Exploration and development in the Carboniferous of the southern North Sea: a 30 year retrospective.

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Abstract

A review is made of the progress of exploration for, and development of, gas fields in the Carboniferous of the UK Southern North Sea in the period since the first significant discoveries were made in 1984. The outcomes of such exploration have generally failed to live up to high initial expectations and exploration targeting of the Carboniferous has declined, the objective having come to be seen by many as difficult and risky. The review includes a summary of the published consensus regarding elements of the Carboniferous petroleum system, and discusses the reasons for the decline in interest, which encompass geological complexity, interpretational and operational problems and other non-technical factors. Five areas of Carboniferous petroleum geology are identified in which the currently accepted status quo is open to challenge. More detailed discussion of these leads to the following general conclusions; 1) The distribution of source rocks and their maturation history remains very poorly understood, largely as a result of the hitherto unquestioned acceptance that Westphalian coals have acted as the dominant gas source; 2) In many early wells the combination of formation damage and shortcomings in petrophysical data acquisition and evaluation has resulted in a failure to identify potential pay in low permeability formations and an overemphasis on the importance of channel sand bodies as reservoir objectives; 3) The controls on seal capacity and integrity within the Carboniferous succession have been little studied and, as a result, an unduly pessimistic view of intra-Carboniferous sealing potential has prevailed; 4) The distribution of sub-basin depocentres, and thus of basinal shale source rocks and potential hydrocarbon migration paths, remains poorly understood; 5) Conceptual models of the large-scale tectonic history of the Carboniferous basin complex have failed to evolve from early and simplistic rift and sag models, which do not adequately explain the observed distribution of stratigraphic thicknesses and are inconsistent with some published burial histories.

Introduction.

When exploration moved offshore into the southern North Sea in the early 1960s the impetus was provided by the discovery of Carboniferous-sourced gas in the lower Permian aeolian sandstone reservoirs of the Rotliegend. At this time there had been a 20 year history of exploration success targeting Carboniferous sandstone reservoirs in the English East Midlands, and there were well-known occurrences of potentially rich oil source rocks in the lower Carboniferous of the Midland Valley of Scotland, and in the basal Namurian of northern England (Falcon & Kent 1960; Corfield – in press). It is therefore not surprising that a number of the earliest wells drilled in the UK offshore sector (38/29-1, 44/2-1, 53/10-1 – all 1965; 41/18-2 - 1966) targeted Carboniferous objectives where these were accessible at the margins of the Mesozoic and Cenozoic basin. These proved disappointing: the sandstone reservoirs encountered were tight, and early indications suggested the presence only of immature gas-prone source rock. Only in 41/18-2 was any flow obtained from a Carboniferous reservoir, and that was at trivial rates. With the discovery of the major Rotliegend gas accumulations in the West Sole, Viking and Leman fields the Carboniferous ceased to be an exploration target, although significant penetrations continued to be made in bottom-hole sections which generally showed a lack of reservoir development. Between the end of the 1960's and the early 1980's the consensus in the exploration and production community was that, while the Carboniferous provided a world-class, regionally developed source rock, it formed economic basement as far as exploration objectives were concerned.

Renewed interest in the prospectivity of the Carboniferous in the early 1980's was driven by a number of factors. Firstly, it was recognised that a number of gas-bearing sandstones in supposed Rotliegend penetrations in Quadrants D and F of the Dutch offshore area were in fact of late Carboniferous age. Secondly, few obvious dip closures remained to be drilled in the area of Rotliegend reservoir development. Thirdly, academic research in the UK highlighted the presence of sand-rich potential reservoir objectives in the red-bed successions in the youngest Carboniferous. Finally, and most importantly, the economic framework for gas exploration in the southern North Sea changed: it had become evident that a UK gas supply shortfall might occur from the year 2000, and the newly elected Conservative government decided to pursue a policy of deregulation and, ultimately, denationalisation. These actions led to potentially more competitive gas prices, and to the opening up of new exploration acreage, and acted as a spur for a renewed drilling campaign targeting the Carboniferous. After the award of licences in the 8th Round a flurry of drilling led to the announcement of the discovery of the first four significant Carboniferous fields (Chiswick, Murdoch, Boulton and Ketch) in the space of only 19 days in November 1984, initiating a scramble for acreage in the ensuing 9th and 10th Rounds.

The objective of this paper is to review what has happened since then, both in terms of the operational experience gained and of the understanding of plays within the Carboniferous. Although mention will be made of results in the Netherlands and Germany, the paper will concentrate on UK acreage. A brief review of the play elements and exploration results is followed by some remarks on production performance of the early fields, and on the combination of unfavourable circumstances that led to delays in commercialisation of Carboniferous discoveries and the growth of a general perception that the Carboniferous represents a risky and "difficult" play. In the following part of the paper a number of general beliefs that have grown up about the Carboniferous geology of the southern North Sea are identified and discussed. Because of the wide informal currency these beliefs have gained they are here referred to as "Founding Myths". It is the author's belief that the correct analysis of the subjects of these myths will lead to the identification of renewed prospectivity and exploration success in what are currently regarded as fairly mature to mature areas of the UK southern North Sea.

Since the initial version of this manuscript was written, a large number of studies carried out by the British Geological Survey have come into the public domain, and significant compilations of data have been released into the public domain by the UK Oil and Gas Authority (OGA). This work, carried out under the OGA's "21st Century Exploration Road Map" initiative, provides an extensive dataset and associated interpretations relating principally to the Mid North Sea High area but extending to cover the northern edge of the Southern North Sea basin. A summary with extensive bibliography is provided by Monaghan *et al* (2017). Some elements of this work and the newly released data have been incorporated into this paper during post-review revision. To fully incorporate this work would have been neither feasible nor desirable, providing as it does a wide ranging overview that starts to address some of the issues raised here.

Exploration history from the mid-1980s.

Large areas of acreage in which the Carboniferous was seen as the main objective were made available in the 8th to 10th rounds of UK offshore licensing (1982 to 1987). This acreage lay principally to the north of the established Rotliegend fairway in UK Quadrants 42 to 44 and the northern part of 49. In this area it was already known that the Leman Sandstone reservoir passes laterally into the mudstone and halite succession of the Silverpit Formation, providing a potential topseal to reservoirs in the Carboniferous. Carboniferous exploration was not limited to these areas, as a combination of government initiatives and the desire to identify additional reserves close to the existing infrastructure also led to the drilling of a number of deep Carboniferous penetrations below the existing Rotliegend fields. In the period between 1984 and 2014 approximately 143 exploration wells were drilled to test Carboniferous objectives in the UK sector (Figure 1). These resulted in approximately 37 discoveries, of which 27 named fields have been placed on production with an estimated recoverable volume of 3.6 TCF of gas (Table 1). The results of drilling, combined with those of TD penetrations of earlier wells and regional seismic interpretation, showed that the southern North Sea area was underlain by a thick Carboniferous succession, folded into a series of NW to SE trending major anticlines and synclines (Figure 1). Valid traps with Carboniferous reservoirs occur in faulted blocks and small-scale folds superimposed on these major structures, particularly in areas where these have been modified by Mesozoic or Cenozoic transpression (Figure 2). In the majority of cases the ultimate topseal is indeed provided by the Silverpit Formation. However, in a number of areas pay has been encountered in Carboniferous reservoirs even where Rotliegend sandstones are present. In some of these (Wollaston, Ravenspurn, Johnston) this is the result of a gas column continuing downwards where the Rotliegend reservoir is very thin. However, in the onshore Saltfleetby field (Hodge 2003) and the offshore discoveries in wells 48/23-3 (Blythe) and 48/24a-3 (Wherry) it is clear that the Carboniferous contains seals that are able to isolate a deep reservoir layer from the regional Rotliegend sand blanket.

Stratigraphy

The Carboniferous succession encountered in the southern North Sea (Figure 3) is similar to that present in adjacent onshore areas (Besly 1998; Kombrink *et al.* 2010; northern England - Fraser &

Gawthorpe 2003; Netherlands – Geluk *et al.* 2007; van Buggenum & den Hartog Jager 2007; Kombrink 2008). This major basin fill, deposited over a period of *c.* 60 ma between approximately 360 and 300 ma, comprises three stratigraphic elements,: a) the infill in early Carboniferous times of a series of major rift basins initiated during the late Devonian; b) a thick and broad regional drape, generally interpreted as a post-rift sag succession, deposited in mid Carboniferous times; and c) a dominantly red-bed succession associated with the early stages of Variscan basin inversion.

In this paper the footwall highs of the rift basins are generally referred to as "blocks" and the rift depocentres as "basins". This is in keeping with a widely used informal classification introduced by Miller & Grayson (1982) which usefully skirts round the problem of exact structural description of complex basin geometries which are not known in detail at depth, and in which the shapes of shallow water areas associated with the footwall highs were subject to change as carbonate ramps evolved into flat topped platforms in the later Visean. The aggregate thickness of Carboniferous succession originally deposited in some parts of the basins may have been more than 6 km. Although large thicknesses have been removed during end-Carboniferous inversion, very thick successions remain. As a result, individual well penetrations seldom prove a significant proportion of the entire basin fill, and the base of the Carboniferous has only been penetrated in a few places offshore, all on the margins of the Mid North Sea High (*e.g.* 42/10b-2, 44/2-1, E2-1, E6-1). The nature of the deeper parts of the basin fills remains virtually unknown, even in the onshore areas (*cf.* Hughes *et al.* 2017, Clarke *et al. in press*).

The fairly simple model of basin evolution outlined above, involving rift, post-rift and deformation phases, is widely accepted, and forms the basis for the following generalised description of the stratigraphic evolution. It should be noted, however, that basin formation in the southern parts of the UK and Netherlands has unambiguously been shown to involve flexural subsidence and the formation of a foreland basin (Burgess & Gayer 2000; Kombrink *et al.* 2008). It proves difficult to reconcile these subsidence histories with those observed in northern England – the classic "rift-and-sag" area – where the unconformities associated with foreland bulge migration predicted by Burgess & Gayer are clearly not developed. Thus the true history of basin development remains unclear, a question that is returned to at the end of the paper.

Generalised stratigraphic evolution

These three main stratigraphic elements have been formalised and named as five stratigraphic megasequences in Northern England by Fraser & Gawthorpe (2003). Although the applicability of parts of this scheme in the North Sea can be questioned, it forms a good first approximation for a brief summary of the stratigraphic history. Of these five megasequences, the first two correspond to the formation and infill of the early Carboniferous rift systems, and the third and fourth to the mid-Carboniferous post-rift sag phases described above.

1) **EC1 – EC2 (Fammenian - Chadian)** In northern England the earliest parts of the rift basin fills are generally inferred to comprise red-beds of Old Red Sandstone facies. Marine transgression during the Tournaisian led to the widespread establishment of carbonate facies as far north as present latitude 55°N. Shallow water carbonate platforms became established on topographic highs formed at the crests of extensional fault blocks, while deeper water areas of the rifts developed deep ramp and basinal successions of shale, carbonate mud, deep water mud mounds and carbonate turbidites. To the north of present latitude 55° N fluvial and lacustrine conditions prevailed during the lower part of this succession in both block and

basinal areas. Little is known of the equivalent succession in the offshore area, except that extremely thick (2 -4 km) Upper Devonian Old Red Sandstone successions are seismically imaged in the Mid North Sea High (S. Corfield, personal communication). It is not known whether these late Devonian thicknesses are also present where the very thick Carboniferous successions occur under the main part of the Southern North Sea complex of basins.

2) **EC4 – EC6 (Arundian - Brigantian)** A major northerly sourced fluvial system became established at some time during the middle part of the Visean, following which deep water sub basin areas were progressively infilled from north to south.

3) **LC1 (Pendleian – early Westphalian A)** In the UK onshore area active rifting ceased at the end of the Visean: deep water successions deposited after this time represent the infilling of residual bathymetry. The end of the Visean was also marked by a pronounced reduction in carbonate production: carbonate platform sedimentation ceased, and shallow marine limestones thereafter were only deposited as a volumetrically insignificant facies associated with sea level highstands in shoalwater delta successions to the north of present latitude 54° N (the so-called Yoredale facies). Between the mid Namurian and the early Westphalian repeated phases of major delta progradation resulted in the elimination of inherited basin bathymetry. These deltas deposited the classic Millstone Grit succession of Northern England. During this period pronounced glacio-eustatic sea level fluctuations resulted in frequent short lived marine flooding events (the so-called "Marine Bands"). Rapid evolutionary change in goniatite faunas allows exceptionally precise stratigraphic correlation in this succession if suitable macrofossil material can be collected. Infill of deep water areas continued to take place from north to south (Collinson 2005): the final deep water area was infilled in the early Westphalian A in UK Quadrants 48 to 49 and the southern part of the Netherlands offshore and onshore areas (see well sections in van Adrichem Boogaert & Kouwe, 1995).

4) **LC2 (Early Westphalian A – late Westphalian C)** Following this shallowing episode a widespread shallow water to subaerial depositional surface became established, comprising shallow lakes, lacustrine deltas, fluvial channels and mires in which the thick and extensive coal seams of the productive coal measures were deposited. Glacio-eustatic Marine Bands continue to allow precise correlation until the Westphalian B/C boundary. A dominance of northern sediment input led to a marked decrease in sand content from north to south (Cole *et al.* 2005; Quirk 1997), reversed only in the late Westphalian C by the appearance of southerly derived sandstones sourced from uplifts in the approaching Variscan Front (Morton *et al.* 2005).

5) **Inversion mega sequence (Late Westphalian C - Stephanian)** From earliest Westphalian times fluvial red beds accumulated along some margins of the basin complex (Besly 1988; Mitchell & Owens 1990): these became more extensive from mid Westphalian B time in response to basin margin uplift associated with the northward progression of Variscan deformation (Besly *op. cit.*) and by late Westphalian C time were the dominant facies in the basin. Red-bed deposition, with minor local coal-bearing facies development, continued in the UK onshore area until at least the earliest Permian and in North Germany until at least the Stephanian. The stratigraphic relationships in the youngest part of the succession are

complicated by poor biostratigraphic resolution and the presence of complex and poorly documented unconformities associated with the early development of Variscan folds.

Stratigraphic problems

As has already been mentioned even the longest well penetrations of Carboniferous strata only intersect a small proportion of the entire basin fill. With the exception of a few key wells most penetrations are of less than 300 metres. The correct identification of absolute horizon and marker beds in such short sections of very thick and usually monotonous clastic successions is fraught with difficulty and ambiguity. In onshore areas of the UK subdivision and correlation of the deltaic and alluvial successions of pre-mid Westphalian C age has for many years been based on thin marine flooding surfaces ("Marine Bands" in the Namurian and Westphalian; widespread thin limestones in the Visean and early Namurian). As these can only be unambiguously identified on the basis of macrofauna it has proved difficult to identify these in the offshore wells, even where core is available. Any attempt to correlate or identify absolute stratigraphic horizons on the basis of wireline response alone is subject to almost insuperable problems of aliasing in generally repetitive cyclic sequences. The resolution of the miospore biostratigraphy – the principal useful fossil group – has improved substantially (McLean *et al.* 2005), and this has led to better relative age determinations; but most of the older well penetrations lack palynological analyses of sufficient number, quality and consistency for reliable biostratigraphically-based correlations to be made, and palynomorphs become degraded and difficult to identify once the rocks reach gas-generating maturities. Subdivision and classification in the late Westphalian to Stephanian red-bed sequences still relies exclusively on lithostratigraphy. Unless based on extensive mineralogical, petrographic and chemostratigraphic data and clearly linked to regional provenance patterns (Besly 2005) lithostratigraphic units named in the red-bed successions may be meaningless.

Early hopes that a combination of fairly simple geochemical indicators used in combination with spectral GR logs (Leeder *et al.* 1990; Archard & Trice 1990) have largely been disappointed (*e.g.* Bristow & Williamson 1998). However, statistical analysis of large and very closely sampled multi-element geochemical data sets does prove to be a powerful tool for local correlation, particularly in the generally unfossiliferous red-beds of the youngest Westphalian (Pearce *et al.* 2005a). The effectiveness of this technique is enhanced by careful integration with palynological, trace element and isotope geochemical studies, leading to possibilities of regional genetic stratigraphic subdivision (Pearce *et al.* 2005b). As yet there is insufficient chemostratigraphic data in the public domain, and this, when coupled with the inadequate availability of reliable palynological data, means that the technique does not as yet provide a basis for a regional genetic stratigraphic framework.

In the absence of regional chronostratigraphic markers attempts to set up a widely applicable genetic stratigraphy that might act as a basis for robust play fairway analysis have been patchy and inconsistent. Preliminary sequence stratigraphic schemes (Quirk 1997; Cole *et al.* 2005) have been restricted to the Westphalian, producing inconsistent results from non-overlapping or incompletely documented well data sets. Other stratigraphic nomenclature schemes have largely –it would seem – been designed to bring some consistency into nomenclature used in well completion logs (Cameron 1993 for UK sector; van Adrichem Boogaert & Kouwe, 1995 – for NL sector). These schemes have resulted in a hotch-potch of stratigraphical nomenclature, some of it based on age considerations, some on extrapolation of onshore lithostratigraphical names that are in practice difficult to apply away from their well-defined onshore type areas. The result is a stratigraphic framework that lacks precision, fails to account meaningfully for some major observed lateral variations (*e.g.* stratigraphic identity in UK well 41/10-1 in Figure 3 of Collinson 2005), and becomes inoperable across the national median lines (Figure 4).

Major play elements in the Carboniferous

The main elements of the Carboniferous play are summarised in a series of annotated cross sections forming Figure 5. Apart from sealing and the nature and timing of trap formation most of the play elements in the offshore area are the same as those in the adjacent UK onshore areas (Fraser and Gawthorpe 2003). The difference in sealing and trapping is the result of the presence of a top seal at the base Permian unconformity that is absent in large areas of the UK onshore, but widely present in the Dutch and German onshore areas (Kombrink *et al.* 2010). This section of this review summarises the consensus view provided by previous publications: some of these views are open to challenge, and further discussion is provided later in the paper.

Source rocks (Figure 5a)

Source rocks are documented at all horizons in the Carboniferous succession from the middle part of the Visean up to the base of the red bed succession in the middle Westphalian. The thick coal seams in the Westphalian are the best-known of these, and have widely been assumed to be the main gas source rock in the southern North Sea (*e.g.* Cornford 1998; Pletsch *et al.* 2010). Thin coals are, however, present throughout the delta and alluvial plain facies of the upper Visean and Namurian, occurring in progressively older strata to the north, reflecting the earlier onset of shallow water deposition in this area. Oil shales of basinal facies are well-known in the English East Midlands, occurring principally in the basal Namurian but also present at shallower horizons up to the Marsdenian (Fraser *et al.* 1990). Minor oil source potential is also present in the Marine Bands in the Westphalian. Further oil shales of shallow lacustrine facies are present in the upper Visean and lower Namurian where these are developed in shoalwater Yoredale facies. In general these are thin and probably insignificant, but, where exceptional local palaeogeographical conditions obtained, thick oil prone lacustrine shales accumulated which in the past formed the basis for the oil retorting industry in the eastern Midland Valley of Scotland (Loftus & Greensmith 1988; Parnell 1988). It is not known whether any similar exceptional development of lacustrine oil shales is present in the offshore, although such developments have been suggested in UK Quadrant 20 (Bruce & Stemmerik 2003).

Although there is extensive literature indicating the presence of source rocks in the Carboniferous there is, with one exception, little published on the quantitative aspects of source rock development. Some indication of organic richness and yield in the basinal shales is given by Fraser *et al.* (1990) and by Pletsch *et al.* (2010), and a compilation of measured and log-derived TOC from 31 wells is given by Gent (2015). In general it seems to have been assumed that the gas generative potential of coal seams has always been more than sufficient to charge conventional traps, and little attention has been paid to the origin of hydrocarbons in areas where the Westphalian coals are absent. The exception to the lack of detailed study of quantitative aspects of source rock development is provided by a recent study of the Pendleian to Arnsbergian Bowland Shale Formation in the Widmerpool Basin in the English Midlands (Gross *et al.* 2015). Here, in rocks that have not reached the oil window, the TOC content of basin mudstones and of fine-grained materials intercalated with turbidites varies between 1.3 and 9.1% (average 4.2%), with HI values ranging from 50 to 425 mg HC/g TOC attesting to the presence of kerogens of both types II and III. The latter type is formed by detrital plant material associated with turbidite inputs inferred to be related to development of lowstand systems tracts. The comparative lack of oil shows in wells drilled in the offshore successions in the North Sea suggests that such oil-prone source rock developments may be the exception rather the norm, reflecting an exceptional combination of paleogeographic circumstances (see also Fig. 20 and associated discussion in Fraser *et al.* 1990).

It should be noted that disseminated plant material is widely present throughout the Carboniferous succession: Barnard & Cooper (1983) have suggested that this may be as important as the organic material contained within coal seams as a potential source material. In-seam coal is roughly twice as abundant as disseminated plant material in the Namurian C and Westphalian in the Ruhr coalfield (Scheidt & Littke 1994), suggesting that coal seams should dominate gas production in the Westphalian. However, the occurrence of dry gases and almost total absence of oil in parts of the stratigraphy that lack bedded coal require disseminated plant material to have acted as the dominant source rock in some areas (e.g. North Yorkshire area, UK onshore: Hughes *et al.* 2017), and both TOC measurements and log-derived profiles in Gent (2015) suggest the presence of large thicknesses of shales with significant TOC contents in the Visean to early Namurian Scremerston and Yoredale Formations and some horizons in the late Namurian to early Westphalian Millstone Grit and Caister Formations. Comparison with studied onshore sections suggests that much of this organic content is likely to be disseminated plant material. The question of the relative contribution of Westphalian coals to generation of currently reservoired gas is returned to in a later section of the paper.

Reservoirs (Figure 5b; Table 1)

The most important reservoirs encountered in the Carboniferous of the southern North Sea occur in fluvial channel sand bodies in the red-bed succession in the upper part of the Westphalian (Ketch Formation in UK, Hospital Ground Formation in NL) and in the basal Westphalian B and Westphalian A (Murdoch Sandstone Member and other un-named sandstone units of Caister Formation in UK, Klaverbank Formation in NL). Further important reservoirs are present in stacked fluvial channel sand bodies and in incised valley fills and associated facies in the Namurian and Visean. In the early stages of exploration prognosis of reservoir development was based on the exposed succession in central and northern England. In retrospect this analogy turns out to have been misleading. The occurrence of a high net-to-gross sandstone reservoir in the late Carboniferous red-bed succession was predicated on the occurrence of such facies in the Westphalian D to early Permian Enville Formation and related units in the English Midlands. The general log shape of the red-bed reservoirs encountered in early wells suggested that this succession had indeed been found offshore (*e.g.* compare log shapes of 44/28-1 in Besly *et al* 1993 with Enville Formation logs illustrated in Besly & Cleal 1997), but the drilling of well 44/21-3 demonstrated that the reservoir succession that is now called the Ketch Formation was a sand-rich unit of Westphalian C age, derived from a previously unsuspected north eastern source area and not present in the onshore area. Similarly, the most significant reservoir in the Westphalian – the early Westphalian B Murdoch Sandstone – is not developed onshore. The targeting of sand-rich potential reservoir successions in the upper part of the Namurian was based on the occurrence of thick and extensive sandstones (the Millstone Grit) in the exposed succession of this age onshore. In practice, Millstone Grit sandstones have proved to have relatively poor reservoir properties offshore, but commercially producible reservoirs have been encountered at this stratigraphic horizon, in the Trent and Pegasus Fields, in a quartzite facies for which no clear onshore analogue is known.

