Remaining exploration potential of the Carboniferous fairway, UK Southern North Sea

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SUMMARY: Since 1984, twenty-three significant gas discoveries have been made in the Carboniferous fairway of the UK Southern North Sea. Almost all of these have been made within valid closures of the base Permian unconformity. Nevertheless, significant numbers of base Permian prospects remain undrilled, the majority comprising fault-bounded compartments. There has been relatively limited exploration of intra-Carboniferous plays so far. Such plays include a range of structural trap styles along with subcrop closures beneath the Permian. Under the aegis of Department of Trade and Industry (DTI) contracts, the British Geological Survey (BGS) has identified 279 undrilled prospects greater than 500 acres in areal extent within the Carboniferous fairway. Most of the largest are intra-Carboniferous closures with a relatively high risk of seal failure. Nevertheless, 148 of the prospects are predicted by BGS to have most likely (P_{50}) reserves in excess of 50 billion cubic feet (bcf). Clearly, the UK's Carboniferous fairway contains a wealth of opportunities, not only to develop the existing discoveries, but also to carry out further exploration of the many undrilled gas prospects that remain. All of the significant gas discoveries so far have been made in the south-east of the Carboniferous fairway, where gas-producing infrastructure is already in place. The west and north of the fairway (most of Quadrant 42 and the northern half of Quadrants 43 and 44) remain at a frontier stage of exploration.

1. SOUTHERN NORTH SEA PLAY FAIRWAYS

In combination, the three principal play fairways of the UK Southern North Sea - the Triassic, Lower Permian and Carboniferous fairways - are currently contributing 35% of annual UK gas production[1]. Only the Hewett, Orwell and Caister B gas fields are still producing gas from Triassic reservoirs[1]; another three Triassic fields ceased production during the 1990s. In the Lower Permian fairway, 76 fields are currently producing gas (Fig. 1), and another 19 significant discoveries await development. Although this fairway is generally perceived to be mature, important new discoveries are still adding significant volumes of gas to its reserves base. These discoveries are being made by integrating new techniques and technologies, with the aim of recognizing ever more subtle traps. Innovative techniques will continue to yield discoveries and new development opportunities in the Lower Permian fairway for many years to come.

By early 2002, eight fields in the Carboniferous fairway were producing 137 bcf gas per year, representing 3.4% of annual UK gas production[1]. There were another fifteen significant Carboniferous discoveries awaiting development, and five of these were scheduled to come on-stream as a cluster development from late 2002 (Conway *et al.* 2002).

The northern limit of the Lower Permian fairway (Fig. 1) is determined by the northward extent of its basal Permian reservoir, the Leman Sandstone Formation. Almost everywhere beyond this limit, the Lower Permian is composed of non-reservoir sabkha and lacustrine silty claystones and minor evaporites of the Silverpit Formation. The only exception known so far is locally in central Quadrant 44, where three wells have encountered gas within thin sandstone beds towards the base of the Silverpit Formation. Elsewhere across the Carboniferous fairway, the Silverpit Formation and overlying Upper Permian tight carbonates and thick evaporites of the Zechstein Group provide an excellent topseal to gas accumulations in uppermost Carboniferous strata.

The Lower Permian and Carboniferous fairways (Fig. 1) are almost but not quite mutually exclusive. Along the northern fringe of the Lower Permian fairway, components of the gas reserves in the Chiswick and 43/21-2 discoveries are found in both basal Permian and subcropping Carboniferous reservoirs. Presumably in these cases, their Carboniferous gas reserves are confined within closure of the top of the Permian reservoir. Another important exception is the Saltfleetby Field in Lincolnshire, where 200 m of argillaceous coal measures provide an effective intraformational topseal to 80 bcf of recoverable gas reserves trapped in basal Westphalian sandstone reservoirs. The success at Saltfleetby confirms the potential for economically viable gas reserves underlying the Lower Permian fairway in the adjacent offshore region.

There is a second Southern North Sea Carboniferous fairway straddling the northern flank of the London-Brabant Massif in Quadrants 53 and 54. Although no significant

[1] http://www.og.dti.gov.uk/information/bb-updates/appendices/Appendix10

gas discoveries have been made from Carboniferous strata here, Tubb *et al.* (1986) and Cameron & Ziegler (1997) speculated on the types of play that might some day prove successful. However, this paper will focus instead on the remaining exploration potential of Quadrants 41-44, where all of the significant gas discoveries have been made from the Carboniferous strata so far.

2. LITHOSTRATIGRAPHY

The stratigraphic nomenclature used in this paper (Fig 2) is that commissioned by UKOOA and recommended by representatives of seven oil companies and the British Geological Survey (Cameron 1993). Their scheme is entirely lithostratigraphic, acknowledging the problems caused formerly by adopting the UK onshore scheme, which subdivides the Carboniferous based on marine bands. These marine bands are often difficult to recognise in offshore wells, particularly in those with limited log suites. Even where they can be recognised, correlation with the established marine bands in NW Europe is unambiguous only where the results of biostratigraphic analyses of cored sections are available. Many of the lithostratigraphic boundaries between the offshore Carboniferous formations are accepted to be regionally diachronous in the UKOOA/BGS scheme.

Besly (2002) and Pearce *et al.* (2002) have demonstrated convincingly that a low-angle sub-regional unconformity occurs at the base of the late Westphalian red beds, which comprise the Ketch Member of the Schooner Formation in the UKOOA/BGS scheme (Fig. 2). The presence of an unconformity explains why sandy coal measures of the underlying Lower Schooner unit are present in southern gas fields including Ketch and Schooner, but are absent in northern gas fields such as Tyne. Uppermost argillaceous coal measures of the Westphalian B to early Westphalian C Westoe Coal Formation are presumably also truncated in the northern gas fields. There is hence a valid case, as Besly (2002) has proposed, for assigning formation status to, and renaming the Lower Schooner unit. Besly (2002) also proposed substituting two formations for the Ketch Member. However, there is also a strong case for assigning all of the late Westphalian red beds into a single formation, and designating member status for lower, sand-rich and upper, sand-poor subdivisions of the red beds where these are recognizable. Since none of these revisions are likely to be adopted by industry in the short term, the UKOOA/BGS scheme is retained for the following discussion.

3. HISTORY OF EXPLORATION

95 exploration wells have so far resulted in 23 significant discoveries in the Southern North Sea’s Carboniferous fairway, representing an exploration success rate of about 1 in 4. Only five wells were drilled prior to 1984, when the discovery of the Ketch and Boulton Fields helped to stimulate a 13-year boom in exploration and appraisal drilling (Fig. 3). There has been a notable decline in exploration drilling since the mid-1990s, largely for two reasons:

(i) Many of the most obvious exploration targets, the pop-up horst-block ridges and anticlinal closures of the base Permian unconformity, have already been drilled. Other play types are still perceived to have a relatively high risk of failure, although few tests of stratigraphic plays or intra-Carboniferous targets have been carried out so far.

(ii) During the mid- to late 1990s, high drilling costs and other economic factors combined to adversely affect the commercial viability of many undrilled prospects in the Carboniferous fairway. Many of these prospects would become more attractive drilling targets if there were a significant rise in gas prices, or a major innovation in either drilling or exploration technology in future years.

A histogram of significant annual gas discoveries (Fig. 4) illustrates that despite the decline in drilling activity, there have been notable successes in recent years. This has led to an incremental increase in cumulative recoverable gas reserves, currently estimated by Robertson Research International Ltd. to be 3.8 trillion cubic feet (tcf) for the Carboniferous fairway. Comparison of Figures 3 and 4 indicates that exploratory drilling success rates have improved to 1 in 2 since the mid-1990s. Much of this improvement can be attributed to the better definition of drilling targets enabled by the availability of 3D seismic datasets across the southeastern part of the Carboniferous fairway.

Significant gas discoveries have been made in Carboniferous strata ranging from Dinantian (42/10b-2Z discovery) to Westphalian C in age (Fig. 2). By far and away, the most productive reservoirs in the Carboniferous fairway are the late Westphalian red beds (Fig. 5), accounting for 65% of recoverable reserves in fields either in production or under development and 30% of reserves in remaining undeveloped discoveries. The next most prolific reservoirs are in the Caister Sandstone unit, of early Westphalian B age, which account for 25% of gas reserves from producing fields and fields under development. Namurian to early Westphalian A sandstones in the Millstone Grit Formation account for more than 50% of estimated reserves in the undeveloped discoveries. Only the Westoe Coal Formation, of Westphalian B to early Westphalian C age, has yielded no significant gas reserves to date, and none are expected since net:gross ratios in this unit are typically less than 5%.

4. SUBDIVISION OF THE CARBONIFEROUS FAIRWAY

The pre-Permian subcrop map (Fig. 6) and the intra-Carboniferous fault pattern (Fig. 7) provide two of the basic building blocks for assessing individual prospects in the Carboniferous fairway. Sub-fairways can also be created, based on the principle that the major lithostratigraphic units have significantly different reservoir parameters on a regional scale. As a consequence, the general chances of exploration success within each of these sub-fairways can be assessed independently. In practice, the Carboniferous fairway is more easily divided on a seismo-stratigraphic basis. The exploration risks associated with the principal trap types that occur in each of the sub-fairways are discussed in Section 5.

4.1 Pre-Permian subcrop

Approximately 20% of the pre-Permian subcrop map illustrated in Figure 6 is based on interpretation of 3D seismic datasets. The subcrop pattern in Quadrant 42, in the north of Quadrants 43 and 44 and in Quadrants 47-49 is based on 2D seismic interpretation.

The pre-Permian subcrop pattern (Fig. 6) illustrates the combined effects of uplift and erosion during separate phases of Variscan basin inversion and Early Permian thermal doming (Quirk & Aitken 1997). The depth of erosion was perhaps only a few hundreds of metres in areas where late Westphalian red beds have been preserved, as in the northwest of Quadrant 49. In contrast, more than 2 km of Carboniferous strata were eroded from the southwest of Quadrant 43, with Stephanian, Westphalian and uppermost Namurian strata no longer preserved here. There was also substantial latest Carboniferous to Early Permian erosion along the northern fringe of the Carboniferous fairway, where Dinantian and locally even Devonian strata subcrop the base of the Permian.

In the south of the Carboniferous fairway, the subcrop pattern contains a predominant NW-SE structural grain imposed by regional-scale Variscan folds of around 20 km wavelength (Fig. 6). In central Quadrants 43 and 44, the subcrop pattern describes an interference pattern, caused by the superposition of large, approximately W-E trending faults on the Variscan folding. Quirk & Aitken (1997) attributed these faults to an Early Permian phase of rifting that occurred in response to thermal doming associated with approximately N-S extension during the so-called Saalian event.

