Lower Permian (Leman Sandstone) play is largely restricted to the southern half of the gas province (Figure 11), because the reservoir facies passes northwards into contemporary playa lake mudstones and evaporites. The discovery of the Cygnus Field 50 km north of the purported pinch-out indicate that the Lower Permian pinch-out exploration play (Figure 13) is not fully explored. High-resolution sequence stratigraphy is now being applied to map the extent of reservoir units around the margin of the contemporary desert lake. The Lower Permian plays are continuing to evolve through the integration of new techniques and technologies with the aim of recognizing ever more subtle traps. For example, pre-stack depth migration is proving a powerful tool in compensating for lateral velocity variation effects caused by the widespread presence in the overburden of diapiric and pillowed salt, hence enabling increasingly accurate depth imaging of drilling targets. Other techniques that are keeping this fairway active include the application of seismic inversion to assess basin-margin plays, the evaluation of diagenetic controls on regional reservoir quality, and careful and detailed fault seal analysis.

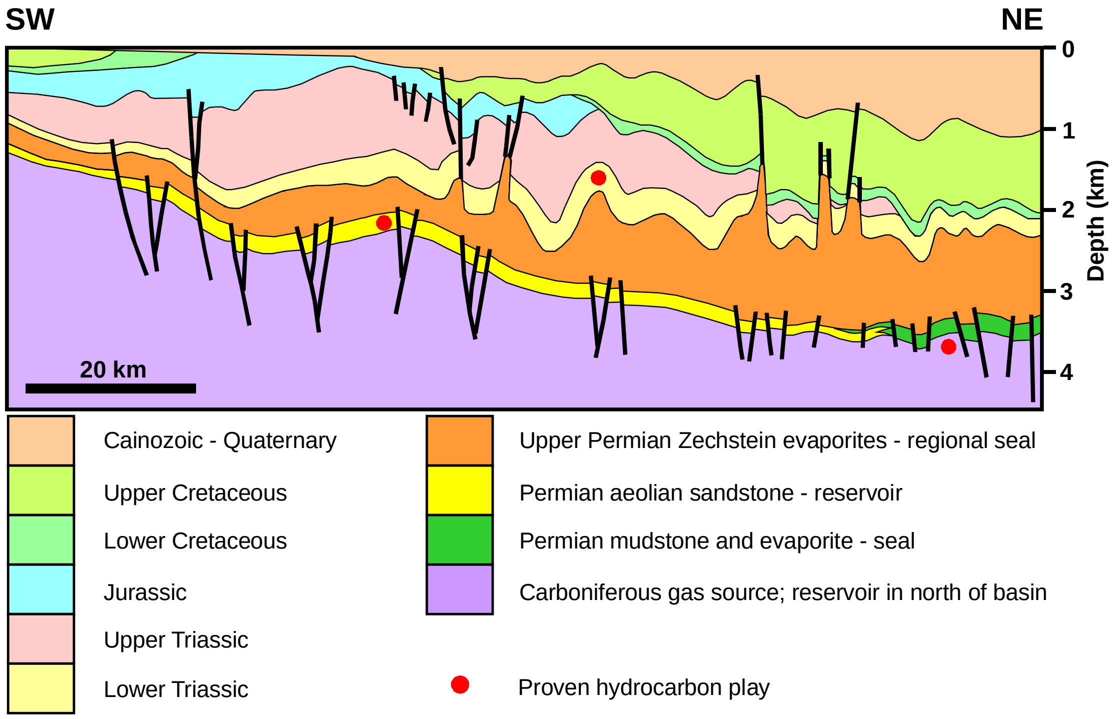

Fig. 12 Schematic section illustrating principal plays in the North Sea Gas Province. See Fig. 4 for location of section

The structure and stratigraphy of the Carboniferous in the northern part of the North Sea Gas Province are summarized in Figure 14. The deep structure of the basin is conjectural, because seismic resolution is generally limited to within 2 km below the base Permian unconformity. Nevertheless, it is believed that, as in the onshore UK, late Devonian to Dinantian rifting established a block and basin deep structure and palaeogeography (Leeder and Hardman, 1990) across the region. Significantly different interpretations exist for the locations of the syn-rift blocks and basins (e.g. Collinson *et al.*, 1993; Cameron and Ziegler, 1997; Besly, 1998). Rift-related subsidence evolved to thermal sag during the early Namurian, when deltas prograding from the north filled the basin. The remainder of the Carboniferous section is characterized by a succession of alluvial and lacustrine beds (Westphalian A to C), passing upward into alluvial red bed facies (Westphalian C to D).

Most of the Carboniferous drilling targets tested so far are defined by structural closure on the base Permian unconformity. Resting on this unconformity, the Lower Permian playa lake sediments and overlying thick Upper Permian evaporites provide an excellent regional seal. The earliest drilling targets were major NW-SE trending 'pop-up' horst blocks bounded by

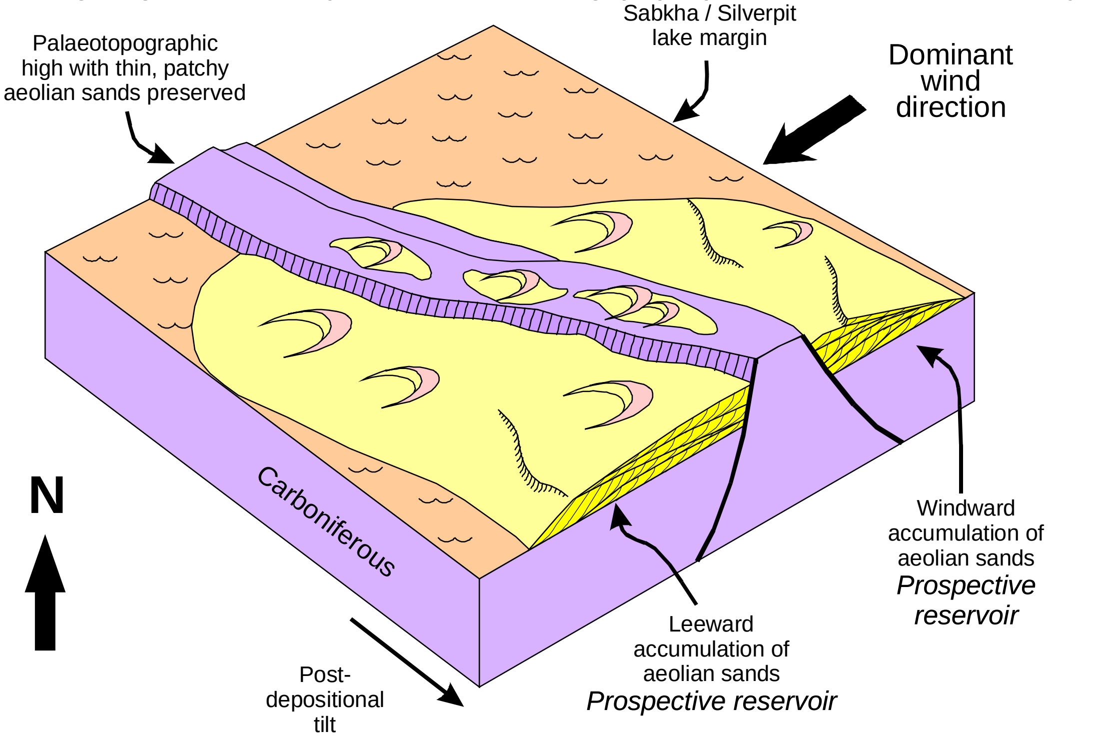

Fig. 13 Lower Permian aeolian sandstone pinch-out play, North Sea Gas Province

reverse faults (Figure 15), such as the Murdoch and Trent ridges (Figure 14). This phase of exploration led to the discovery of most of the fields that are now in production or under development. It established that potentially productive fluvial sandstone reservoirs are widespread in the Westphalian C-D red beds, and at specific intervals within the late Namurian to Westphalian C coal measures and deltaic sediments.

The potential for stratigraphic plays within the Carboniferous has been lightly addressed so far, mainly due to the limitations of seismic data available during the early phase of exploration to resolve such plays, and the need for a better understanding of the distribution and geometry of intraformational seals. The South Tyne Field (Figure 11) is a success story for the combined structural and stratigraphic trap found at the erosional limit of the late Westphalian C-D alluvial red beds. As 3D seismic coverage has extended across the region, isolated wedges of the red beds have been resolved as outliers on the hanging walls of E-W to ENE-WSW oriented faults in central Quadrant 44 (Figure 14). Furthermore, the 3D data has resolved a much greater complexity of faulting within the Carboniferous interval than previously recognized from 2D data (Oudmeyer and de Jager, 1993). In almost all cases, the wedges of red beds do not occur within a structural closure of the base Permian unconformity, and hence they require lateral fault seal (Figure 15). Numerous stratigraphic traps of a similar wedge-like geometry are anticipated for older Westphalian reservoirs as they rise to pre-Permian subcrop (Figure 14).