Seals and Traps (Figures 2, 5c, 6)

Exploration for Carboniferous objectives in the southern North Sea has hitherto almost exclusively relied on the identification of traps that ultimately have the halite and shale facies of the lower Permian as their top seal (Silverpit Formation in UK; Ten Boer Member in NL). There is no UK onshore analogue for this play. The concentration on exploration for traps of this type has largely been driven by the comparative ease with which structures at base Permian can be mapped, and the comparatively low risk attached to this topseal. Although traps of this type may contain elements of Variscan structure, they are essentially formed by folding and development of positive flower structures associated with Mesozoic or Cenozoic tectonic events. Even in these traps, careful examination of the structure shows the possibility of elements of topseal provided by intra-Carboniferous shales and / or lateral seal provided by fault juxtaposition against the Silverpit Formation or against Zechstein salts (e.g. Murdoch Field, Conway & Valvatne 2003b; Figure 2b). Intra-Carboniferous seals are also demonstrable in fields containing multiple pay horizons having different gas-water contacts (*e.g.* Boulton field - Conway & Valvatne 2003a: Figure 2a).

In a number of accumulations it is clear, however, Variscan structure provides the dominant or only control on trap geometry, and that effective seals must be present within the Carboniferous. In neither the Cavendish field (Block 43/19) nor the recent Pegasus discovery (Block 43/13) is there a mappable closure at base Permian level and the trapping mechanism must involve a combination of base Permian and intra-Carboniferous seals (Figures 2d, 6) in which a significant element of dip closure is provided by Variscan folding. Variscan dip closures may involve folding related to Variscan shortening (*e.g.* the Boulton F and Pegasus structures, Figures 2a, 2d), or may be related to compactional drape over basement highs (e.g. Saltfleetby Field, Figure 2d). The Kepler accumulation (Block 43/20b) is a Variscan structure entirely sealed by a Carboniferous shale seal (Cameron *et al.* 2005). Intra-Carboniferous seals must also be present in some stratigraphic traps that rely on seat seal (*e.g.* the Ketex discovery in well 49/3-3).

Given the plentiful occurrence of fine grained clastics in the Carboniferous and the ample burial they have undergone, there is absolutely no reason why viable seals should not exist throughout the Carboniferous section. This is supported by the obvious occurrence of some very long gas columns in wells that have not been regarded as discoveries. The question of viability and risking of intra-Carboniferous seals is further discussed later in this paper.

Maturation and timing

The consensus view in the literature would appear to suggest that the maturation history of Carboniferous source rocks in the Southern North Sea is well known (*e.g.* Cornford 1998). The deeper parts of the Carboniferous basin fills first entered the hydrocarbon generation window during Carboniferous burial: any oil and gas that had already migrated during this early burial phase is likely to have escaped during a major phase of fluid expulsion that accompanied the end-Carboniferous Variscan deformation episode (*e.g.* Hollis 1998). In most of the Southern North Sea area the Carboniferous succession reached its maximum burial during the Mesozoic and Cenozoic (Figure 7a-c: Cornford 1998: Figure 11.41, Leeder & Hardman 1990; Pearson & Russell 2000). Source intervals entered the gas window during the Jurassic or Cretaceous, and are presently at or near maximum burial over wide areas. Over most of the area neither the volume of generated gas nor the relationship of generation and migration to trap timing have been perceived as risks.

This simple picture is complicated by three factors: the inversion of source kitchens and deeply buried reservoirs in a number of tectonic episodes during the late Jurassic to late Cretaceous; widespread regional tilting in the Neogene, mainly affecting the west of the UK area; and the progressive thinning of the post-Variscan overburden to the north and west.

Inversion episodes of Mesozoic depocentres in the late Jurassic and late Cretaceous ("late Cimmerian" and "sub-Hercynian / Laramide" phases of Glennie & Boegner 1981) are interpreted to have led to multiple episodes of migration and remigration in the Rotliegend reservoirs. During initial deep burial primary migration of gas occurred from deeply buried source kitchens into marginal areas. Subsequent inversion phases led to remigration into newly formed structures in the cores of the inversion axes. This process appears not to have been documented in detail, but is widely accepted (see summaries in Glennie 1998: pp164-167 and Johnson & Fisher 1998: pp 516-519).

Neogene regional tilting is very well documented, but its causes remain poorly understood (Japsen 1997; Japsen & Chalmers, 2000). It is clearly differentiated from the Paleogene regional uplift related to the Iceland thermal plume (White & Lovell 1997). Although the earlier phases of the tilting may be related to widespread regional late Miocene ('Alpine') inversion, the later phases cannot be so explained and remain incompletely understood (Blundell 2002). Plio-Pleistocene isostatic uplift may be involved, as may be flexural responses to more localised patterns of denudation (Watts *et al.*, 2000). The tilting has the effect of bringing highly mature source material to shallow depths in the western part of the UK sector and the UK onshore area. Various approaches to quantification of this uplift have been attempted (analysis of sonic velocities - Whittaker *et al.* 1985, Hillis 1995a, 1995b; vitrinite reflectance – Pearson & Russell 2000; AFTA – Bray *et al.* 1992, Green 2005), but it proves difficult to reconcile them, partly because of the non-linear nature of some of the parameters involved (Japsen 2000), and partly because the uplift and burial histories are probably more complex than was originally suspected (*e.g.* Japsen 1997). The regional tilting has undoubtedly had major consequences for the integrity and geometry of gas accumulations. It may be speculated that uplift may have led to seal failure, and further large-scale remigration may be inferred. In this case, as in the case of remigration associated with late Cretaceous or earlier Cenozoic inversion, a laterally extensive blanket of permeable Rotliegend reservoir / aquifer is required. The likely impacts of the switching off of source kitchens and remigration in the less well-connected and lower net-to-gross Carboniferous successions have not as yet been studied.

The effects of ***progressive thinning of the post-Variscan overburden*** can be inferred from the burial history curve for the UK onshore well Weeton-1 (Figure 7c). Here, maximum burial of the base Namurian source interval (and by implication all source intervals in at least the Tournaisian, Visean and Namurian successions) occurred during Carboniferous burial. It may be inferred that some of the hydrocarbons generated were lost during Variscan deformation and there has been little or no subsequent hydrocarbon generation. This combination of deep pre-Variscan and modest post-Variscan burial must occur over a wide zone in the Mid North Sea High and the UK onshore area, and form a northern and western limit beyond which prospectively is much reduced. This area has yet to be delineated, but a number of wells in which this effect may have been produced are documented by Vincent (2015). The same pattern is general in more southerly parts of the basin that form an obvious Variscan foreland downwarp, where peak maturity is documented to have been reached prior to Variscan inversion throughout the Ruhr coalfield and adjacent areas (Littke *et al.* 2000), in the UK Oxfordshire coalfield (Green *et al.* 2001) and in the South Wales coalfield (review in Hower & Gayer 2002).

Gas composition

Gas derived from the Carboniferous – in both Carboniferous and younger reservoirs – is generally regarded as dry. This is largely true, condensate to gas ratios of less than 5 bbls/MMscf being widely recorded in the central part of the Rotliegend reservoir fairway (figures compiled from papers in Abbotts 1991 and Gluyas & Hichens 2003). However, there are significant variations, with condensate contents of more than 10 bbls/MMscf present in the Cavendish, Boulton, Schooner and Tyne Fields (Kersten *et al.* 2013; Conway & Valvatne 2003a, b; Moscariello 2003), and of more than 20 bbls/MMscf in the Amethyst West and Saltfleetby Fields (Garland 1991; Hodge 2003). In the Cavendish Field fluid banking of retrograde condensate has proved a productivity impairment mechanism (Kersten *et al.*, *op. cit.*).

Other compositional factors that have impeded development of Carboniferous gas accumulations have been the local occurrence of high contents of nitrogen and carbon dioxide (Corbin *et al.*, 2005).

The high nitrogen contents conform to a gross regional pattern of increasing nitrogen content in both Carboniferous and Rotliegend reservoirs towards the east (Lokhorst 1998, Gerling *et al.* 1999). There is a consensus that the nitrogen derives from two main sources (Gerling *et al.* 1998), one related to the release of nitrogen from coals at very high maturities (Krooss *et al.* 1995, Gerling *et al.* 1997); the second resulting from the thermal degradation of both organic and inorganic nitrogen-bearing components in the mainly pre-Westphalian marine source rocks (Mingram *et al.* 2005). Both of these processes are encouraged by the generally increased burial of all Carboniferous source intervals moving eastwards from the UK towards the north west German plain. For high nitrogen fields to be commercialised it has been necessary either to export gas to the European network via the Netherlands (in order to exploit the higher accepted nitrogen content in the European transmission systems), or to blend the gas with low nitrogen gas to meet UK specifications (Corbin *et al.* 2005).

The occurrence of gases with high carbon dioxide contents is much more patchy, with isolated accumulations having anomalously high CO_2 (*e.g.* the undeveloped accumulations in UK 43/20b-2 [Kepler] and 49/5a-5 ["Coca Cola"] – see Figure 9 in Corbin *et al.* 2005). Studies on the controls on CO_2 occurrence have yet to be published: it may be speculated that these anomalous high CO_2 bullseyes are related to Cenozoic magmatic activity, the two occurrences cited above both being located near areas known to be affected by Palaeogene dyke intrusion. Isotope data that might allow more precise determination of the origin or origins of the CO_2 isotope have yet to be published. As with nitrogen-rich gases, development has been predicated by the ability to blend the gas to marketable specification: this has enabled the development of the Breagh Field (initial CO_2 content *c.* 7% - DECC 2013), which is blended with gas from the Central North Sea at its landing point in Teeside to reduce the CO_2 to transmission grid specification.

Exploration challenges presented by the SNS Carboniferous

Difficulty of prospect definition

Exploration for Carboniferous objectives in the southern North Sea is bedevilled by a complex set of interpretation problems that make it difficult to define prospects and calculate unambiguous volumetric estimates. Most of these are summarised by Corbin *et al.* (2005).

The principal problems are related to the exceptionally complex overburden, which leads to severe imaging problems (Figure 8). These result from extensive mobilisation of the Zechstein salt (Stewart & Coward 1995), which has led to salt pillows and diapirs – the latter in places having overhang geometries – and to areas of more or less complete salt withdrawal. The presence of the Zechstein salts results in the partitioning the effects of Mesozoic and Cenozoic extension and inversion. Below the salt post Mesozoic structuration involves movement of rigid blocks, while detachment in the salt leads to thin-skinned extensional and wrench-generated structures in the younger Mesozoic and Cenozoic. The resulting ray path complexity causes severe imaging difficulties. Interpretation is compounded by the problems of depth conversion in such a structural setting. Apart from the complex ray paths, that can only be satisfactorily managed by several phases of pre-stack depth migration (pre-SDM), differential burial in the Mesozoic succession leads to a complex velocity structure, particularly in the Upper Cretaceous Chalk (Davis, 1987). A graphic example of the range of uncertainty of prospect definition that can result from salt in the overburden is provided by Corbin *et al.* (2005; Figure 9), and an example of the application of pre-SDM is given by Jones *et al.* 2005.

The imaging problems caused by overburden heterogeneity are compounded by two major problems inherent to the stratigraphy of the base Permian unconformity (BPU) and subjacent Carboniferous. Local facies variation at the base of the Permian - the presence or absence of a basal sand facies and / or salt layer – leads to marked changes in acoustic impedance at the BPU, which may as a result be seismically invisible (Figure 10a; see also discussion in Cooper *et al.* 2005 pp. 323-325). Mapping of structure at BPU level may require an indirect approach involving the picking of a horizon some way above the BPU and the construction of isopachs to map the unconformity itself. Similar difficulties arise in identifying the stratigraphic horizon in the Carboniferous that subcrops beneath the unconformity, a key uncertainty in prospect evaluation since it controls the presence or absence of reservoir within closure. Seismic character within the Carboniferous succession varies markedly over short distances, and some key objectives – particularly in the upper part of the Namurian and in the late Westphalian Ketch Formation – are seismically featureless (Figure 10b). When combined with the stratigraphic difficulties already mentioned and the presence of significant faulting in the succession, these features lead to dangers of aliasing the interpreted stratigraphic horizon. The discovery of numerous small fields in the Ketch reservoir in the CMSIII development (Cooper *et al. op. cit.*) and the delineation of complex stratigraphic trapping geometries in the subordinate Ketch reservoir in the Cygnus Field (Catto *et al.* 2016) has required detailed and accurate mapping of the subcrop to the BPU. This has involved careful multidisciplinary stratigraphic analysis of offset wells to determine reliable seismic markers in the Carboniferous, and the construction of local isopach maps to project the seismic interpretation into stratigraphic sections that lack seismic resolution. Even with such studies wells can miss their reservoir targets, either because of seismic mis-picks or lateral facies variation (O'Mara *et al.* 1999: p.814). Where seismic quality is poor and well control is distant, well results have differed markedly from prognosis: for instance, in well 41/10-1 top Visean came in 3000 ft shallower than predicted pre-drill (released operator's completion report).

Drilling problems and difficulties in formation evaluation

A key characteristic of the Carboniferous objective is that the wells needed to target them are generally deep, complex and expensive (see *e.g.* O'Mara *et al.* 1999, 2003b). Except around the margins of the basin (Mid North Sea High, Quadrants 41, 42 and 53) top Carboniferous is at more than 10,000 ft TVDSS, and the overburden comprises a complex succession including salts and highly overpressured dolomite stringers in the Zechstein, and bedded evaporites in the Silverpit Formation facies of the Rotliegend. The latter are prone to flow, causing casing deformation or collapse. If the complications and cost of reaching the Carboniferous were not enough, drilling good quality well sections within the Carboniferous presents a set of challenges that differ entirely from those to which the industry is accustomed in the Southern North Sea. The highly heterolithic nature of the Carboniferous clastic successions, in which fairly thin-bedded units of mechanically strong sandstone alternate with mechanically weak and / or brittle shale and coal, leads to extensive caving and borehole collapse unless drilling is carefully managed. Many of the early wells were drilled with heavily weighted salt-saturated water-based mud which resulted in severe caving and the development of ledges. The resulting wireline logs were in many cases of poor quality (Figure 11a). Salt-saturated muds were the inevitable result of leaving openhole sections that had exposed Rotliegend and / or Zechstein salts between the deepest casing point and the drilled Carboniferous section. In at least some cases this resulted from the enforced choice of casing points at depths shallower than had been planned following well control incidents in the Zechstein (McPhee & Byrne 2009). More careful mud formulation and /or the use of oil-based fluids can largely eliminate this problem (Figure 11b).

Apart from problems caused by poor log quality, the use of significantly overweight mud has led to ambiguities in both petrophysical evaluation and the interpretation of test results. Where the petrophysical method is detailed in well completion reports it would appear that in some cases evaluation has relied on standard methods with no consideration given to the likelihood of deep invasion resulting from the combination of significant fluid pressure overbalance and low permeability sandstone reservoirs. A particularly striking illustration of the detrimental effects that these have is provided by McPhee *et al.* (2008). In their careful study of the discovery well of the then-undeveloped Breagh Field they used SCAL to demonstrate that the use of excess overbalance (400 psi) while drilling had led to up to 60 inches of invasion of filtrate from the brine water-based mud. Well test analysis showed a skin ranging from +24 to +175. Redrilling of the well using oil-based mud with minimal overbalance led to negligible invasion and eliminated the skin. The resulting nearly six-fold increase in flow rate demonstrated the commercial viability of the field (Figure 12).

Development challenges and unpredictable field performance

Development of Carboniferous accumulations in the UK sector of the SNS has been characterised by generally long lead times. Of the first ten fields discovered, the shortest interval between discovery and production start-up was 8 years (Caister Field: discovered 1985, start-up 1993), while the longest so far has been 23 years (Chiswick Field: discovered 1984, start-up 2007).

This delay was partly due to the lack of infrastructure to the north of the Rotliegend pinchout line, but was also a consequence of the dramatic collapse in oil and gas prices in 1985, immediately after the discovery of the first Carboniferous fields (Figure 13). Apart from the restriction in budgets that this caused, widespread redundancies and wholesale relocation of exploration departments from London to Aberdeen led to the break-up of teams that had built competence in the Carboniferous, and to the loss of experienced individuals. The modest revival of the mid 1990's was followed by a second price slump that led to another large-scale restructuring in the industry at the end of 1998 which was accompanied by a similar fragmentation and loss of expertise. The same period saw major changes in the organisation and priorities of both academic and statutory organisations, such as the British Geological Survey, which might otherwise have provided research support to an emerging Carboniferous play. Research groups that had long histories of Carboniferous studies were downgraded and expertise was lost through retirements. The intense research effort that had accompanied the opening-up of the Rotliegend and Jurassic plays in the North Sea was not replicated. A telling example is provided by the development of stratigraphic concepts. From a start of virtually no knowledge in the early 1970's, understanding of Jurassic stratigraphy in the central and northern North Sea had advanced to a fully documented genetic stratigraphy including the latest sequence stratigraphic concepts by the early 1990's (Partington *et al* 1993). By contrast, there is still, in 2017, no agreed genetic stratigraphy for the Carboniferous succession in the UK offshore – let alone the wider North Sea area - despite more than 100 years of intense litho- and biostratigraphic research in the adjoining UK and Netherlands onshore areas.

The slow pace of development was not only driven by commodity price and infrastructure issues. When targeted exploration for Carboniferous objectives started in 1984 there was already a large volume of undeveloped reserves in the Rotliegend (Figure 14). These had remained undeveloped for a combination of reasons that rendered them uncommercial at the low prevailing gas price. Many accumulations were in reservoirs that were tight owing either to diagenetic modification or to unfavourable facies development. These would not produce at viable rates using the drilling and completion methods that were then standard. Projects were also rendered unviable by lack of ullage in the evacuation systems and high tariffs demanded for pipeline access. With more favourable gas prices, decline in the first generation fields and improved sub-surface technology (identification of fracture systems, underbalanced drilling) these accumulations, located in shallow water near existing infrastructure, became the main focus for development in a low-price environment. At the same time, improvements in imaging and depth conversion brought about by the universal adoption of 3D seismic, and the improvement in pre-stack seismic processing and interpretation led to the delineation and discovery of additional reserves in the main Rotliegend fairway (Figure 14). Viewed in this context the volumes discovered in the Carboniferous are relatively small, and, given their remote location and the other technical difficulties in developing them, it is not surprising that development was so slow.

Even when development has proceeded it has been accompanied by much greater uncertainties than would have been the case in most Rotliegend fields. The primary uncertainty relates to the distribution of the reservoir, particularly in undrilled fault blocks. This arises from a combination of two factors. It is often difficult to predict the occurrence of a particular reservoir horizon at the erosionally-truncated subcrop to the base Permian unconformity surface; and the channelised nature of the reservoir sands means that they are not developed in a predictable manner over the area of a field. The overall low net-to-gross ratio in most of the succession introduces uncertainty regarding connectivity, which may be ether enhanced or further degraded by faulting, much of which is below seismic resolution (Bailey *et al.* 2002). Generally low porosity and permeability, together with uncertain connectivity, give rise to uncertainties as to whether sufficient volumes of gas are connected to the wellbore to achieve economic flow rates and volumes. Finally, all of these difficulties are embedded in a situation where uncertainty is introduced into the overall structure by the complex overburden and difficulties in depth conversion.

The question of well cost has already been mentioned as an exploration challenge, but this challenge becomes even more acute when a development plan has to access all parts of an accumulation beneath the complex Zechstein overburden. Finding windows through the potentially overpressured Plattendolomite leads to long and complex well paths: the alternative requires drilling and casing contingencies to manage the possible overpressure zones. Well cost has been further increased by the need to employ heavy casing in the Silverpit Formation, where, in many of the early development wells, there has been widespread occurrence of casing crimps or collapse as a result of movement in the Rotliegend salts.

The production histories of some of the early Carboniferous fields reflect all these uncertainties and technical issues. Field performance has varied widely, with large divergences between predicted recoverable volumes and actual performance (Table 2). Without access to detailed sub-surface and production data any analysis of this variation is speculative, but some general trends emerge, by inference mainly related to issues of reservoir connectivity. Fields relying on the Murdoch reservoir have performed more or less as predicted, reflecting the laterally extensive sheet-like nature of this unit, where developed (Conway & Valvatne 2003b; Cameron *et al.* 2005). Fields having reservoirs in the Ketch Formation have, by contrast, shown highly variable performances, the Boulton B and Murdoch K fields having produced about twice their published estimated recoverable volumes with two and one development wells respectively, while the Schooner Field has managed less than half with 11 development wells (Figures 15a, 15b). Some fields producing from the Namurian (Trent, Cavendish) appear to have produced more than their initial GIIP, suggesting drainage from surrounding reservoir sections that were not initially considered as part of the net reservoir. A final example – the Watt Field – marks the only attempt to date to develop a reservoir in the Cleaver Formation. Although the sand bodies in this unit look sedimentologically similar to those in the Ketch Formation, the Cleaver clearly has a much lower net-to-gross ratio and lacks large-scale connectivity. The Watt development accordingly failed after draining a very restricted volume of gas.

The widely varying performances of the Ketch Formation reservoirs deserve further comment. In Schooner, increased understanding of the reservoir geology during the long development history has led to a downgrading by the present operator of the GIIP from the published 1059 BCF (Moscariello 2003) to 654 BCF (Faroe Petroleum, private communication). The disparity between estimated and actual recovery in the Ketch reservoir reflects the difficulty of extrapolating and averaging net-to-gross ratios in fluvial deposits, and the much better than assumed connectivity between fluvial channel sand bodies. In the Boulton B and Murdoch K cases, better than assumed connectivity in a fairly high net-to-gross, more proximal position in the Ketch depositional system has been a positive feature, allowing ready access to all of the gas in the accumulation from a small number of wells. Schooner, by contrast, is located in a more distal position in the depositional system and has lower net-to-gross (Stone & Moscariello 1999). Here, the large well count results in part from major problems of well stability and scale development, but reservoir connectivity has also been an important factor. The assumptions made regarding sedimentological compartmentalisation (*cf.* Mijnssen 1997) proved to be ill-founded, successive development wells encountering progressively more depleted reservoir, even when located far from the initial core production area. It is not clear whether the greater than anticipated connectivity in this case is the result of sedimentological / stratigraphic juxtapositions of sand bodies, or of greater than anticipated fault juxtaposition. It was known at the time of the initial development that 3D seismic revealed a much greater degree of minor faulting than was initially apparent from the 2D surveys on which the first generation of Carboniferous discoveries had been initially mapped (Oudmeyer & de Jager 1993). More recent studies in the Yorkshire mining area in the UK onshore (Bailey *et al.* 2002) have shown that sub-seismic faulting is likely to bring about complete connectivity in channelized sandstone bodies in the Coal Measure succession in that area, so, in retrospect, it is likely that early assumptions regarding sedimentological heterogeneity were overplayed.