4.2 Intra-Carboniferous fault pattern

On Figure 7, those intra-Carboniferous faults that continue upwards through the overlying Lower Permian strata to terminate in the Zechstein Group evaporites are segregated by colour from remaining faults truncated by the base Permian unconformity. This enables those faults that have been active spasmodically until as recently as the Tertiary to be differentiated from those with no significant movement since the onset of Lower Permian sedimentation. The widths of the fault traces provide an indication of the amount of vertical throw within the Carboniferous section. There are three principal fault trends in the Carboniferous fairway.

The majority of a WNW-ESE to NW-SE group of faults have undergone significant reactivation since Permian times. If this reactivation occurred synchronously with regional halokinesis of the Zechstein Group evaporites, then the bulk of their post-Permian fault movement occurred during a mid-Tertiary, possibly Alpine, tectonic phase. Particularly in the south, many from this group form trains of anastomosing faults or pairs of faults bounding narrow extensional fault graben. Farther north, the overwhelming majority of the faults throw down to the south. The apparent sense of displacement on some faults changes from normal to reverse along strike, implying a component of strike-slip in their movement history. For many of the faults, amounts of intra-Carboniferous displacement are very similar to those of the Lower Permian strata. An important exception is the northern boundary fault of the Murdoch Ridge, a regional-scale pop-up horst (Fig. 7), which was seemingly one of the few in this group to have been a significant feature prior to its post-Permian reactivation.

A second group of W-E to SW-NE trending faults is limited to central and northern parts of the Carboniferous fairway (Fig. 7). Although this group includes the largest faults of the region, with intra-Carboniferous displacements of up to 1 km, few have been reactivated since Permian times, and amounts of reactivation on those that have been reactivated are relatively small. With only one important exception, occurring in east-central Quadrant 44, all of these faults throw down to the south.

A third group of relatively minor SW-NE trending faults is confined to the southern fringes of the Carboniferous fairway. These faults appear to have acted as transfers in the regional stress regime. For instance, one such fault offsets a NW-SE trending fault train by 0.8 km in the Ketch Field (Fig. 7). Both sinistral and dextral transfers are represented, and although they all appear to be truncated by the base Permian unconformity, this does not rule out wrench reactivation since Permian times.

The three groups of faults appear to have evolved as part of a basinwide linked fault system. Their principal influence on prospectivity is that they have imparted a strong degree of structural compartmentalisation to the Carboniferous strata, hence influencing the geometry of exploration targets both at base Permian level and within the Carboniferous section. They also provide potential sites for leakage of gas out of closure, so that predicting the effectiveness of fault seal forms an important component in risk assessment for virtually all prospects in the Carboniferous fairway.

4.3 Ketch Member (Westphalian C-D red beds) sub-fairway

In the Ketch Member sub-fairway, gas is currently being produced from the Boulton, Ketch, Schooner, Tyne North and Tyne South Fields, and production is imminent from the Boulton H, Hawksley and Murdoch K discoveries. The 30 exploration wells drilled have resulted in 17 gas discoveries, including the fields listed above, representing an exploration success rate for this sub-fairway of 1 in 1.76. The preserved thickness of the Ketch Member is highly variable on a regional scale. It has its maximum thickness of more than 1 km on the hanging walls of some of the largest W-E trending faults in Quadrant 44.

Single and multi-storey braided-channel sandstone reservoirs within the Ketch Member are mostly less than 10 m thick, but they are occasionally more than 20 m thick. Both low sinuosity and meandering channel forms are probably represented (Besly *et al.* 1993), and the fluvial channels were relatively narrow, perhaps only around 1 km in width (Mijnssen 1997). Many sandstone beds are fine- or medium-grained, but some are coarser and contain abundant pebbles of quartzite and vein quartz. They are notably clean, or are only slightly argillaceous. Sandstone permeability in the Schooner Field commonly exceeds 100 mD and can be up to 2.1 D (Stone and Moscariello 1999). Maximum porosity there is 18.9%, while average sandstone porosities in the Boulton and Ketch Fields are 11% and 13% respectively.

Production data have revealed that net:gross ratios and the connectivity of reservoir sandstones are generally highest towards the base of the Ketch Member in the Schooner Field. Stone and Moscariello (1999) interpreted this as indicating evolution from a dynamic channel system with frequent avulsion to a more mature system with relatively stable, thicker channel belts, but with lower lateral connectivity. In a number of unreleased wells, clusters of sandstone beds also occur at higher stratigraphic levels, suggesting that, on a regional scale, productive reservoirs are not necessarily confined towards the base of the Ketch Member.

Besly (2002) subdivided the Ketch Member into a lower sand-rich succession interbedded with gley and ferruginous palaeosols, and an upper sand-poor succession that includes non-marine limestones and caliche soils, and locally also contains units of grey coal-bearing facies. Net:gross ratios in the sand-rich succession range up to 40%, or are even higher in some Tyne Field wells. Besly (*op. cit.*) regarded the upper succession as being non-prospective. However, this raises the possibility of the upper succession providing an intraformational topseal for gas accumulations in those traps in which both the sand-rich and sand-poor facies are represented. Isopach maps illustrating the preserved thickness of the Ketch Member are an important component of prospect risk assessment in this sub-fairway.

In Quadrants 43 and 44, the extent of the Ketch Member sub-fairway is entirely constrained by the limit of preserved late Westphalian red beds beneath the base Permian unconformity (Fig. 8). Farther south, the extent of the sub-fairway is also effectively constrained by the northern limit of the directly overlying Leman Sandstone Formation. Gas reserves have been proven across all but the sub-fairway's northern fringe, implying there are no significant barriers to migration of gas from underlying coal measures source rocks. The latter are known to be mature for gas generation at base Permian level in the south of Quadrants 43 and 44 (Bailey *et al.* 1993), and are probably mature more widely than this at depth.

4.4 Composite Westphalian B to early Westphalian C (Caister Sandstone unit, Westoe Coal Formation and Lower Schooner unit) sub-fairway

In this upper coal measures sub-fairway, gas is currently being produced from the early Westphalian B Caister Sandstone unit in the Murdoch and Caister Fields, with production imminent from the McAdam discovery (Fig. 9). One other discovery is awaiting development. The Westoe Coal Formation has yielded no gas discoveries, but production from the Lower Schooner unit is imminent in the Watt discovery, and there are two additional discoveries. Of 18 exploration wells drilled in this composite sub-fairway, 7 have resulted in gas discoveries, representing an exploration success rate of 1 in 2.6.

Up to 200 m thick, late Westphalian B to early Westphalian C sandy coal measures of the Lower Schooner unit are now known to be progressively eroded northwards beneath a regional low-angle intra-Westphalian C unconformity (Besly 2002). Hence, they are probably absent from all of north-central Quadrant 44. The low-angle unconformity is not directly observable on seismic data. Quirk (1997) interpreted the sandy coal measures as highstand deposits that accumulated during relative fall in level of a basinwide lake system. This enabled deltas to prograde across parts of the lake basin, depositing both fluvial deposits and mouth bars, the latter being characterised by upward-coarsening gamma-log profiles. Quirk (*op. cit.*) suggested that individual mouth bars have limited lateral extent, and hence low reservoir capacity. The fluvial sandstone beds provide the reservoirs for all of the discoveries made so far, and these are up to 10 m thick, relatively clean, and mostly fine- to medium-grained. Although net:gross ratios for the Lower Schooner unit are commonly less than 20%, this unit is a valid exploration target. There are no data available on its reservoir properties.

The extent of the Lower Schooner unit component of the sub-fairway is determined by its erosional limits beneath both the base of the Permian (Fig. 9) and a sub-regional intra-Westphalian unconformity. However, all of the significant discoveries so far have been made within the limit of its subcrop beneath the Permian. This is because, as reservoir sandstone units are widespread towards the base of the Ketch Member, the Lower Schooner unit has limited potential for gas reserves in intraformational traps, except as add-on reserves at the base of Ketch Member closures.

The Westoe Coal Formation comprises between 150-200 m of mudstones, siltstones, frequent coal seams, and only a few thin sandstone beds in the south of Quadrants 43 and 44. Farther north, its uppermost beds may be truncated by the regional intra-Westphalian C unconformity. This dominantly argillaceous succession was deposited during a protracted period of relatively high lake level within a basinwide lake system (Quirk 1997). As its net:gross ratios are typically less than 5%, the Westoe Coal Formation is effectively a non-reservoir unit. However, it has significant potential for providing an efficient intraformational topseal for gas reserves trapped in underlying late Westphalian A to early Westphalian B reservoir units.

Up to 75 m thick, the Caister Sandstone unit contains between one and four beds of sandstone with subsidiary mudstones and only minor thin coal seams. The sandstones have been interpreted by Quirk (1997) to be the fill of braided or low-sinuosity channels, deposited by aggradation and avulsion during the early stages of relative rise in the level of the basinwide Westphalian B lake system. Their base is locally erosional in the Caister Field (Ritchie and Pratsides 1993). However, the basal sandstone is so widespread across southern blocks of Quadrant 44, occurring at an approximately constant thickness above the *A. Vanderbeckei* marine band, that it cannot be interpreted as the fill of an incised valley. On a regional scale, this sandstone has a sheet-like geometry.

The sandstones of the Caister Sandstone unit are commonly more than 10 m thick. Although mainly fine- to medium grained, they also contain scattered pebbles, mostly of quartzite and vein quartz, and further pebbles occur in poorly sorted lags and along cross-lamination foresets (Ritchie and Pratsides 1993). At the Caister Field, average sandstone porosity is 11%, with permeability ranging up to 400 mD (Ritchie and Pratsides *op. cit.*).

Net sandstone thickness of the Caister Sandstone unit is typically more than 30 m towards the north of this composite sub-fairway and in the Murdoch and Caister Fields (Fig. 10). In these areas the Caister Sandstone unit includes between 2-4 sandstone beds, or it is composed of a single multistorey bed. There is generally less than 20 m of net sandstone in southern blocks of Quadrant 44 (Fig. 10). The basal sandstone bed appears to be the most areally extensive, with overlying beds passing laterally into thin, argillaceous sandstones.

There is a conspicuous depocentre for early Westphalian B sandstones on the hanging wall of the northern boundary fault of the Murdoch Ridge (Fig.10). It is tempting to invoke a structural control on net sandstone thickness, with the thickest and potentially best quality early Westphalian B reservoirs being preferentially located along zones of maximum accommodation space, such as on the hanging walls of the major syn-sedimentary faults of the region. Guion and Fielding (1988) have noted the influence of syn-sedimentary fault movement on reservoir thickness of the early Westphalian A Crawshaw Sandstone in the East Midlands.