Successful identification of such drilling targets requires detailed mapping on 3D seismic data, and careful fault seal analysis.

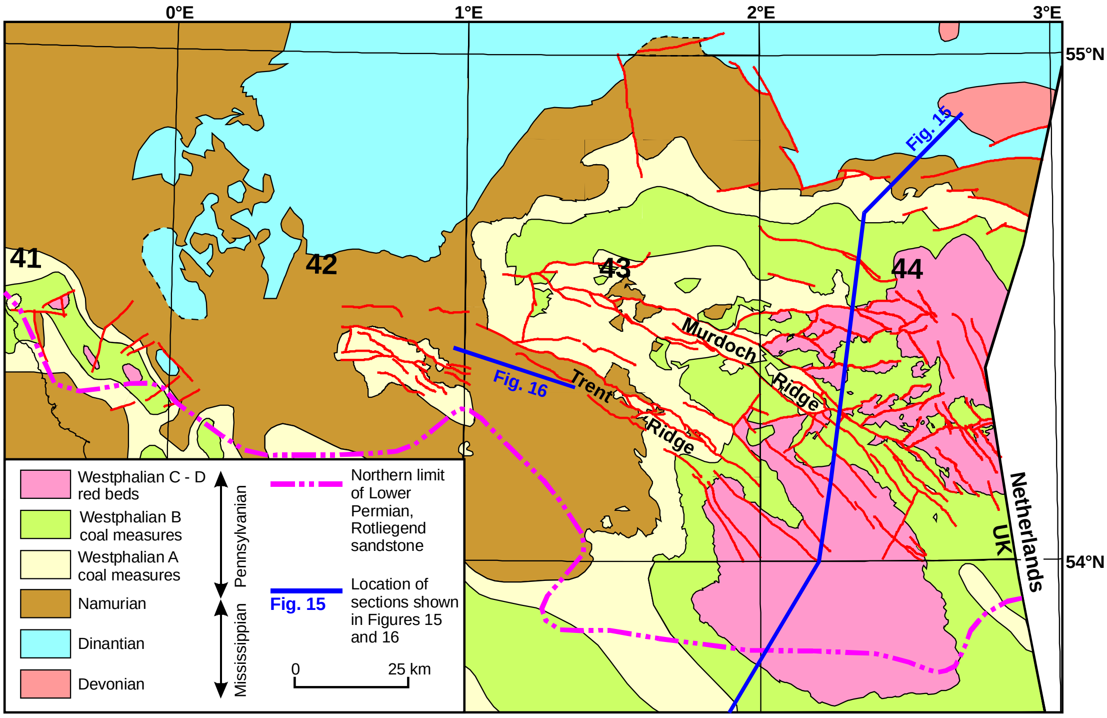

Fig. 14 Subcrop of pre-Permian strata in the northern part of the North Sea Gas Province

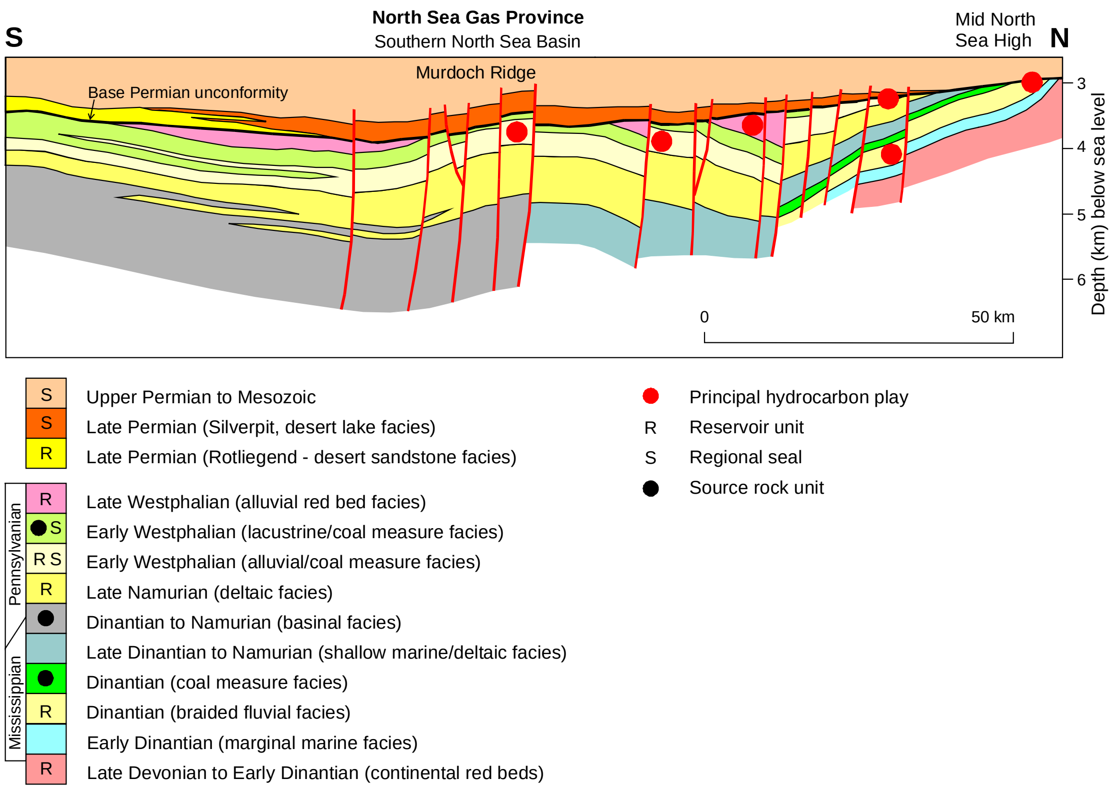

Fig. 15 Schematic section summarising principal Carboniferous plays in the North Sea Gas Province, See Fig. 14 for location

Deeper Carboniferous plays remain speculative, because the geology of the Dinantian to Namurian succession is poorly constrained across much of the southern North Sea. Few wells have penetrated more than a few hundred metres of this section. A notable exception is well 43/17-2, which proved 2454 m of mudstone-dominated late Dinantian to early Namurian sediments from within a deep syn-rift basin (Besly, 1998). Laterally equivalent basinal mudstones are the source rocks onshore for the East Midlands oil province, but have reached maturity for gas generation offshore. Basin-floor fan sandstones, which make up at least 10% of the succession in this well, have excellent reservoir potential for structural and stratigraphic entrapment (Figure 16).

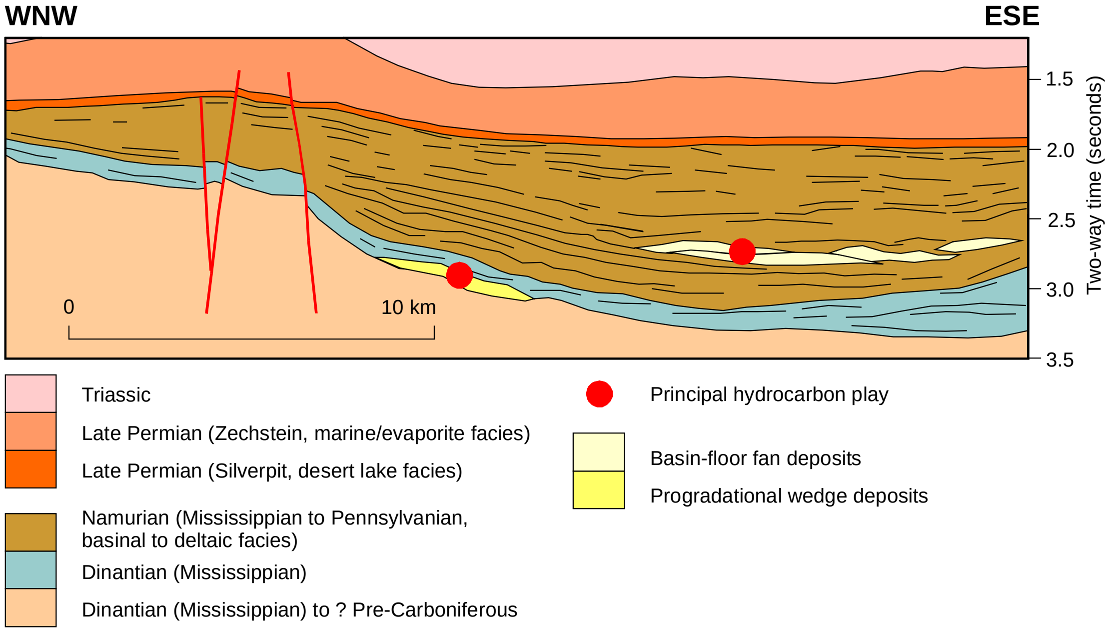

Fig 16 Geoseismic section illustrating undrilled Lower Carboniferous plays, North Sea Gas Province (adapted from Cameron and Ziegler 1997). See Fig. 14 for location