Taken overall, all of the Carboniferous fields show initially rapid rate declines followed by long tails in which production remains more or less steady over a period of years (Figure 15). This pattern replicates that seen in Palaeozoic-reservoired oil fields in the Central North Sea (Argyll, Buchan) where rapid early decline has been followed by much longer than anticipated periods of low but consistent flow rates reflecting slow depletion of a labyrinthine reservoir of generally low permeability.

Understanding the Carboniferous petroleum system: recognising and challenging the Founding Myths

The understanding of the petroleum geology of a basin or sub-basin involves the collation of lines of evidence to formulate a play concept that acts as the basis for continuing exploration. Plays thus defined exhibit diminishing returns, usually expressed through the creaming curve, unless new ideas come forward (the "paradigm shifts" of Kuhn 1962) to allow new insights and rejuvenate exploration through the identification of new play fairways.

The Carboniferous play in the Southern North Sea is no exception to this generalisation, but, through a combination of circumstances, the paradigm shifts that might allow innovative thinking have not occurred. As a result, attitudes to the petroleum geology have stagnated. In this section I examine five fundamental areas of Carboniferous petroleum geology which merit re-examination. Attitudes in these areas have largely remained frozen in time since the early days of exploration of the Carboniferous fairway. I here refer to them as the "Founding Myths" of North Sea Carboniferous geology, in reference to their resemblance to the immutable accounts found in traditional societies that describe the absolute truth about events that made the natural world the way it is (*cf*. Eliade 1975 p. 23).

Founding Myth 1: "The gas comes from Westphalian coals"

From very early in the exploration and development of the Southern North Sea basin it has been generally accepted that the gas in Rotliegend and younger reservoirs is derived from the coals in the Westphalian. This interpretation was first articulated by Patijn (1964) and has since been repeated without question in all general accounts of the petroleum system in the basin (*e.g.* Glennie 1998: p 140). It is not difficult to see why this interpretation has been so widely accepted. Cornford (1998: pp. 428-430) summarises the coal thicknesses and published maturities in the Westphalian, and it is obvious from source rock/ reservoir mass balance calculations that the known volumes of reservoired gas represent only a fraction of the total gas volume that has been potentially generated. Thus, although other sourcing possibilities have been identified (*e.g.* in Cornford *op. cit.*), the Westphalian is still cited as the dominant source (*e.g.* de Jager & Geluk 2007), even in areas requiring long and improbable migration paths (*e.g.* Rodriguez *et al*. 2014).

Two features of the gas occurrences do, however, suggest that the pattern of gas sourcing is more complex, or even that in many areas the assumption of sourcing from Westphalian coals is incorrect.

Maturity patterns

Published maturity data for Carboniferous source rocks in the UK are sparse, with large areas – notably the Carboniferous heartland in Quadrants 44 and 49 – having no published data. Data that have been published are scattered through a wide variety of literature sources, with much data, while nominally in the public domain, having hitherto been difficult to access. Where data have been published, for instance in the Southern Permian Basin Atlas (Kombrink *et al.* 2010) or for the reference well 48/3-3 (Leeder *et al.* 1990: see Figure 7a), they may be difficult to interpret, either comprising only a very small number of data points, covering a very limited depth range, or lacking accompanying information on data quality. In the Netherlands the situation is quite different, the data release policy being such that vitrinite reflectance and pyrolysis data for a large number of released wells are in the public domain and can be freely downloaded from the Netherland Geological Survey portal (www.nlog.nl; *e.g.* Fermont & Jegers 1991). This source does not always contain information on the quality of the data quality, some of which is clearly poor.

Pending availability of more complete data of better quality a degree of caution is required in interpreting patterns of Carboniferous maturity from vitrinite reflectance data.

1) Vitrinites in the Carboniferous can be divided into at least three populations (Figure 16a): so-called 'low-reflectance vitrinite', *in-situ* vitrinite, and semi-fusinite or partially oxidised vitrinite. The first of these may be related to the presence of liptinitic maceral components in coal source material (Murchison & Pearson 2000, Murchison 2004), but may also simply result from caving. The third is the result of penecontemporaneous oxidation, possibly associated with reworking. Clearly only data from the second population can contribute to correct modelling of maturity. Unless vitrinite types are explicitly identified the apparent maturation profiles obtained may be confusing or misleading (*e.g.* Figure 16b).
2) Vitrinite reflectance is a subjective measurement and there is variability between laboratories and interpreters (Figure 16c).
3) Some workers claim that there are marked differences in maturation gradient between different parts of the depositional area which are interpreted to result from prolonged differences in thermal gradient (Creaney *et al.* 1985; Murchison 2004). These are generally believed to relate to residual heat flow derived from Devonian granite masses underlying the basement highs that flank the early Carboniferous rift depocentres. The presence of clearly defined differences in maturation gradient in wells that are not obviously near any of the mapped granite bodies (Figure 16d) suggests that this explanation may be simplistic, although there might be a link to the position relative to the rift depocentres.
4) The maturities developed in vitrinites in coal seams may be significantly affected by the overlying lithology: sandstone seam roofs, having a higher thermal conductivity, give rise to a lowering of maturity relative to that developed in seams with shale roofs (Murchison 2004). While this should average out over long stratigraphic sections it is another potential cause of inaccuracy in limited datasets, although possibly be within the noise of the calibration measurements employed. Assumptions regarding lithology of overburden sections removed by erosion can have major effects on the outcomes of maturity modelling (Pearson & Russell 2000).
5) In an extensive study in the Ruhr coalfield there is a consistent mismatch between reflectance results obtained from coal and those obtained from dispersed vitrinite in clastic sediments, the latter consistently showing lower reflectances, particularly in the oil window (Scheidt & Littke 1994). These authors ascribe this to a combination of differences in diagenetic reactions affecting the vitrinite within or outside the coal seam, and to differences in quality of the reflectance measurement controlled by the lower availability of ideal material for measurement in dispersed vitrinite samples.
6) There are widespread occurrences of a suite of tholeiitic basalt intrusions of latest Carboniferous age, known at outcrop and in wells in northern England, where they form the Whin Sill and

Causey Dyke complexes, and in wells in Quadrant E in the Netherlands. These have major thermal anomalies associated with them (Pearson 1988, Ridd *et al.* 1970; Figure 16e).

7) Where good quality data are available, the vitrinite reflectance profiles clearly demonstrate the effects of the Cenozoic uplift already alluded to (Figure 16f).

Any or all of these factors need to be considered in interpreting reflectance profiles. In particular, it may be difficult to identify which, if any, points in a small data set are anomalous, particularly if: a) there is no quality control report; b) the data are limited to a small vertical interval; c) the data are sparse and / or widely separated; or d) the data are derived from immediately below the base Permian unconformity.

A number of sub-regional and regional maps have been published showing maturity at top Carboniferous (Cope 1986; Leeder & Hardman 1990; Bailey *et al.* 1993; Kombrink *et al.* 2010). All concur in showing that, at subcrop, the Carboniferous is at best marginally mature for gas generation in most areas, and that many gas fields occur in areas where the Westphalian is either immature or absent (Figure 17). Clearly charge in these cases is derived from deeper horizons within the Carboniferous, which have always been assumed to be coals in lower parts of the Westphalian. Where reasonable maturity data are in the public domain it is by no means certain that this is the case. Thus, the map of maturity at the Westphalian A/B boundary in the Netherlands published by TNO (available from www.nlog.nl) shows marginal maturity at depth within the main part of the coal-bearing succession; and the distribution of migrated gas in the Gainsborough Trough area (UK onshore) is clearly incompatible with a Westphalian source (Figure 18). Where Rotliegend sandstones containing gas fields occur above immature Carboniferous source rocks (for instance in the southern part of the Sole Pit area, UK Quadrant 48 – Figure 17) this can satisfactorily be explained by remigration within the Rotliegend (see discussion above). However, to charge a field such as Breagh from a Westphalian source in the absence of Rotliegend sandstones involves an improbably complex migration path.

Isotope data

To obtain a better understanding of the origins of gases throughout the North West European Basin, a collaborative research project was undertaken in the mid 1990's by the Geological Surveys of the UK, the Netherlands, Germany, Denmark and Poland, which included the compilation of a large set of gas isotope data ("Northwest European Gas Atlas": Gerling *et al.* 1998; Lokhorst 1998). Among the data collected, measurements of carbon isotope ratios in co-occurring methane and ethane allow identification of both source rock type and source rock maturity, using the method of Berner & Faber (1996). As the investigators were expecting to confirm the Westphalian coal origin of the gases, the diversity of the results came as a considerable surprise (Gerling *et al.* 1998: p. 223). These unexpected results do not appear to be of unreliable quality or anomalous. While the exact provenance of the individual gas samples remains confidential, the number of samples analysed is such as to preclude experimental error (P. Gerling, personal communication 2016). The reliability of the data is confirmed by an independently generated duplicate data set from the UK sector only (Figure 19d).

In the following discussion of the isotope results the conclusions of the authors cited above are taken at face value. It should, however, be stated in advance that the interpretation of such isotopic results should be attempted with caution. Berner & Faber (1996) recognise that the quality of any relationship between hydrocarbon and source depends on the correct specification of the bulk δ13C value in the source organic material, which is unknown in this case. For humic source rocks their calibration below maturities of 1.5% Ro is based, in the absence of any experimental data, on an extrapolation of experimental results from source material of higher maturity, backed up by empirical observations of gas isotope compositions. They are at pains to point out that generation of methane at maturities lower than 1.5% Ro involves several reactions that may give rise to inhomogeneity in isotope content. This may in part reflect the different mechanisms involved in methane formation in sapropelic and humic source material (breakage of C-C bonds in the former, condensation of aromatic rings in the latter – Galimov 2006). The approach adopted by Berner & Faber (1996) is strongly criticised by Galimov (*op. cit*: p. 1238) on the grounds that it relies on the incorrect assumption that laboratory pyrolysis results can be used as a proxy for maturation processes occurring in natural systems.

In the area in and around the Southern North Sea three populations of gas can be identified in the Northwest European Gas Atlas data. Population 1 (Figure 19a) comprises gases from Rotliegend and Carboniferous reservoirs in the UK and Netherlands offshore areas: here gases uniformly indicate predominant derivation from marine sapropelic source rocks at maturities of $\%R_o$ between 1.6 and 2.5. Population 2 (Figure 19b) comprises gases from Rotliegend and Carboniferous reservoirs in the Netherlands onshore, having a gas composition indicative of a mixture of humic and marine sapropelic sources: here maturities in the sapropelic source appear somewhat higher ($\%R_{o\,=}$ 2.0 to 2.5) with admixed gas from the coal source suggesting generally lower maturity ($\%R_o$ = 0.8 to 1.6). The gases in population 3 (Figure 19c) are from Rotliegend reservoirs in the North German Plain, showing derivation from humic source rocks at generally higher maturities ($\%R_o$ consistently > 1.6).

Although presented at a conference in London in 1998 and subsequently published in a widely circulated book (Gerling *et al.* 1999) the two radical implications of these results have yet to be fully appreciated.

1) Most if not all of the gas discovered in the offshore area of the Southern North Sea (Population 1) is not derived from the Westphalian Coal Measures, but must instead be sourced from the marine shales in the Namurian and possibly Lower Carboniferous (equivalents of the Upper and Lower Bowland Shale of the UK onshore area and Geverik Member in the Netherlands). This is exactly consistent with the inferences that can be made in the UK Gainsborough Trough (Figure 18) and with the situation in the Breagh Field where basal Namurian shales accompanied by strong gas shows are encountered in the maturity range $\%R_o$ 1.3 to 1.42 in well 42/16-1 located 35 km downflank of the structure to the SW (Geolab UK, 1994). Moving eastwards, the gases in the Netherlands onshore (Population 2) appear to comprise a mixture of gas derived from a high maturity (= more deeply buried) Namurian marine source rock and less deeply buried, presumably Westphalian coals. Only in areas of much deeper Mesozoic burial in the North German onshore do the Westphalian coals appear be the dominant source of migrated gas: this corresponds to areas of deeper burial in which the earlier Carboniferous marine shales are post-mature (Teichmüller *et al.* 1979), and is consistent with the higher nitrogen contents of gases in these areas.
2) In almost no cases have any of the reservoired gases apparently been derived from source rocks in the early to middle parts of the conventionally accepted gas window. The generation window for gas in the Southern North Sea has generally been taken between $\%R_o = \pm$ 1.1 and $\%R_o = \pm$ 2.0. The isotope results suggest that these thresholds are misleading for Carboniferous coals in the Southern North Sea: this question is further discussed below.

Source rock distribution and play fairways

If it is the case that most Southern North Sea gas is derived from Lower Carboniferous and Namurian basinal shales rather than from Westphalian coals the entire understanding of the Southern North Sea petroleum systems needs revision. The area of potential source rock development is larger (see subcrop map in Figure 17). The distribution of effective source rocks is no longer a question of preserved subcrop, but instead will rely on much better understanding of stratigraphic relationships and basin architecture *within* the Carboniferous succession. Whereas previously source presence and effectiveness has not been regarded as a high risk, it becomes necessary to map intra Carboniferous horizons at a regional scale, and to define exploration play fairways that relate to both source rock presence (from mapping facies relationships), source rock quality and maturity within individual source-prone stratigraphic units.

The question of stratigraphic distribution of potential source rocks other than the Westphalian coals remains insufficiently studied. Lateral facies relationships in the onshore area demonstrate a northern limit to basinal shales in the Namurian (*e.g.* Fraser & Gawthorpe 2003) which can be replicated in parts of the offshore area where there are well penetrations (Figure 20). However, in the majority of the main gas-bearing parts of the offshore area there are no wells that penetrate enough of the Namurian to allow such mapping. Coal seams have a wide distribution in the coeval shallow water facies in the basal Namurian and underlying Asbian to Brigantian in the Mid North Sea High and the northern parts of Quadrants 41 to 44 (Yoredale and Scremerston Formations of Cameron 1993), but the detail of the succession onshore shows significant changes in facies and thickness (*e.g.* Trueman 1954: pp. 293-297) that are glossed over in Cameron's unilateral extension of the onshore lithostratigraphy into the offshore area. The extent of these coals, particularly in Quadrants 41 to 44 cannot be taken for granted. The shallow water facies of the Asbian to Alportian is also known to contain oil shales, some of which are geographically widespread (Archer 1926; Carruthers *et al.* 1927, 1932; Trueman 1954: p. 295): these have not been systematically documented or studied but have the potential to act as sources of both oil and gas if locally developed in sufficient volume (Powell *et al.* 1976). Although the Asbian to Pendleian succession in northern Northumberland appears to contain few and thin oil shales, it should be borne in mind that the rich oil shales in the succession of the same age in Scotland were developed in an aerially restricted sub-basin of only some 40 x 20 km extent, bounded by a combination of volcanic topography and syn-depositional extensional faulting (Loftus & Greensmith 1988). The perceived scarcity of oil shale facies in Northumberland cannot be taken as evidence for their absence in the sparsely drilled areas of the Mid North Sea High or deeper sections that have not yet been penetrated by the drill bit in Quadrants 41 to 44.

The final and unanswered question concerns the possibility of an effective source in the deeper part of the Lower Carboniferous. Such a source, if present, has the potentially widest geographical distribution of any source rock and the best potential for maturation. It would also underlie, and potentially charge, the widespread sandstone reservoirs in the Chadian to Holkerian Fell Sandstone Formation. The possibility of such a source is hinted at by the occurrence of reservoired gas in the Fell Sandstone in the Northumberland Trough (UK onshore well Errington-1, communicated in presentation given by Parsons & Trythall 2015). These authors suggested sourcing of this gas from coals in the stratigraphically overlying Scremerston Formation, but this seems unlikely in view of the low maturities reported at outcrop (%R_o = 0.7 in Namurian coal at outcrop 6 km to NW – Burnett 1987; %R_o = 1.0 reported at 610 metres depth in the Stonehaugh Borehole 19 km to NW - Scott & Colter 1987). These shows must be sourced from deeper horizons in the Visean or Tournaisian, sections that have largely been regarded as devoid of source material on the basis of a few well penetrations in UK Quadrants 41 and 44. Some encouragement may be offered by the presence of coaly material accompanied by gas shows in the deepest section, of Arundian to Holkerian age, penetrated at the western, most marine influenced end of the Northumberland Trough in well West Newton-1 (OGA released well data). The dominance of more terrestrial environments in the pre-Asbian succession on the eastern end of the Northumberland Trough might be taken to imply a lower probability of source rock development in this interval; however, coal and mudrocks with moderate TOC contents are recorded in the Chadian to lower Holkerian Cementstone Formation just above TD in well 41/10-1 (operator's well completion report released by UK OGA; Gent 2015). The occurrence of bitumen throughout the pre-Asbian section penetrated in the Seal Sands borehole (Johnson *et al.* 2011) also requires a deeper, pre-Scremerston source rock.

The "missing gas" problem

As well as revealing the unexpected patterns of gas sourcing, the isotope data discussed above raise a significant problem. There appears to be little or no reservoired gas in the Southern North Sea or Netherlands onshore area that has been sourced from coals or disseminated terrestrial material in the lower part of the conventionally accepted peak gas generation window (%R_o = 1.2 to 1.6). This is despite the presence of very large volumes of coal in the Westphalian that must be in this maturity window, which conventional wisdom would dictate to be a volumetrically overwhelming source of gas.

Unlike the oil source rocks of the central and northern North Sea, in which every aspect of the primary hydrocarbon expulsion mechanism has been intensely studied (see summary in Cornford 1998: pp. 410-414), the conventional oil industry has paid little attention to the processes by which gas is generated in and expelled from the coal seams and associated organic matter in the Carboniferous. This makes it difficult to fully analyse the "missing gas" problem. However, a number of preliminary suggestions can be made.

1) As has already been mentioned, the basic assumptions underlying the interpretation of the dominance of sapropelic source material may be incorrect. Berner & Faber's (1996) maturation trend for humic source materials below maturities of Ro = 1.5 is extrapolated, albeit with empirical supporting evidence. The true maturation trend, in combination with different assumptions regarding the initial dC13 composition of the organic matter, might bring the isotopic ratios of gases derived from coals at low maturities closer to those of sapropel-derived gas.
2) The underlying assumption still remains that the gas is derived from the bedded coals in the succession, and that those coals are dominantly humic in composition. The reality is that both the make-up and distribution of source material in the Westphalian is much more diverse. Coals of this age in the UK onshore have a wide range of compositions, in many cases containing significant volumes of oil-prone algal and cuticle material (*e.g.* BCURA 2002). These occur both within the main body of a coal seam dominated by humic material (see *e.g.* Smith 1965), and in intimately associated units of cannel coal and boghead coal formed by the accumulation of algal material in lakes and pools associated with the coal swamp (Sullivan 1959). Leaving the bedded coals aside, Gent *et al* (2015) identify thick units (up to 15 metres) of mudrocks having TOC of 2 -4% in the Westphalian A and upper parts of the Namurian. Evidence from the UK onshore suggests these may correspond either to the fairly abundant Marine Bands known at these levels, or to lacustrine oil- shales that have localised occurrences throughout the English coalfields (*e.g.* Flintshire, North

Staffordshire – Giffard 1938). It is thus likely that maturation of a typical Westphalian succession in the conventional early to peak gas window Ro = 1.1 to 1.6) will generate gas from both humic and sapropelic sources. Because of the differences in expulsion efficiency between bedded coals and sapropelic material disseminated in shale (Pepper & Corvi 1995) the sapropel-sourced gas may dominate in the expelled and migrated product.

3) Most burial history models for the Carboniferous succession in the Southern North Sea assume limited overburden removal during Variscan inversion (Figure 7a and b), and the onset of significant gas expulsion at the lower threshold of the generally accepted 'gas window' of %Ro > 1.1 or 1.2. As a result it is generally believed that the onset of gas generation postdates Variscan uplift. However, both of these assumptions are open to question, and it may be postulated that the generative capacity of the coal seams has been impaired by an early phase of gas loss associated with pre-Variscan burial and Variscan inversion.

Generation and expulsion of gas from coal seams commences at maturity levels significantly below the lower threshold of the generally accepted 'gas window' of $\%R_o > 1.1$ or 1.2. Cornford (1998) places the onset of wet gas generation in humic source rocks at $\%R_o$ = c. 0.8, and the gas yield curves reported by Gaschnitz (2001) for Westphalian coals from the Ruhr coalfield show methane generation starting at levels of $\%R_o$ = c. 0.65, with the yield exceeding the sorption capacity of the coal (as defined by the curves created by Hildenbrand *et al.* 2006) at a maturity level of $\%R_o = \pm 0.8$. This implies that gas expulsion from coals starts much earlier than is generally envisaged in conventional assessments of bedded coal source rocks, as is suggested by Galimov (2006). Gaschnitz's data suggest that by the time more 'typical' gas window maturities are reached some 40% of the ultimate methane generation has already occurred.

It may therefore be suggested that, even in successions where pre-Variscan maturation failed to reach, or only just reached the 'conventional' gas window, significant amounts of gas were generated during late Carboniferous burial and expelled during Variscan uplift before the onset of the Mesozoic and Cenozoic burial that is supposed to control the present disposition of gas kitchens. This de-gassing may have impaired the generative capacity of the coals during subsequent, deeper burial. The extent of Variscan de-gassing can be assessed in the Ruhr area in Germany and the Campine Basin in Belgium, where maximum burial and maturation occurred before the Variscan uplift (Littke *et al.* 2000). Studies undertaken in these areas in the course of coal-bed methane evaluation have shown that the changes in gas sorption capacity that accompany post Variscan uplift and subsequent reburial do indeed result in significant loss of any gas generated during pre-Variscan burial (Juch *et al.* 2004; Hildenbrand *et al.* 2006). Except where in-seam migration has occurred the coals are significantly undersaturated (Hildebrand *et al.*, *op. cit*; Freudenberg *et al.* 1996), showing that no further gas generation has occurred during post-Variscan re-burial. However, it is clear from Gaschnitz's data that, even if 40% of potential gas has been lost from the coals that had reached maturities of *c.* $\%R_o = 1.1$ prior to Variscan uplift, more than enough replacement gas can be generated if post-Variscan reburial brings the coals into the higher maturity ranges ($\%R_o = 1.0 – 1.6$: see Figure 7a) that are currently found in the Southern North Sea area.