Being directly overlain by the low net:gross Westoe Coal Formation, the Caister Sandstone unit is an attractive exploration target in both base Permian closures and in intraformational traps. For the latter, depth beneath the Permian is an inhibiting factor. This is because only one of the gas discoveries within the Carboniferous fairway so far has been made at more than 200 m below the base Permian unconformity.

Reservoir properties, especially permeability, deteriorate with depth below the unconformity over large parts of the fairway, although there are important exceptions (see Section 4.6). There is potential for early gas charge to have preserved relatively good reservoir properties beneath an efficient intraformational seal in such cases.

4.5 Composite Westphalian A sub-fairway

In the UKOOA/BGS lithostratigraphic scheme, the boundary between the Millstone Grit Formation and the Caister Coal Formation is defined along the base of the latter unit's basal cluster of Westphalian A coal seams (Cameron 1993). Unlike in England, the Millstone Grit Formation therefore continues for up to 50-100 m above the *Gastrioceras subcrenatum* marine band in those wells in which this can be identified. Hence, the Westphalian A sub-fairway incorporates the uppermost beds of the Millstone Grit Formation with the Westphalian A component of the Caister Coal Formation.

A minor component of gas production at the Trent Field is from Westphalian A distributary channel sandstones (O'Mara *et al.* 1999), and uppermost Westphalian A reservoirs will produce add-on reserves to Westphalian B production in the McAdam discovery (Conway *et al.* 2002). Only the Cavendish discovery so far has its principal reservoirs within the Westphalian A strata, although gas shows have been encountered in a number of other wells. Of 13 exploration wells drilled, 6 have resulted in significant discoveries, representing a Westphalian A exploration success rate of 1 in 2.2.

Generally between 400-550 m thick, the Westphalian A strata are largely composed of shallow-water lake, swamp and fluvial distributary channel facies (*cf.* Guion & Fielding 1988). Net:gross ratios are typically between 20-40%, and none of the mudstone units drilled so far are sufficiently thick to provide effective intraformational seals. Most of the sandstone beds are fine- to medium-grained, but some of the thickest contain pebbly horizons and intervals of argillaceous and carbonaceous detritus that accumulated during periods of channel abandonment. Distributary channel sandstone porosity and permeability in the Trent Field range between 4.7-12.8% and 50-160 mD respectively (O'Mara *et al.* 1999).

The exploration parameters for the Westphalian A sub-fairway are summarised in Figure 11. Except where offering add-on reserves to overlying basal Westphalian B reservoirs, the Westphalian A strata are unlikely to provide attractive targets in intraformational traps. Their best exploration potential is within closures of the base Permian unconformity.

4.6 Namurian sub-fairway

Namurian deltaic reservoirs provide most of the gas production from the Trent Field and secondary reserves in the Cavendish discovery, with five further significant discoveries awaiting development in Quadrants 43 and 44 (Fig. 12).

O'Mara *et al.* (1999) interpreted the lower of two late Namurian, Marsdenian reservoirs in Trent as the fill of an incised valley. They described the reservoir as comprising a 20-30 m thick multistorey, coarse-grained, pebbly sandstone that was deposited as a series of stacked and erosive barforms aligned NE-SW, sub-parallel to the prevailing palaeocurrent. Core porosity ranges up to 12%, but sandstone permeability only exceeds 1 mD in the coarsest parts of the reservoir. This is because kaolinite replacement of feldspar has severely reduced both permeability and porosity in the fine-grained portion.

An upper, tidally reworked facies contains the best-quality reservoir in the Trent Field, comprising a clean, fine-grained, well-sorted quartzose sandstone up to 20 m thick, associated with a very low, blocky gamma-ray profile. This sandstone forms a transgressive wedge of estuarine channel or tidal channel deposits, representing the uppermost fill of an incised fluvial channel (O'Mara *et al.* 1999). The sandstone is notably deficient in both kaolinite and clay minerals that are ubiquitous in the Namurian fluvial sandstones of the region. Its core porosity ranges between 8-13%, and permeability is up to 320 mD. Well correlation has revealed that this reservoir sandstone is restricted to the central core area of the Trent Field (O'Mara *et al. op. cit.*).

On a regional scale, the prospective Namurian reservoirs are dominated by incised valley fill and fluvial sheet sandstones (Hampson *et al.* 1999), and both facies are notably feldspathic. Tidal channel facies are rare but are non-feldspathic. By comparison with northern England, Hampson *et al.* (1997) deduced that the incised valleys are between 5 and 25 km wide, whereas the sheet sandstones are relatively extensive, suggesting deposition in fluvial braidplains. The latter are often not as coarse-grained, and they tend to have relatively poor reservoir properties.

Net:gross ratios in the Namurian deltaic strata generally range between 20-40%, with many of the sandstones being concentrated towards the top of the Kinderscoutian, Marsdenian and Yeadonian stages. These sandstones are now regarded as lowstand deposits (Hampson *et al.* 1997), whereas mudstone-rich units that sometimes overlie them represent highstand and transgressive deposits. Where such mudstone units are sufficiently thick, they have the potential to provide efficient intraformational seals, as in the 43/20b-2 and 44/16-1Z discoveries (Fig. 13). These wells tested gas from uppermost Alportian reservoirs at depths of 481 m and 641 m beneath the Permian respectively, and such depths would normally be associated with sub-commercial reservoir properties. Core porosity in well 43/20b-2 is up to 12%, and although Alportian sandstone permeability is mostly less than 1 mD in this well, it ranges up to 18 mD in block 44/16. The presence of an efficient intraformational seal may have enabled early gas charge to preserve relatively good reservoir properties in this case.

Turbidite sandstone units, such as those interbedded within early Namurian basinal mudstones in well 43/17-2, are unlikely to provide attractive exploration targets. Their distribution in the subsurface is conjectural, and unless enhanced by early gas charge, their commercial reservoir properties are likely to be adversely affected by depth of burial, commonly more than 1 km, beneath the base Permian unconformity.

It would require a tortuous migration route for gas from Westphalian coal measures to have charged the Alportian reservoirs in blocks 43/20 and 44/16. There are no data available on the composition of this gas, but its more likely source is in the Dinantian to early Namurian basinal marine mudstones that are known to underlie parts of the Carboniferous fairway; these have been proven in wells 43/17-2 and 48/3-3. Indeed Gerling *et al.* (1999) used nitrogen isotope ratios and carbon dioxide levels to deduce that a significant component of gas in many Southern North Sea fields was derived from Upper Dinantian to Lower Namurian marine strata, even in areas where mature coal measures might be expected to be the primary source.

Of 15 exploration wells drilled, 7 have resulted in significant discoveries, representing an exploration success rate for the Namurian sub-fairway of 1 in 2.1. Nevertheless, this sub-fairway is at a relatively immature stage of exploration. Its primary reservoir targets are in incised valleys, and although these may be very widespread in the subsurface, there are few criteria for predicting the optimum locations for exploration yet. O'Mara *et al.* (1999) speculated a basement structural control on the Trent valley system, but it remains to be proven whether this observation is valid on a regional scale. There are no criteria for identifying the most prospective intraformational traps either, as the gas-bearing Alportian intervals in blocks 43/20 and 44/16 are not associated with distinctive attributes on seismic data.

4.7 Dinantian sub-fairway

Only 19 wells have been drilled in a composite Dinantian sub-fairway that incorporates the Yoredale, Scremerston, Fell Sandstone and Cementstone Formations in the UKOOA/BGS scheme (Cameron 1993). These wells have resulted in 3 gas discoveries, 42/10b-2, 42/13-2 and 42/15a-2. In the latter discovery, the potentially producible reserves are largely in overlying Upper Permian carbonates. With its low well density, and with no 3D seismic datasets available for interpretation, the Dinantian sub-fairway is at a frontier stage of exploration.

Maynard and Dunay (1999) concluded that the Dinantian strata exhibit a delicate balance between reservoir presence and quality, seal, and hydrocarbon charge, making for a high risk but potentially rewarding play. The Fell Sandstone Formation is the most attractive exploration target, comprising sheet sandstones that were deposited in low-sinuosity braided streams. In six offshore wells, the formation is between 250-425 m thick, and net:gross exceeds 70%. Its measured core porosity ranges between 8-18%, and its geometric mean permeability is 11.8 mD (range 0.4-120 mD). Maynard and Dunay (*op. cit.*) noted that there are also reservoir units of braided sheet sandstones within the overlying Scremerston Coal and Yoredale Formations.

As elsewhere in the Carboniferous fairway, detailed seismic mapping of prospective reservoir units through the subsurface is an important first step towards minimizing the exploration risk for individual drilling targets. Base Permian closures provide the most attractive targets for the Dinantian strata. This is because there are relatively few thick mudstone units above the Fell Sandstone Formation and above potential reservoirs in the Scremerston Formation to provide efficient intraformational topseals. Although mudstone units are more abundant and up to 50 m thick within the Yoredale Formation, there are fewer prospective reservoirs in this unit.

The principal exploration risks in the Dinantian sub-fairway are summarised in Figure 14. Tortuous migration routes might be expected, especially in the north, where potential coal-measures source rocks in the Scremerston Formation are almost certainly immature and the nearest mature Westphalian coal measures are some tens of kilometers to the south. No gas compositional data are available from the 42/15a-2 discovery or from the gas shows encountered in wells 41/10-1 and 41/15-1, but the most likely source for these is Dinantian to Lower Namurian basinal mudstones buried beneath the Namurian sub-fairway.

5. PRINCIPAL TRAP TYPES

5.1 Base Permian structural closures

Almost all of the drilling successes in the Carboniferous fairway so far have targeted structural closures of the base Permian unconformity. Many of the largest traps occur along the crests of pop-up ridges bounded by one or more NW-SE trending reverse faults. Amongst these, the Caister and Murdoch Fields and the Cavendish discovery occupy the Murdoch Ridge (Fig. 15), and the Trent Field lies at the crest of the Trent Ridge. Heights of closure for the remaining undrilled base Permian traps tend to be relatively small. Nevertheless, now that 3D seismic imaging has revealed the strongly fault-compartmentalized nature of the Carboniferous fairway (Fig. 7), there remains significant potential for untested base Permian traps that are bounded between three or even four faults within the network of intra-Carboniferous faults. Such traps require that all boundary faults provide efficient lateral seals, and many may have only limited relief at base Permian level.

Interpreted seismic profiles can be used as a first step in assessing the exploration risks for individual base Permian drilling targets. There are three potential targets on Figure 16, an interpreted profile crossing the Murdoch Ridge. On this profile, target B has the Caister Sandstone unit and sandy Westphalian A coal measures within closure, and an exploration well here would have a good chance of encountering at least one viable reservoir above spill point. In contrast, targets A and C have mainly argillaceous Westphalian B coal measures of the Westoe Coal Formation within closure, and hence have limited potential for encountering viable reservoir above spill point.

