Regional tectonics in relation to Permo-Carboniferous hydrocarbon potential, Southern North Sea Basin

From Earthwise

Jump to navigation Jump to search

From: Carboniferous hydrocarbon resources: the southern North Sea and surrounding onshore areas, edited by J. D. Collinson, D. J. Evans, D. W. Holliday, N. S. Jones. Published as volume 7 in the Occasional Publications series of the Yorkshire Geological Society , Copyright Yorkshire Geological Society 2005.

Figure 1 The Iapetus Ocean flanked by Laurentia–Greenland and Baltica, with the separate microcontinent of Avalonia.

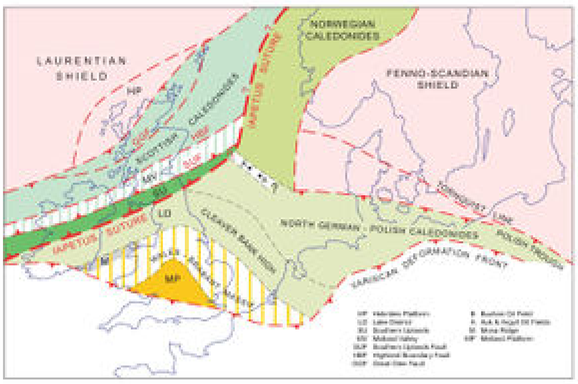

Figure 2 Following the closure of the Iapetus Ocean, several different segments probably affected the future structural pattern within the British Isles, Norway–Sweden and northeast continental Europe.

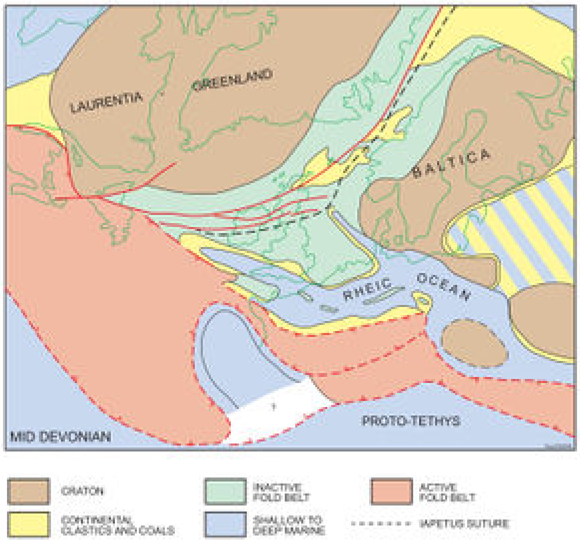

Figure 3 Mid-Devonian. Closure of the Iapetus Ocean resulted in the creation of a large Devonian (Old Red Sandstone) continent that covered eastern Laurentia–Greenland and modern Scandinavia.

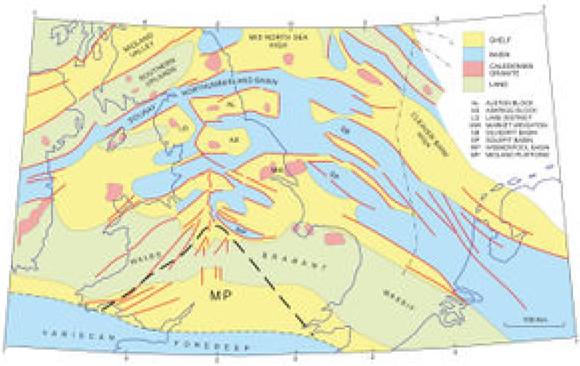

Figure 4 The Early Carboniferous structural pattern across southern Britain and the Southern North Sea is draped around the Midland Platform (MP).

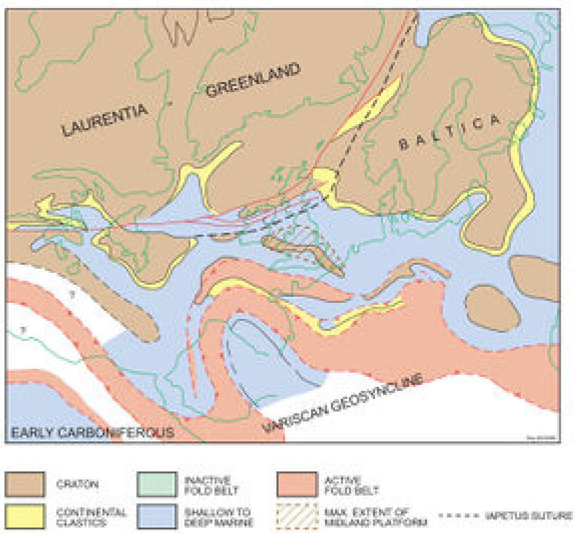

Figure 5 Early Carboniferous, Viséan. Deformation in the Hercynian (Variscan) Fold Belt began to encroach on southern

England ahead of the northward-migrating leading edge of Gondwana.

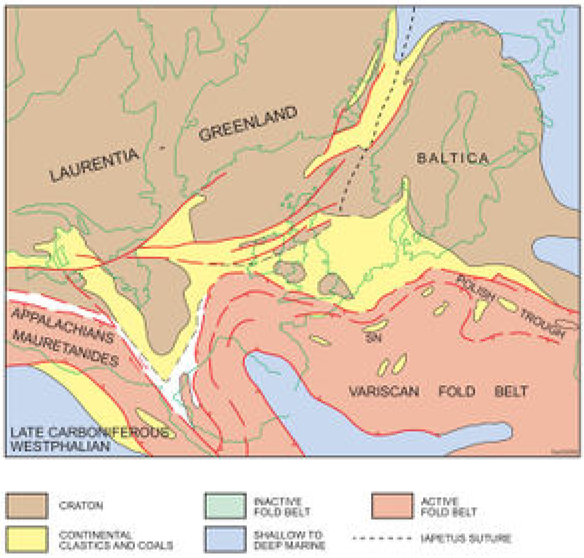

Figure 6 Late Carboniferous, Westphalian.