The loss of early generated gas therefore only appears to form an acceptable explanation for the "missing gas" problem if burial and maturation during the late Carboniferous were substantially greater than is currently accepted. The general acceptance that maturation and gas generation in the Westphalian coals is the result of post Variscan burial relies on burial history analysis from various parts of the basin (*e.g.* Leeder & Hardman 1990; Pearson & Russell 2000), supported by a variety of maturity indicators (AFTA, sonic velocities etc.: see review by Green 2005). The main emphasis in all of this work has been to establish the post-Variscan burial history and very little attention has been paid to the extent of late Carboniferous burial and maturation. Thus, Pearson & Russell (*op. cit.*) evaluate several different burial models for the key UK onshore calibration well Up Holland-1 (Fig. 21). One of their models ('Model A') envisages maximum burial of Carboniferous source rocks at the end of the Carboniferous or in the early Permian. In this model the maturity profile in the Carboniferous penetration is identical to that produced in their preferred model ('Model D'), which involves maximum burial during the late Cretaceous. Despite this inherent ambiguity, their preference for the model involving maximum burial in the Mesozoic was based on the occurrence of one published well section (Bardney-1: Fraser *et al.* 1990) in which the relationship of maturation gradient in both Carboniferous and post Carboniferous sediments could be observed, and the consensus established from the various AFTA studies (Bray *et al.* 1992; see also Green 2005). The Up Holland-1 study demonstrates the key failing of this assumption. Multiple burial histories can generate the same observed outcome; and no studies to date have attempted to differentiate between coals that reached a given level of maturity during Carboniferous burial that has only been equalled or very slightly exceeded following post-Variscan burial from those that have undergone the most significant portion of their maturation during a more recent phase of burial. While the second group may have reached their present maturity levels with the capacity to generate and expel significant volumes of gas, the generation potential of first may have been significantly impaired.

A possible calibration of the generally accepted burial models is provided by Creedy (1991) who summarises the many years of work done by the British Coal Corporation in their attempts to model gas occurrences as a mining hazard. His analysis of an extensive data set concludes that the current distribution of gas within the coal seams results from peak maturation having been reached before Variscan uplift, which was accompanied by significant loss of gas. Fortuitously the geological cross section in Creedy's 1991 paper passes close to the well Gainsborough-2, for which maturity indicators and modelled burial history are given by Pearson & Russell (2000). Creedy's interpretation directly contradicts Pearson and Russell's model, and suggests that, in this area at least, a burial history similar to their 'Model A' (Figure 21) would be more appropriate. Such a burial history would be compatible with the recently published maturity profile from the Kirby Misperton Field in North Yorkshire which shows a divergence in maturation gradient between the sections over- and underlying the Variscan unconformity, with a maturation leap at this interface implying maximum burial of the Carboniferous prior to Variscan uplift (Hughes *et al.* 2017).

The extent of end-Carboniferous and early Permian burial is further considered in a later section of this paper. To conclude the present section, it suffices to point out that in the adjoining East Irish Sea Basin more extensive burial history studies show that the patterns of burial history are much more diverse than is currently envisaged in the Southern North Sea area (Green *et al.* 1997). Studies of shale gas prospectivity in this area have shown that, at least in some areas, a burial history involving a high degree of burial and uplift in the late Carboniferous is appropriate (Andrews 2013: burial history analysis of wells Thistelton-1 and Hesketh-1). It is thus likely that superficially similar maturity profiles in the Carboniferous succession may have been produced by varied burial and exhumation histories, some entailing peak maturity being reached prior to Variscan inversion and others entailing a history of gas generation and migration related to post-Variscan burial. In the absence of much more extensive AFTA calibration than is presently available it is difficult to distinguish between these possibilities. It should be remembered that AFTA and other related data can only constrain the extent to which burial of Carboniferous source rocks is a function of post Variscan burial.

Why is the "missing gas problem" important? In areas where there is a demonstrably functioning source rock and migration system – that is, in all of the areas of established discoveries – it is really only of academic interest. However, future success in the Southern North Sea will involve pushing exploration beyond the existing fairways, and in particular will rely on successful identification of a play fairway sourced by the abundant coals in the upper part of the Visean and lower Namurian in the shallow water facies flanking the Mid North Sea High. If, for whatever reason, the generative capacity of these coals has been impaired by an early phase of maturation and de-gassing related to Variscan burial and inversion the prospectivity of these areas is greatly downgraded.

Founding Myth 2: "Carboniferous reservoirs are confined to channel sands"

Almost all production from Carboniferous fields in the Southern North Sea has hitherto come from fluvial channel sandstones. The reservoir quality of these sands appears to be highly variable, with significant degradation due to diagenetic clay (O'Mara *et al.* 2003a; Collinson 2005) and pre-Variscan compaction (Bailey *et al.* 1993), and variable degrees of post-depositional enhancement, possibly related to weathering beneath the base-Permian unconformity (Bailey *et al.*, *op. cit.*) and / or grain dissolution related to fluid flow events associated with fluid migration events that occurred during the Mesozoic and which are unrelated to the base Permian unconformity (Johnson *et al.* 1995). Bailey *et al.* (1993) suggest that reservoir quality decreases with increasing depth in the original stratigraphic thickness as a result of compaction, but that secondary enhancement is present in the topmost 200 metres beneath the base Permian unconformity. Without their original data it is difficult to substantiate this, but it is evident that the best quality in such supposedly enhanced reservoirs occurs in the coarsest grained deposits, and this reinforces the consensus view that effective reservoirs occur in channel sands.

The only productive reservoirs that are not interpreted as fluvial sand bodies occur in the Trent, Cavendish and Pegasus fields, where production comes from clean, quartzitic sandstones in the upper Namurian and basal Westphalian. These were originally interpreted to be the products of reworking by wave or tidal processes (O'Mara *et al.* 2003a), but recent work suggests that they may be related to diagenetic enhancement due to leaching of feldspar and clays in flow paths related to regional seals (J. Collinson, personal communication).

The dominance of channel sands can be called into question. Two aspects of petrophysical understanding and exploration concepts combine to demonstrate that a much wider range of reservoirs can be successfully developed, especially when hydraulic fracture stimulation is applied (Chiswick Field - Nesbit & Overshott 2010; Breagh Field – Sterling Resources 2016),

1) **Recognition of the extent of formation damage.** As has already been mentioned, petrophysical re-evaluation that preceded the successful appraisal of the Breagh Field demonstrated that drilling Carboniferous sections with significantly overbalanced water-based mud leads to extreme formation damage. The damage mechanism is described by McPhee *et al.* (2008), involving filtrate retention, fines migration and mud solids invasion in a pore system dominated by micropores as a result of clay diagenesis.

A quick review of a number of the wells included in the OGA public data release in early 2016 shows that drilling with a significant overbalance has been a common practice in the UK sector of the Southern North Sea. The difficulty of petrophysical interpretation in such cases (see above) and the likelihood of extreme formation damage combine to suggest that producible reservoir sections may have been overlooked in many wells in any sandstone facies. While the majority of sandstone reservoirs above mid-Namurian levels will of necessity be found in channel sandstone deposits, significant sand bodies of probable turbidite origin have been found in the lower part of the Namurian (Collinson 2005) which may form a viable exploration objective. This play has been identified by Cameron & Ziegler 1997, but not, apparently, specifically targeted in any exploration well to date, the handful of penetrations being found in deep stratigraphic tests (e.g. 42/17-2, 42/21-2).

2) **Recognition of unconventional plays.** The past decade has seen the beginning of exploration for unconventionally reservoired gas in the Carboniferous in the UK onshore area, driven by perceived similarities between British Carboniferous sections and the successful Carboniferous Barnett Shale plays in the United States. Potentially commercial discoveries have been made in the Bowland Basin, Lancashire (Clarke *et al.* in press) and in North Yorkshire, where deeper stratigraphic horizons beneath the small Namurian-reservoired Kirby Misperton Field may, if successfully stimulated and tested, contain a very large recoverable resource (Hughes *et al.* 2017). The Bowland Basin discovery is in a shale gas reservoir, which, while providing invaluable additional insights into Carboniferous petroleum systems, is not a realistic exploration target in the offshore area under current commercial conditions. The Greater Kirby Misperton discovery is, however, not a shale gas discovery: the gas is contained in a hybrid play comprising finely interbedded mudstones and naturally fractured tight siltstones and fine sandstones. The reservoir potential of these sandstones was missed in early log interpretations: their thin-bedded nature makes them invisible on conventional logs, and the failure to apply appropriate shaly sandstone methods in petrophysical evaluation led to underestimation of their porosity and overestimation of their water saturation. The sandstones have porosities of up to 10% and permeabilities in the microdarcy range. They are probably of pro-delta turbidite origin.

   Although no such accumulation has previously been developed offshore, the presence of a natural fracture system suggests an inherently greater permeability than in a pure shale gas play, while the dominance of sandstone suggests that more stable completions and longer well lives might be expected. An offshore development in such a reservoir might be feasible. A number of wells in UK Quadrants 41 and 42 have penetrated thick successions that bear a strong resemblance to, and are of roughly the same age as the newly recognised unconventional reservoirs at Kirby Misperton: at least two of these wells contain significant (± 1000 ft) gas columns.

While channel sandstones will still form the default reservoir when exploring for Carboniferous objectives, a new approach to choice of drilling fluids and practices and to petrophysical evaluation means that all Carboniferous sand bodies should in future be regarded as potential objectives. Diagenetic reservoir degradation need not preclude effective reservoir development, and hitherto unrecognised pay in thin-bedded fine-grained turbidites offers a new exploration target.

<u>Founding Myth 3: "Intra-Carboniferous seals are risky"</u>

Although shales comprise a significant proportion of all Carboniferous clastic successions their sealing potential is compromised by the silt-rich nature of most of the mudrocks deposited in proximal deltaic and alluvial plain settings (Fraser *et al.* 1990). It is assumed that effective seals are only provided by the shales deposited in marine flooding events, although these are generally only 1 – 2 metres thick and are thus vulnerable to breach by even minor faulting. In the Namurian and basal Westphalian some specific Marine Bands have been identified as effective seals (Cameron *et al.* 2005, Hodge 2003). In other cases (Cavendish field, Boulton 'F' field, Ketex discovery) the exact stratigraphic horizon of the seal is not known, although it is clear in the latter two cases that the seal must be formed by a lacustrine shale, since no Marine Band is present at the requisite stratigraphic horizon.

In only one instance has a confident evaluation of the sealing capacity of a Carboniferous shale been published. The Calow field in the UK onshore is a clearly underfilled dip-closed Variscan inversion anticline, having a structural closure in excess of 100 m and containing a gas column of 30 to 40 m (Fraser *et al.* 1990). This structure is at a very shallow depth in an area of considerable Cenozoic to Recent uplift and stress release. It may be argued that the restricted columns in this case are unlikely to be representative of the situation at depths typically encountered in the offshore area. However, the combination of this published case and generally thin nature of intra Carboniferous seals has led to a generally pessimistic view of the possibility of sealing structures within the Carboniferous succession. This may be one of the reasons why comparatively few structures that lack a base Permian closure have been drilled.

A further paradox is introduced by the fact that while shales at base Westphalian and intra-Namurian level have been demonstrated to be effective field-scale seals, there is widespread evidence for vertical migration of gas through the same stratigraphic horizons (*e.g.* isotope data cited above; empirical source to reservoir relationships in the East Midlands – Fraser and Gawthorpe 2003; Ward *et al.* 2003; Figure 18). Clearly there is more going on than simple constraints on seal capacity imposed by effective seal thickness coupled with typical fault offsets. This remains a subject area that is virtually unstudied. It is evident from coal mine gas studies in the East Midlands that migration of hydrocarbons derived from the Namurian shale source kitchens is occurring at the present day along faults (Creedy 1985: pp 238-242; Stevenson 1999). Anecdotal evidence reported by Creedy suggests that current active migration is associated with small faults rather than with larger structures, a suggestion supported both by Stevenson and by recent observations made by the author of a major gas and oil influx at Maltby Colliery, South Yorkshire. Here, inflow was associated with subsidiary Riedel Shear fractures rotated at about 35° to the major bounding faults of the Gainsborough Trough. These fractures are currently oriented normal to the current minimum horizontal *in-situ* stress (*i.e.* having orientations most likely to create open flow paths).

A model of sealing capacity for intra-Carboniferous shales must therefore take three factors into account: the thickness and capillary properties of an individual candidate shale seal; the extent and magnitude of any faulting affecting the structure; and the *in-situ* stress conditions which may dictate whether or not the faults are likely to form fluid migration conduits. The presence of the effective intra-Carboniferous top seal in the Saltfleetby field demonstrates that all three criteria can be satisfactorily achieved. It should therefore be possible to identify and map candidate seals that, in suitable structural situations, can form the sealing element of separate play fairways within the Carboniferous succession. Furthermore, the discovery of a "giant" gas column at Kirby Misperton, greatly exceeding the 1000 ft of mapped structural closure (Hughes *et al.* 2017) requires the presence of multiple seals, and may suggest some form of stratigraphic or continuous trapping that expands the spectrum of Carboniferous exploration targets.

Founding Myth 4: "Basin geometries are fully characterised"

In the past 20 years studies of the basin history of the Carboniferous in northern England have coalesced around a fairly generally accepted megatectonic framework of fault-bounded Lower Carboniferous highs separated by contemporaneous rift basins. These affect facies development far beyond the active rifting phases, continuing to control depocentre positions and sediment transport pathways well into the Westphalian as a result of minor tectonic accommodation, infill of relic topography and differential compaction. The megatectonic framework maps (Corfield *et al.* 1996, Fraser & Gawthorpe 2003) have become so familiar and so often republished that it is easy to forget that they are to a degree interpretative. Thus, for instance, the pattern of thinning and onlap in the Brigantian to Pendleian within the Alston Block is not at all as would be implied from the generally accepted map, which implies rapid northward thickening over the Ninety Fathom Fault (the northern bounding fault of the 'Block') rather than the gentle northward thickening and southward onlap actually observed (Ridd *et al.* 1970; Chadwick *et al.* 1995). In detail, it is clear that the bounding structures of the highs and lows are highly variable in style, locally consisting of a single large fault but elsewhere comprising a complex set of flexural structures and ramps (Fig. 22). The present-day expression of the structures at the land surface, or at the sub-Permian subcrop surface, is the result of their response to Variscan inversion, and does not always correspond to the position of the major structure at depth (Kimbell *et al.* 1989). Detailed understanding of these structural relationships is key to understanding sediment routing and fluid migration paths.

If the basinal geometries in the onshore area are more complex than generally envisaged, the situation in the offshore is even less clear. Here the deep geometries of the sub-basin areas are not known from drilling, and mapping of depocentres has relied entirely on seismic interpretation and gravity modelling, the latter both to locate positions of granite bodies embedded in basement highs and to delineate deep basin areas. In the UK sector many publications have recycled the offshore 'block and basin' map of Corfield *et al.* (1996), to the extent that it has effectively become the standard. There are in fact four published interpretations of the distribution of highs and basinal areas (Fig. 23). The striking feature of these is the extent of disagreement between them: even in the comparatively well-known onshore area major differences of interpretation are apparent, while in the offshore there is a lack of agreement as to the location of major basin areas, which fault systems mark major elements in the Carboniferous structural framework and whether bodies interpreted as granite-cored highs on the basis of gravity anomalies might in fact be basin depocentres.

Pointing out the differences between these interpretations does not imply any criticism: it is extremely difficult to unravel the deep structure given: a) the distorting effects of the post-Variscan succession – especially of the mobile Zechstein salt - on the pattern of gravity anomalies; and b) the difficulty in differentiating between primary data and multiples in the seismic from the deep Carboniferous basin areas (see *e.g.* Fig. 13 in Cameron & Ziegler 1997). However, the detail of the disposition of the basin segments must play a key role in controlling source and reservoir facies, source rock maturity gradients, and migration paths, especially in the less explored targets in the lower Namurian and

Lower Carboniferous. Understanding of these play elements needs improved definition of the basin geometries.

Founding Myth 5: "Basins formed in rift and sag episode(s)"

The final "myth" concerns the very fundamentals of understanding the structural and stratigraphic evolution of a sedimentary basin: the gross tectonic environment in which it formed, and the stress regimes and resulting subsidence patterns under which sedimentary accommodation space was created.

Because of the extensive stratigraphic and sedimentological work that had taken place on the Carboniferous of northern England in the 1960's and 1970's it is not surprising that these basins should have been among the first for which subsidence histories were analysed and suggestions made as to their overall plate tectonic setting following the radical changes in basin formation concepts of McKenzie (1978) among others. Leeder (1982) postulated that the 'block and basin' geometry in northern England resulted from a phase of late Devonian and early Carboniferous rifting followed by a phase of thermal relaxation, possibly accompanied by some wrench faulting, in the Namurian and Westphalian. Leeder and McMahon in a subsequent paper (1988) undertook a decompaction exercise on four areas, concluding that the Northumberland, Stainmore and Bowland Basins had formed in a phase of Visean to early Namurian extension, followed by widespread thermal subsidence in the later Namurian and Westphalian in which former highs such as the Alston 'Block' were onlapped and incorporated into the depositional area. Subsequent authors have refined this interpretation, modifying Leeder and McMahon's extension factors, which were generally perceived to be too large (Kimbell *et al.* 1989), identifying timing differences between the major extensional phases in different sub-basins (Fraser & Gawthorpe 2003), and suggesting at least local inversion related to a wrench deformation episode in the Namurian (Chadwick *et al.* 1995). These subtle modifications have not had any impact on the wholesale adoption of a model of Tournaisian – Visean rifting followed by Namurian – Westphalian thermal subsidence, which is now deeply embedded in the British literature.

It was not Leeder's intention to write the tectonic history of the British Carboniferous on tablets of stone. At the time the papers were written he was proposing hypotheses, and, in the 1988 paper it is specifically stated that "the present knowledge of basin evolution for northern Britain is at a primitive stage of development". The latter paper also identifies departures from the ideal model subsidence patterns, with accelerations of subsidence in the Westphalian in Lancashire and Durham that do not fit the simple model. At the time of these studies it was difficult to compile enough data on stratal thicknesses to analyse subsidence patterns throughout the region, and it was not always clear whether data compiled was representative of a basin as a whole, assembled as it was largely from outcrops of the inverted margins of the depocentres. The publication of more comprehensive stratigraphic sections by the British Geological Survey (summarised in Waters *et al.* 2011), together with released results of some significant deep onshore wells, allow compilation of a more extensive set of subsidence curves (Fig. 24). Although no decompaction has been carried out, the patterns are striking. The depocentres studied in Leeder & MacMahon's 1988 paper (Fig. 24a) generally show the expected rapid phase of Visean rift subsidence followed by a slowing that can be equated to a thermal relaxation phase in the Namurian: the anomalous acceleration of subsidence in the Westphalian is confirmed. However, other depocentres within the overall "Pennine Basin" rift and sag area (Fig. 24b) are dominated by accelerated subsidence in the Westphalian, with little evidence for early

Carboniferous rifting. In most cases the overall pattern of accommodation is comparable to that seen in generally accepted foreland flexure areas in South Wales (Kelling 1988) and the Ruhr Basin (Littke *et al.* 2000) (Fig. 24c).

It is not clear what is causing these varied subsidence histories in the basins to the north of the Brabant Massif. Modelling by Kombrink *et al.* (2008) eliminates the possibility that it is caused by foreland flexure, the effects of which do not extend beyond a few hundred km north of the contemporaneous thrust front. The wrench-related deformation and subsidence effects identified by Chadwick *et al.* (1995) may be of much greater importance than hitherto recognised; indeed it has been suggested that all Carboniferous basin development in northern England, and by implication the Southern North Sea, should be interpreted in terms of a long-lived regional transtensional regime (de Paola *et al.* 2005). Such a model makes it easier to integrate into a general model the highly diachronous nature of the extension events when viewed over a wider area than just the north of England. A major Namurian rifting event is inferred in the Netherlands by Kombrink *et al.* (2008); and continuation of extension into the Westphalian is described in the Central Irish Sea Basin by Maddox *et al.* (1995).

The main effect that adherence to a 'rift and sag' model for the evolution of basins in the UK area is that it has influenced the generally rather small thicknesses of late Carboniferous overburden that are assumed to have been removed by Variscan uplift. Most published burial history models for the UK area involve removal of less than 1000 metres of upper Carboniferous sediment in the Variscan deformation event (see *e.g.* Figs. 7a and b; Pearson & Russell 2000), reflecting an assumption of gradual decline in thermal subsidence with time. These amounts are clearly inconsistent with the majority of the Carboniferous basin subsidence curves illustrated in Fig. 24. The burial history plot for well 48/3-3, compiled before stratigraphic relationships in the Southern North Sea were fully understood, is not even consistent with what is now known about regional stratigraphic thicknesses. The 700 metres of removed section in Fig. 7a compares with a demonstrable removed section of 1800 metres (compilation forming Fig. 6.12 in Kombrink *et al.* 2010). This should be regarded as a minimum estimate for this area: if thicknesses of latest Westphalian D and Stephanian observed or inferred in the English Midlands are added the removed section might reach thicknesses of between 2600 and 3300 metres. End-Carboniferous burial of this extent (Fig. 25), similar to that proposed in Model 'A' by Pearson & Russell (2000) and by Andrews (2013) for wells in Lancashire, has the potential to cause significant pre-erosional maturation and provides a mechanism to explain the lack of coal-derived gas of early mature origin, identified above as the "missing gas" problem.

In Germany, where thinking has not been dominated by the 'rift and sag' model, extensive thermal, rheological and numerical modelling has led Littke *et al.* (1994, 2000) to conclude that, contrary to previous interpretations (*e.g.* Ziegler 1990), there was a widespread and thick late Westphalian and Stephanian cover in the Ruhr Basin and north west Germany, with up to 3000 metres of erosion associated with the Variscan deformation. In areas proximal to the present Variscan Front the large thickness results from flexural foreland subsidence. In more distal areas the accommodation may be interpreted to result from a complex subsidence history that includes one or two phases of latest Carboniferous and early Permian extension, with the localised formation of deep pull-apart grabens as a result of wrench faulting resulting from regional sinistral transpression (Coward 1993; Schroot & de Haan 2003). It is, however, difficult to create a convincing global interpretation as the time gap between the youngest preserved Carboniferous succession and the base of the overlying Permian is so large (at least 30 Ma), and it is known that this period encompasses a number of phases of basin formation and uplift elsewhere in the basin complex and adjacent intramontane basins (*e.g.* Roscher & Schneider 2006). A clearer understanding of the latest Carboniferous and early Permian subsidence and burial history patterns will not be obtained until detailed modelling of the type carried out by Littke *et al.* (1994, 2000) for the Ruhr Basin is undertaken throughout the UK onshore and Southern North Sea areas.