Quirk and Aitken (1997) stressed the importance of considering the reservoir potential for base Permian closures in three dimensions. Hence, traps A and C on Figure 16 should not be written off as drilling targets on the basis of a single interpreted profile. Strike sections should also be analysed for such traps to determine whether there are more reservoir-prone Carboniferous sections elsewhere within closure. Some of the early Carboniferous exploration wells only failed to encounter viable reservoir because the 2D seismic data available before the late 1980s was of insufficient quality to determine optimum reservoir-prone sections within base Permian closure. Quirk and Aitken (*op. cit.*) advocated a programme of remapping for the written-off closures, as in many cases their primary exploration wells were poorly located for intercepting viable reservoir units within closure.

A seismic profile across an untested base Permian horst-block trap in southern Quadrant 44 is illustrated on Figure 17. This trap is interpreted to have late Westphalian red beds of the Ketch Member within closure, similar to those from which gas is being produced in the Ketch and Schooner Fields nearby. Silty claystones and evaporites of the Silverpit Formation provide both topseal and lateral fault seal. There is an excellent chance that this trap contains gas-filled reservoirs within closure.

5.2 Intra-Carboniferous closures

Two types of intra-Carboniferous trap are clearly imaged on the seismic profiles: structural closures of reservoir units within the Carboniferous section and reservoir subcrop traps beneath the base Permian unconformity. In practice, none of the regionally mappable seismic events correspond exactly to reservoir target horizons. Instead, they are imaging approximately the geometry of stacked reservoir units occurring above and below the mapped seismic event (Fig. 16). In reality, the most attractive drilling targets will be those traps in which the prospective reservoirs are buried less than 200 m below the base Permian unconformity. Viable reservoir properties are rarely encountered at greater depths, although early gas charge may preserve enhanced permeability in deeply-buried reservoirs on a local scale (Section 5.4).

All of the structural traps within the Carboniferous section require an efficient mudstone topseal to prevent gas leakage out of closure. The Saltfleetby Field in Lincolnshire (Fig. 1), with recoverable reserves of 80 bcf[2] is a good example of successful entrapment of gas beneath mudstone-dominated coal measures. In this case the Westphalian A coal measures overlying the producing basal Westphalian reservoir are 200 m thick. Comparable mudstone-dominated coal measures of Westphalian B age are between 150-200 m thick in the southeast of the Carboniferous fairway, and have the potential to provide topseal for gas in underlying Caister Sandstone reservoir units (*e.g.* target D in Fig. 16). Other potentially important intraformational seals occur in the upper part of the Ketch Member, locally beneath the basal Westphalian A coal seams, and locally also in early to mid-Namurian deltaic sections (*e.g.* targets E and F in Fig. 16).

For those subcrop traps in which the dip of the target reservoirs is opposed to the dip of the base Permian unconformity (*e.g.* targets G and H in Fig. 16), an efficient Carboniferous mudstone topseal is required to prevent gas leakage along the unconformity. In the relatively common case in which the subcropping Carboniferous reservoirs dip more steeply (*e.g.* targets I and J in Fig. 16), but in the same general direction as the unconformity, an efficient bottom seal is required to prevent leakage up dip along the base of the Permian.

In Figure 18, examples of both types of intra-Carboniferous trap are illustrated on a seismic profile from Block 44/19. In this example, the base Westphalian B regional seismic event is imaging an intra-Carboniferous structural closure of overlying Caister Sandstone reservoir units. The prospect relies on topseal by mudstone-dominated Westphalian B coal measures and lateral seal across all boundary faults. A second trap is defined by subcrop of the base of the Westphalian C Ketch Member beneath the base Permian unconformity. In practice, the base late Westphalian red beds seismic event is imaging only one of a succession of laterally stacked Ketch Member subcrop traps. In this case, intraformational topseal by an upper sand-poor unit of the Ketch Member (see Section 4.3) is required to prevent leakage up dip along the base Permian unconformity.

6. EXPLORATION POTENTIAL

Under the aegis of successive DTI contracts, the BGS has carried out prospectivity studies across the whole of the Carboniferous fairway between 1988-2001. Mapping was based on interpretation of 3D seismic datasets in the south of Quadrants 43 and

[2] http://www.og.dti.gov.uk/information/bb-updates/appendices/fields/saltfleet.htm

44, and on 2D datasets over the remaining 80% of the fairway, where 3D seismic data is not yet available.

The mapping has led to creation of a portfolio for the DTI of 279 undrilled prospects greater than 500 acres in area within the Carboniferous fairway. Almost half of these prospects lie entirely within unlicensed acreage. Of the undrilled prospects, 76 are closures of the base Permian unconformity, and the remainder are intra-Carboniferous traps. Figure 19 illustrates the distribution of those undrilled traps that lie in currently unlicensed acreage in the southeast of the Carboniferous fairway. The distribution of traps occurring within each of the sub-fairways is listed in Table 1.

	Ketch Member sub-fairway	Westphalian B to early Westphalian C sub-fairway	Westphalian A sub-fairway	Namurian sub-fairway	Dinantian sub-fairway
Base Permian closure	19	8	6	25	14
Intra-Carboniferous trap	67	49	33	36	28

For all 279 prospects, maximum, most likely and minimum estimates have been made for a range of parameters including area, net reservoir within closure, porosity, hydrocarbon saturation and recovery factor. These parameter ranges formed the input to a Monte Carlo simulation that was used to calculate P_{90}, P_{50} and P_{10} estimates of recoverable gas reserves for each of the prospects. All of these calculations are unrisked.

Based on the Monte Carlo simulation, 148 of the BGS prospects are calculated to have P_{50} recoverable gas reserves of greater than 50 bcf (Fig. 20). For comparison, initially recoverable gas reserves in the eight currently producing Carboniferous gas fields range between 71 and 559 bcf[3] Carboniferous gas discoveries with recoverable reserves of less than 50 bcf would be marginally economic or uneconomic to develop in the Southern North Sea at current gas prices.

30% of the BGS Carboniferous prospects lie within the Ketch Member sub-fairway (Fig. 20), which has the highest exploration success rate, largely because its reservoirs are some of the most prolific in the Carboniferous fairway (Section 4.3). Reservoir risk for the 20% of prospects in the composite Westphalian B to early Westphalian C sub-fairway is highly variable, depending on whether sandy coal measures of the Lower Schooner unit and Caister Sandstone unit or argillaceous coal measures of the Westoe Coal Formation predominate within mapped closure. Reservoirs are almost ubiquitous within closure throughout the Westphalian A, Namurian and Dinantian sub-fairways, but sandstone permeability can be highly variable on a local scale. Reservoir effectiveness is a key exploration risk in all of the sub-fairways, with commercially viable permeability commonly restricted to the uppermost 200 m of Carboniferous strata preserved beneath the base Permian unconformity.

The presence of mature source rocks is not a significant exploration risk in the three Westphalian sub-fairways. Basinal Dinantian to early Namurian mudstones provide viable source rock intervals beneath the southern part of the Namurian sub-fairway. Tortuous migration routes need only be invoked for the minority of prospects deemed to be remote from mature source rocks along the northern and north-western fringes of the Carboniferous fairway.

3 http://www.og.dti.gov.uk/information/bb-updates/appendices/fields_index.htm

Of the 72 BGS prospects calculated to have P_{50} recoverable reserves of more than 100 bcf gas, only 10 are closures of the base Permian unconformity, with a low risk of seal failure. Seal risk for the remaining 62 large prospects is dependent on the gross lithology of the overlying Carboniferous succession for intra-Carboniferous structural traps and some subcrop traps, and of underlying Carboniferous strata for the remaining subcrop traps.

7. CONCLUSIONS

Drilling during the first phase of exploration of the Carboniferous fairway has led to 36 gas discoveries being made, estimated by DTI and Robertson Research to contain 3.9 tcf cumulative reserves of recoverable gas. Of the 14 fields that will be in production by end 2003, 13 are in the south of Quadrant 44. This part of the fairway would seem to be at a mature stage of exploration, with extensive infrastructure already in place and widespread coverage by 3D seismic data. By contrast, the west and north of the Carboniferous fairway in Quadrants 40-42, 43 north and 44 north have a relatively low well density, and with only 2D seismic data available for interpretation, this area is at a frontier stage of exploration.

The first phase of drilling in the Carboniferous fairway has concentrated on exploring for gas in structural closures of the base Permian unconformity. With many of the largest traps fully tested, this play has reached a mature stage of exploration. Nevertheless, 3D seismic mapping has now revealed that the Carboniferous strata are compartmentalised by a dense network of faults, many of which have not been reactivated since early Permian times. This provides potential for an additional range of sub-Permian traps that, despite having no significant relief at base Permian level, are bounded on two, three or even all four sides by intra-Carboniferous faults.

There has been only limited exploration of intra-Carboniferous drilling targets so far. These targets include both structural closures of reservoir units within the Carboniferous section and reservoir subcrop traps beneath the base Permian unconformity. This category includes many of the largest undrilled prospects in the region, but many have a relatively high risk of topseal or lateral seal failure.

A programme of seismic mapping by BGS has revealed that a wealth of opportunities remains for exploration of base Permian and intra-Carboniferous traps in all parts of the Carboniferous fairway. In the short term, exploration is expected to concentrate on infill drilling of relatively low-risk targets between currently producing fields in the south of Quadrants 43 and 44. In future decades, the greatest challenge will be to extend Carboniferous production towards the northern and western, frontier regions of the Carboniferous fairway. The Saltfleetby discovery in Lincolnshire has confirmed that commercially viable reserves of gas may even await discovery in intra-Carboniferous traps beneath the Lower Permian fairway. In summary, a revitalisation of exploratory drilling in the Carboniferous fairway of the Southern North Sea is required to enable the fairway to continue as a major gas-producing region of the U.K. beyond the first decade of the 21^{st} century.