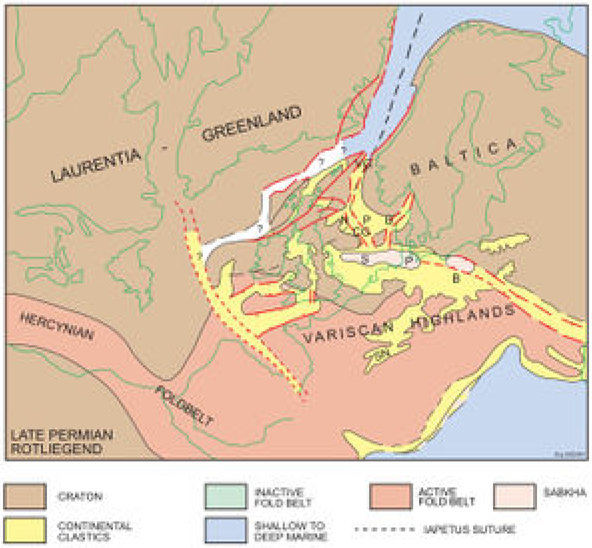

Figure 7 Late Permian, Upper Rotliegend 2 sedimentation began with subsidence of the Southern and Northern Permian basins early in the Late Permian at about 266–264 Ma.

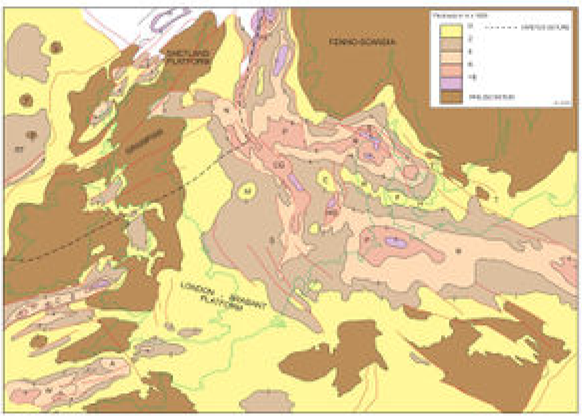

Figure 8 An isopach map of post-Rotliegend strata.

Age (Ma)	Boundary	
251.4	Top Permian and Top Zechstein	Top Changhsingian
258?	Rotliegend/Zechstein boundary	
263/4	Marker horizon – Illawarra magnetic reversal	
264/5	Base Upper Rotliegend 2 (UR2)	~Base Capitanian
	UR2 underlain by Altmark Unconformity	
289–290	Base Upper Rotliegend 1 (UR1)	
	Lower Rotliegend capped by Saalian Unconformity	
291.6	Carboniferous/Permian time boundary	Asselian/Gzhelian
299/300	Proposed base of Lower Rotliegend in central Germany	
354	Base Carboniferous	Base Tournaisian

Table 1 Some key Permo-Carboniferous boundaries.

By K. W. Glennie

From: Pages 1–12 of Carboniferous hydrocarbon resources: the southern North Sea and surrounding onshore areas. Regional tectonics in relation to Permo-Carboniferous hydrocarbon potential, Southern North Sea Basin

☐

Contents

Summary

The tectonic development of the Southern North Sea Basin during the Permo-Carboniferous was the outcome of geological events that began in the Early Palaeozoic when Scotland–Greenland and England–Baltica were on opposite sides of the Iapetus Ocean, which lay within the Southern Hemisphere. Closure of the Iapetus Ocean, completed by the end of the Silurian, resulted in the formation of the Scottish and Scandinavian Caledonides, and associated Siluro-Devonian granite intrusions. Gondwana-derived Avalonia (Nova Scotia–England) drifted northwards across the Equator more rapidly than Laurentia–Baltica did. Closure of the more southerly Rheic Ocean began in the Viséan, eventually forming the Hercynian–Variscan Fold Belt across Appalachia and central Europe. The northward drift had a strong climatic influence on the sediment types deposited from the Devonian to the end-Permian. Reactivated structural relief inherited from the Caledonian

Orogeny-controlled Early Carboniferous sedimentation. The Carboniferous sequence was deformed and truncated prior to deposition of the Late Permian Rotliegend reservoir rocks. Equatorial Carboniferous coals are probably the source all the gas found in the overlying Rotliegend desert sandstones of the Southern Permian Basin. The latest Permian Zechstein Sea transgressed the area via a young Viking–Central Graben system. Post-Permian subsidence carried Coal Measures to depths and temperatures at which methane was generated. Gas in Late Westphalian–Stephanian red sandstones is capped by Rotliegend claystones and salts, and in Rotliegend reservoirs by Zechstein salt, which forms an almost perfect top seal.

Introduction

Carboniferous coals provided much of the energy that drove the Industrial Revolution in Britain during the eighteenth and nineteenth centuries. Coals and associated carbonaceous shales are the source of major volumes of methane, especially in The Netherlands and beneath the southern North Sea, which have been exploited only since the 1960s. These coal-bearing beds are distributed in an apparently simple west–east zone that, prior to the opening of the Atlantic Ocean, extended from the Appalachian Mountains of North America (e.g. Ziegler, 1987, 1990; Calder, 1998; Scott, 1998), across South Wales (where many coals have been converted to anthracite), central England, the Midland Valley of Scotland, and beneath especially the southern North Sea, The Netherlands, northern Germany and Poland to Russia. In detail, the depositional and structural history of the belt is relatively complex.

The Carboniferous rocks of the British Isles are underlain by older Palaeozoic marine sedimentary rocks, similar to those of the Welsh highlands and the Lake District and, locally, by Devonian sequences (mostly terrestrial). These rocks are the product of deposition in and around the Iapetus Ocean, and their deposition was associated with the relative movement of crustal plates that led, in the Late Silurian and Devonian, to the Caledonian Orogeny and a more or less unified British Isles.

1. Iapetus Ocean and the Caledonian Orogeny

It is fascinating to follow the history of the world’s major plates in time and space as deduced from palaeomagnetic data and depicted in recent years by, for example, Scotese & McKerrow (1990) and Torsvik et al. (1990, 1996), or more pertinently, the outline history of the Iapetus Ocean (Figure 1). Here, we are not so much concerned with the detailed history of that ocean but more with its final closure and the structural framework that resulted, which was an important forerunner to the pattern of Carboniferous deposition in central England and the greater North Sea area.