Discussion and conclusions

Fraser & Gawthorpe (2003) started their monumental 'Atlas of Carboniferous basin evolution' with the challenge: "Perhaps all we really know about the Carboniferous is no more than skimming the surface". Despite decades of research, they concluded – correctly – that a thorough integration of local and regional, surface and subsurface data would yield insights into the structure and stratigraphy of the Carboniferous that would far exceed the sum of the component parts. The same is true for the broader study of the Carboniferous as a petroleum system, or set of petroleum systems, spread across the larger area of the UK and Dutch Southern North Sea. Here, in addition to the challenges of integrating surface and subsurface data, there are the complexities introduced by complex overburden, poor imaging, significant parts of the stratigraphy having little or no well penetration, a range of data gathering problems induced by technical difficulties in drilling very deep wells, strongly differing local traditions and attitudes to geological interpretation, and language barriers. Add to these the huge stratigraphic thickness of the Carboniferous succession and it becomes less surprising that an integrated basin-wide understanding of the petroleum systems is still in its infancy.

What is evident from this review of the Founding Myths of Carboniferous geology is that the Carboniferous, far from being a single play, is made up of a number of play fairways comprising different sources, migration paths, reservoirs, seals and trap configurations. A large number of conventional prospects have been known about for some time (Cameron *et al.* 2005), but not drilled. Potential gas discoveries have probably been overlooked in the way that the Breagh Field was, owing to a combination of sub-optimal drilling practice and inadequate petrophysical evaluation. It seems almost certain that hybrid conventional / unconventional accumulations of the type found recently in the deep extension of the Kirby Misperton field are present in the offshore area, and that, if the technological and cost challenges can be overcome, these will dwarf previous Carboniferous discoveries. The challenge of effectively exploring the immense body of hydrocarbon-bearing rock is daunting, but there is no reason why, with thorough application of the basic principles of play fairway analysis, it should not be successful.

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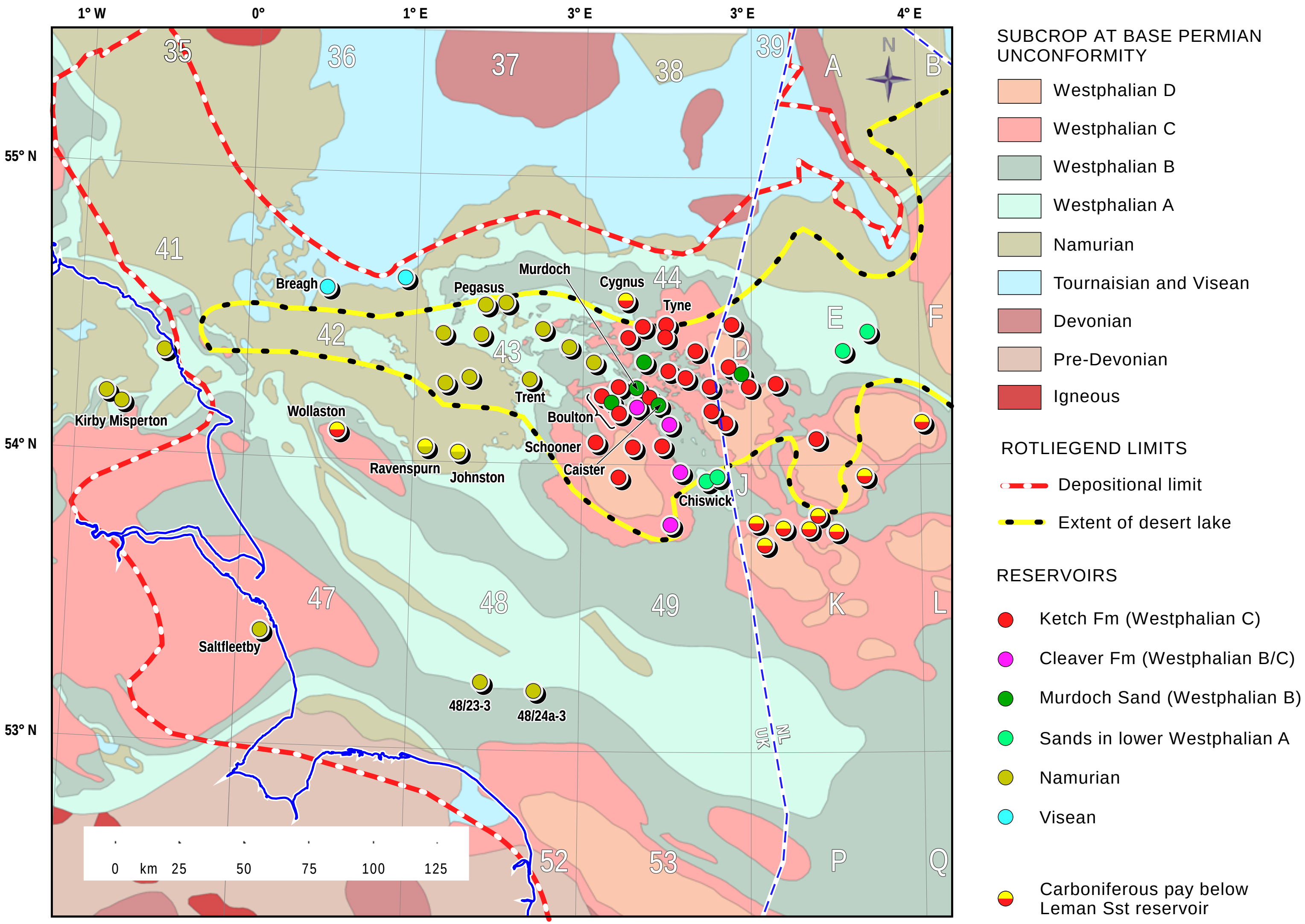


Fig. 1 Carboniferous subcrop below the base Permian unconformity in the UK Southern North Sea and adjacent areas, showing established gas fields some key discoveries in Carboniferous reservoirs and limits of Rotliegend facies belts that control the presence of a top seal at the unconformity. Named wells and fields are those mentioned in the text. Subcrop map reproduced with permission from Kombrink 2008.

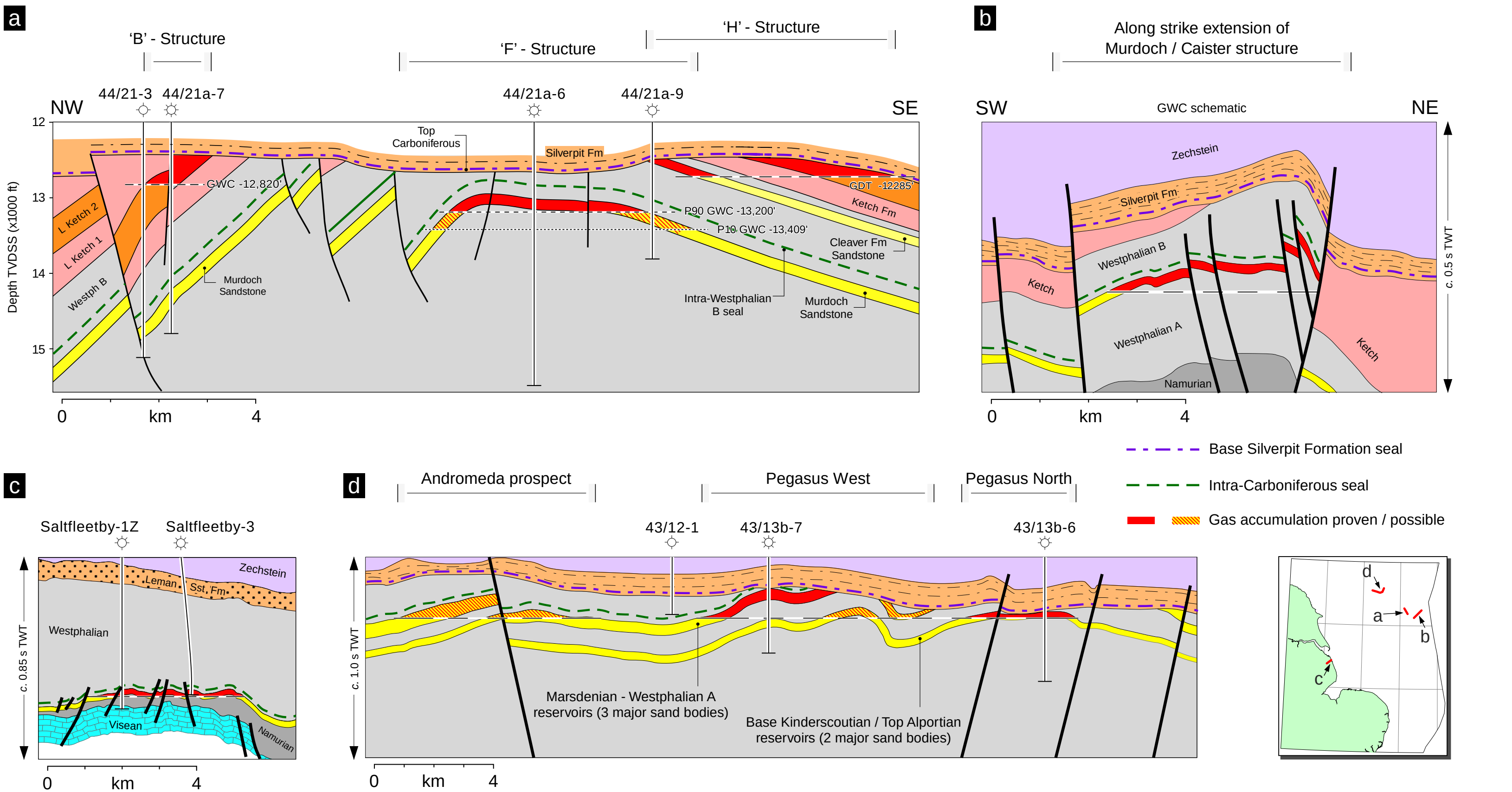


Fig. 2 Examples of Carboniferous trap configurations: a) Boulton Field - Variscan anticlinal trap, structurally modified during Mesozoic / Cenozoic transpression, containing both intra-Carboniferous dip closure (Boulton 'F') and truncation traps sealed by Silverpit Formation (Boulton 'B' and 'H'); b) Murdoch and Caister Fields – Variscan anticline modified by development of positive flower structure during Mesozoic / Cenozoic transpression, gas in Murdoch Sandstone trapped by combination of intra-Carboniferous and base Permian seals and lateral fault seal; c) Saltfleetby Field – Variscan drape fold over Lower Carboniferous footwall high, relying entirely on intra-Carboniferous (base Westphalian A) top seal; d) Pegasus Fields – set of Variscan anticlines truncated by but lacking structural closure at base Permian unconformity and reliant on combination of base Permian and intra-Carboniferous seals. Sources: a) partly after Conway & Valvatne 2003a, reproduced with permission of Petroleum Exploration Society of Great Britain; b) after Corfield et al. 1996; c) after Hodge 2003; d) adapted by permission of Centrica from presentation at DEVEX 2015

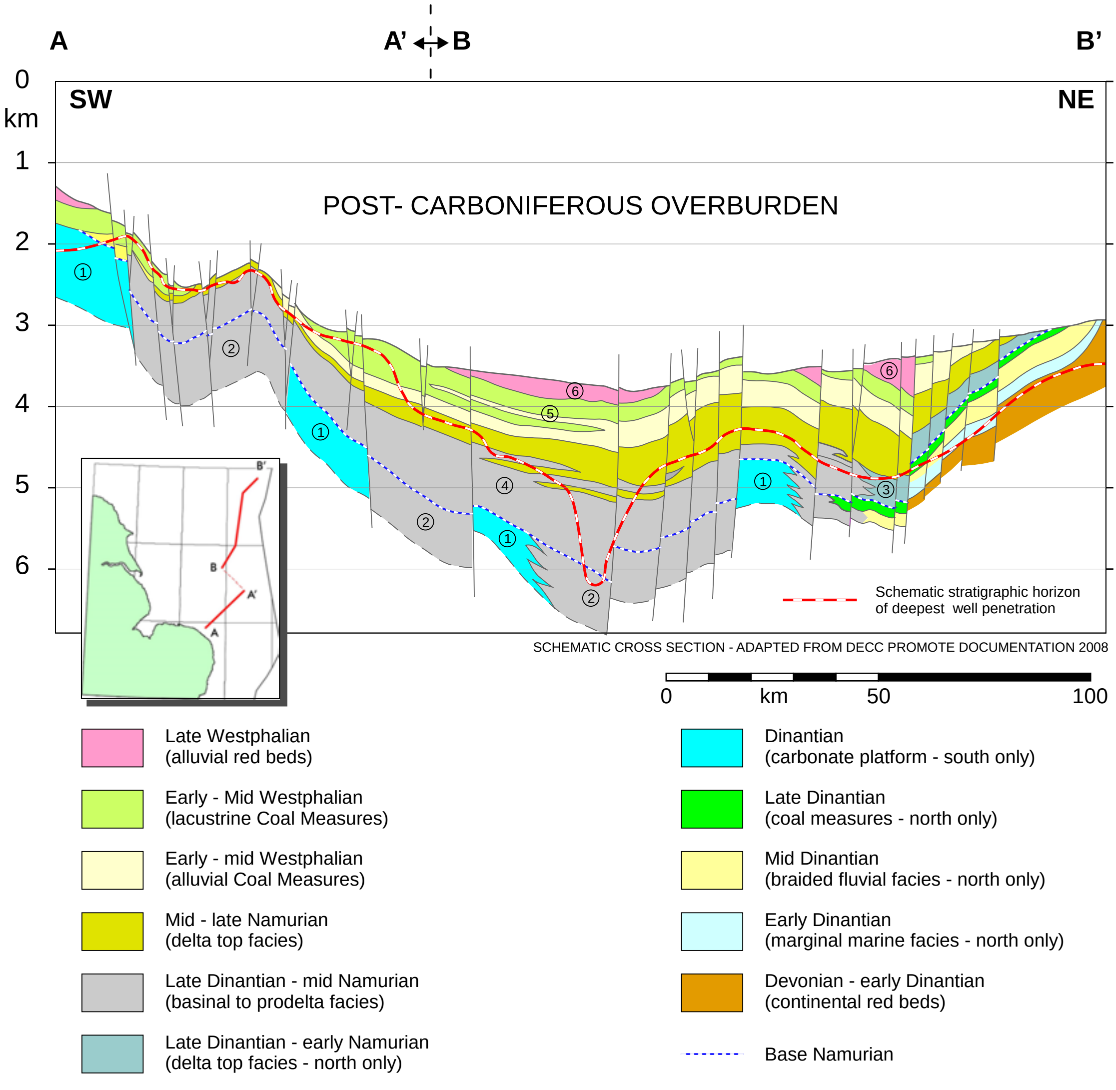


Fig. 3 Generalised stratigraphic cross-section through Carboniferous succession underlying the Permian and later fill of the Southern North Sea basin. 1) Lower Carboniferous platform carbonate facies developed at basin margins and on intra-basinal footwall highs – except in extreme south distribution is speculative. 2) Lower Carboniferous basinal facies developed in rifted depocentres – distribution speculative. 3) Exact geographical location of deep to shallow water transition in early Namurian not accurately known (see also Fig. 20). 4) Stratigraphic position of deep to shallow water transition in mid and late Namurian only locally known in a few well penetrations in Quadrant 43. 5) pronounced proximal to distal decrease in sand content in both Namurian and early to mid Westphalian from NE to SW. 6) Late Westphalian alluvial red beds restricted to inliers in cores of eroded Variscan anticlines.

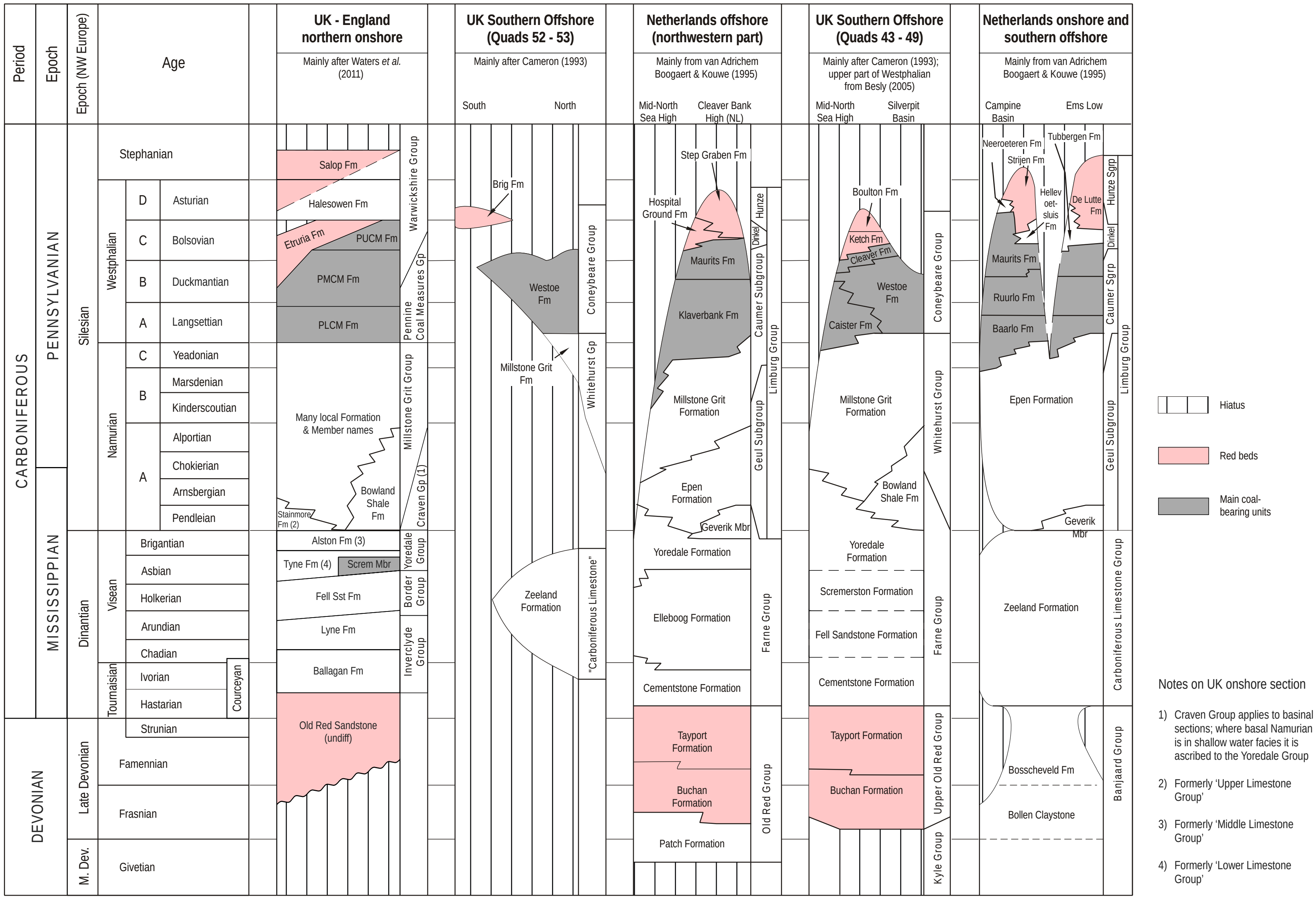


Fig. 4 Approximate summary of Group and Formation names currently employed in onshore and offshore areas of the UK and the Netherlands, illustrating the complexity and ambiguity of lithostratigraphic usage. Modified from regional correlation panel in https://www.dinoloket.nl/carboniferous, with additions and modifications as detailed in individual columns.

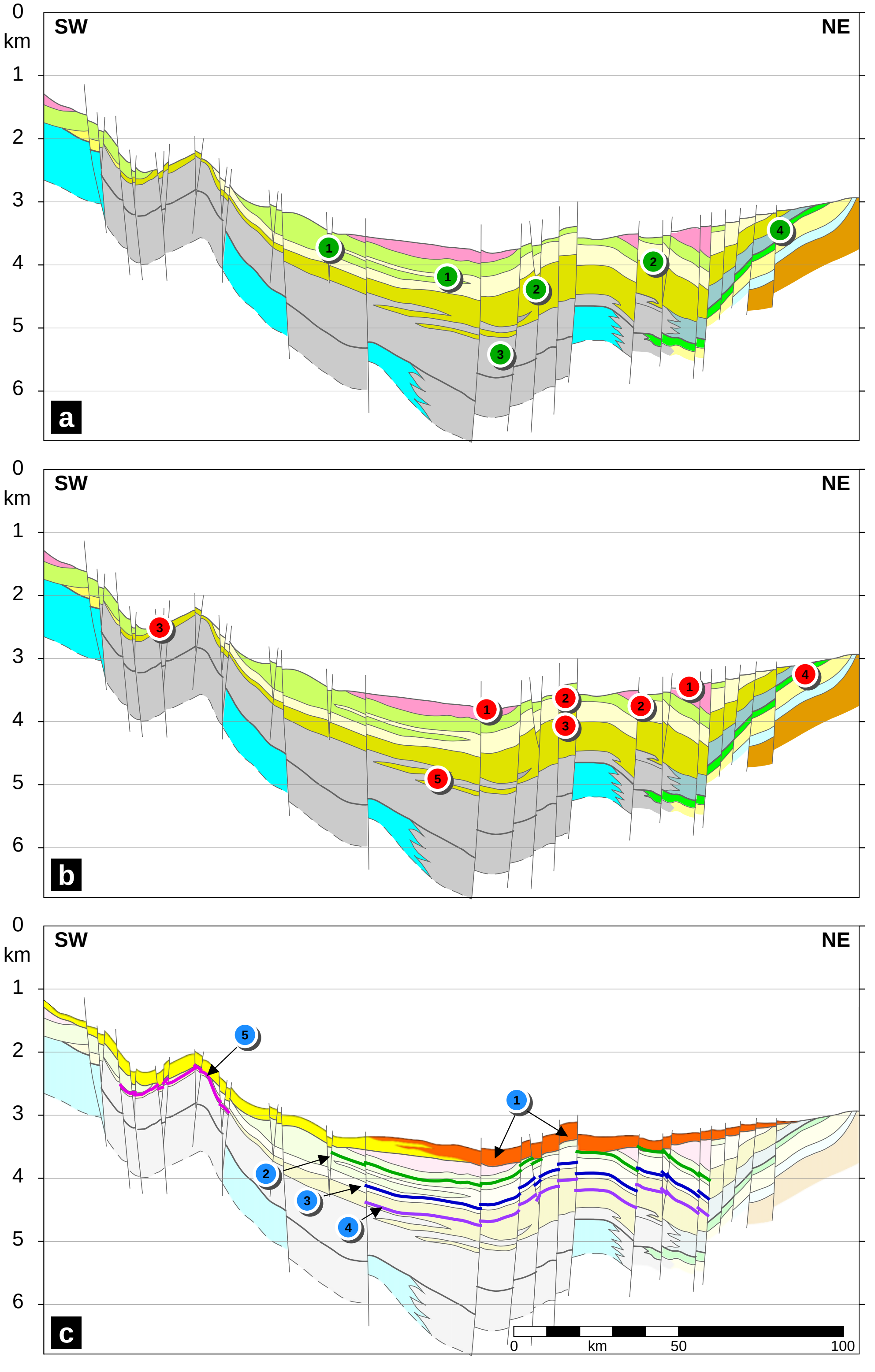


Fig. 5 Generalised stratigraphic cross section annotated with elements of the petroleum system: a) major source intervals [1 – coals and carbonaceous mudrocks in Westphalian; 2 – Minor coals and disseminated humic material in middle – upper Namurian; 3 – basinal shales in lower Namurian and Visean; 4 – coals and oil shales in Visean]; b) main reservoirs [1 – Ketch Formation; 2 – Murdoch Sandstone; 3 – Sands in Caister Formation and upper Namurian; 4 – fluvial channel sands in upper Visean; 5 – basinal facies in lower Namurian]; c) seals [1 – Sub-regional top seal formed by Rotliegend where developed in lacustrine facies of Silverpit Formation; 2, 3, 4 – mudrocks in Westphalian B (2), basal Westphalian A (3) and Alportian (4) known to form effective seals in UK Quadrants 43, 44 and 49; 5 – basal Westphalian or uppermost Namurian forming effective seal in UK Quadrant 48 and onshore]. - . Stratigraphic legend as in Figure 3. See text for further discussion.