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FIGURE CAPTIONS

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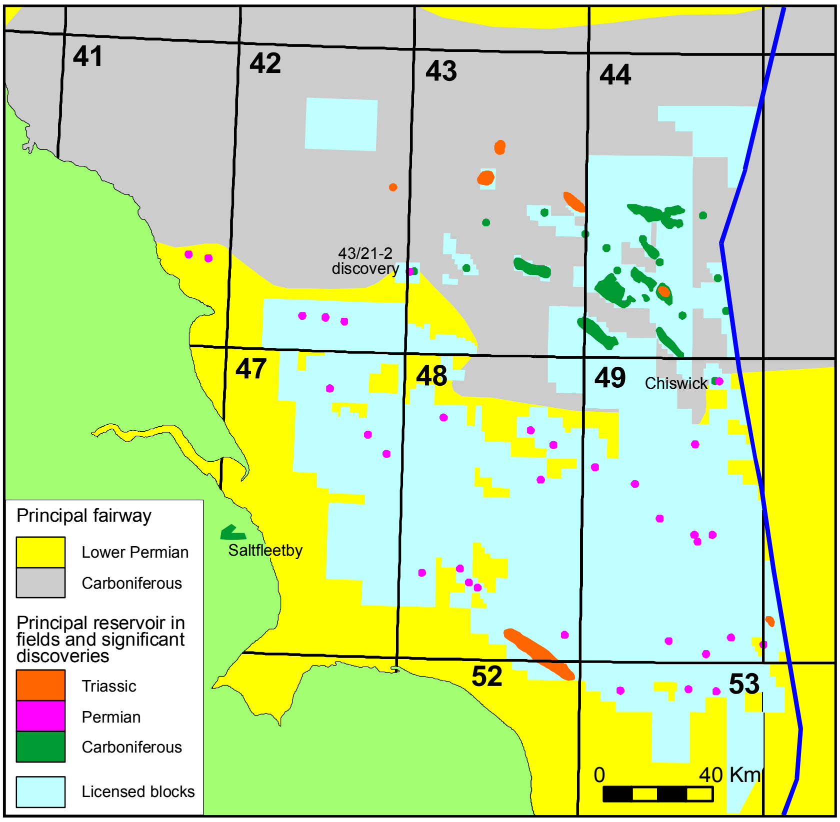

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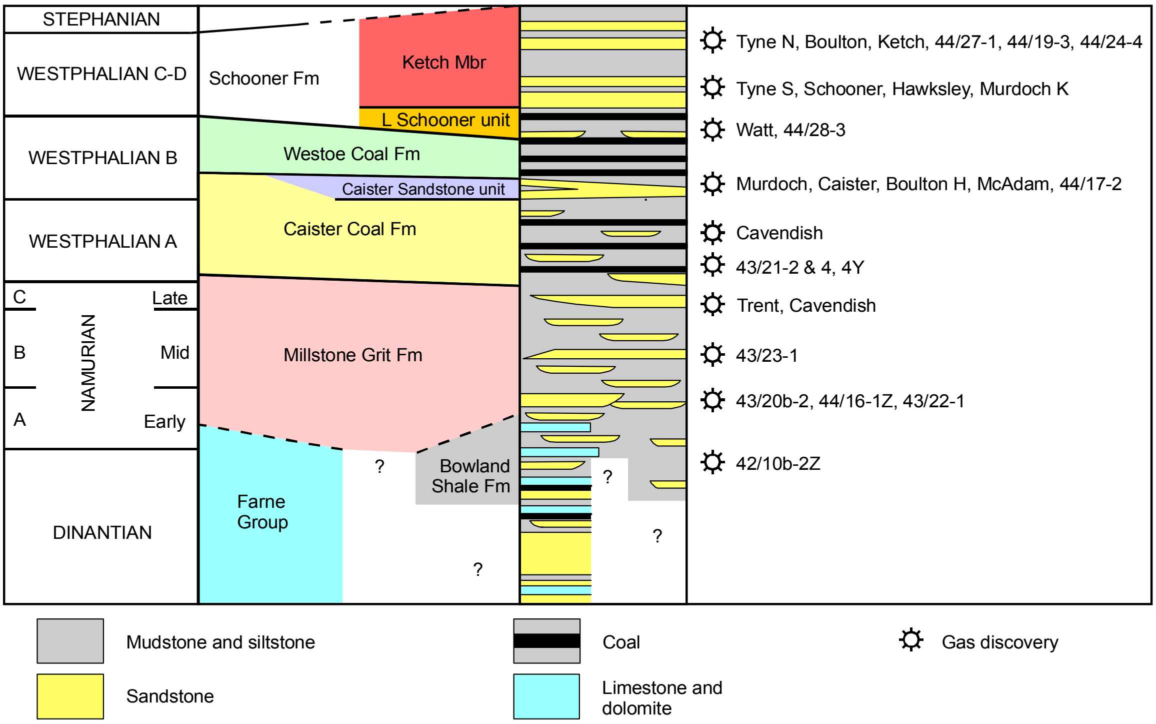

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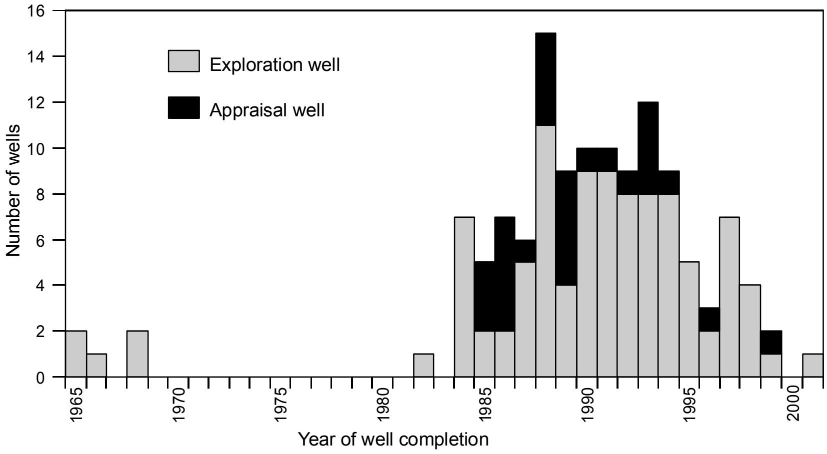

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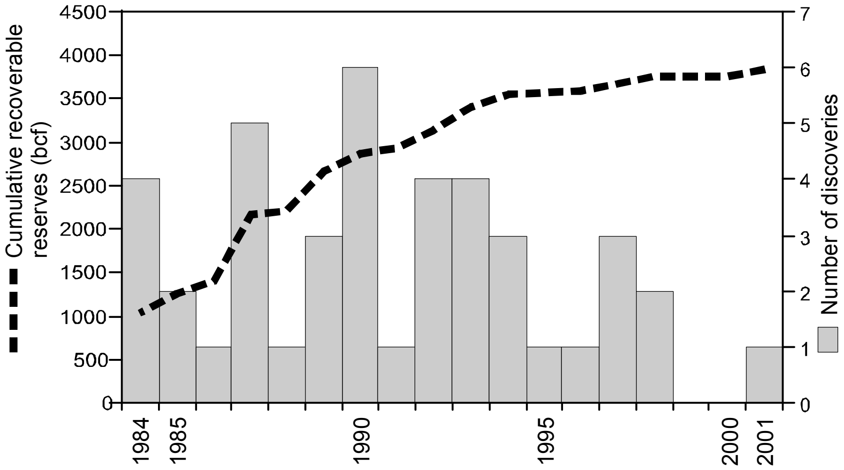

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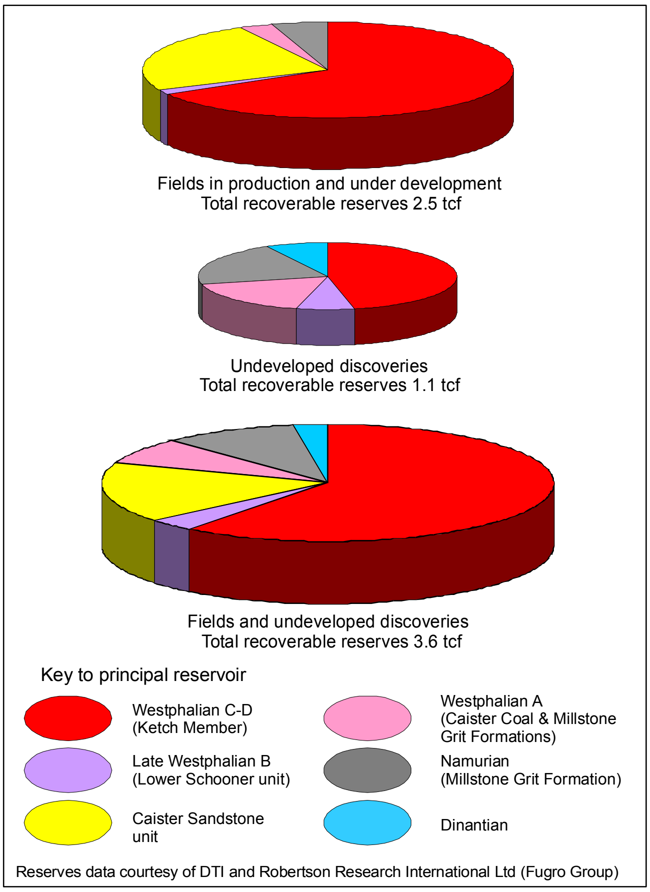

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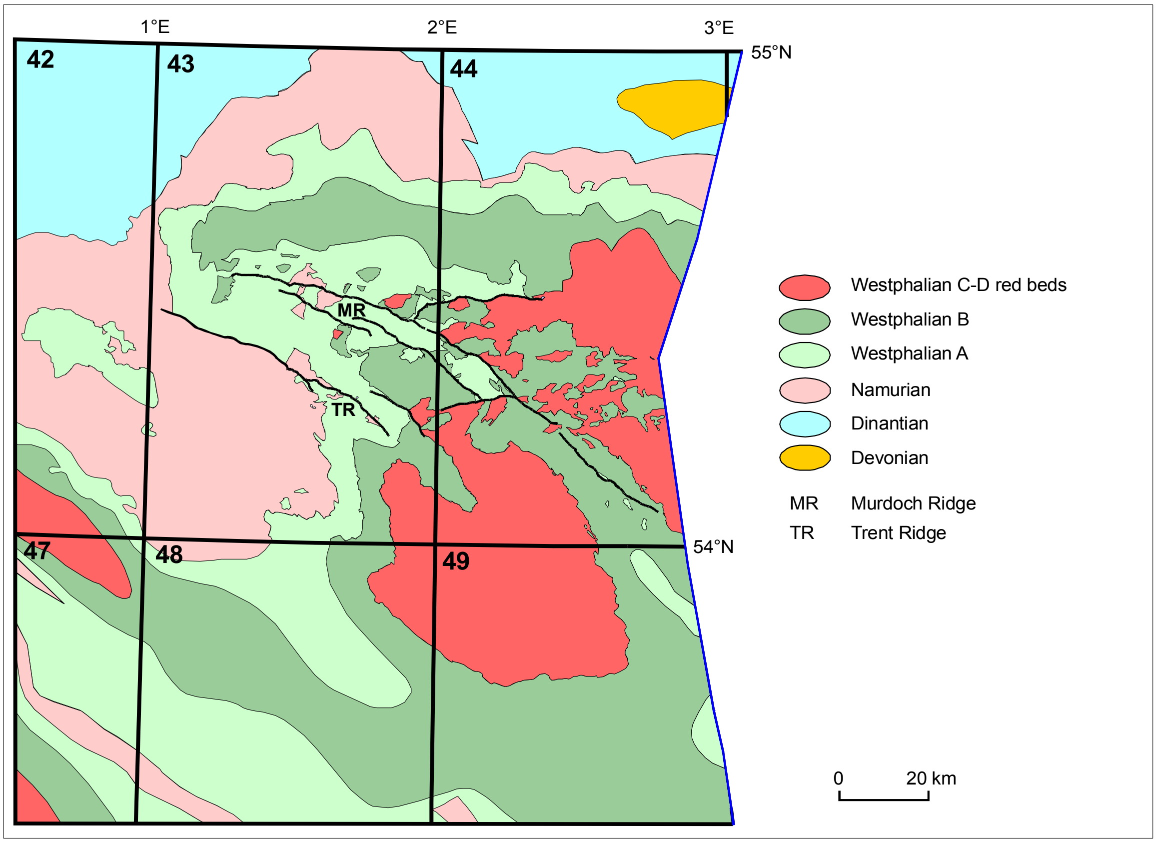