Although its early depositional history was probably related to previous plate movements, a recognizable Iapetus Ocean was already in existence by the Early Cambrian (Scotese & McKerrow, 1990; Van Staal et al., 1998), with Laurentia to the northwest and Baltica to the southeast. The Scottish Highlands and northwest Ireland formed part of the southeast margin of Laurentia–Greenland, whereas Avalonia (Nova Scotia and southeast Newfoundland together with southern Ireland, England and southern Denmark) formed a microcontinent that earlier had been calved from the southern megacontinent Gondwana (Figure 1). The Late Ordovician closure of the Tornquist Sea, between eastern Avalonia and Baltica (Fennoscandian Shield), resulted in a line of structural weakness that today extends through southern Denmark to the Polish Trough and marks the southern edge of Baltica (Figure 2).

The Iapetus Ocean mostly lay within the Southern Hemisphere throughout its existence and it was wide enough for some faunal differences to be recognized in the vicinity of opposing coastlines (see limited palaeontological evidence in Cocks & Fortey, 1982, and the cautions on faunal climatic control in Cocks & Torsvik, 2002). Palaeomagnetism is the key to the reconstruction of the individual plate movements. Oceanic sediments were deposited over much of what is now southern Ireland, Wales, northern England and the Lake District. As their counterparts, the North German–Polish Caledonides (Figure 2), are known in northern Germany and Poland, similar sediments were probably deposited beneath the southern North Sea and The Netherlands.

Closure of the northern Iapetus between Laurentia and Baltica, completed by the end Silurian, led to the development of the Scottish–Scandinavian Caledonides with their high-grade metamorphic rocks. The northeast USA and Nova Scotia–Newfoundland, the Highlands of Scotland and eastern Greenland formed the western part of the orogen, with Baltica forming most of the eastern flank. The Highlands of Scotland and western Baltica were strongly deformed, subjected to varying degrees of metamorphism, and were intruded by many Siluro-Devonian granites.

The above contrasted with the less severe (only low-grade metamorphism) Late Silurian–Early Devonian collision, perhaps oblique, between Avalonia and Laurentia–Baltica. This event resulted from Gondwana-derived Avalonia (Nova Scotia–England) drifting northwards across the Equator more rapidly than Laurentia–Baltica, thereby leading to the southern (broadly west–east) leg of the Caledonian orogeny, as clearly displayed by Torsvik et al. (1990).

During the Ordovician and Silurian, new oceanic crust had been generated at the Iapetus spreading axis between the Highlands of Scotland and the Lake District; the ocean-floor sediments on the northward-moving sector of oceanic crust were slowly scraped off in the subduction trench beneath the Midland Valley of Scotland as a series of thin tectonic slices that became the Southern Uplands. To the south, Late Ordovician subduction in the opposite direction had already led to extrusion of the Borrowdale Volcanic Group and the intrusion of almost coeval granites in the Lake District (Watson & Dunning, 1979).

Between the main plates and microcontinents, sinistral movement brought different terranes into their present relative positions in Scotland, whereas dextral movement may have occurred between the margins of the former Tornquist Sea (Figure 2). Northwest Europe had acquired something like its present configuration and was to remain contiguous with North America until the Paleocene opening of the North Atlantic Ocean.

2. Post-Caledonian plate movements

Following the Caledonian Orogeny and the creation of a long southwest–northeast-trending mountain range, Devonian erosion of the Caledonian landmass resulted in deposition of the terrestrial Old Red Sandstone (Figure 3). The British Isles lay just south of the Equator, and both Lower and Upper Devonian sequences contain dune sands and sabkhas in southwest Ireland (Richmond & Williams, 2000) and in northeast Scotland and the Orkney Isles (Marshall et al., 1996; Marshall & Hewett, 2002) that indicate a degree of aridity in an otherwise moderately humid (fluvio-lacustrine–sabkha) environment. Within and north of Scotland, Devonian clastic sedimentation flanked the Great Glen Fault and the Iapetus suture. Rogers et al. (1989) inferred dextral movement along the Great Glen Fault during the Mid-Devonian, whereas Friend et al. (2000) suggested that a Middle Devonian lacustrine sequence, 4–9 km thick, adjacent to the fault was a consequence of such movements. The northern extent of Mid-Devonian strata (Fig. 3) implies that the Iapetus suture was overlain by a considerable thickness of clastic strata in rapidly subsiding continental basins that presumably were induced by transtensional pull-apart.

The west–east trending Rheic Ocean lay to the south between the British Isles and Gondwana (Figure 1), (Figure 3). In the late Mid-Devonian, a marine embayment, documented by the presence of marine limestones of that age in both the Auk and Argyll oilfields (Robson, 1991; Trewin &

Bramwell, 1991; Marshall et al., 1996) and well 38/3-1, extended into the central North Sea. Although given a south-southeast trend by Ziegler (1987), the orientation of the embayment possibly bisects the obtuse angle formed by the bend in the Iapetus suture where its northern North Sea and Northumberland–Solway segments meet due east of the Midland Valley of Scotland; if so, the third arm of this trilete junction may have had a more southeasterly trend. Such an interpretation is strengthened by Kockel's (1995) observation that fragments of coral occur in the middle of the Devonian succession in the German offshore well Q-1 (block G/3), about midway between the southern ends of the Central and Horn grabens (Figure 3). This embayment may have resulted from early Variscan north–south compression generating torsion that gave rise to southwest–northeast tensional stresses during the final Devonian stages of Iapetus closure. The inferred newly created zone of crustal weakness is subparallel to the suture of the former Tornquist Sea, along which Late Silurian to Early Devonian dextral movements may have initiated the location and trend of the Mid-Devonian embayment, parallel to the similarly trending Trans-European Fault of Coward (1990) across southern Denmark and northern Germany. There is possibly also a structural connection with the much younger northwest–southeast trending Texel–Ijsselmeer High and associated structures in The Netherlands.

During the Devonian, both Laurussia and Gondwana were moving northwards, the latter slightly more rapidly than the former, so that inevitably they collided, resulting in the closure of the Rheic Ocean, to create the roughly west–east trending Hercynian–Variscan orogenic belt that sutured Laurentia and Gondwana into the rather unstable megacontinent Pangaea (Scotese & McKerrow, 1990). Collision seems to have begun during the Viséan and culminated in the Late Carboniferous to Early Permian. In England, collision resulted in deformational structural trends parallel to those in the underlying Caledonian basement, which drape around the leading northern corner of the roughly triangular microcontinent, the Midland Platform (Figure 2). As noted by Corfield et al. (1996), structures east of the platform tend to be aligned northwest–southeast subparallel to the Tornquist Line, whereas those in the west have a distinctly southwest–northeast Caledonian trend (Figure 2), (Figure 4), (Figure 5).