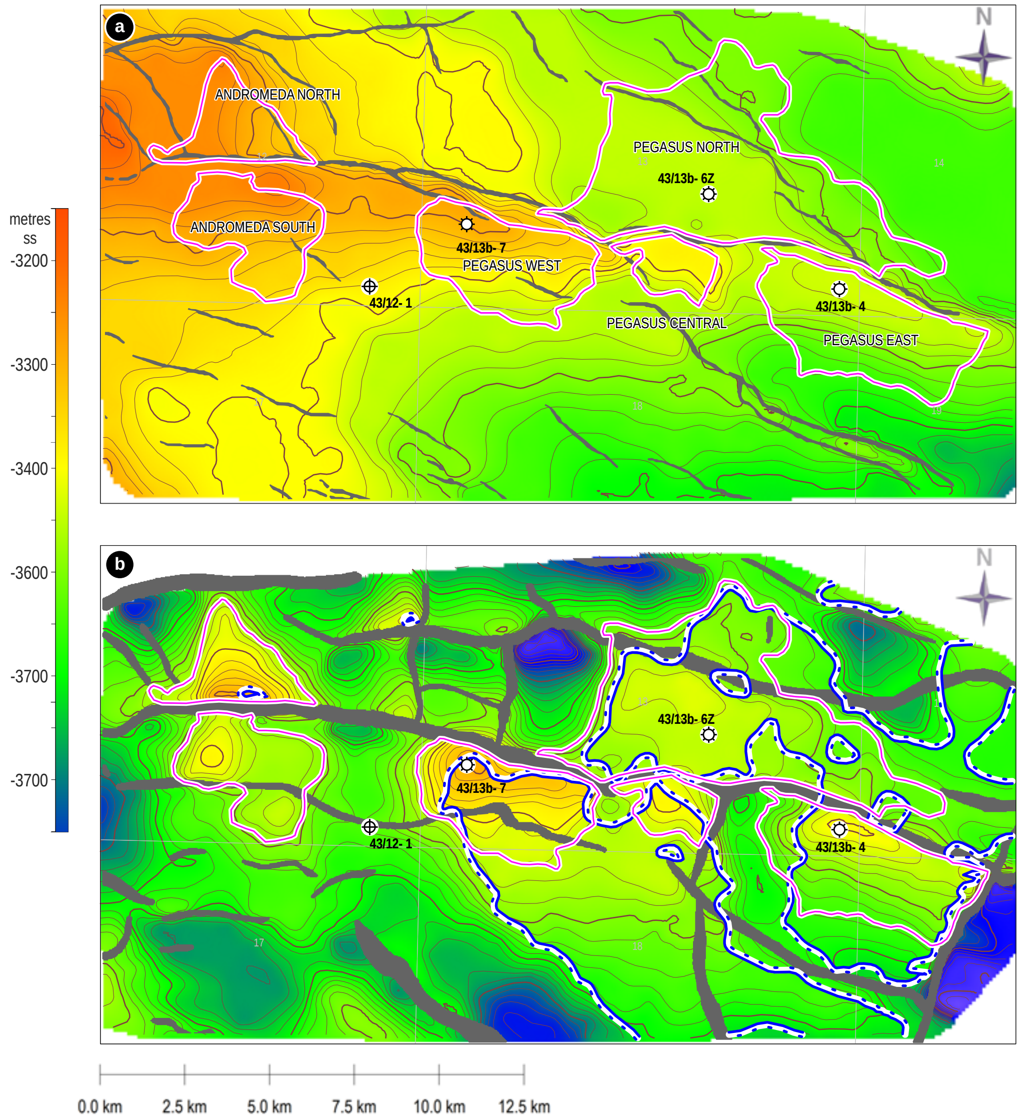


Fig. 6 Example of a gas accumulation requiring combination of base-Permian and intra-Carboniferous seals: Pegasus Field, UK block 43/13: a) base Permian depth map showing lack of closure of field and prospect outline polygons; b) top reservoir map – blue line shows subcrop of Westphalian A seal at base Permian unconformity, with ticks indicating the parts of the accumulations and prospects for which dip closure is provided by the intra-Carboniferous seal. Adapted with permission from 2016 PESGB presentation by Centrica.

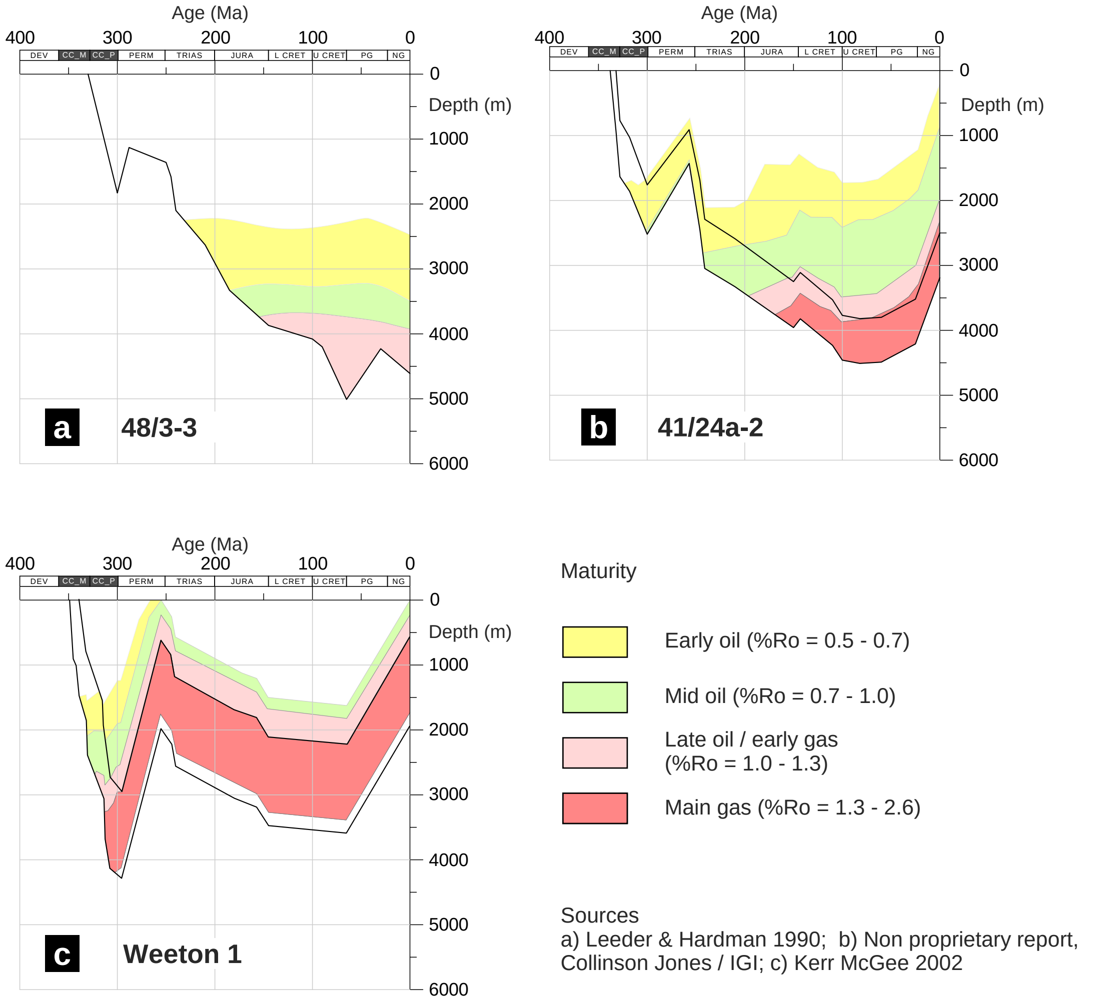


Fig. 7 Burial history plots illustrating varied maturation histories in different parts of the UK Southern North Sea and adjoining onshore areas: a) Sole Pit Basin, after Leeder & Hardman 1990; b) offshore Cleveland Basin, redrawn with permission from non-proprietary report by Collinson Jones Consultants; c) onshore Leeds Basin, after Kerr McGee 2002. CC_M - Mississippian; CC_P – Pennsylvanian. See text for discussion.

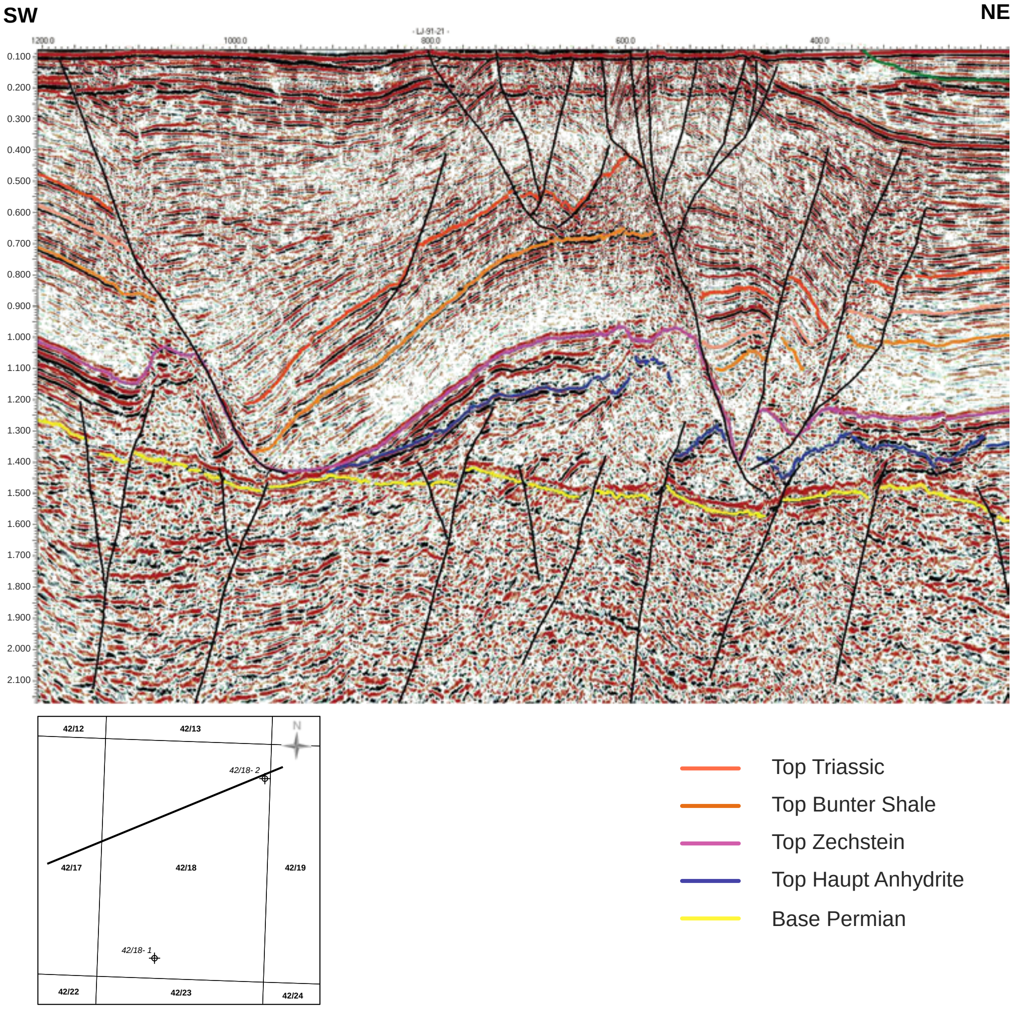
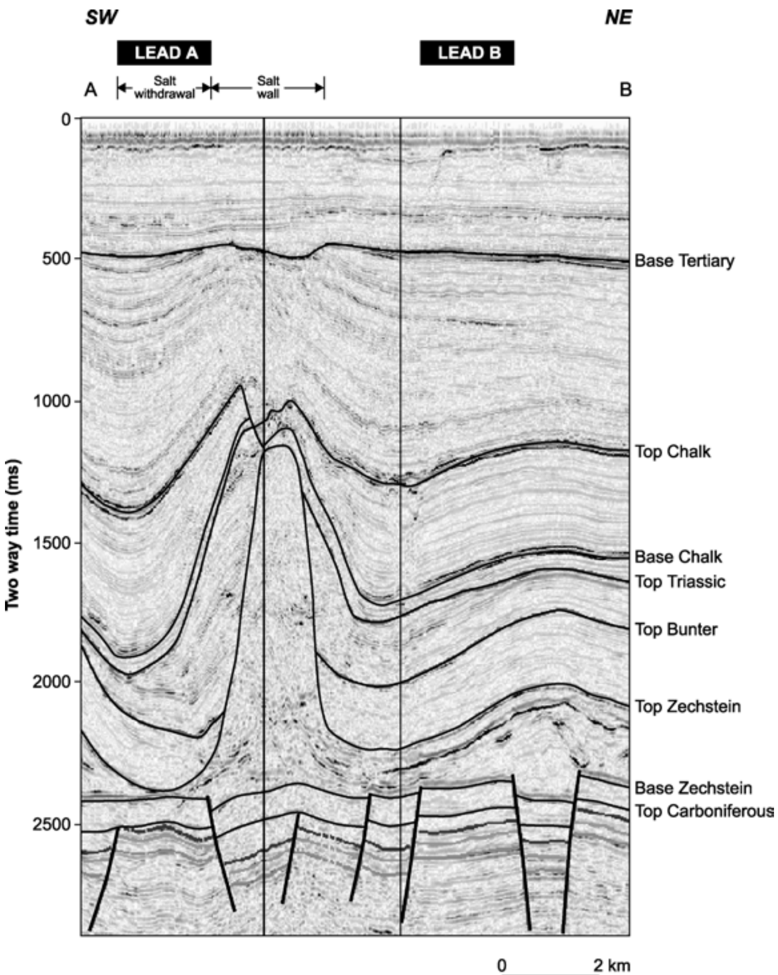
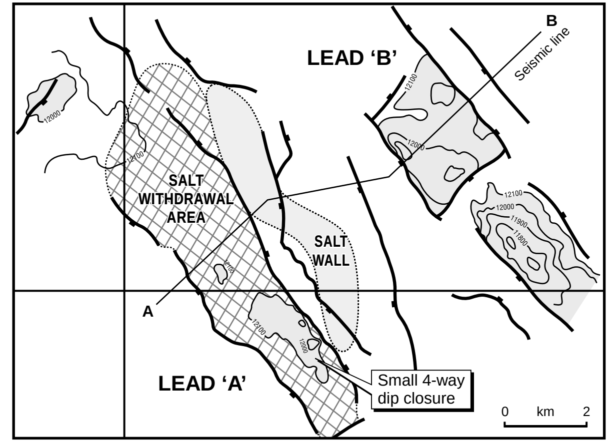


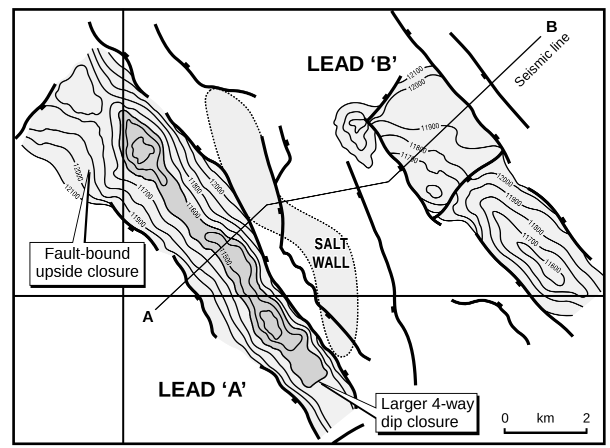
Fig. 8 Seismic line illustrating some of the problems encountered when imaging the Carboniferous beneath the complex overburden in the UK Southern North Sea. Note: faults cutting the post-Permian succession sole out in the Zechstein salt; thick localised Mesozoic sediments occupying a collapse graben immediately adjacent to a residual salt swell, producing complex lateral velocity distributions; lateral impersistence and changes in seismic character in Carboniferous associated with heterogeneity in overburden



Seismic line through salt wall and salt withdrawal areas.



Depth-conversion method 1: Top Carboniferous depth map, showing Lead A as a small four way dip-closed structure.



Depth conversion method 2: Top Carboniferous depth map, showing Lead A as a large four way dip-closed structure with upside fault-closed potential.

Fig. 9 Examples of ambiguity in structural mapping produced by alternative depth conversion methods, from Corbin et al. 2005. The location of the structures is not specified in the original publication; the Zechstein salt diapir map forming Fig. 3.30 of Pharaoh *et al.* (2010) suggests a location in the eastern part of UK Quadrant 44.

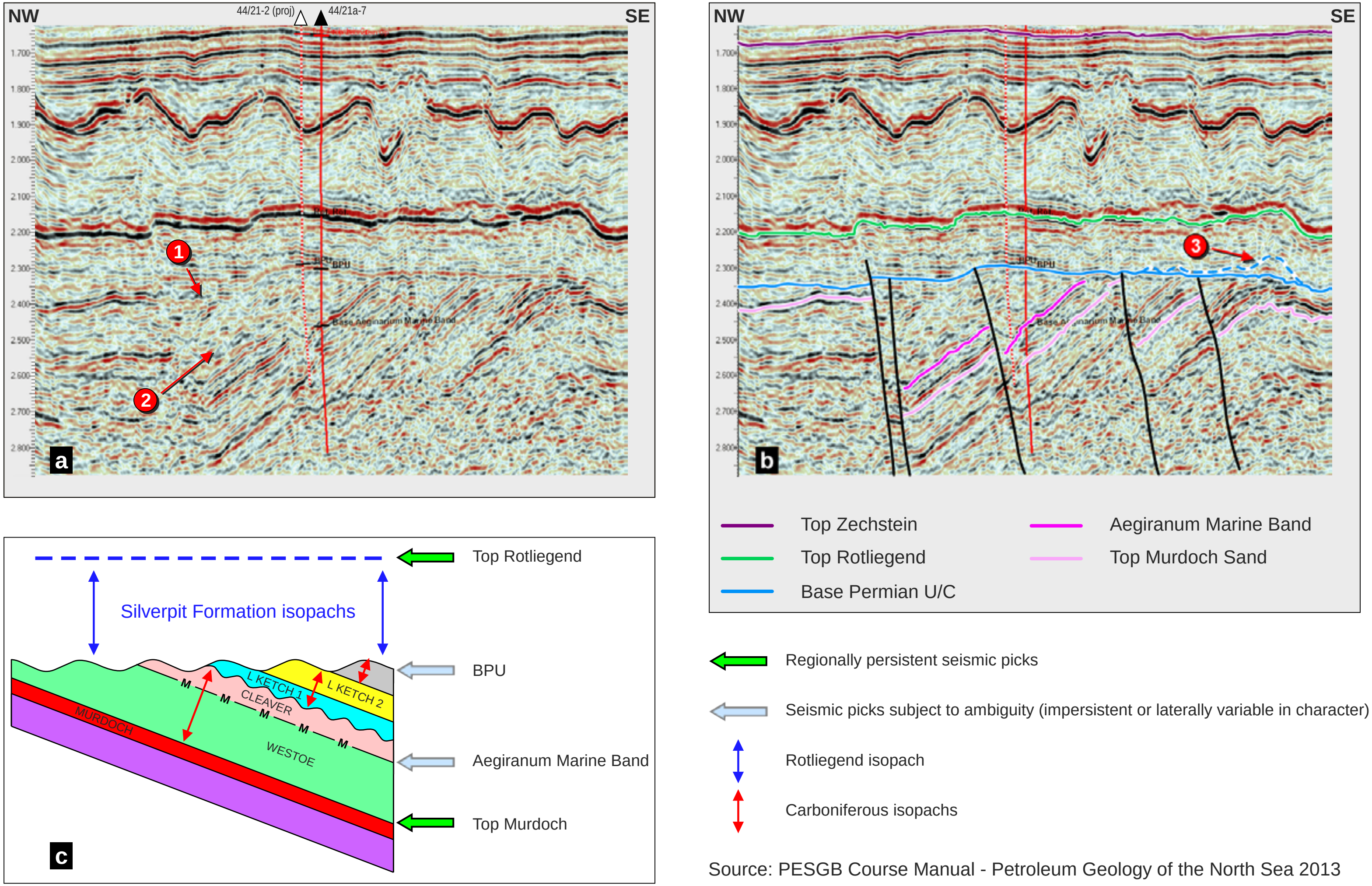


Fig. 10 Base Permian unconformity and intra-Carboniferous imaging problems: example from the Boulton 'B' Field: a) uninterpreted seismic line; b) interpreted seismic line; c) summary of isopach methods for reconstruction of base Permian geometry and mapping of subcrop. Note: lateral variability and local discontinuity of base Permian reflector (1); accoustically transparent zone incorporating the Ketch and Bouton Formations (2); possible ambiguities introduced in base Permian mapping by combination of seismic and isopach derived picks (3). Section line corresponds to left-hand half of Figure 2a. Images supplied by Engie E&P UK Ltd. Published with permission of the Petroleum Exploration Society of Great Britain.