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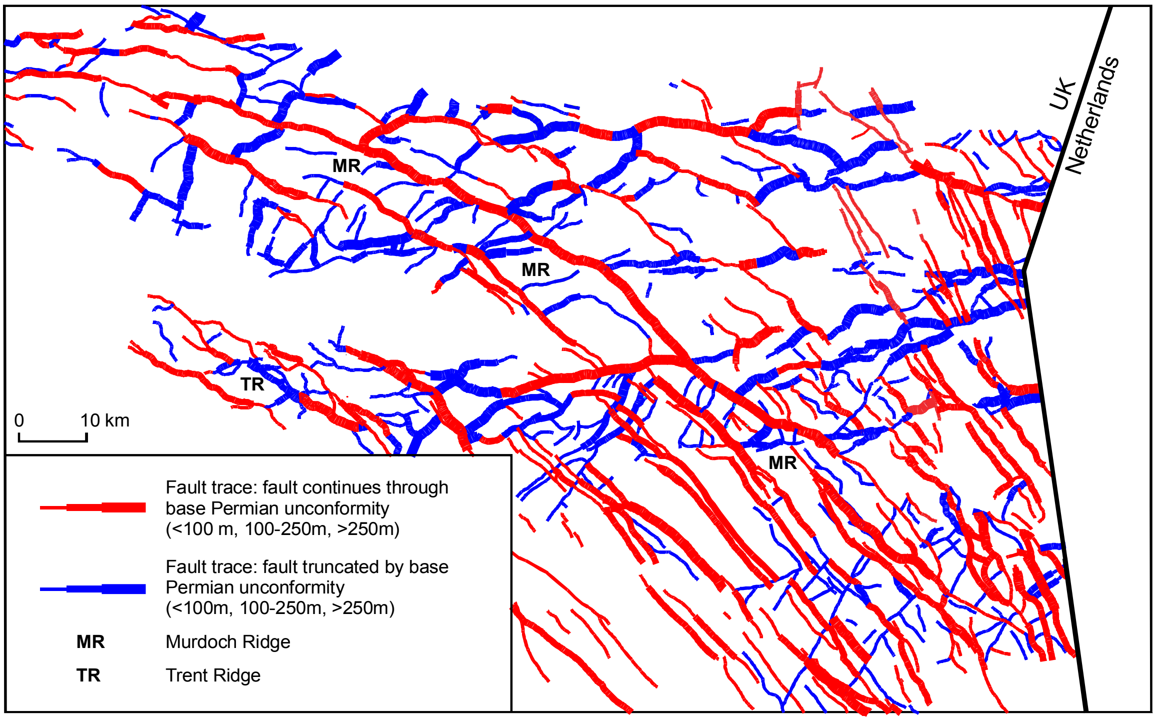

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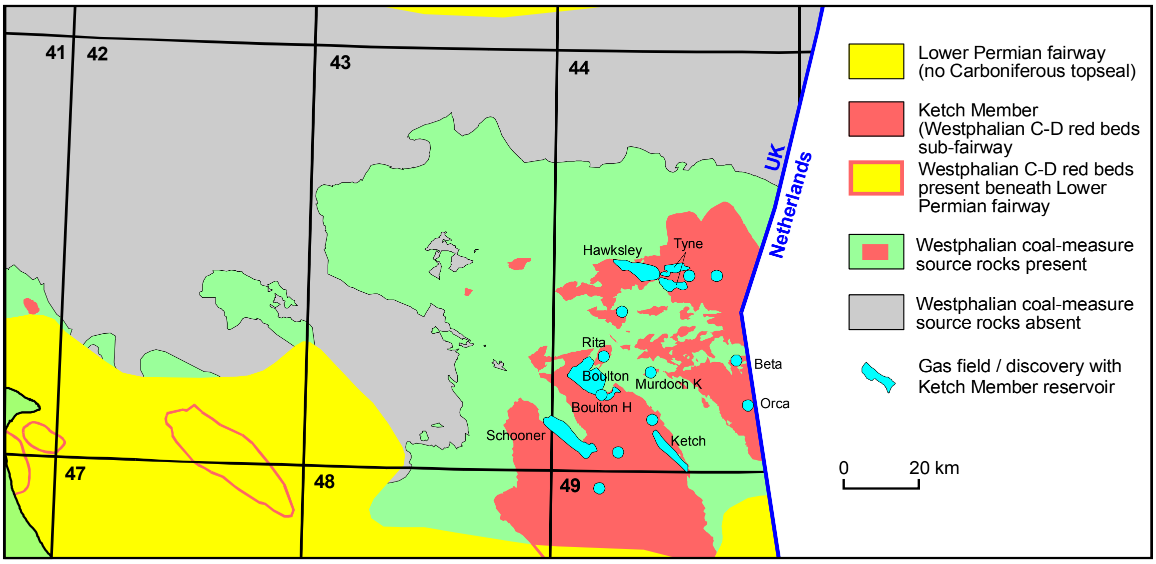

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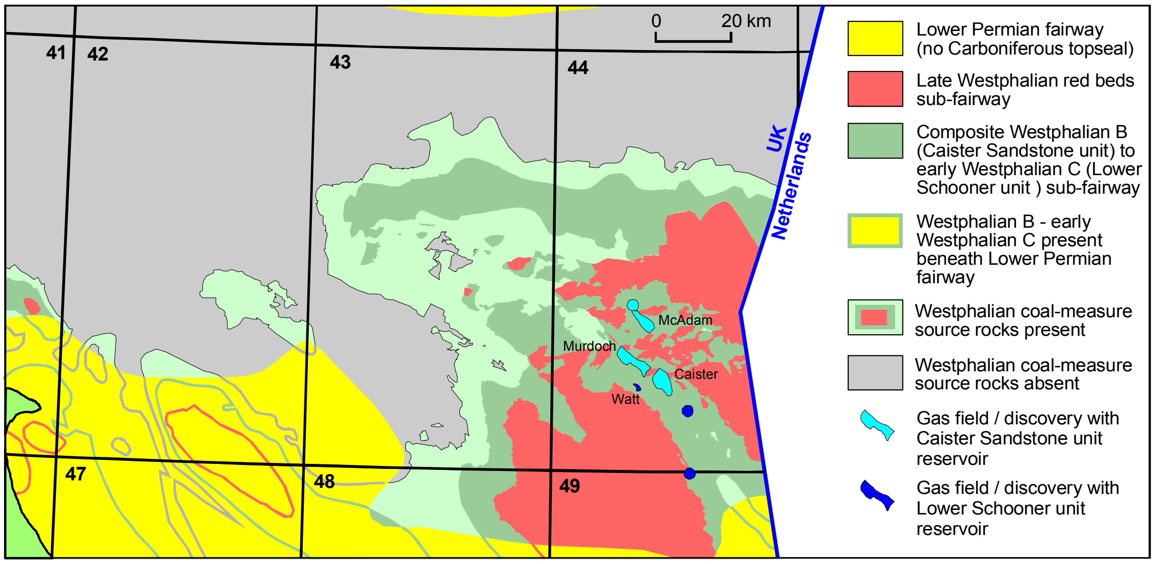

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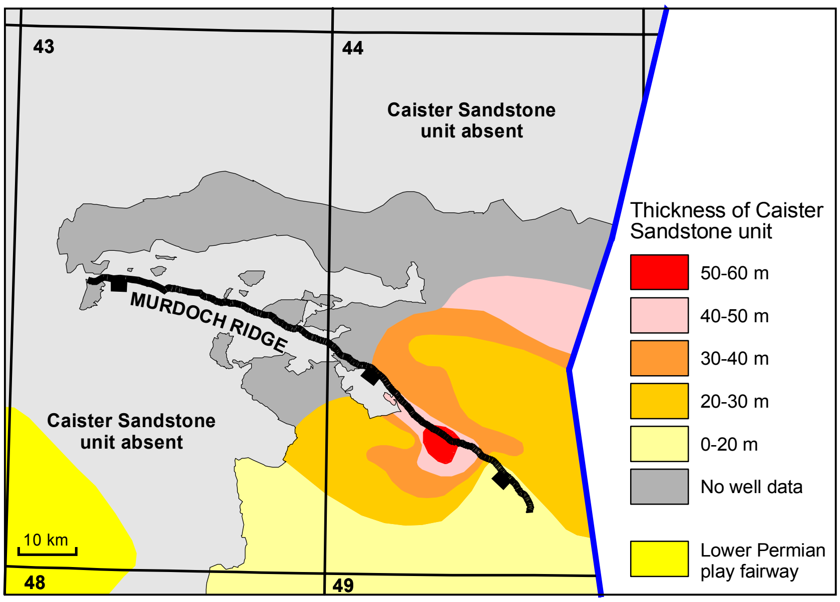