Cameron and Ziegler (1997) suggested that significant new opportunities remain in the largely untested basal part of the Carboniferous section. In particular they highlighted a progradational wedge play of Dinantian detrital carbonates, derived from an adjacent platform succession in UK Quadrant 42 (Figure 16). Carbonate shelf-margin facies recorded from the UK onshore include carbonate shoals, build-ups, talus, debris flows and turbidites (Fraser and Gawthorpe, 1990), and secondary porosities of up to 30% characterize carbonate debris flows where dolomitized (Gawthorpe, 1987). Another play envisaged by Cameron and Ziegler (1997) relies on the possibility that the normally gas-prone Westphalian coal measures could have generated significant volumes of oil along the southern margin of the North Sea Basin. This play has oil migrating from these coal measures into conventional structural traps with potentially stacked Devonian to Westphalian reservoirs.

To summarise, the North Sea Gas Province contains 10.7% of maximum undiscovered recoverable resources (Figure 8). Future exploration is expected to focus on stratigraphic plays such as the northward pinch-out of the Leman Sandstone, and on increasing the proportion of production from Carboniferous reservoirs. This will be achieved by extending the geographical range of existing plays, by targeting subcrops of proven reservoirs beneath the regional base Permian unconformity, and by testing hanging-wall wedges of these strata adjacent to the major intra-Carboniferous faults.

Irish Sea Basins

East Irish Sea Basin

With 8.30 tcf of gas and 209 million barrels of oil estimated by the field operators as ultimate recovery from 12 producing fields (DECC, unpubl.), the

East Irish Sea Basin (Figure 17) is at a mature exploration phase. Early Namurian basinal mudstones are the source rocks for these hydrocarbons. Production from all fields is from fault-bounded traps of Lower Triassic, principally aeolian Sherwood Sandstone reservoir, top-sealed by younger Triassic continental mudstones and evaporites. Future exploration will initially concentrate on extending this play, but there remains largely untested potential also for gas and oil within widespread Carboniferous fluvial sandstone reservoirs. This play requires intraformational mudstone seal units to be present, as there is no top-seal for reservoirs subcropping the regional base Permian unconformity in the east of the basin, and Carboniferous strata crop out at the sea bed in the west.

Caernarfon Bay Basin

The Caernarfon Bay Basin (Figure 17) contains up to 7 km of Permian and Triassic syn-rift sediments in an asymmetrical graben that is bounded to the north and south by Lower Palaeozoic massifs. Only two exploration wells have been drilled so far, and there remain numerous undrilled targets in tilted fault block plays (Figure 18). As in the East Irish Sea Basin, the principal target reservoir is the Lower Triassic, Sherwood Sandstone, top-sealed by younger Triassic mudstones and evaporites. Wells in the Irish Sector to the west (Figure 17) have demonstrated that pre-rift, Westphalian coal measures are excellent hydrocarbon source rocks, and are at peak maturity for gas generation (Maddox *et al.,* 1995). Seismic profiles clearly image these strata continuing beneath a basal Permian unconformity into at least the western part of the Caernarfon Bay Basin. The timing of gas generation presents the greatest exploration risk. Maximum burial of, and primary gas migration from, the source rocks could have terminated as early as the Jurassic, whereas many of the tilted fault blocks were reactivated or created during Paleogene inversion of the basin. However, it is also possible that a secondary gas charge occurred during regional heating associated with intrusion of Paleogene dykes, such as those that crop out nearby on the coastline of north Wales. Floodpage *et al.* (1999) have invoked this second phase of Paleogene hydrocarbon generation as an important factor in the charging of the East Irish Sea Basin’s oil and gas fields. It is not clear as yet whether aeromagnetic anomalies in the south-east of Caernarfon Bay are imaging a continuation of the dyke swarm into this area too, or whether they are instead associated with deeply buried Permian syn-rift volcanics. Alternatively, the fault block traps could have been recharged by exsolution of methane from formation brines as a direct result of the Tertiary uplift (*cf.* Doré and Jensen, 1996).

Cardigan Bay Basin

The Cardigan Bay Basin forms a continuation into UK waters of Ireland’s North Celtic Sea Basin (Figure 1), which has four producing gas fields.