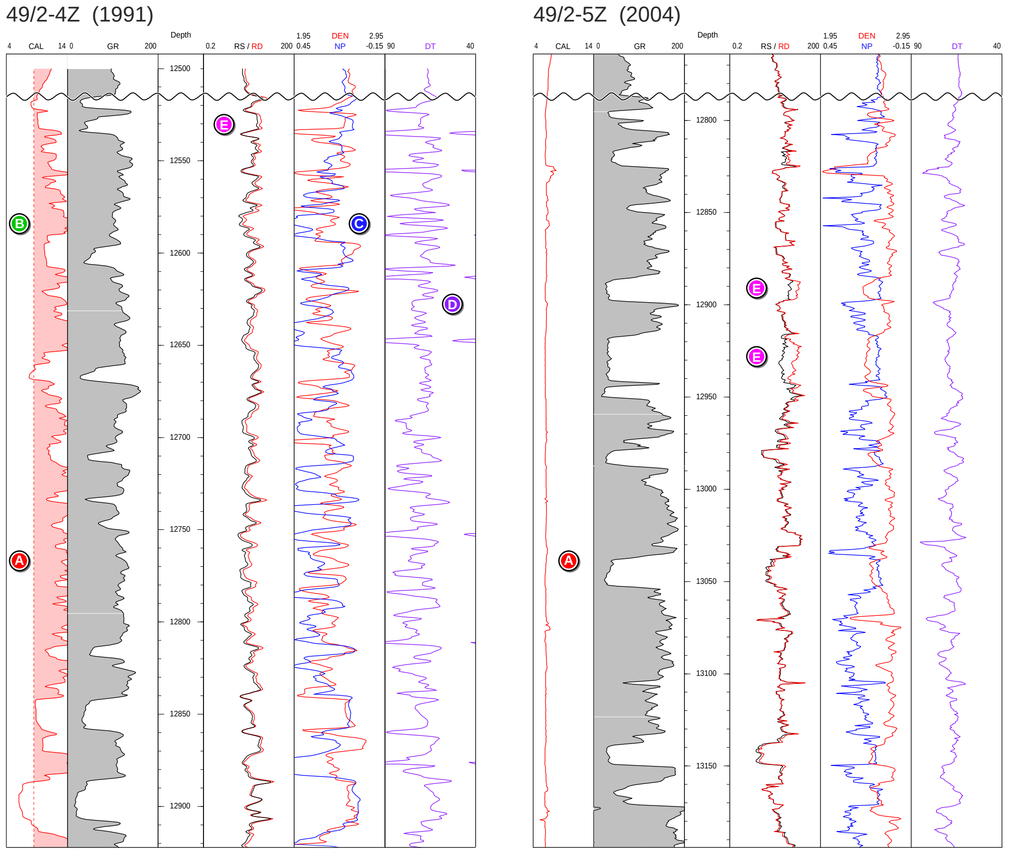
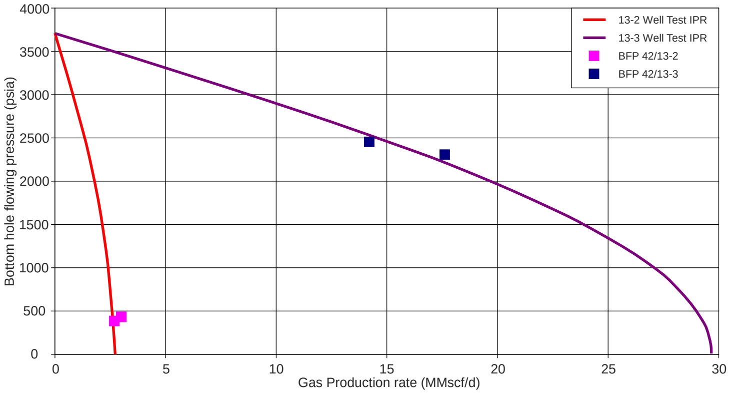


Fig. 11 Contrast in quality of wireline logs in similar stratigraphic penetrations in adjacent boreholes drilled without (a) and with (b) careful attention to mud formulation. Sections are in the Ketch Formation and are hung on a datum at the base Permian Unconformity. Note: A) severe caving and B) development of ledges in earlier well; C) degradation of pad-mounted density / neutron logs and D) noisy sonic with frequent cycle-skipping in oversize rugose hole sections; E) suppression of true resistivity in gas-bearing sandstone owing to deep invasion.



42/13-2 (1997)

Heavy salt brine mud
400psi overbalance

155 ft perforated (5 intervals)
Max flow 3.0 MMscfd

Skin +47 (+24 to +175)

Water-based mud filtrate
invasion up to 60 inches

42/13-3 (2007)

Oil-based mud
Minimal overbalance

110 ft perforated
Max flow 17.6 MMscfd

Skin 0 to +2
Negligible invasion

Fig. 12 Comparison of well test results and interpretation in Breagh Field discovery well 42/12-2 and appraisal well 42/12-3. Contrasting bottom-hole flowing pressures (BFP) and gas production rates between the two wells drilled with different mud compositions and weights define sharply differing inflow performance relationships (IPR). Use of correctly weighted oil-based mud leads to an increase in productivity of a factor of 10. See text for discussion. IPR plot from McPhee & Byrne 2009. Copyright 2009, Society of Petroleum Engineers. Reproduced with permission of SPE. Further reproduction prohibited without permission.

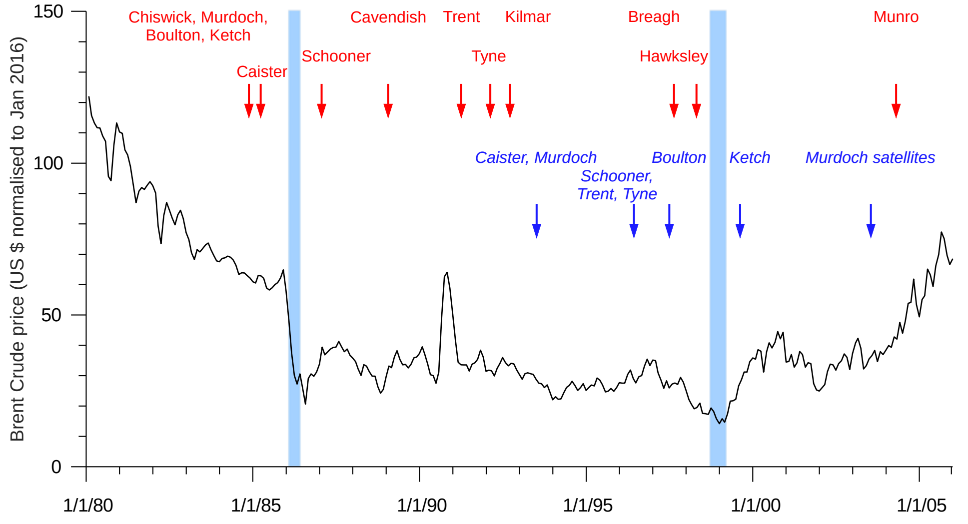


Fig. 13 Plot of oil price (normalised to January 2016) vs. timing of discovery (red upright text) and production start (blue italic text) of principal Carboniferous gas fields in the UK Southern North Sea. Vertical blue bars mark the timing of significant industry retrenchment and re-organisation. Major retrenchments followed initial discoveries and the start-up of most production, leading to fragmentation of the knowledge base and loss of expertise.

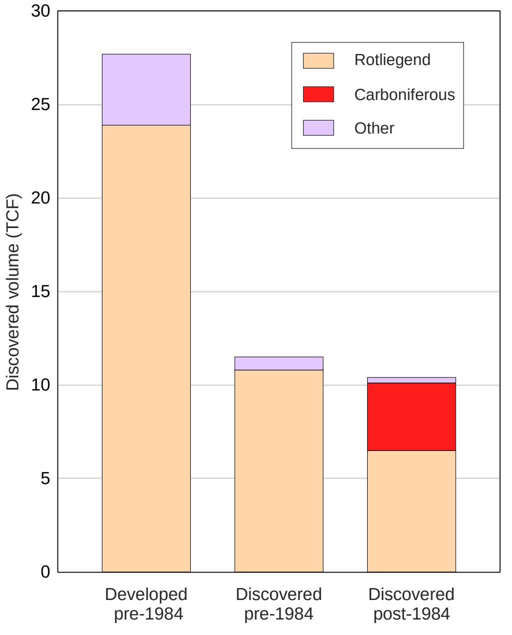


Fig. 14 Context of discovered volumes of gas in Carboniferous reservoirs before and after beginning of targeted exploration in 1984. Note that Carboniferous volumes are dwarfed by volumes in the Rotliegend that were undeveloped in 1984 and significantly smaller than Rotliegend volumes discovered since that date.

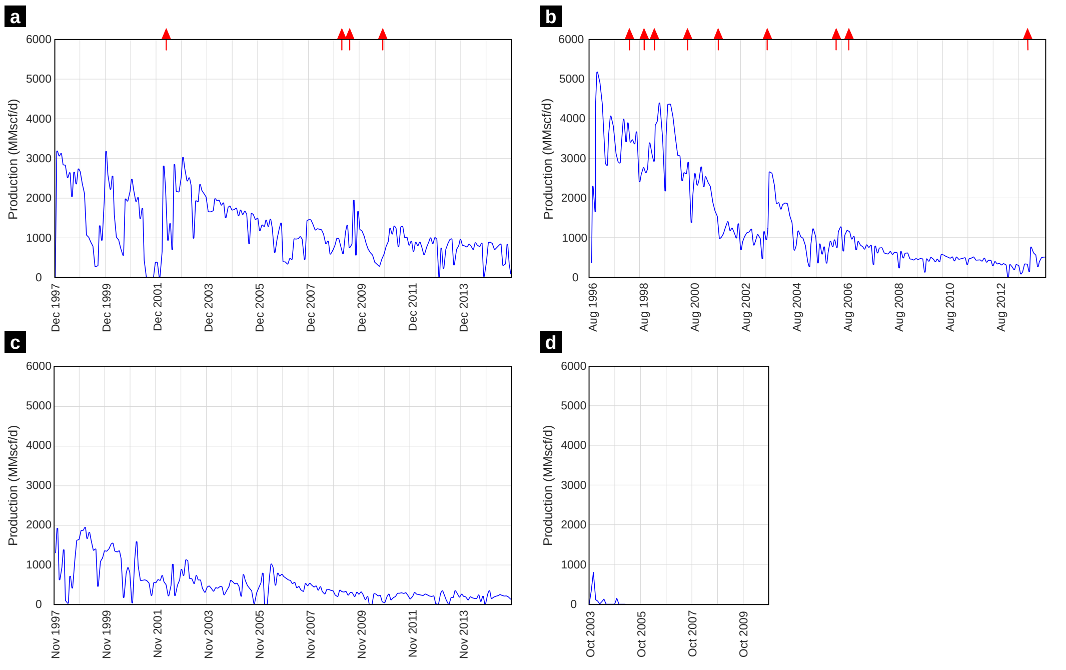


Fig. 15 Field decline curves showing first 6500 days of production for four selected UK Carboniferous fields: a) Boulton 'B'; b) Schooner; c) Trent; d) Watt. Production commenced though 1, 3, 2 and 1 wells respectively: triangular symbols mark start-up of additional wells. Data from UK OGA website. See text for discussion.

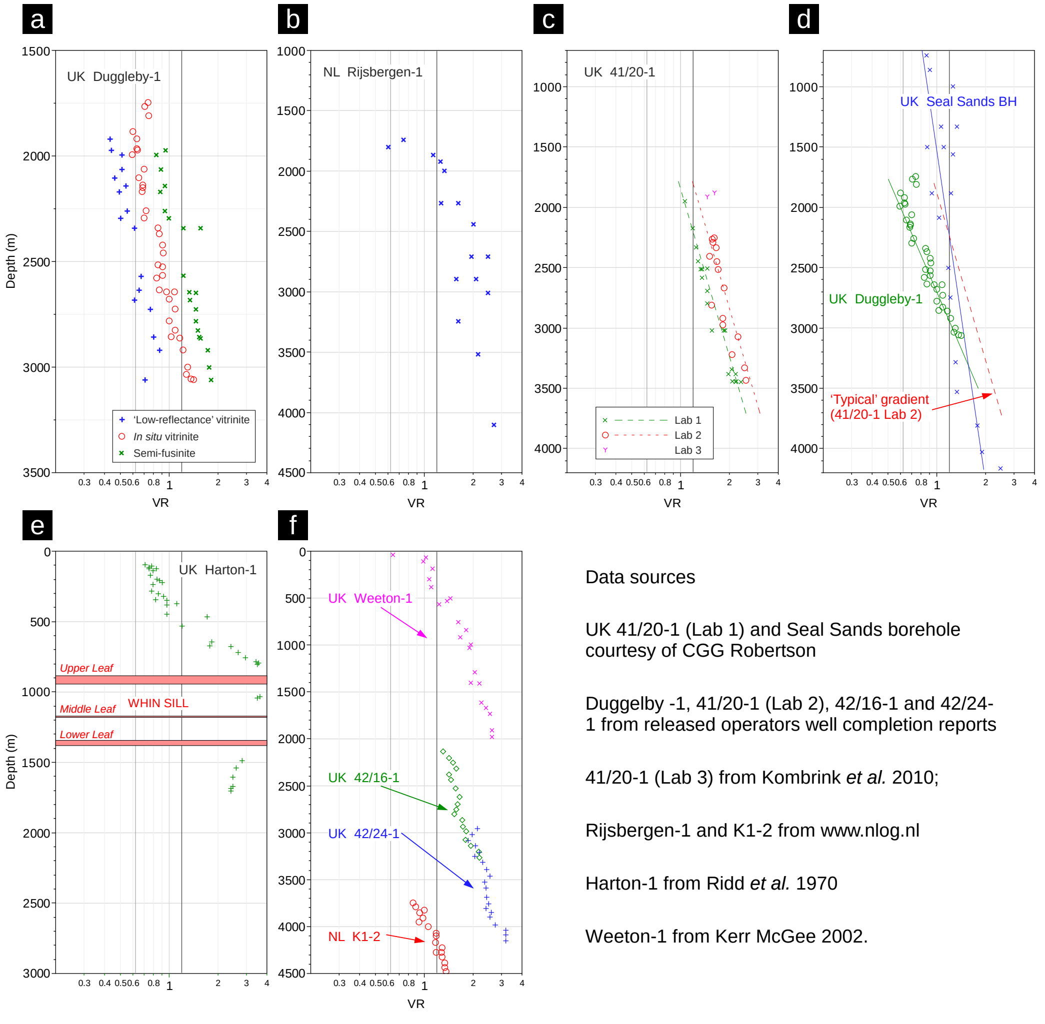


Fig. 16 Examples of vitrinite reflectance data from the Southern North Sea and adjoining areas: a) wide dispersal of data resulting from presence of multiple vitrinite populations; b) ambiguous apparent maturation gradients in a data set for which no quality control information is available; c) inconsistent maturation profiles in analyses of samples from the same well by multiple laboratories; d) different maturation gradients in wells located on a granite-cored high (Duggleby-1) and in a deep Lower Carboniferous graben (Seal Sands borehole); e) thermal anomalies associated with late Carboniferous tholeiitic intrusion; f) effect of Neogene uplift. Note that scaling of vertical axis varies. The Carboniferous section in well K1-2 (plot f) is currently at maximum burial: all other wells in these plots have been subject to some degree of Neogene uplift.

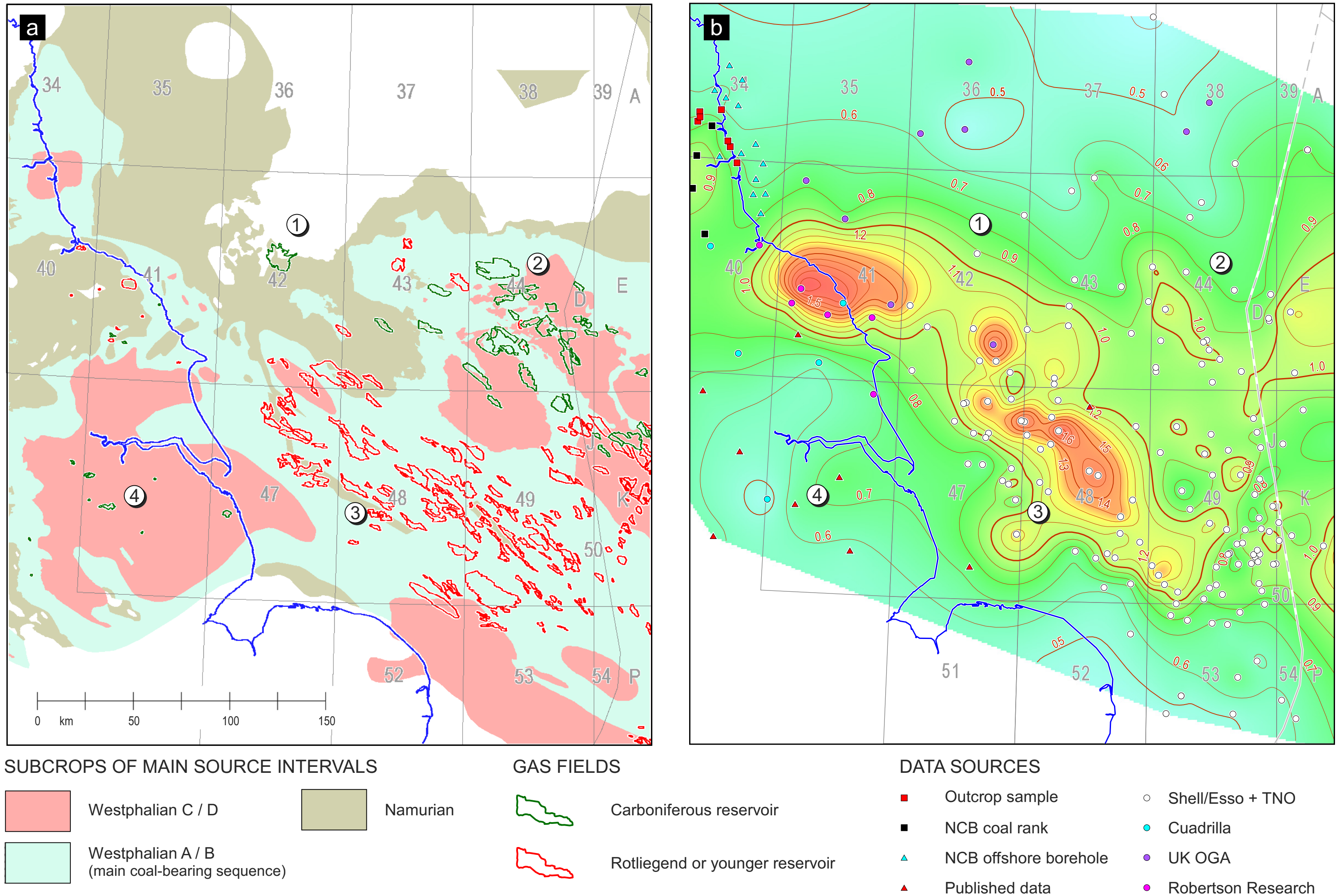


Fig. 17 Regional maps showing distribution of gas fields in relation to Carboniferous subcrop (a) and maturity at Top Carboniferous (b). Numbered reference points: 1) Breagh Field; 2) Cygnus Field and adjoining fields in northern Silverpit area; 3) southern Sole Pit; 4) Gainsborough trough, UK onshore. See text for discussion. . Majority of database for this compilation is derived from released data from the Netherlands oil and gas portal [www.nl.nl] and from the Shell/ExxonMobil Geochemistry Database for the Southern North Sea released by UK Oil and Gas Authority (OGA) [http://data-ogauthority.opendata.arcgis.com/]; onshore outcrop data from Burnett, 1987; approximate VR equivalences from coal rank data in onshore Durham coalfield from National Coal Board 1960; VR data from National Coal Board offshore boreholes from Pearson 1988; other published data points from Andrews 2013; Bray et al. 1992; Fraser et al. 1990; Pearson 1988; other published data from Hughes et al. 2017; Kerr McGee 2002; Leeder & Hardman 1990; Pearson & Russell 2000; data for other offshore wells from OGA well release packages for UK 30th Licencing Round [download from OGA Open Data site as above]; remaining onshore data published by kind permission of Cuadrilla Resources and Robertson Research International Ltd.

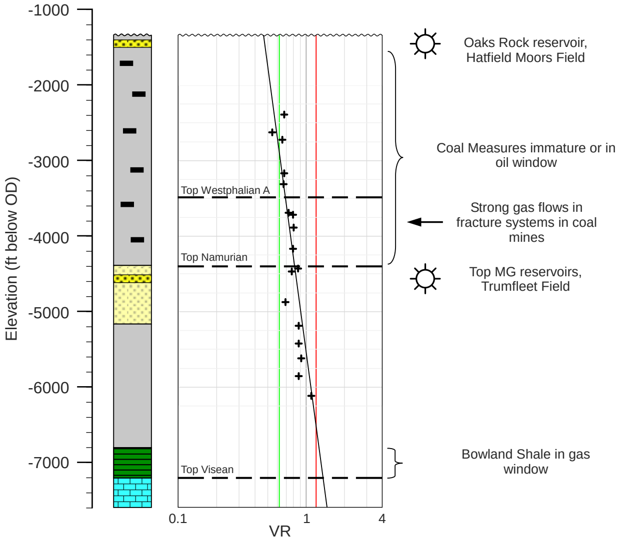


Fig. 18 Source rock maturity profile and reservoired gas horizons, UK Gainsborough Trough. VR data from Pearson & Russell 2000; stratigraphic profile from same source (well Gainsborough-2) supplemented with data from Ward et al. 2003

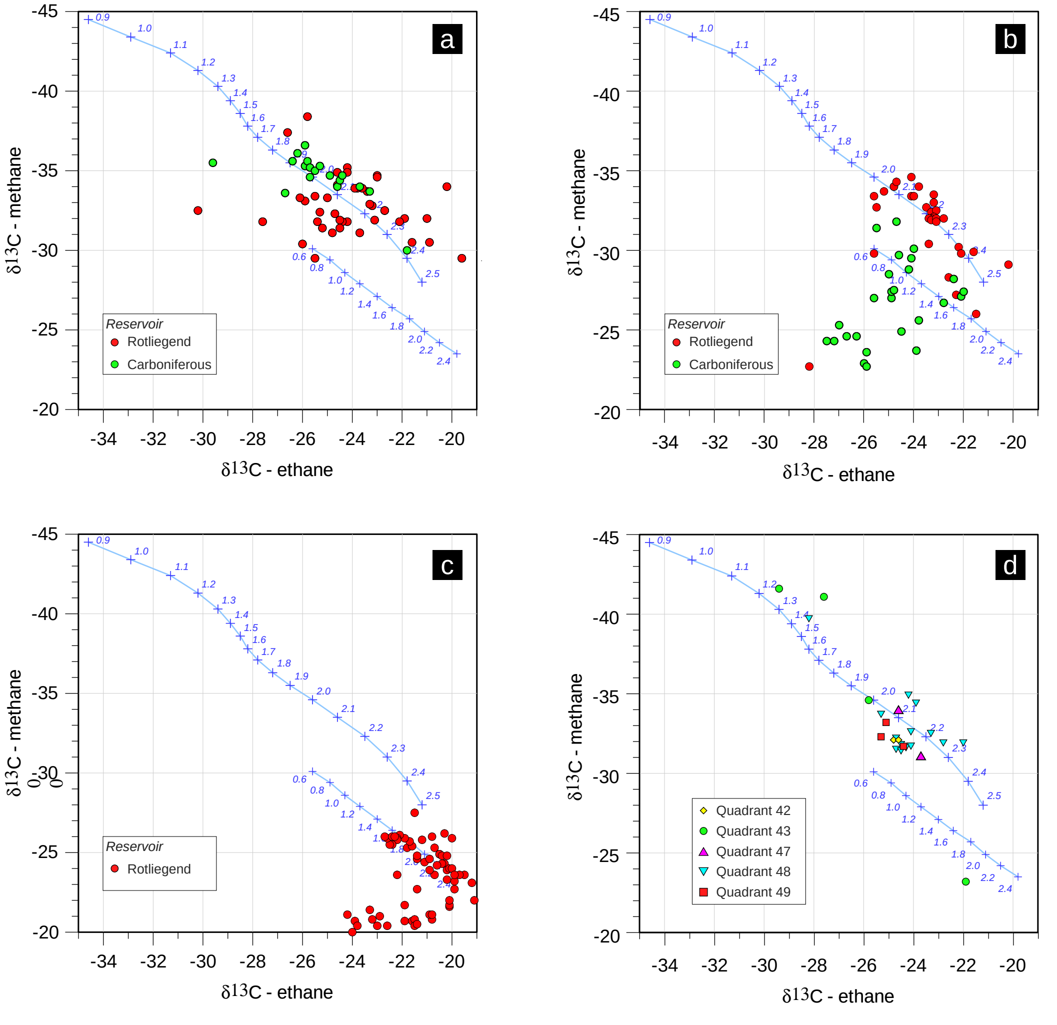


Fig. 19 dC13 isotope data plots for gases in Rotliegend and Carboniferous reservoirs in different areas of the Southern Permian Basin: a) UK and Netherlands offshore; b) Netherlands onshore; c) NW Germany onshore; d) UK Sector only. a) to c) from Lokhorst 1998; d) proprietary data provided by Applied Petroleum Technology (UK) Ltd.