3. Plate tectonics and climate change

Northward drift carried the area now occupied by the British Isles across the Equator during the Carboniferous, reaching the southern limit of the Northern Hemisphere desert belt (*c.* 10°N) by the latest Carboniferous (Stephanian). The climatic changes involved with this drift played a major role in controlling the types of sediments deposited: coral-bearing marine limestones and semi-arid to arid terrestrial sediments (including aeolian sandstones) in the Devonian; Early Carboniferous limestones, equatorial coal-forming swamps from the late Namurian through much of the Westphalian, and reversion to fluvial red beds in the Westphalian C–D and Stephanian; the dominance of aeolian Upper Rotliegend sands in the early Late Permian and, following the even later Permian marine transgression, the carbonates and evaporites of the Zechstein. This succession of sedimentary sequences partially controlled by climate was to prove very important to the modern hydrocarbon industry; in the ideal case, the Carboniferous coal-measure source rocks for gas were overlain in turn by high-quality Rotliegend terrestrial (especially aeolian) reservoir rocks and the almost perfect top seal of Zechstein halite.

Although coal-bearing strata are mostly of Late Carboniferous age (Namurian–Westphalian) in southern and central England, they began to form in the Early Dinantian in northern England and the Midland Valley of Scotland (Scotland crossed the Equator before central England). Such strata do not extend northwards over the strongly metamorphosed Caledonian rocks of the Scottish and Scandinavian highlands, except very locally in southwest Scotland (southern Kintyre Peninsula). With regard to our more specific interest in the southern North Sea, the effective northern limit can be placed along the Mid North Sea–Ringkøbing–Fyn High, although Lower Carboniferous strata with minor thicknesses of coal occur locally across the central North Sea on trend with the Midland Valley and also below the outer Moray Firth (Bruce & Stemmerik, 2003).

In the south, our direct interest is limited by the Variscan deformation front (Figure 2), (Figure 6). As implied earlier, this front marks the northern edge of a series of northward-prograding (Variscan) orogenic processes that had been developing more or less continuously throughout the Carboniferous as a broad zone of structural deformation. In that context, it should noted that relics of relatively extensive coal-bearing Carboniferous basins also occur south of that front in France and central Germany (Figure 6).

During the final phases of the of the Variscan Orogeny in the early Late Permian, two important west–east trending basins formed across the North Sea area, of which the much larger Southern Permian Basin became an important area for the late twentieth-century exploration for gas of Carboniferous origin (Figure 7). Because of a general lack of Carboniferous coals in the Northern Permian Basin, the Rotliegend is not a reservoir for Carboniferous gas but rather for oil of Late Jurassic origin (e.g. Glennie et al., 2003).

4. Outline of Carboniferous structural development

Early Carboniferous sedimentation was controlled by reactivation of structural relief inherited from the Caledonian Orogeny, coupled with the effect of draping around the Midland Platform, caused by the northward push of the Variscan Orogeny (Figure 2), (Figure 4), (Figure 5). There is a distinct difference in the sedimentary history of the somewhat linear fault-bounded structural highs (many of which are underlain by Ordovician and Devonian granites) and the intervening lows. For example, alternating limestones and clastic deltaic strata of Tournaisian and Viséan age locally exceed a thickness of 4000 m in the Northumberland–Solway Basin (Figure 4) but are only *c*. 500 m thick (and mainly late Viséan in age) over the Alston Block to the south. In these more northerly areas, where sedimentation was able to keep pace with subsidence, basin infill was achieved in part by braided fluvial systems derived from the exposed Caledonian highlands, which fed Yoredale-type deltaic sediments prograding from the northeast into a shallow marine environment. Farther south, where carbonate sedimentation predominated on the highs, sedimentation was not always able to match subsidence and much of the basin infill comprises shales and turbiditic limestones laid down in relatively deep water. The structural relationships of Dinantian strata in northern England are well displayed by Fraser & Gawthorpe (1990), Chadwick et al. (1995) and Kirby et al. (2000).

Fault-related subsidence ceased, mainly but not totally, by the end of the Viséan, giving way to more widespread regional subsidence. The extensive shallow-marine depositional environment extending to both east and west of southern Britain (Figure 5) gave way later to terrestrial deposition over much the same area during the later Carboniferous (Figure 6). The Millstone Grit deltaic sediments were also mostly sourced in the Caledonian and Old Red Sandstone highlands in the north, intervening barriers to sediment transport having been crossed or bypassed. In early Westphalian times, a westerly sediment source became prominent. Pro-delta marine shales near the base of the Millstone Grit Group have long been known to form source rocks for oil and gas in the East Midlands. The developing Variscan Orogeny in the south provided a northward-moving southern limit to the Carboniferous basin. Low-lying coal-bearing sequences of Namurian to early Westphalian age are interbedded with some 70 extensive marine bands (Besly, 1998), which must indicate an almost planar surface that extended from northern Appalachia to Germany. Where the marine waters entered the basin (North America or eastern Europe?) is not known for certain (Figure 6), the evidence either lying still buried or having been removed by erosion. Apart from continued subsidence to create accommodation space, most of the marine bands probably resulted from fluctuations in sea level related to the repeated melting of Gondwanan ice caps (cf. Scotese & Barrett, 1990; Crowell, 1995) rather than from any direct tectonic influence. Guion et al. (2000) estimated that the glacially induced changes in sea level fluctuated by some 60±15 m, or about half that caused by Pleistocene glaciations; presumably the Gondwanan icecaps, operating individually, were much smaller than their Pleistocene equivalents.

From Westphalian B (Duckmantian) times, the rising Variscan highlands in the south began to provide sediment to the Carboniferous basin (Besly, 1998; Hallsworth & Chisholm, 2000), while periodic extension led to local volcanism at the southern margin of the Pennine Basin (Glover et al., 1993). At the same time, the slow northward drift of the now weakly united Laurussia–Gondwana (Pangaea) had brought England and the southern North Sea area into a zone that lay at the margin between an equatorial and a sub-Saharan climate; marginally arid red-bed deposition began and continued in basinal areas until the end of the Carboniferous Period.