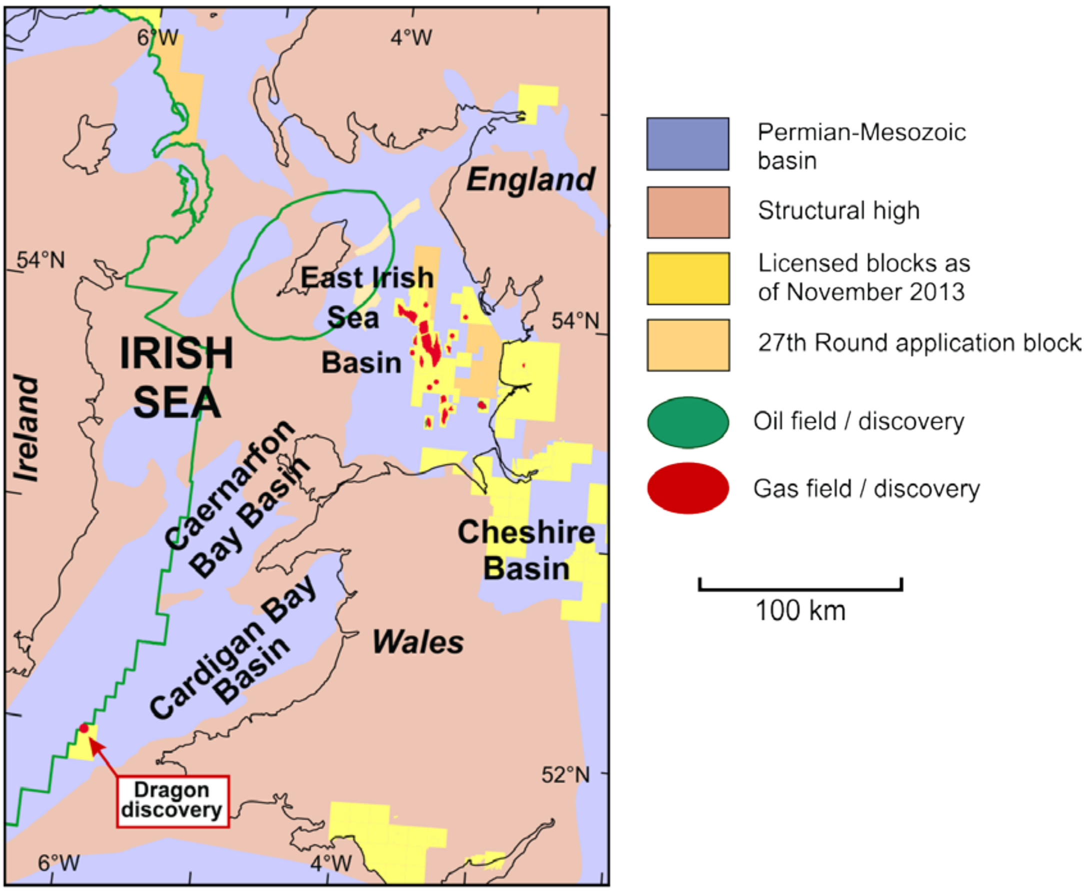

Fig. 17 Hydrocarbon fields and discoveries in the UK Irish Sea Basin

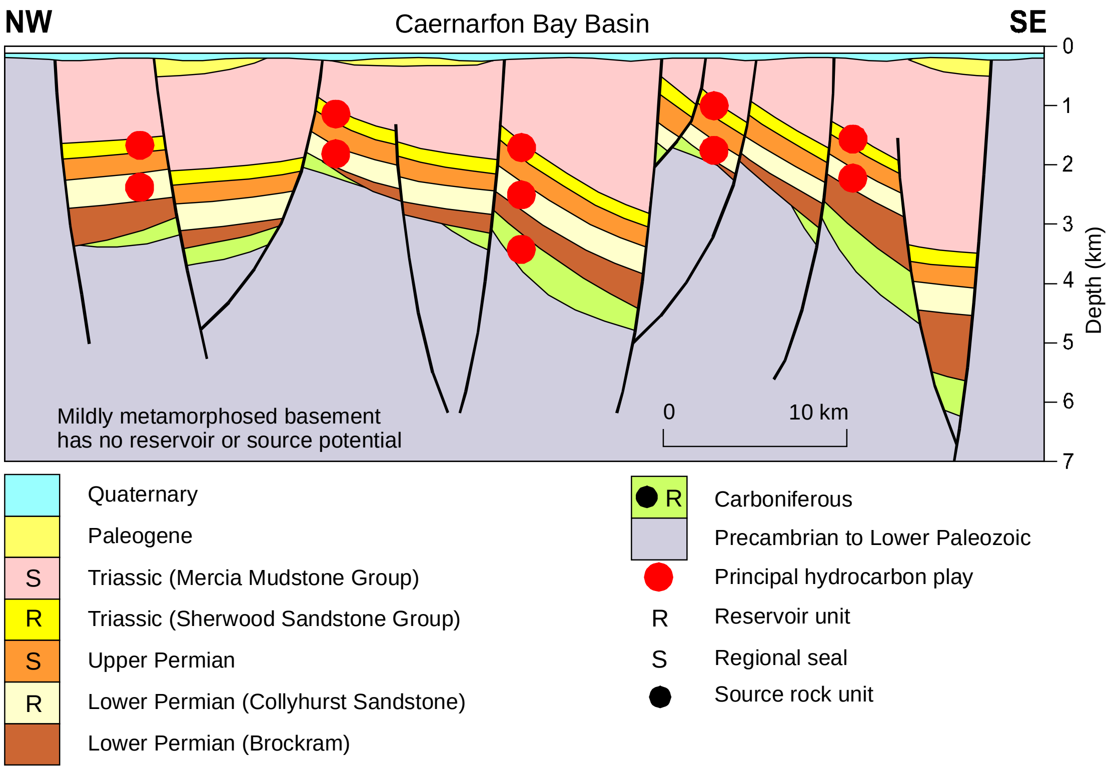

Fig. 18 Schematic play diagram for the Caernarfon Bay Basin, Irish Sea

The basin comprises a south-easterly deepening half-graben near the Welsh coastline, although its internal structure becomes increasingly complex towards the south-west. Permian to Triassic, syn-rift sediments within the basin are less than 3 km thick and are overlain by up to 4 km of Jurassic strata, and locally also by up to 2 km of Paleogene fluvio-deltaic sediments. The basin has a proven petroleum system, with potentially producible gas reserves at the Dragon discovery near the UK/Ireland median line (Figure 17), and oil shows in a further three wells.

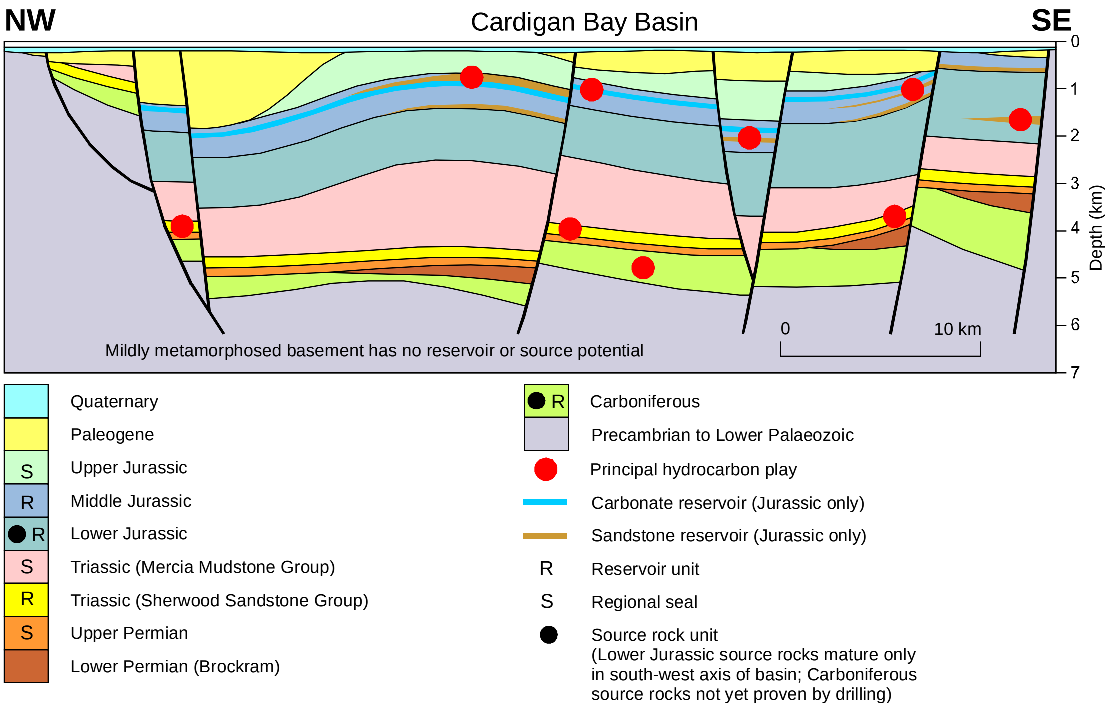

Fig. 19 Schematic play diagram for Cardigan Bay Basin, Irish Sea

The Cardigan Bay Basin contains multiple reservoir targets (Figure 19), which include the Lower Triassic (Sherwood Sandstone), Middle Jurassic shallow-marine sandstones and limestone (Great Oolite), and Upper Jurassic fluvial sandstone. The most likely hydrocarbon source rocks are early Jurassic marine mudstones (Lias Group). These are fully mature for oil generation in the west of the UK sector, and are mature for gas generation nearby in the Irish sector. Gas-prone, Westphalian pre-rift coal measures may also be present at depth locally. The Cardigan Bay Basin was subjected to two Tertiary phases of compressive uplift, whereas maximum burial that terminated primary hydrocarbon generation was probably around the end of the Cretaceous, or earlier if Cretaceous strata, now missing, were never deposited in the basin. Despite the Tertiary structuration, the Dragon discovery (Middle Jurassic sandstone reservoir) has proved that potentially commercial volumes of hydrocarbons were retained at least locally in Cardigan Bay. In addition to undrilled structural traps, the basin contains untested potential for stratigraphic entrapment of hydrocarbons near synsedimentary faults, especially in the Middle Jurassic section.

Atlantic Margin

UK designated waters north-west of Britain lie on the north-east Atlantic Margin. They include the Faroe-Shetland Basin, and parts of the relatively unexplored Rockall Basin, Hatton Basin and Hatton Continental Margin (Figure 20). Water depths in these areas locally exceed 2 km. The Faroe-Shetland Basin has been the main focus of hydrocarbon exploration in this province to date.

The opening of the North Atlantic between Greenland and north-west Europe was accompanied by Paleogene basaltic volcanism across an area some 2000 km in diameter. The igneous activity resulted from the development of the Iceland mantle plume shortly before continental break-up (White, 1989).