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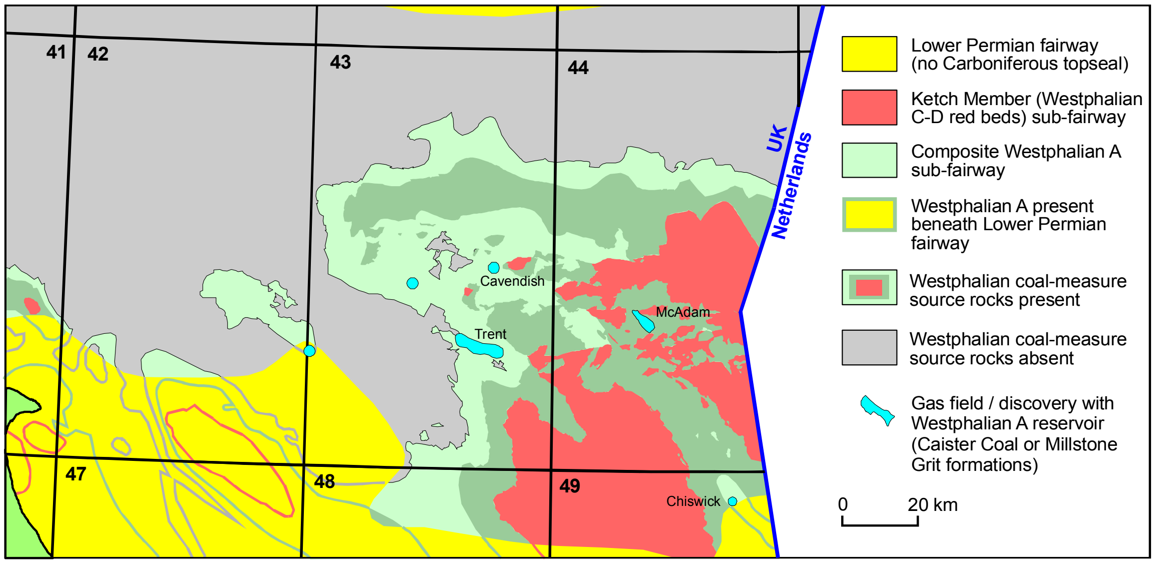

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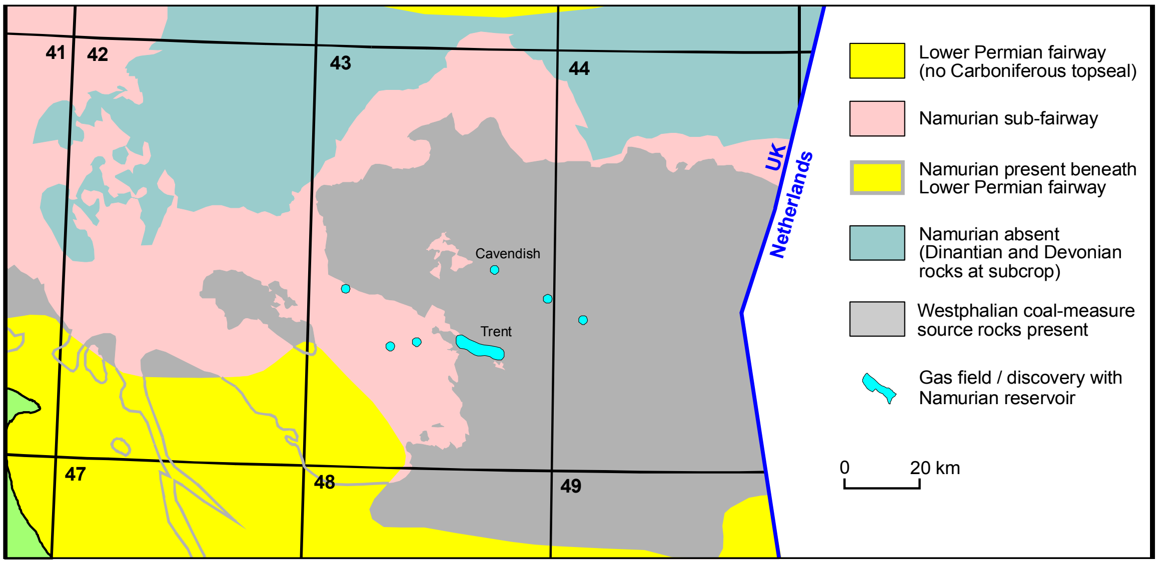

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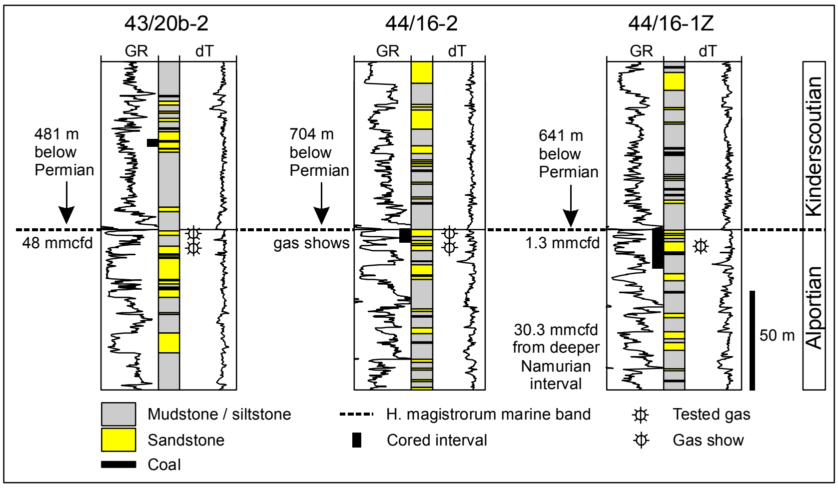

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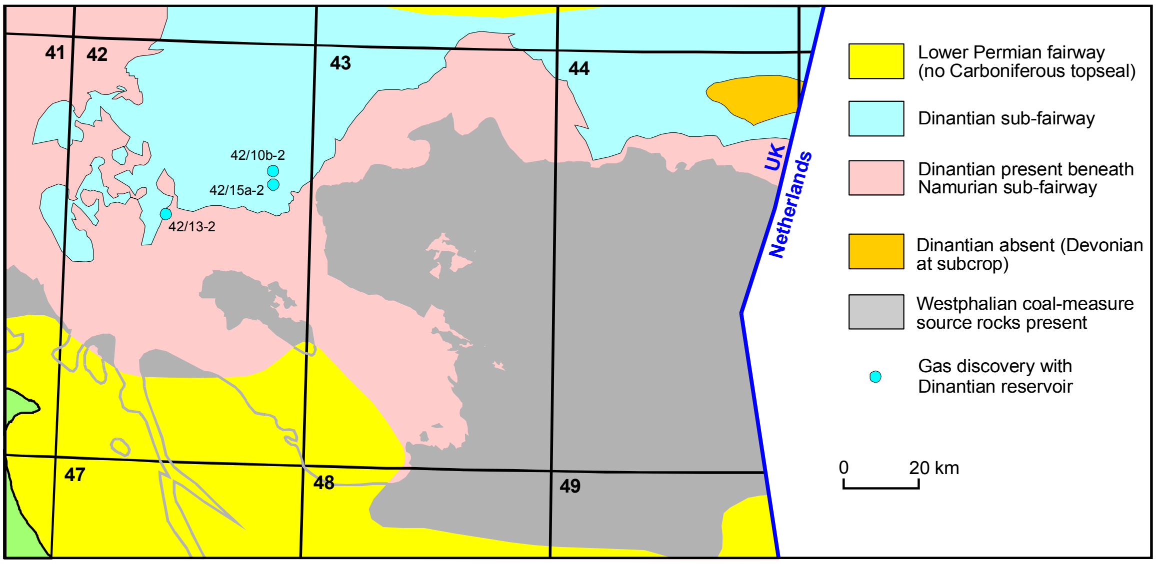

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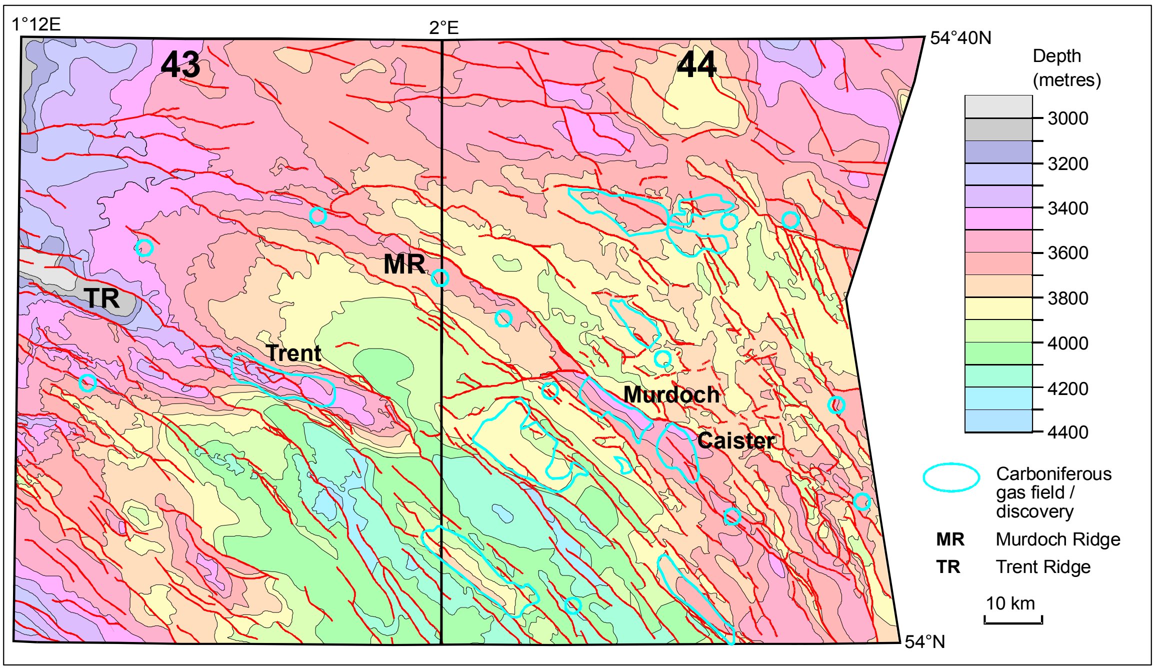