5. Post-Carboniferous maturation of coals, and gas generation in Rotliegend basins

We know little about sedimentation over England and the southern North Sea area during the Early Permian, because most of the evidence was removed by uplift associated with the continuing Variscan Orogeny. Indeed, Fraser & Gawthorpe (1990) estimated that erosion may have removed 3000 m of strata in parts of northern England, and the Pennines probably came into existence in the Early to early Late Permian cf. (Figure 6), (Figure 7). Late Carboniferous to Early Permian orogenic movements were responsible for creating the small onshore traps that contain oil and gas in reservoirs of Carboniferous age. The distribution and orientation of some of the structural elements involved in the Carboniferous of England and, less clearly, beneath the southern North Sea (e.g. gas-bearing Carboniferous of the Caister and Murdoch fields in blocks 44/23 and 44/22; Hollywood & Whorlow, 1993; Ritchie & Pratsides, 1993) indicate that they too are partly inherited from an older Caledonian history (e.g. Coward et al., 2003) that had involved the differential movement of several crustal plates (Figure 1), (Figure 2).

The general distribution of Carboniferous strata beneath the Permian indicates that the area had been folded relatively gently (e.g. Ziegler, 1990; Glennie, 1997) and, from the viewpoint of this paper, erosion extended down to pre-Carboniferous strata only over the margins of what was to become the Southern Permian Basin: the London–Brabant Platform and Mid North Sea–Ringkøbing–Fyn High.

As mentioned earlier, the northward Permian drift of Laurussia took the British Isles and northwest continental Europe into the climatic equivalent of the modern Sahara. The known Early Permian (Lower Rotliegend) sedimentation was confined to intermontane basins in central and southern Germany (e.g. Schneider. 2001) and southwest England (Edwards et al., 1997), where fluvial and lacustrine sediments indicate a relatively warm but wet climate, the humidity perhaps being induced by the surrounding areas of high relief. Volcanic activity also occurred in these depositional areas, much of it straddling the Carboniferous–Permian time boundary in central Germany (e.g. Schneider et al., 1995), together with parts of the Midland Valley of Scotland (Francis, 1991; Glennie, 2002) and the eastern Norwegian–Danish Basin (Stemmerik et al., 2000; Glennie et al., 2003).

5.1 Late Permian Upper Rotliegend

Mainly because it is a fossil-poor red-bed sequence, the timespan of deposition of the Rotliegend seems to change with each new publication, and dates for the start and end of the Permian period have varied even in recent years. The latest time boundaries of the Carboniferous and main Permian units are shown in Table 1.

By using faunas from grey rather than red beds of the Rotliegend within the different basins of eastern Germany, Hoffman et al. (1988), Gebhardt et al. (1991) and Schneider & Gebhardt (1993) were able to demonstrate that the Upper Rotliegend could be divided into two major stratigraphical units: Upper Rotliegend 1 (UR1) and Upper Rotliegend 2 (UR2). UR1 crops out in some basins of central Germany, and locally is part of a continuous sedimentary sequence that began in the Late Carboniferous (e.g. the Saar–Nahe Basin; Schneider, 1996); in this basin, UR1 includes the Kreutznach aeolian sandstones as an indicator of increasing aridity. UR1 is represented over much of what was to become the Southern Permian Basin by the important Saalian Unconformity, which resulted from uplift and erosion associated with the northward development of the Variscan Orogeny. Above the unconformity lie the economically important gas-bearing aeolian sandstones of the UR2 sedimentary sequence, which occupied much of the Southern Permian Basin prior to the latest Permian deposition of the marine Zechstein.

Table 1 Some key Permo-Carboniferous boundaries. Ages are based on Menning (1995), Jin et al. (1997), Wardlaw (2000), Schneider (2001) and UNESCO (2002).

Age (Ma)	Boundary	
251.4	Top Permian and Top Zechstein	Top Changhsingian
258?	Rotliegend–Zechstein boundary	
263–4	Marker horizon – Illawarra magnetic reversal	
264–5	Base Upper Rotliegend 2 (UR2)	~Base Capitanian
	UR2 underlain by Altmark Unconformity	
289–290	Base Upper Rotliegend 1 (UR1)	
	Lower Rotliegend capped by Saalian Unconformity	
291.6	Carboniferous–Permian time boundary	Asselian–Gzhelian
299–300	Proposed base of Lower Rotliegend in central Germany	
354	Base Carboniferous	Base Tournaisian

The start of Upper Rotliegend 2 sedimentation (the Upper Rotliegend of the main gasfields of the southern North Sea, The Netherlands and Germany) coincided with the beginning of thermal subsidence of the Southern and Northern Permian basins (Figure 7) following the earlier widespread volcanic activity. This occurred early in the Late Permian at about 264 Ma BP, just before the creation of that key red-bed marker, the Illawarra magnetic reversal, at 263 Ma (Menning, 1995, modified by Schneider, 2001). Earlier interpretations of the Permian palaeogeographical development of northwest Germany can be found in Gralla (1988) and, for northern Germany, in Plein (1993, 1995).

At about the same time as sedimentation began in the Northern and Southern Permian basins, the Viking–Central graben system was initiated in the northern and central North Sea. The Viking Graben probably utilized the north–south portion of that relatively weak crustal lineament, the Iapetus Suture (Glennie, 2002; Glennie et al., 2003), perhaps driven by the wedge effect of the Midland Platform and its northern drape of Carboniferous structures pushed northwards by the advancing Variscan deformation front (Figure 2). The wedge would have induced dextral strike-slip movements between structures of Tornquist orientation (e.g. the Mid-Devonian seaway; the northwest–southeast-trending portion of the Central Graben) and sinistral movements parallel to the southwest Iapetus trend (e.g. Northumberland–Solway Trough). Graben initiation can be dated, especially in Danish waters, by the association of earliest Rotliegend lacustrine shales, with volcanic activity in the range of 269±4 to 261±4 Ma (Stemmerik et al., 2000; Glennie et al., 2003).

With England and the southern North Sea areas located in the Permian climatic equivalent of the southern Sahara, associated aridity ensured that unconsolidated surface sands were mobilized by the wind, causing sand dunes of the Southern Permian Basin to migrate westwards under the influence of northeast tradewinds. The axis of the Southern Permian Basin subsided more rapidly than the rate of sediment infill, with the result that the central basin floor intersected the regional water table to form a large shallow saline lake surrounded by a sabkha. With ensuing fluctuations in climate, the lake precipitated up to 16 beds of halite, controlled, it is thought (e.g. Glennie, 1998), by Gondwanan glacially induced increases in aridity and related falls in both global sea level and terrestrial water tables. The greatest rate of subsidence occurred over Germany, where the Upper Rotliegend 2 has a post-compaction thickness of almost 2500 m (McCann, 1998), compared to a maximum thickness of about 300 m in the UK southern North Sea (cf. Glennie & Boegner, 1981; Glennie, 1997).