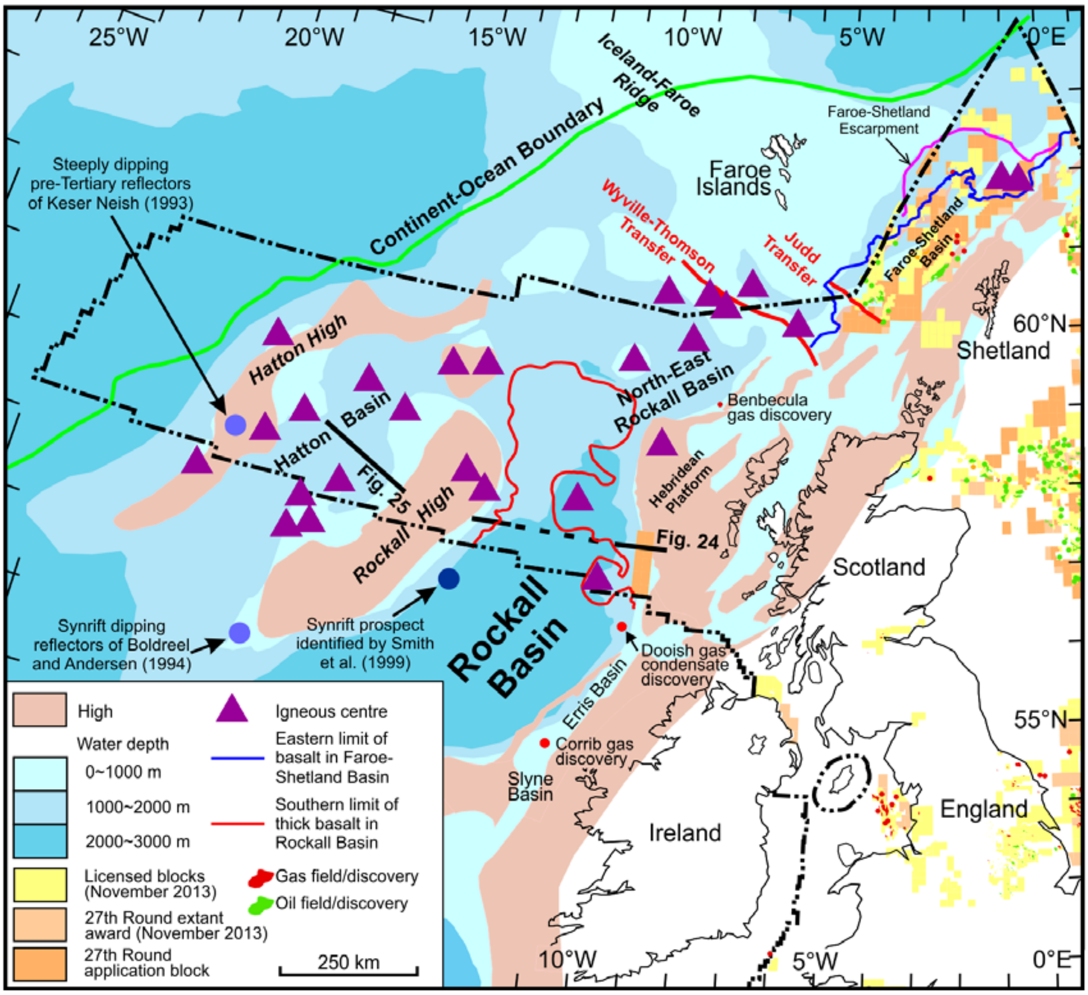

Fig. 20 Location of the hydrocarbon-producing basins and frontier basins of the Atlantic Margin

Present across large parts of the Atlantic Margin acreage, lavas and sills within the sedimentary section severely attenuate and disperse the seismic signal, degrading the subsurface imaging at depth. This has significantly hindered our understanding of the pre-Tertiary geological history of the region, although seismic refraction profiles and wide-angle seismic reflection data have both been collected to enable models to be constructed for the crustal structure along the Atlantic Margin (e.g. Joppen and White, 1990; Keser Neish, 1993; Shannon *et al.,* 1994).

Play fairways along the Atlantic Margin can be divided into Upper Palaeozoic to Middle Jurassic pre-rift, Upper Jurassic to Lower Cretaceous syn-rift, and Upper Cretaceous to Tertiary post-rift categories (Pegrum and Spencer, 1990; Knott *et al.,* 1993). Tertiary inversion structures, probably associated with ridge-push, are regionally widespread (Boldreel and Andersen, 1994; Doré *et al.,* 1997), presenting multiple opportunities for structural entrapment. Late Jurassic, organic-rich, basinal-marine mudstones (Kimmeridge Clay Formation) are the principal oil-prone source rocks in the Faroe-Shetland Basin, but they have not been proven yet in the Rockall Basin or the Hatton Basin. Scotchman and Broks (1999) have shown that rich oil-prone early to middle Jurassic source rocks also occur in the Atlantic Margin province, and that oil in the Foinaven and Schiehallion fields (Figure 21) can be correlated to these sources. Early Cretaceous organic-rich basinal marine source rocks that are known to occur in the Møre Basin on the Norwegian Atlantic Margin (Riis *et al.,* 2004) may also be present in parts of the UK Atlantic Margin.

A viable petroleum system has been established in the Rockall Basin by the Benbecula and Dooish discoveries (Fig. 20), but not yet in the Hatton Basin. The Hatton and Rockall basins contain the last truly frontier acreage in the UK designated waters.

Faroe-Shetland Basin

Although oil was found on the eastern flank of the Faroe-Shetland Basin as early as 1974, it was not until 1992 that economically viable reserves were discovered in the Foinaven Field (Figure 21). Both the Foinaven and the nearby Schiehallion fields are utilising floating production systems with offshore loading, as there is no existing infrastructure in the region. Much greater volumes of oil have been proved in the Clair Field (Figure 21), the largest oilfield offshore of north-west Europe, which commenced production in 2005.

Paleocene and Eocene basin-floor fan reservoirs are the principal targets along the north-western flank of the Faroe-Shetland Basin. Pre-rift and syn-rift plays are also likely to be present here (Figure 22), and are relatively shallow, but individual prospects are currently difficult to image. This is because the Upper Cretaceous to Lower Paleocene section is extensively intruded by Paleogene sills, which hamper seismic interpretation. Furthermore, Paleogene lavas are also present in parts of this area (Figure 21). Where they occur, wide-angle seismic data suggest that the thickness of sub-lava sediments varies between 1.25–3.75 km, with the greatest thickness in the north (Richardson *et al.,* 1999).

Pre-rift strata are too deeply buried to be prospective along the axis of the Faroe-Shetland Basin. The Clair Field sits on the Rona Ridge, which forms the eastern margin of the basin (Figure 21), and fractured Precambrian to Devono-Carboniferous rocks provide its oil reservoir. Oil and gas/condensate shows have been recorded in other wells along this ridge, and also on the

North Rona High (Figure 21) that forms the southern margin of the basin. Middle Jurassic sandstones preserved on a fault terrace flanking the Rona Ridge have yielded oil and gas shows. South-east of the Faroe-Shetland Basin, the Solan and Strathmore discoveries (Figure 21) contain oil in Jurassic and Triassic reservoirs within the contiguous West Shetland Basin. Pre-rift prospects in both basins are topsealed by Upper Jurassic, Cretaceous or Paleocene mudstones.