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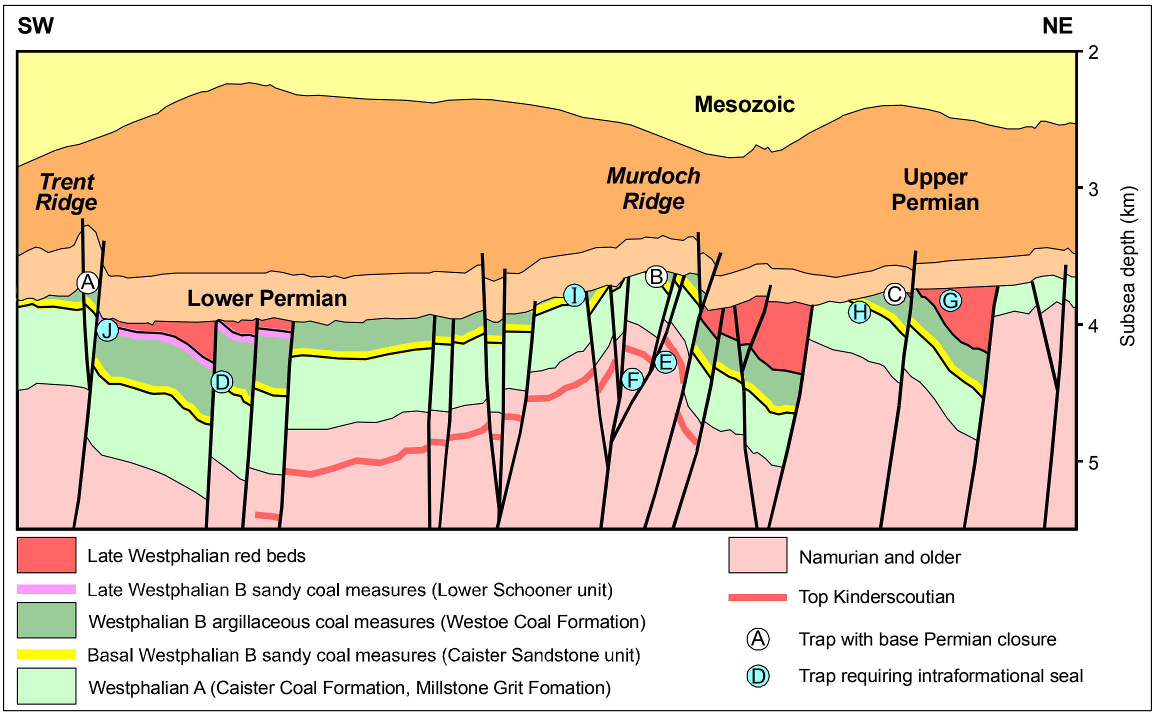

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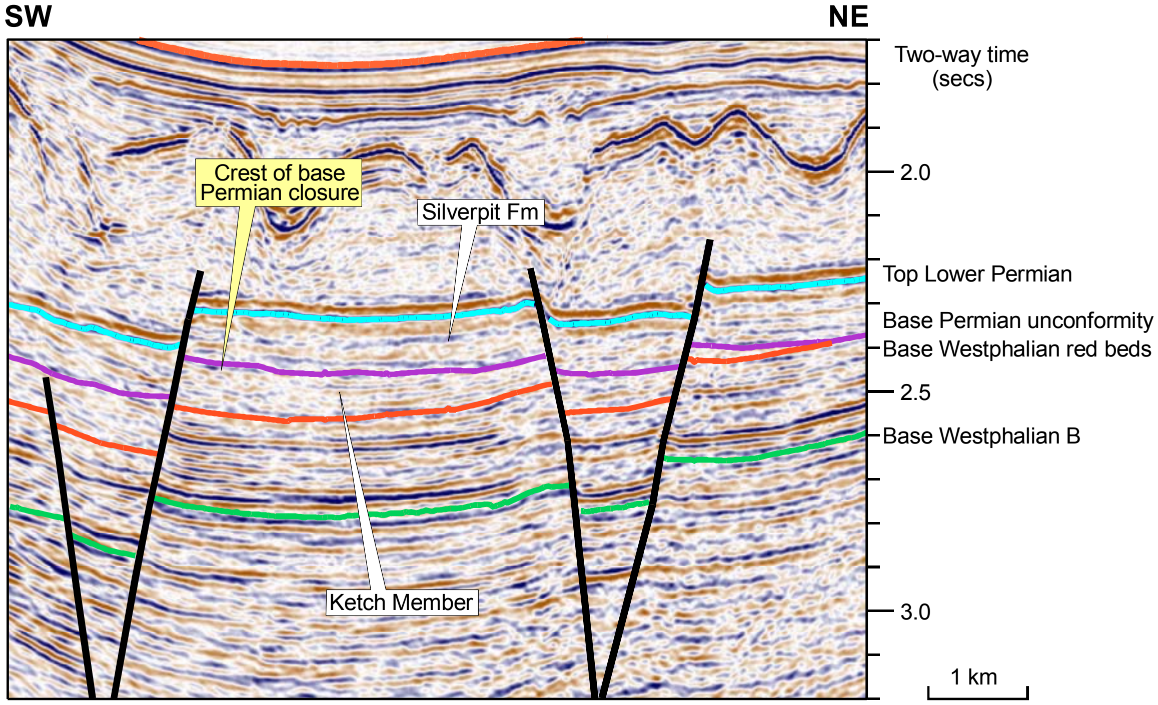

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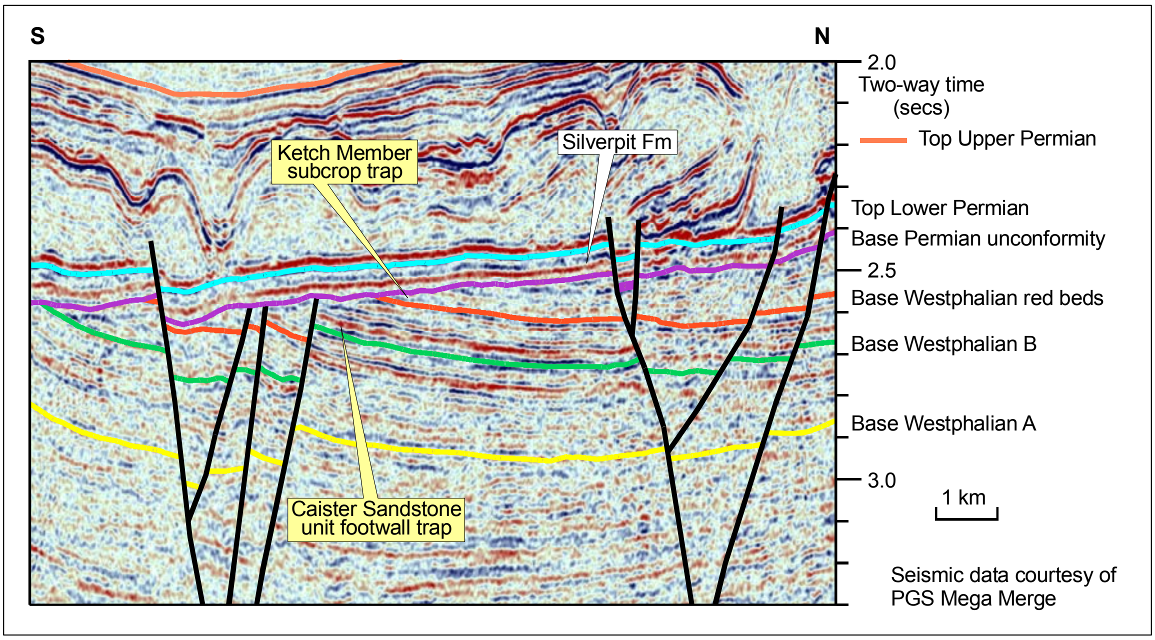

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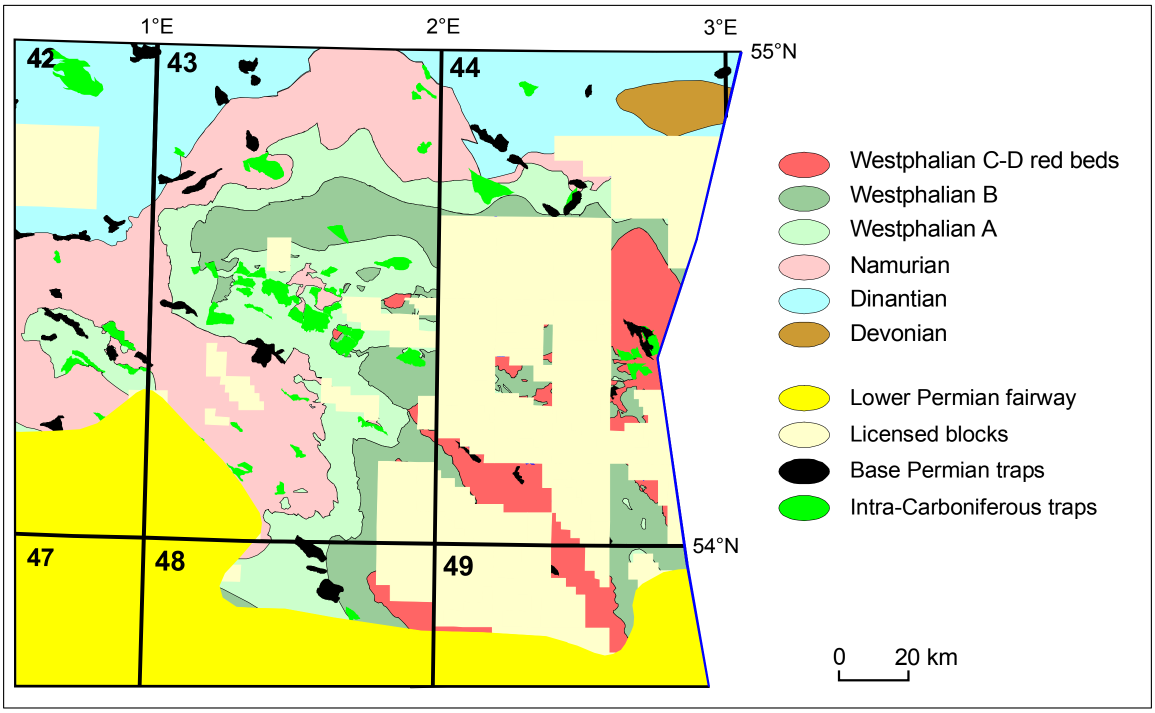

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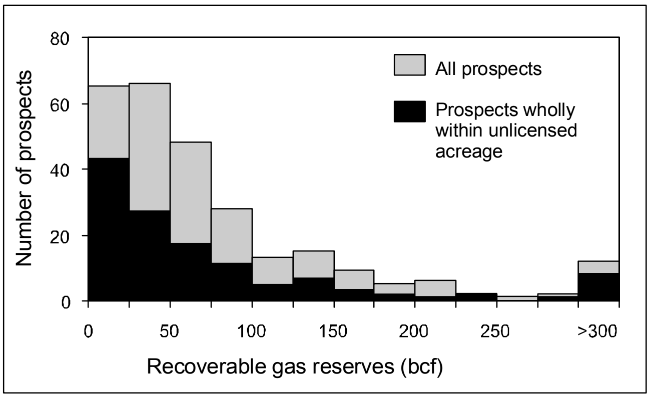

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