5.2 Zechstein transgression

The rising level of a boreal sea transgressing southwestwards between Greenland and Norway was probably the result of yet more interglacial melting of Gondwanan icecaps; it eventually caused seawater to flow southwards along the incipient Viking and Central graben systems and rapidly flooded both the Northern and Southern Permian basins. At that time, because of subsidence, the surfaces of the two Permian basins are estimated to have been as much as 250–300 m below global sea level (Smith, 1979; Ziegler, 1990; Plein, 1993; Glennie, 1998). The seas that resulted within these enclosed tropical basins at first became the sites of Zechstein limestone deposition. With each successive depositional cycle, limestone was progressively succeeded by evaporites, including halite, thick sequences of which were to form almost perfect seals for the Carboniferous gas that later filled Rotliegend reservoirs.

The importance in continental Europe of the line of weakness formed by the closure of the Tornquist Sea, marking the southern edge of the Ringkøbing–Fyn High, has already been mentioned. Arguably of greater structural importance today is the Sorgenfrei–Tornquist–Teisseyre zone of shearing that extends across the Kattegat and northern Denmark to the Polish Trough (e.g. fig. 10 in Vejbaek, 1997). Its development was probably heralded by the latest Carboniferous creation of half-grabens and associated volcanic activity; an underlying Upper Carboniferous clastic sequence was deposited before rifting began. As the rift sequences are overlain by Zechstein-age siliciclastic strata, most fault rotation is presumed to have occurred during Rotliegend time (Michelsen & Nielsen, 1993). Low-grade metamorphism marks the flank of the Polish anticlinorium adjacent to the Tornquist–Teisseyre zone.

6. Outline of post-Rotliegend structural development

As the pattern of crustal tension and compression changed with time, subsidence continued intermittently in much of the North Sea area, punctuated by more localized episodes of uplift and erosion. Such subsidence histories are characterized by many published burial curves (e.g. van Wijhe et al., 1980; Glennie & Boegner, 1981; Oele et al., 1981). Coals generate gas when they are buried and affected by warming to perhaps 100°C or so (e.g. Cornford, 1998). At a depth of about 6 km (~180°C, depending on a temperature gradient of, say, 25–35°Ckm^{-1}) coals are post-mature for gas generation. For optimum exploration, therefore, it is important to know the likely burial history and temperature ranges to which the coals have been subjected, in order to predict the possible presence or absence of gas in any particular sub-basin or structure.

As can be seen in (Figure 8), the greatest burial depths for Rotliegend rocks of 8 km or more are in parts of the Viking and Central grabens, along the Sorgenfrei–Tornquist zone of shearing (where

Triassic and Middle Jurassic tectonically controlled depocentres became areas of inversion in the Late Cretaceous and Early Tertiary), and in the central part of the Southern Permian Basin, where subsidence, initiated in the early Late Permian, has obviously continued for much of its ensuing history. Deep troughs also occur locally in the Western Approaches, where Coal Measures are not known to exist, and in the eastern Celtic Sea where possibly they do.

Deep burial of Rotliegend reservoir sandstones has resulted in several diagenetic changes that, depending on proximity to Carboniferous shales across faults, for example, include the creation of permeability-destroying illite whiskers below about 3000 m (Glennie et al., 1978; Gaupp et al., 1993). (Figure 8) also shows that the Ringkøbing–Fyn High has remained a relatively stable area since the Permian, with an accumulation of no more than 2000 m of strata over its crestal area; this also applies to a lesser extent to the Mid North Sea High.

7. Conclusions

The Carboniferous to Permian depositional environment of England and the greater southern North Sea area inherited structural controls that date back to the Siluro–Devonian Caledonian closure of the Iapetus Ocean and the ensuing Permo–Carboniferous Variscan Orogeny. The main features are:

- Iapetus related
    - Inheritance in the early Late Permian of the Iapetus Suture by the north–south trending Viking Graben of the northern North Sea, and its southwest–trending arm between England and Scotland.
    - Inheritance of the suture formed by closure of the Tornquist Sea, which led to development of the northwest–southeast-trending Mid-Devonian seaway picked out by alignment of the Auk, Argyll, 38/3-1 and German Q-1 wells; the suture probably controlled the orientation of the northwest–southeast-trending portion of the Central Graben between the Mid North Sea and Ringkøbing–Fyn highs.
- Tornquist Sea-related: minor Late Ordovician shearing related to closure of the Tornquist Sea by the docking of Avalonia along the southern edge of Baltica.
- Variscan Orogeny: progressive collision between the united Laurentia–Baltica and the northward-moving Armorica and Gondwanan plates led to the Variscan Orogeny.
    - The earliest evidence of this collision is possibly the sharp 45° bend in the Iapetus Suture and its intersection with the Tornquist Suture in the Mid-Devonian.
    - The Early Carboniferous structures draped around the Midland Platform have a southwest trend west of England subparallel to the western Iapetus Suture and a southeast trend over and to the east of England subparallel to the Tornquist Suture.
    - From at least the Mid-Devonian onwards, a major west–east orientated linear basin developed between Appalachia and central Europe, parallel to the Variscan orogenic front. A successor to this basin was the site of extensive coal deposition. As the Variscan Orogeny advanced northwards, the linear Late Carboniferous basin became narrower as southern components were uplifted and deformed, leading to many intermontane basins in northern France and central Germany.
    - North of the Variscan deformation front, the basin's Late Devonian and Carboniferous sedimentary fill was gently folded and locally eroded during the Early Permian, a time of widespread volcanism, especially in Germany.
    - Thermal cooling, coupled with a continuing orogenic push from the south, resulted in the coeval development of the Southern and Northern Permian basins and their intervening structural high. At the same time, the southern push seems to have initiated development of the Central and Viking graben system by inducing west–east tension across the area.

The economic importance of the Carboniferous was based on its coals, which not only fuelled the Industrial Revolution of the eighteenth and nineteenth centuries but also sourced the large volumes of methane found in so many of the Rotliegend and, to a much lesser extent, Carboniferous gasfields that are spread across the southern North Sea, The Netherlands and northwest Germany; halites of the latest Permian Zechstein succession form excellent top seals to the accumulations of Rotliegend gas.