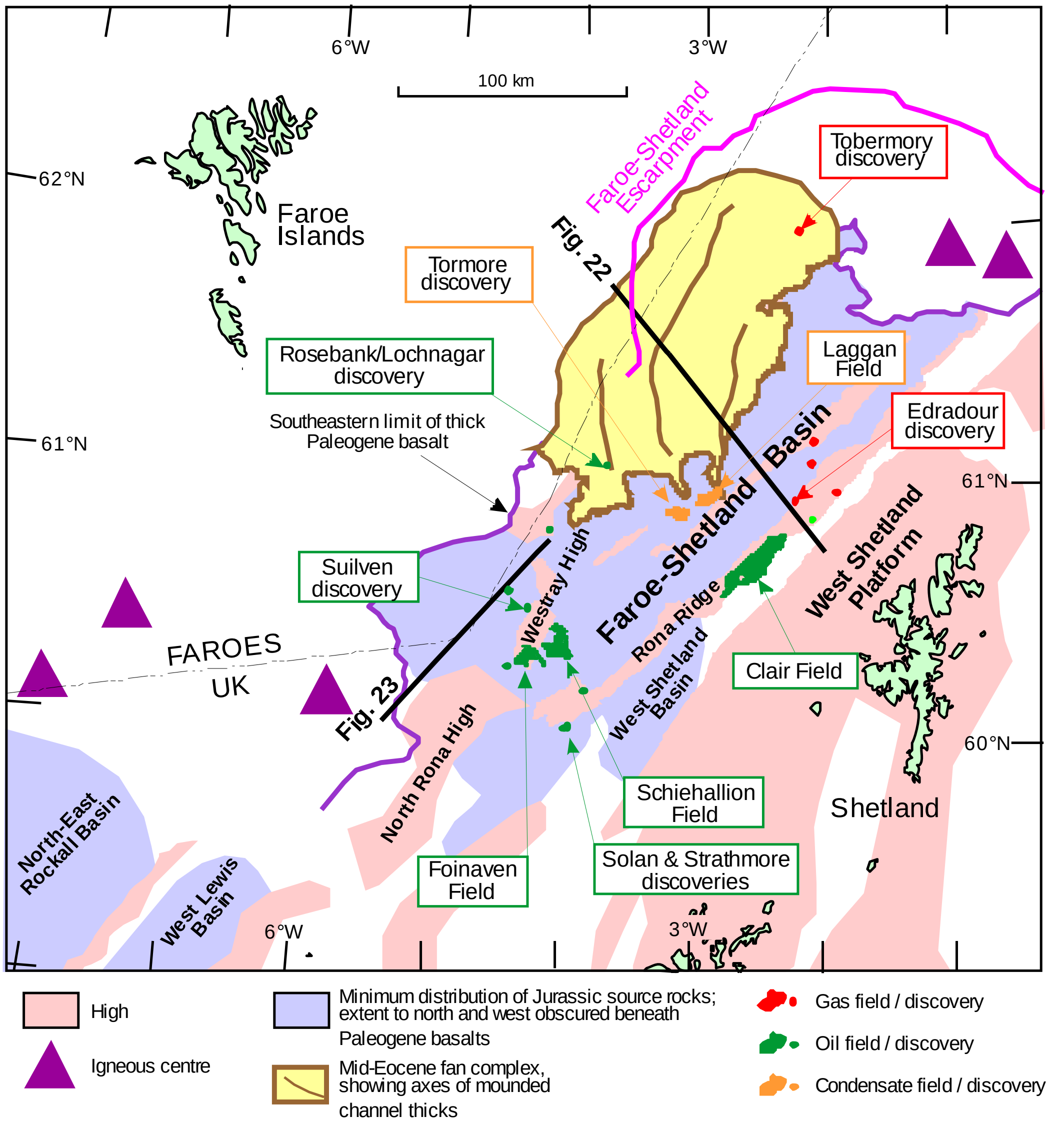

Fig. 21 Structural elements and location of mid Eocene fan complex, Faroe-Shetland Basin

Syn-rift plays are relatively lightly explored, although at least twelve wells have encountered oil or gas shows in Upper Jurassic or Lower Cretaceous sandstones within or bordering the Faroe-Shetland Basin. Two currently uneconomic gas discoveries on the eastern margin of the basin have Lower Cretaceous, syn-rift apron fan and basin-floor sandstone as their reservoirs. Underlying Upper Jurassic sandstones are encased in Kimmeridge Clay Formation source rocks to provide drilling targets in combined structural/stratigraphic traps. In the south-west, Lower Cretaceous shallow-marine sandstones penetrated on the Westray High constitute a syn-rift retrogradational shelf play (Figure 22), although in well 204/19-1 they are overlain by deep-water sandstone facies (Ritchie *et al.,* 1996) and may thus locally lack a topseal. Along the axis of the Faroe-Shetland Basin, depth of burial is a prohibitive factor for syn-rift plays. Upper Cretaceous mudstones locally exceed 3800 m in thickness to provide an excellent topseal throughout most of the region.

Post-rift, Upper Cretaceous slope-apron sandstones, of Cenomanian to Turonian age, are locally up to 327 m thick along the eastern flank of the Faroe-Shetland Basin, where they are stacked against the Rona Fault. Oil shows have been recorded from these sandstones, although doubts remain about the seal integrity of their boundary fault. Grant *et al.* (1999) speculated that if there are detached fan complexes present down-dip, these may offer more attractive drilling targets.

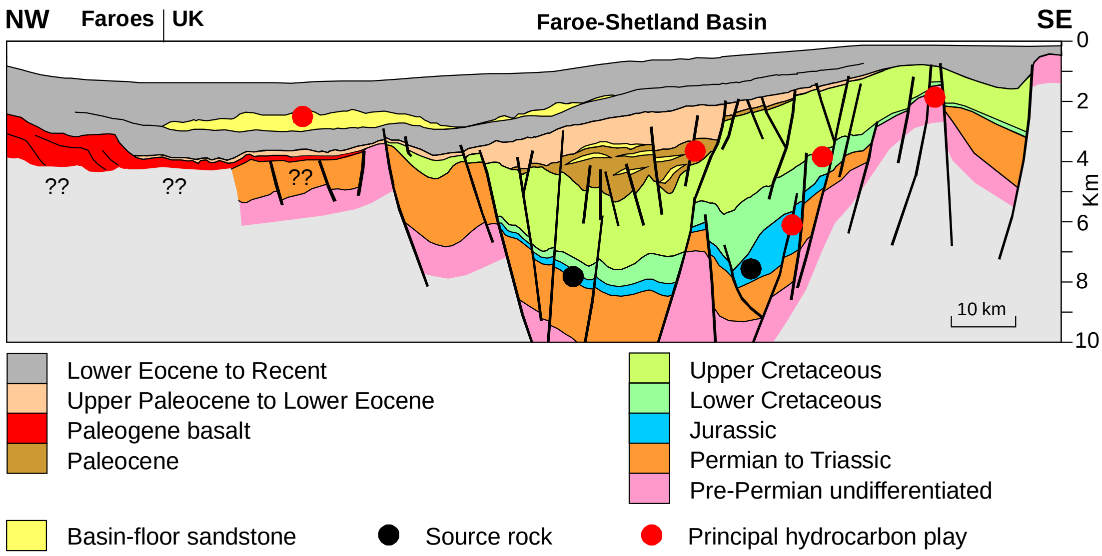

Fig. 22 Schematic play diagram for the Faroe-Shetland Basin. See Fig. 4 and 21 for location

The discovery of oil in the Foinaven Field completely revitalised the post-rift play within the Atlantic Margin Province. This discovery was followed up by the nearby Schiehallion Field and Suilven discoveries (Figure 21). However, the play is quite subtle, requiring accurate definition of stratigraphic pinch-out by 3D mapping, in combination with structural closure in a zone of monoclinal basinward dip. The occurrence of an intraformational mudstone seal is also critical; those mudstones associated with regional flooding surfaces have proved to be the most effective. The Paleocene succession reaches a maximum thickness of almost 3.5 km, and contains excellent quality sandstone reservoirs within basin-floor fan, slope fan and shelfal facies. Porosities in excess of 25% and permeabilities of greater than 100 mD can be anticipated where the sandstones are buried less than 2.5 km below sea bed (Ebdon *et al.,* 1995). Equivalent reservoirs that occur at greater depth in the north of the Faroe-Shetland Basin are of much lower quality (Johnson and Fisher, 1998), and have yielded only gas shows. Ebdon *et al.* (1995) recognized eight seismically resolvable sequences within the Paleocene, whereas Mitchell *et al.* (1993) identified nine sequences within the same interval. The relationship between these two interpretations is complicated, because Ebdon *et al.* (1995) used maximum flooding surfaces to divide their sequences, while Mitchell *et al.* (1993) based their work on identifying Type 1 unconformities (*cf.* Mitchum, 1977). Both authors have mapped distinct shelf, slope and basinal systems, and compiled generalised depositional environment maps for each sequence. Their approach is a vital step towards identifying potential stratigraphic targets. Mapping of seismic attributes and AVO analyses have played a critical role in current discoveries, but have yet to be applied on a regional scale. There is a particularly high potential for success in Paleocene prospects near the Foinaven Field. The crest of a major E-W trending Oligocene-Miocene inversion axis traces across this area, and numerous stacked potential reservoir targets can be anticipated in four-way dip closures (Figure 23). As in much of the Faroe-Shetland Basin, aggradational basin-floor sandstones characterize the lower part of the Paleocene here, and are likely to be sealed by both lowstand and highstand mudstones. Overlying Upper Paleocene to Lower Eocene sandstones include a greater proportion of shelfal and deltaic deposits, with a potentially higher risk of imperfect seals. Vertical and lateral migration vector determination is of key importance in this area due to local overpressuring, and a complex basin evolution (Illiffe *et al.,* 1999).