Equivalent VR value calibration lines use pre-cursor δ13C values of -29‰ for sapropelic and -23‰ for humic material.

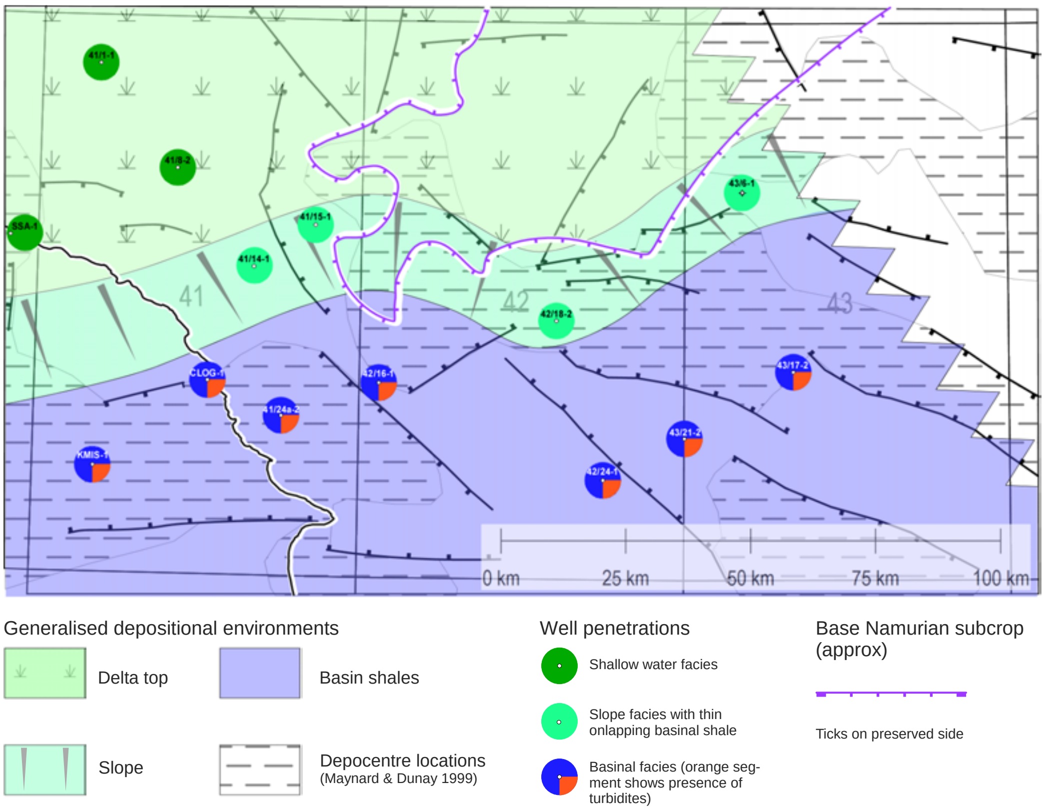


Fig. 20 Palaeogeographical map of the north-western area of the main gas fairway in the UK Southern North Sea, showing the position of the shallow to deep water facies transition at the time of deposition of the main Namurian basinal shale source rock of Pendleian age. Very sparse well control means that boundaries are approximate, particularly given the complex controls on bathymetry arising from the poorly understood framework of late Visean rift depocentres and footwall uplifts. Wells marked as containing slope deposits are those in which the Bowland shale is recognisable by a thin, possibly onlapping development of high GR shale intercalated within non-basinal deposits. Lack of well penetrations prevents extension of this map to the north-east.

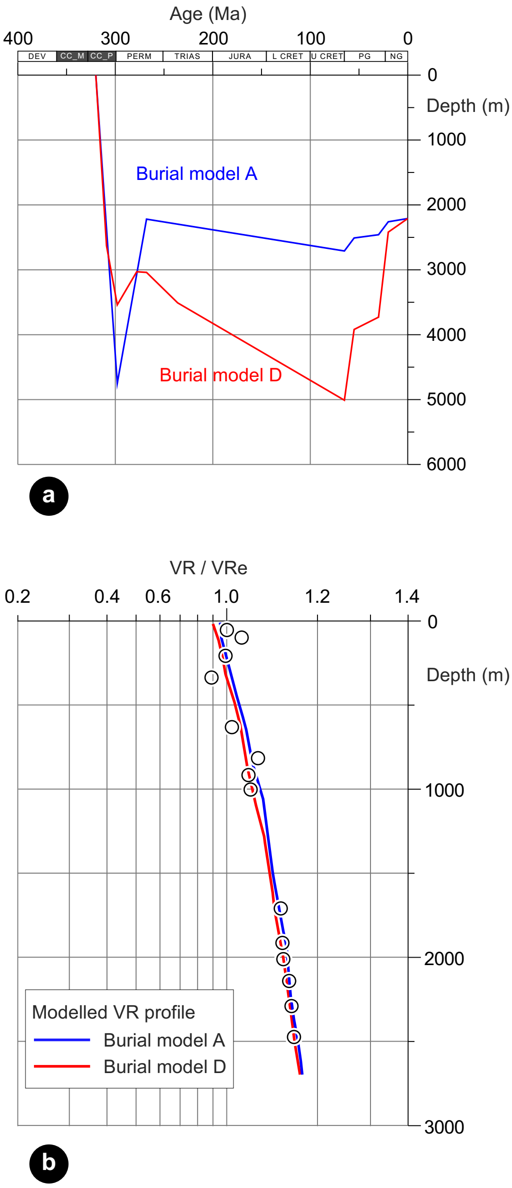


Figure 21 Alternative burial histories (a) and resulting modelled VR profiles (b) for Westphalian and Namurian section in UK onshore well Up Holland-1. Depth profiles in b) have been corrected for offsets of Tertiary age faulting. Note the similarity of maturity profile produced by contrasting burial histories. Redrawn from Pearson & Russell (2000). See text for discussion. CC_M - Mississippian; CC_P – Pennsylvanian.

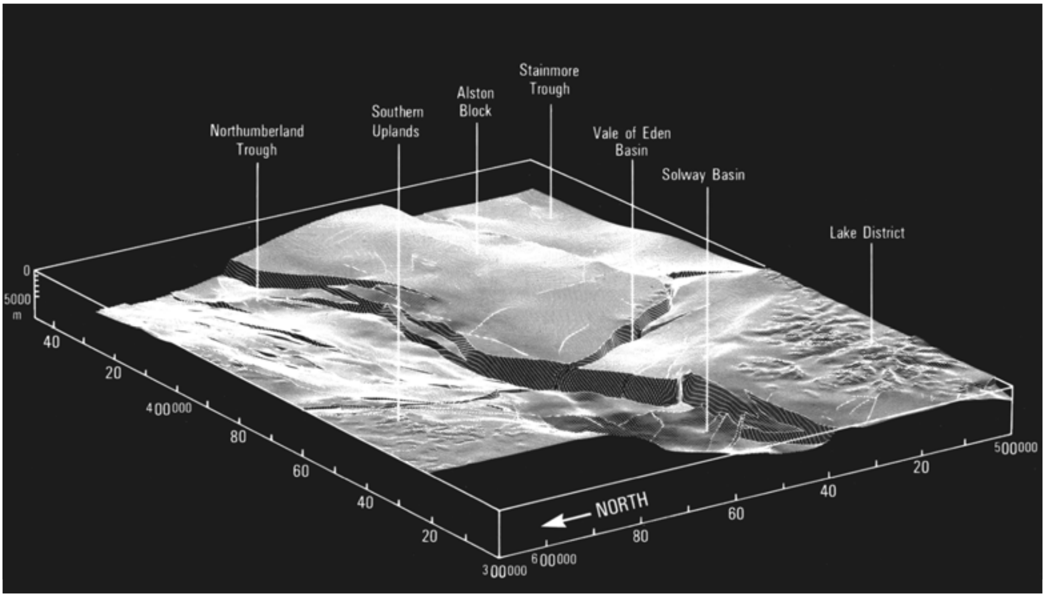


Fig. 22 Variability in structural style of Carboniferous basin depocentres: Northumberland Trough example (Chadwick et al. 1995, Fig. 7), showing variation in style of extensional fault systems bounding Lower Carboniferous rift basins with development of complex ramp geometries. Reproduced with the permission of the British Geological Survey ©NERC. All rights reserved

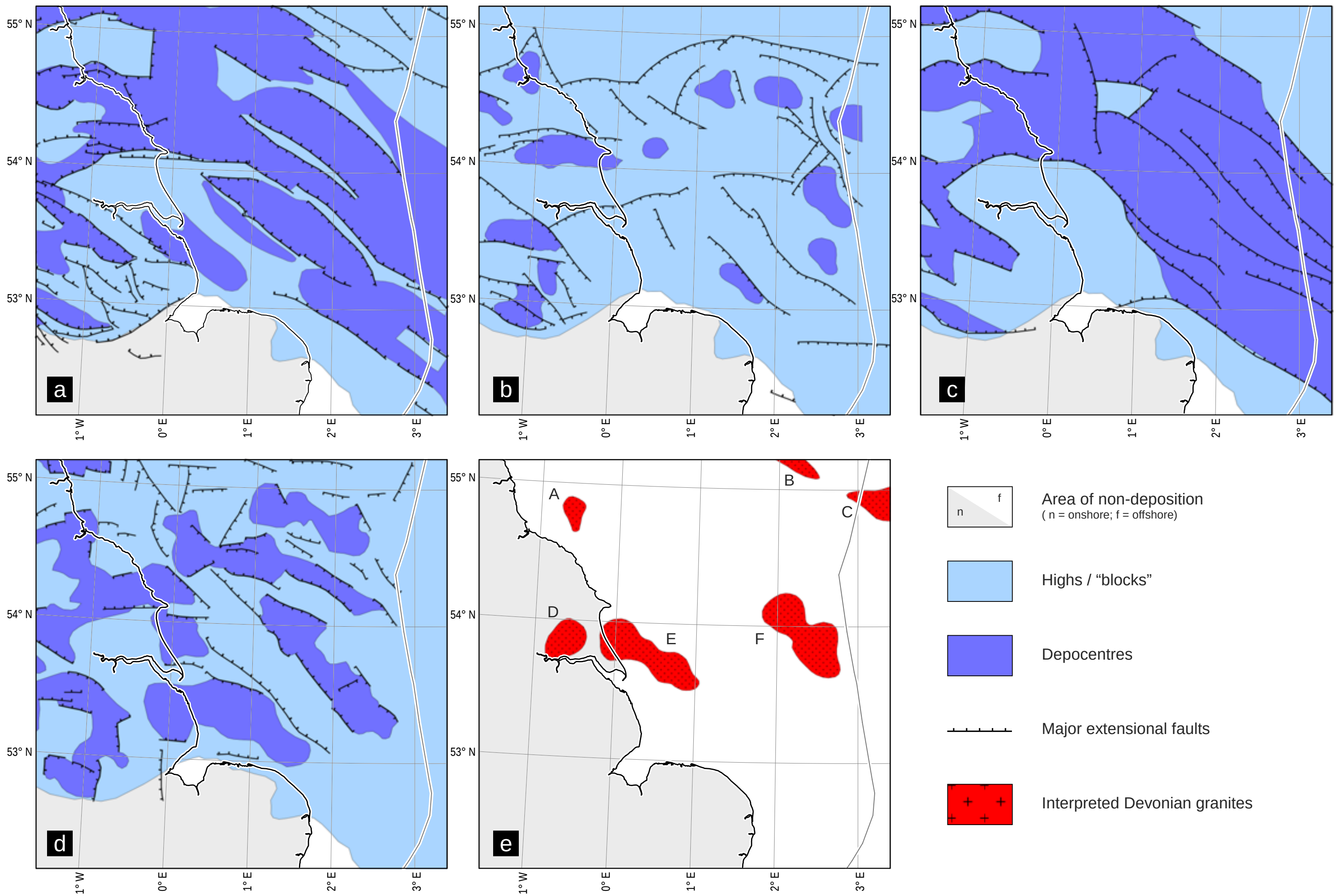


Fig. 23 Comparison of published interpretations of locations of Lower Carboniferous highs and basinal depocentres in the UK offshore area: a) Fraser & Gawthorpe 2003 (UK onshore), Corfield et al. 1996 (UK offshore), Kombrink 2008 (Netherlands); b) Collinson et al. 1993; c) Cameron & Ziegler 1997; d) Maynard & Dunay 1999; e) positions of inferred granites in underlying basement highs (Donato et al. 1983, Donato & Megson 1990, Donato 1993; EBN 2015).

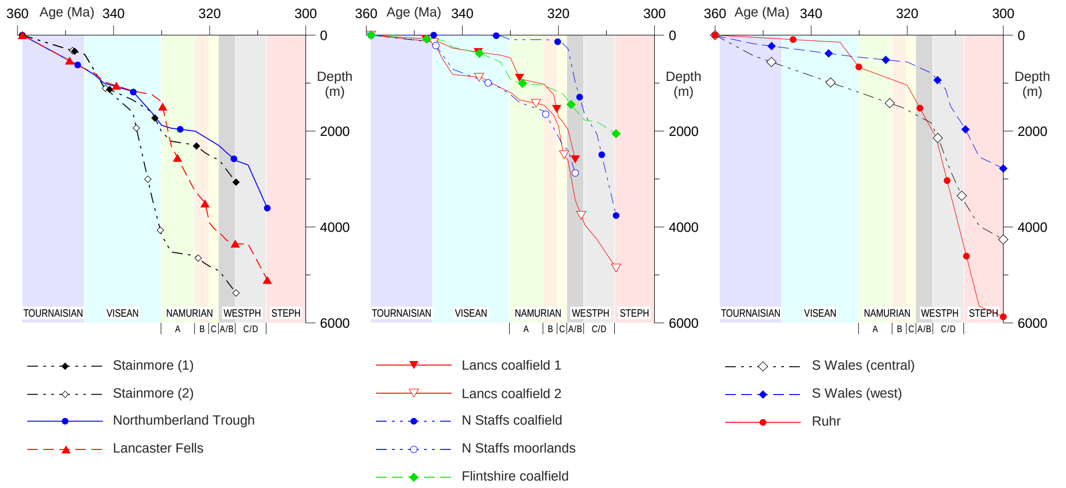


Fig. 24 Compilation of undecompacted Carboniferous subsidence curves for various sub-basin areas in onshore areas surrounding the Southern North Sea: a) basin segments previously interpreted to show the classic “rift and sag” subsidence history; b) other basin segments in or near the centre of the supposed post-rift thermal sag ‘bulls-eye’ (cf. Fig. 12 in Fraser et al. 1990); basin segments in Variscan foredeep area. Data generally from Waters *et al.* 2011 except as follows: Seal Sands borehole (Stainmore 2); South Wales data from Kelling (1988); Ruhr data – Isselburg-3 well from Littke et al. 2000.

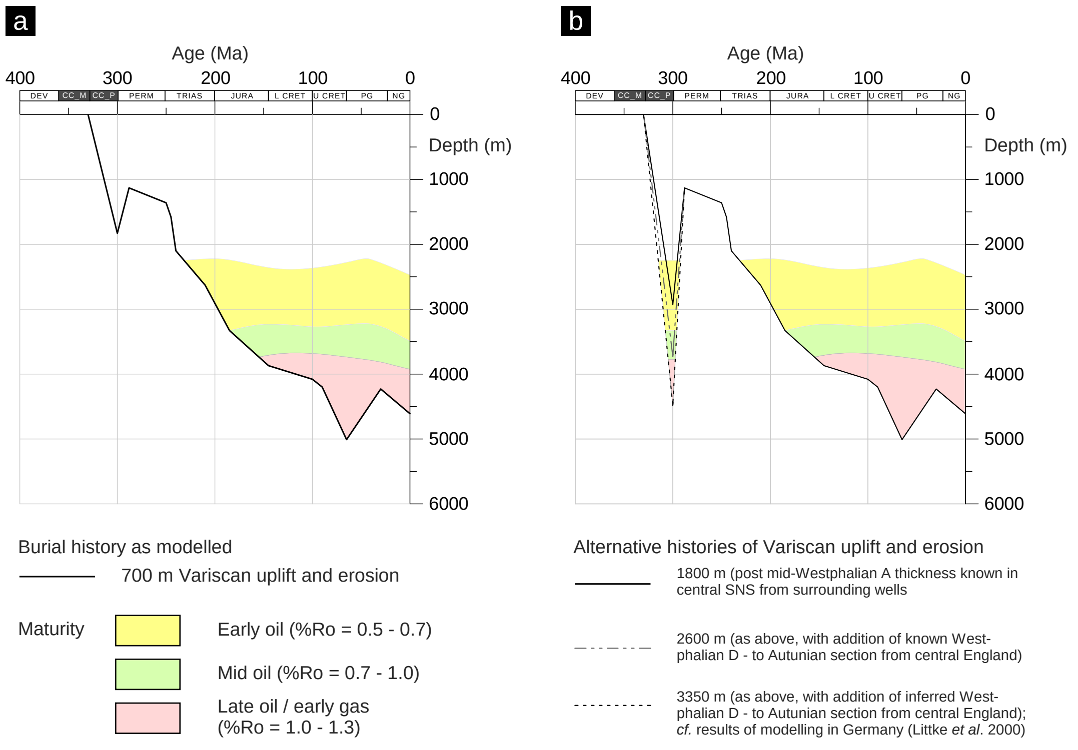


Fig. 25 Alternative possibilities for burial history, UK well 48/3-3 (redrawn after Leeder & Hardman 1990), showing possibilities for enhanced early maturation of the Westphalian succession: a) as published; b) with realistic alternative values of Variscan denudation. Note that post Variscan maturation history has not been re-modelled. The combination of greater pre- Variscan burial and loss of early-generated hydrocarbon during Variscan uplift result in present day maturity being similar to or only slightly greater than that reached prior to Variscan uplift. CC_M - Mississippian; CC_P – Pennsylvanian.

Field	Discovery year	Discovery well	Production start	Published account(s)
Boulton B	1984	44/21-2	1997	Conway & Valvatne 2003a
Boulton H	1989	44/21a-4	2004	Cooper *et al.* 2005
Breagh	1997	42/13-2	2013	Documents at www.sterling-resources.com; [McPhee *et al.* 2008]
Caister C	1985	44/23-4	1993	Ritchie & Pratsides 1993
Cavendish	1989	43/19-1	2007	[Kersten *et al.* 2013]
Chiswick	1984	49/04-1	2007	Nesbit & Overshott 2010
Hawksley	1998	44/17a-4	2002	Cooper *et al.* 2005
Katy	2007	44/19b-6	2013	
Kelvin	2005	44/23b-11	2007	
Ketch	1984	44/28-1	1999	
Kilmar	1992	43/22-1	2006	
McAdam	1990	44/17-1	2003	Cooper *et al.* 2005
Minke	1993	44/24-4	2007	
Munro	2004	44/17b-7	2005	
Murdoch	1984	44/22-1	1993	Conway & Valvatne 2003b
Murdoch K	2002	44/22a-10Z	2003	Cooper *et al.* 2005
Orca	1993	44/29b-4	2013	
Rita	2008	44/22c-9	2009	
Saltfleetby	1996	Saltfleetby-1Z	1999	Hodge 2003
Schooner	1986	44/26-2	1996	Moscariello 2003; [Mijnssen 1997]
Topaz	1987	49/01-3	2009	
Trent	1991	43/24-1	1996	O'Mara *et al.* 1999, 2003a
Tyne North	1993	44/18-2	1996	O'Mara *et al.* 2003b
Tyne South	1992	44/18-1	1996	O'Mara *et al.* 2003b
Tyne West	1994	44/18-4A	1996	O'Mara *et al.* 2003b
Watt	1990	44/22b-8	2003	Cooper *et al.* 2005
Wingate	2008	44/24b-7	2012	

Table 1 Carboniferous gas fields in the UK Southern North Sea area. Publications in square brackets describe specific technical issues without providing a full description of the field.

Field	Production start	Reservoir	Status (April 2017)	Published volumes (BCF) Recoverable	GIIP	RF (%)	Source	Production to April 2017	% of published recoverable
Boulton B	1997	Ketch Fm	Producing	142	206	69	Conway & Valvatne 2003a	279	196%
Hawksley	2002	Ketch Fm	Ceased	*42*	60	*71*	Cooper *et al.* 2005	52	124%
Murdoch K	2003	Ketch Fm	Producing	*94*	134	*71*	Cooper *et al.* 2005	223	237%
Schooner	1996	Ketch Fm	Producing	612	1059	58	Moscariello 2003 (¶)	308	50%
Tyne North	1996	Ketch Fm	Ceased	82	163	50	O'Mara *et al.* 2003b	39	48%
Tyne South	1996	Ketch Fm	Ceased	54	61	89	O'Mara *et al.* 2003b	91	169%
Watt	2003	Cleaver Fm	Ceased	*40*	57	*71*	Cooper *et al.* 2005	2	5%
Murdoch	1993	Murdoch Sst	Producing	348	478	73	Conway & Valvatne 2003b	378	109%
McAdam	2003	Caister Fm / Murdoch Sst	Producing	*137*	196	*71*	Cooper *et al.* 2005	140	102%
Trent	1996	Millstone Grit Fm / Caister Fm	Ceased	92	111	83	O'Mara *et al.* 2003a	113	123%
Saltfleetby	1999	Millstone Grit Fm	Producing	72.5	114	63.25	Hodge 2003	67	92%

¶ Operator has subsequently redetermined GIIP as 654 BCF (see text)

Table 2 Comparison between volumes produced up to April 2017 and previously published estimates of recoverable reserves for selected Carboniferous gas fields. Recoverable volume figures printed in italics are calculated from published GIIP figures where no recoverable volume was published, calculated using an average of all published recovery factors. Cumulative production figures from UK OGA website.