A continuing history of structural tension and compression has resulted in both basin development and inversion over different parts of the Southern Permian Basin. Differential uplift, especially in the Late Jurassic and Late Cretaceous, halted gas generation locally, only for it to resume again locally after Late Cainozoic subsidence.

Acknowledgements

Shell UK is thanked for draughting six of the figures and Barry Fulton of Aberdeen University for the other two.

*References

Besly, B. M. 1998. Carboniferous. In *Petroleum geology of the North Sea: basic concepts and recent advances* (4th edn), K. W. Glennie (ed.), 104–136. Oxford: Blackwell Science.

Bruce, D. & L. Stemmerik 2003. Carboniferous. In *The millennium atlas: petroleum geology of the central and northern North Sea*, D. Evans, C. Graham, A. Armour, P. Bathurst (eds & coordinators), 83–9. London: Geological Society.

Calder, J. H. 1998. The Carboniferous evolution of Nova Scotia. In *Lyell: the past is the key to the present*, D. J. Blundell & A. C. Scott (eds), 261–302. Special Publication 143, Geological Society, London.

Chadwick, R. A., D. W. Holliday, S. Holloway, A. G. Hulbert 1995. *The structure and evolution of the Northumberland–Solway Basin*. Subsurface Memoir, British Geological Survey, Keyworth, Nottingham.

Cocks, L. R. M. & R. A. Fortey 1982. Faunal evidence for oceanic separation in the Palaeozoic of Britain. *Geological Society of London, Journal* 139, 465–78.

Cocks, L. R. M. & T. H. Torsvik 2002. Earth geography from 500 to 400 million years ago: a faunal and palaeomagnetic review. *Geological Society of London, Journal* 159, 631–44.

Corfield, S. M., R. L. Gawthorpe, M. Fraser, A. J. Gage, B. M. Besly 1996. Inversion tectonics of the Variscan Foreland of the British Isles. *Geological Society of London, Journal* 153, 17–32.

Cornford, C. 1998. Source rocks and hydrocarbons of the North Sea. In *Petroleum geology of the North Sea: basic concepts and recent advances* (4th edn), K. W. Glennie (ed.), 376–462. Oxford: Blackwell Science.

Coward, M. P. 1990. The Precambrian, Caledonian and Variscan framework to NW Europe. In *Tectonic events responsible for Britain's oil and gas reserves*, R. F. P. Hardman & J. Brooks (eds), 1–34. Special Publication 55, Geological Society, London.

Coward, M. P., J. F. Dewey, M. Hempton, J. Holroyd 2003. Tectonic evolution. In *The millennium* *atlas: petroleum geology of the central and northern North Sea*, D. Evans, C. Graham, A. Armour, P. Bathurst (eds & co-ordinators), 17–33. London: Geological Society.

Crowell, J. C. 1995. The ending of the Late Paleozoic ice age during the Permian period. In *Permian of northern Pangea*, P. Scholle, T. M. Peryt, N. Scholle-Ulmer (eds), 62–74. Berlin: Springer.

Edwards, R. A., G. Warrington, R. C. Scrivener, N. S. Jones, H. W. Haslam, L. Ault 1997. The Exeter Group, south Devon, England: a contribution to the early post-Variscan stratigraphy of northwest Europe. *Geological Magazine* 134, 177–97.

Francis, E. H. 1991. Carboniferous–Permian igneous rocks. In *Geology of Scotland* (3rd edn), G. Y. Craig (ed.), 393–420. London: Geological Society.

Fraser, A. J. & R. L. Gawthorpe 1990. Tectono-stratigraphic development and hydrocarbon habitat of the Carboniferous in northern England. In *Tectonic events responsible for Britain's oil and gas*, Hardman, R. F. P. & J. Brooks (eds), 49–86. Special Publication 55, Geological Society, London.

Friend, P. F., B. P. J. Williams, M. Ford, E. A. Williams 2000. Kinematics and dynamics of Old Red Sandstone basins. In *New perspectives on the Old Red Sandstone*, P. F. Friend & B. P. J. Williams (eds), 29–60. Special Publication 180, Geological Society, London.

Gaupp, R., A. Matter, J. Platt, K. Ramseyer, J. Walzebuck 1993. Diagenesis and fluid evolution of deeply buried Permian Rotliegende gas reservoirs, northwest Germany. *American Association of Petroleum Geologists, Bulletin* 77, 1111–28.

Gebhardt, U., J. Schneider, N. Hoffmann 1991. Modelle zur Stratigraphie und Beckenentwicklung im Rotliegenden der Norddeutschen Senke. *Geologische Jahrbuch* 127, 405–427.

Glennie, K. W. 1997. Recent advances in understanding the Southern North Sea Basin: a summary. In *Petroleum geology of the southern North Sea: future potential*, K. Ziegler, P. Turner, S. R. Daines (eds), 17–29. Special Publication 123, Geological Society, London.

Glennie, K. W. 1998. Lower Permian–Rotliegend. In *Petroleum geology of the North Sea: basic concepts and recent advances* (4th edn), K. W. Glennie (ed.), 137–73. Oxford: Blackwell Science.

Glennie, K. W. 2002. Permian and Triassic. In *The geology of Scotland* (4th edn), N. H. Trewin (ed.), 301–321. London: Geological Society.

Glennie, K. W. & P. Boegner 1981. Sole Pit inversion tectonics. In *Petroleum geology of the continental shelf of northwest Europe*, L. V. Illing & G. P. Hobson (eds), 110–20. London: Institute of Petroleum.

Glennie, K. W. & J. R. Underhill 1998. Origin, development and evolution of structural styles. In *Petroleum geology of the North Sea: basic concepts and recent advances* (4th edn), K. W. Glennie (ed.), 42–84. Oxford: Blackwell Science.

Glennie, K. W., G. C. Mudd, P. J. C. Nagtegaal 1978. Depositional environment and diagenesis of Permian Rotliegendes sandstones in Leman Bank and Sole Pit areas of the UK southern North Sea. *Geological Society of London, Journal* 135, 25–34.

Glennie, K. W., J. Higham, L. Stemmerik 2003. Permian. In *The millennium atlas: petroleum geology of the central and northern North Sea*, D. Evans, C. Graham, A. Armour, P. Bathurst (eds & co-ordinators), 90–103. London: Geological Society.