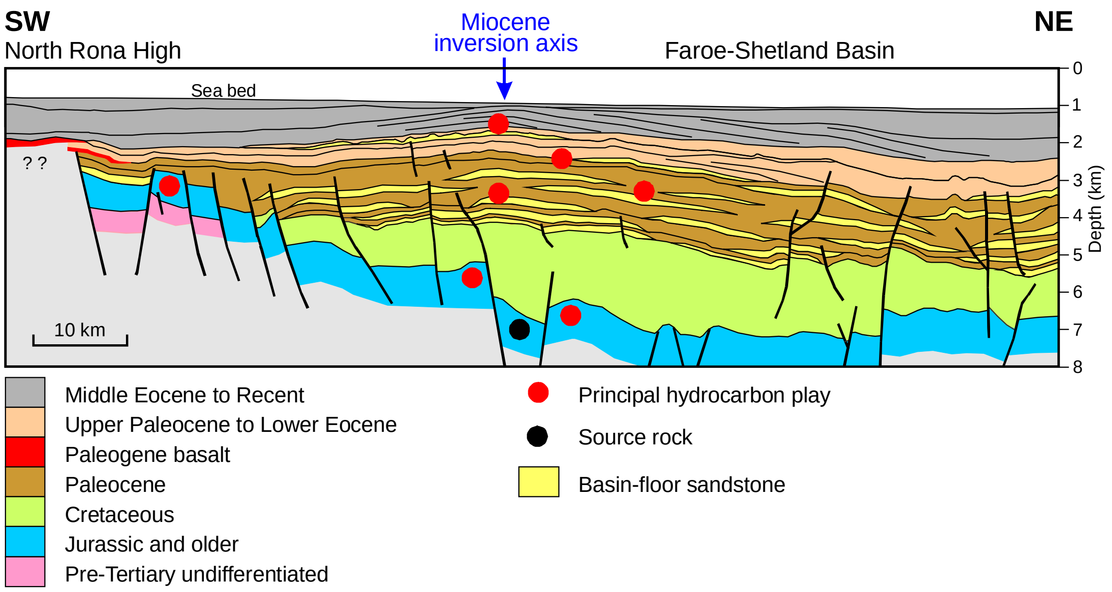

Fig. 23 Schematic play diagram for the south-western part of the Faroe-Shetland Basin. See Figure 21 for location

Comparison with the Bressay area of the East Shetland Platform suggests that similar Paleogene palaeogeomorphic traps might be expected to the west of the Shetlands (Underhill, 2001). This play results from the deep incision and subsequent infill of Paleogene deltaic sediments.

Overlapping, linear basin floors fans of probable mid-Eocene age trace across the north-western part of the Faroe-Shetland Basin, and extend into the Faroes sector (Figure 21). Three principal submarine canyon entry points have been identified on the margin of the broadly NE-SW trending palaeoshelf, and the fan deposits appear to have flowed across the basin floor in a northerly to north-easterly direction. The fan complex is more than 100 km long and over 50 km wide, and it attains a maximum thickness of 760 m. Internal geometry of the fans is complex, with zones of high-amplitude, layered seismic facies bordered and underlain by an eroded unit with relatively high-amplitude chaotic reflections. The principal exploration risks for this play include a risk of biodegradation due to the shallow depth of burial (approximately 1,000 m below sea bed) of the basin-floor fans, and uncertainty as to the validity of migration routes through the underlying Paleocene section.

Rockall Basin

More than 80% of the Rockall Basin has never been licensed for hydrocarbon exploration. Although several tranches of blocks were awarded in the 1997 UK 17th Round of Offshore Licensing, most of that acreage has been relinquished subsequently (Figure 20). Only twelve wells have been drilled in the basin and on its eastern flanking basement horst to date, of which eleven are now released into the public domain. The released wells include Benbecula discovery well 154/1-1 that tested potentially commercial volumes of gas from Paleocene basin-floor sandstones. Although none of the wells drilled proven source rocks, the Benbecula and Irish sector Dooish discoveries have confirmed that there are working petroleum systems at least locally within the Rockall Basin.

The Rockall Basin is a failed rift formed during the opening of the North Atlantic. Some authors (*e.g.* Tate *et al.,* 1999) suggest it may be separated from the Faroe-Shetland Basin by the Wyville-Thomson Transfer Zone, although Doré *et al.* (1997) argued that the Judd Transfer further north (Figure 20) is the more likely boundary. Numerous WNW-ESE to NW-SE oriented lineaments traverse the Rockall Basin and offset its eastern margin. Some of these have been linked to boundaries of pre-Caledonian basement terranes (*e.g.* Musgrove and Mitchener, 1996). The initiation of rifting in the basin has been variously ascribed to the late Carboniferous, Permian, Triassic, Jurassic or Cretaceous (*e.g.* Smythe, 1989; Knott *et al.,* 1993; Musgrove and Mitchener, 1996).

Critically, if the Rockall Basin was not initiated until Cretaceous times, then there is no potential for Jurassic source rocks, and Cretaceous to Tertiary organic-rich basinal marine mudstones are required to be mature for a working petroleum system. If instead, a proto-Rockall Basin developed as a contiguous late Jurassic to early Cretaceous rift with the Faroe-Shetland Basin, there may be Jurassic source rocks within one or more pre-Cretaceous basins beneath the Rockall Basin, but these basins must be of limited extent and connectivity. This is because all palaeomagnetic reconstructions for the Atlantic Margin indicate that the pre-Cretaceous seaway was very narrow in the Rockall area (Ziegler, 1988; Knott *et al.*, 1993; Doré *et al.,* 1999). An alternative model presented by Brown and Beach (1999) provides some scope for significant Jurassic deposition in the region under a transtensional regime. From their models of the crustal evolution of the Rockall Basin area, Cole and Peachey (1999) and Nadin *et al.* (1999) similarly concluded that an earlier pre-Cretaceous rift basin is located beneath the present-day Rockall Basin.

The western margin of the Rockall Basin comprises a series of tilted fault blocks throwing down to the east (Joppen and White, 1990), but the nature of the eastern margin is less certain because it is masked by the early Paleogene volcanics of the Hebridean Escarpment. According to Musgrove and Mitchener (1996), the syn-rift succession in the basin has a westerly-thickening geometry, thus implying asymmetric rifting accommodated through a series of easterly-dipping faults across the entire basin. The deep seismic reflection profile WESTLINE provides evidence for such easterly-facing syn-rift faults on the eastern margin of the basin (England and Hobbs, 1997).

Hydrocarbon exploration of the Rockall Basin is driven to a considerable extent by the knowledge that Upper Palaeozoic and Mesozoic sections that include source rocks do occur in adjacent, parallel half-graben basins, such as the West Lewis Basin and Erris/Slyne Basin (Figure 20). British Geological Survey boreholes on the flanks of the West Lewis Basin have proved organic-rich Middle Jurassic mudstones with excellent oil-prone source potential there (Hitchen and Stoker, 1993). Rich, oil-prone Lower Jurassic source rocks have been proved in the Slyne Basin (Scotchman and Thomas, 1995). The Corrib gas discovery in Irish waters demonstrates that Carboniferous coal measures also have source potential in the Slyne Basin region (Spencer and McTiernan, 1999). This discovery increases the possibility that Carboniferous source rocks also occur beneath parts of the Rockall Basin. The Irish Dooish and UK Benbecula discoveries both prove a working petroleum system within the Rockall Basin (Figure 20).

Figure 24 shows a range of possible exploration plays in the Rockall Basin. Lower Cretaceous syn-rift and Paleocene-Eocene post-rift plays are generally thought to offer the best potential for significant quantities of undiscovered hydrocarbons. The potential for pre-rift Carboniferous to Jurassic plays is highly speculative. The south-eastern part of UK designated waters may contain Westphalian, Permo-Triassic and Middle-Upper Jurassic pre-rift plays, as well as Paleocene-Eocene plays similar to those described by Nolan *et al.* (1999) from across the median line in the Irish sector. In that area, the upper part of the pre-Cretaceous section is modelled as being within the mid to late oil window at the present day.

The south-western part of the UK Rockall Basin has potential for prospects in large pre-rift tilted fault blocks, similar to those described by Smith *et al.* (1999) from the Irish sector nearby. The age and nature of the reservoir, source and seal rocks for such prospects remain entirely speculative. However, if the geological history bears comparison with the Slyne and Erris basins to the south-east, then Triassic to Middle Jurassic reservoirs can be anticipated, with a Jurassic, or possibly Carboniferous source. There may also

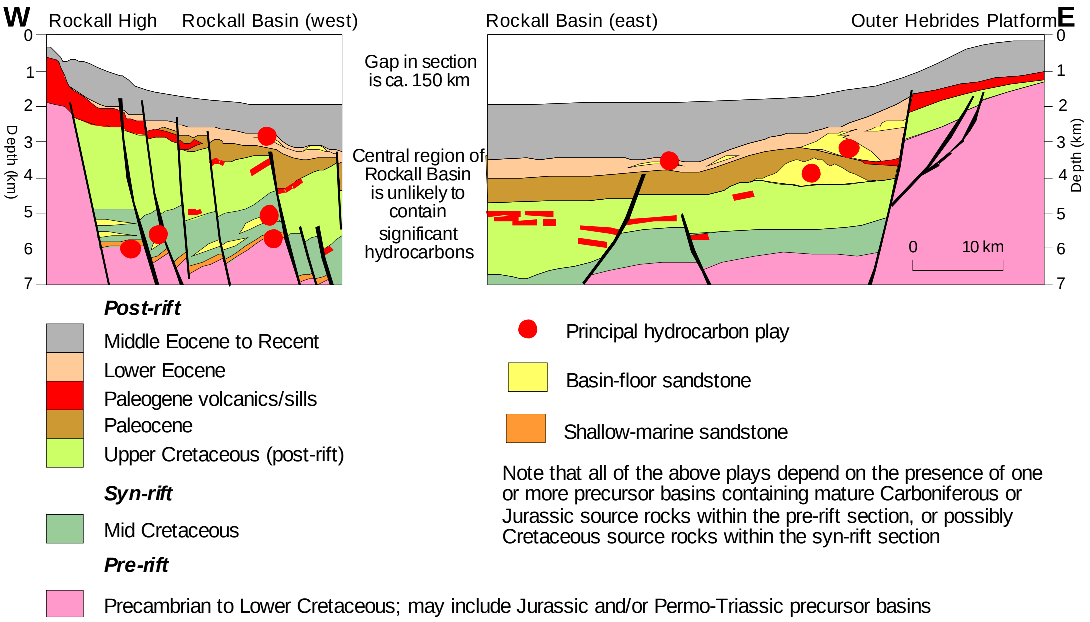

Fig. 24 Schematic play diagram for the Rockall Basin. See Fig. 21 for location

be potential for syn-rift prospects in Lower Cretaceous basin-floor sandstones here. This play requires that significant volumes of coarse clastic debris were shed into this part of the Rockall Basin during contemporary footwall uplift and erosion of the Rockall High.

The distribution of Paleocene basin-floor sandstones within the Rockall Basin is poorly known. Knott *et al*. (1993) speculated that such sandstones are confined to the north-eastern corner of the Rockall Basin, and that contemporary retrogradational shelf deposits occur locally along its south-eastern margin. Several examples of Eocene slump masses and basin-floor mounds have been observed on seismic profiles from the south-eastern and north-eastern margins of the Rockall Basin, and one of these is featured as a lead on the DECC's Promote UK 2013 CD. As with contemporary Eocene fans observed by McInroy *et al.* (2006) on the western margin of the Rockall Basin, these leads are presumed to be sealed by basinal mudstones.

Rockall Plateau: Hatton Basin and Hatton Continental Margin

The Hatton Basin is a NE-SW trending, intra-continental basin situated within the Rockall Plateau, on the westernmost part of the UK designated area. Bounded to the west and east by Hatton High and Rockall High respectively, water depths across the basin are mostly between 1000 and 1300 metres (Figure 20). Seismic data coverage across the Rockall Plateau remains very sparse, and much of the data was acquired during the 1970s. Accordingly, the geological history of the basin remains speculative. Recent palaeogeographic reconstructions (*e.g.* Doré *et al.,* 1999) suggest that the Hatton Basin was possibly initiated during the Cretaceous. However, studies of wide-angle seismic data suggest that a Carboniferous-Jurassic layer up to 3 km thick underlies the basin nearby in the Irish sector (Jacob *et al*., 1995; Shannon *et al*., 1995). Two opposing syn-rift half-graben have been modelled there, separated by an intra-basinal high. Seismic profiles show a mounded slope-apron unit bordering the volcanic escarpment on the western margin of the basin (Figure 24). By analogy with the Faroe-Shetland Escarpment to the north-east, this interval can be interpreted as late Paleocene to early Eocene in age.

On those parts of the Hatton Bank where Paleogene volcanic rocks are thin or absent, a series of steeply-dipping, tilted fault blocks has been imaged on seismic profiles (Keser Neish, 1993). These structures may continue westwards to underlie the Hatton Continental Margin. Similar steeply dipping reflector packages have been identified in the Irish sector, from the south-eastern part of the Hatton Basin (Boldreel and Andersen, 1994). The age of these pre-Tertiary dipping strata remains open to speculation. Prograding Eocene strata penetrated by a BGS shallow borehole on the eastern flank of the Rockall High contain Carboniferous and Jurassic/Cretaceous palynomorphs that may have derived by reworking from Upper Palaeozoic and Mesozoic rocks within the Rockall Plateau area (Stoker and Hitchen, pers. comm.).

The Hatton Continental Margin is the westernmost sedimentary basin within UK designated waters, lying adjacent to the Continent-Ocean Boundary (Figure 20). Shannon *et al*. (1995) modelled the basin as comprising 0.5 km to 1.3 km of heavily intruded Cretaceous sediments. O'Reilly and Readman (1999) suggested that a Triassic to Jurassic age is also plausible for these sediments. A thin post-rift Eocene to Recent succession unconformably overlies the basin.

Pre-rift and syn-rift plays remain highly speculative across the Hatton Basin to Hatton Continental Margin area. If underlain by Carboniferous-Jurassic strata, the Hatton Basin has arguably the best potential for source rocks, and the presence of tilted fault blocks along its margins may provide opportunities for structural closure (Figure 25).

However, Cretaceous post-rift mudstones are either thin or absent, reducing the potential for effective topseal in this play. Tertiary slope-apron and basin-floor fans are likely to be present in the Hatton Basin, but their derivation from a hinterland dominated by volcanic rocks may reduce their reservoir potential.

To summarise, the frontier basins of the Atlantic margin may have the greatest potential to replace existing UK hydrocarbon production by the discovery of major new oil and gas fields. It is currently estimated that 42.5% of the UK's undiscovered recoverable resources could lie within the Atlantic Margin (Figure 8), although this estimate does not include the gas potential of the Rockall Basin and Hatton Basin/Continental Margin. The Faroe-Shetland Basin is established as an oil-producing province, and opportunities remain for further discoveries of oil, both in the established Paleogene basin-floor sandstone play and in syn-rift and pre-rift plays along the margins of the basin. The 1990's also saw the discovery of potentially economic gas reserves in the Faroe-Shetland Basin.

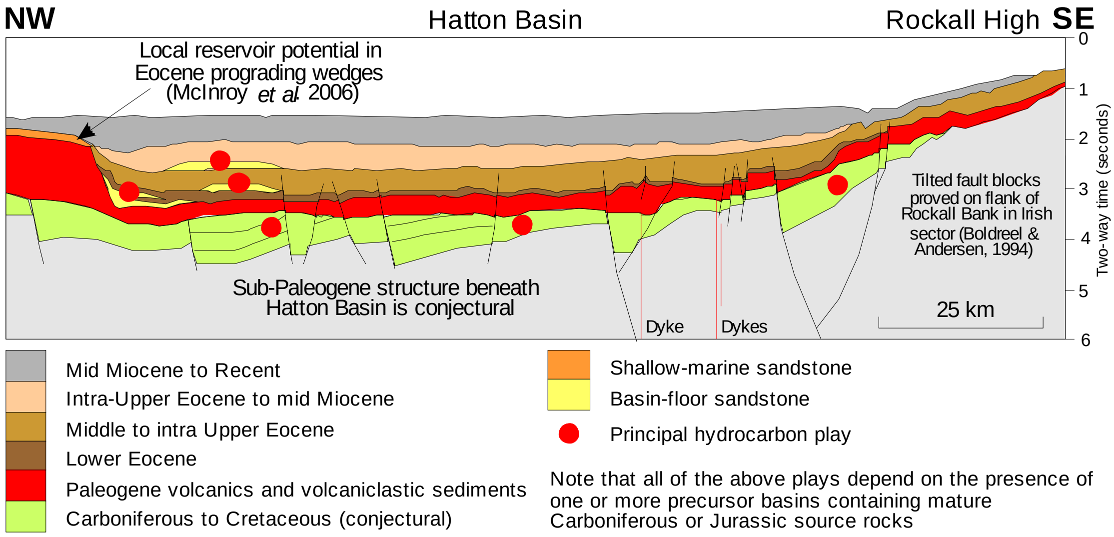

Fig. 25 Schematic play diagrm for the Hatton Basin. See Fig. 20 for location

A viable petroleum system has been proved for the Rockall Basin by the Dooish and Benbecula discoveries. A remaining challenge is to establish a viable petroleum system for the Hatton Basin and Hatton Continental Margin farther to the west. Initial exploration of these basins has led to the discovery of potentially attractive tilted fault-block plays. The presence and maturity of significant source rocks remain to be proved.

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