Glover, B. W., J. H. Powell, C. N. Waters 1993. Etruria Formation (Westphalian C) palaeoenvironments and volcanicity on the southern margins of the Pennine Basin, south Staffordshire, England. *Geological Society of London, Journal* 150, 737–50.

Gralla, P. 1988. Das Oberrotliegende in NW-Deutschland – Lithostratigraphie und Faziesanalyse. *Geologisches Jahrbuch A* 106, 5– 39.

Guion, P. D., P. Gutteridge, S. Davies 2000. Carboniferous sedimentation and volcanism on the Laurussian margin. In *Geological history of Britain and Ireland*, N. Woodcock & R. Strachan (eds), 227–70. Oxford: Blackwell Science.

Hallsworth, C. R. & J. I. Chisholm 2000. Stratigraphic evolution of provenance characteristics in Westphalian sandstones of the Yorkshire coalfield. *Yorkshire Geological Society, Proceedings* 53, 43–72.

Hoffmann, N., H-J. Kamps, J. Schneider 1988. Neuerkentnisse zur Biostratigraphie und Palaodynamik des Perms in der Nordostdeutschen Senks – ein Diskussionsbeitrag. *Zeitschrift für Angewandte Geologie* 35, 189–207.

Hollywood, J. M. & C. V. Whorlow 1993. Structural development and hydrocarbon occurrences of the Carboniferous in the UK Southern North Sea Basin. In *Petroleum geology of northwest Europe: proceedings of the 4th conference*, J. R. Parker (ed.), 689–96. London: Geological Society.

Jin, Yugan, B. R. Wardlaw, B. F. Glenister, G. V. Kotlyar 1997. Permian chronostratigraphic subdivisions. *Episodes* 20, 10–15.

Kirby G. A., H. E. Baily, R. A. Chadwick, D. J. Evans, D. W. Holliday and 5 other authors 2000. *The structure and evolution of the Craven Basin and adjacent areas*. Subsurface Memoir, British Geological Survey, Keyworth, Nottingham.

Kockel, F. 1995. *Structural and palaeogeographical development of the German North Sea sector*. Berlin: Gebrüder Borntraeger.

Marshall, J. E. A. & A. Hewett 2002. Devonian. In *The millennium atlas: petroleum geology of the central and northern North Sea*, D. Evans & C. Graham (eds), 65–81. London: Geological Society.

Marshall, J. E. A., D. A. Rogers, M. J. White 1996. Devonian marine incursions into the Orcadian Basin, Scotland. *Geological Society of London, Journal* 153, 451–66.

McCann, T. 1998. The Rotliegend of the NE German Basin: background and prospectivity. *Petroleum Geoscience* 4, 17–27.

Menning, M. 1995. A numerical timescale for the Permian and Triassic periods: an integrated time analysis. In *Permian of northern Pangea*, P. Scholle, T. M. Peryt, N. Scholle-Ulmer (eds), 77–97. Berlin: Springer.

Michelsen, O. & L. H. Nielsen 1993. Structural development of the Fennoscandian Border Zone, offshore Denmark. *Marine and Petroleum Geology* 10, 124–34.

Oele, J. A., A. C. P. J. Hol, J. Tiemans 1981. Some Rotliegend gas-fields of the K and L blocks, Netherlands offshore (1968–1978) – a case history. In *Petroleum geology of the continental shelf of northwest Europe*, L. V. Illing & G. D. Hobson (eds), 289–300. London: Institute of Petroleum.

Plein, E. 1993. Bemerkungen zum Ablauf der paläeogeographischen Entwicklung im Stephan und Rotliegend des Norddeutschen Beck-ens. In *Perm im Ostteil der Norddeutschen Senke* [*Geologisches Jahrbuch A* 131], E. P. Müller & H. Porth (eds), 99–116. Stuttgart: Schweitzerbart’sche.

Plein, E. (compiler) 1995. Norddeutsches Rotliegendbecken, Rotliegend-monographie, Teil II: Stratigraphie von Deutschland. *Courier Forschungsinstitut Senckenberg* 183.

Richmond, L. K. & B. P. J. Williams 2000. A new terrane in the Old Red Sandstone of the Dingle Peninsula, southwest Ireland. In *New perspectives on the Old Red Sandstone*, P. F. Friend & B. P. J. Williams (eds), 147–83. Special Publication 180, Geological Society, London.

Ritchie, J. S. & P. Pratsides 1993. The Caister fields, block 44/23a, UK North Sea. In *Petroleum geology of northwest Europe: proceedings of the 4th conference*, J. R. Parker (ed.), 759–69. London: Geological Society.

Robson, D. 1991. The Argyll, Duncan and Innes fields, blocks 30/24 and 30/25a, UK North Sea. In *United Kingdom oil and gasfields, 25 years commemorative volume*, I. L. Abbotts (ed.), 219–325. Memoir 14, Geological Society, London.

Rogers, D. A., J. E. A. Marshall, T. R. Astin 1989. Devonian and later movements on the Great Glen Fault system. *Geological Society of London, Journal* 146, 369–72.

Schneider, J. W. 1996. Biostratigraphie des kontinentalen Oberkarbon und Perm im Thüringer Wald, SW-Saale-Senke – Stand und Probleme. *Beitrage zur Geologie von Thüringen* 3, 121–51.

Schneider, J. W. 2001. Rotliegendstratigraphie – Prinzipien und Probleme. *Beitrage zur Geologie von Thüringen* 8, 7–42.

Schneider, J. W. & U. Gebhardt 1993. Litho- und Biofaziesmuster in intra- und extramontanen Senken des Rotliegend (Perm, Nord- und Ostdeutschland). In *Perm im Ostteil der Norddeutschen Senke*, E. P. Müller & H. Porth (eds), 57–98. *Geologisches Jahrbuch A* 131.

Schneider, J. W., R. Rössler, B. Gaitzsch 1995. Time lines of the Late Variscan volcanism – holostratigraphic synthesis. *Zentralblatt für Geologie und Palaontologie* 1, 477–90.

Scotese, C. R. & S. F. Barrett 1990. Gondwana’s movement over the South Pole during the Palaeozoic: evidence from lithological indicators of climate. In *Palaeozoic palaeogeography and biogeography*, W. S. McKerrow & C. R. Scotese (eds), 75–85. Memoir 12, Geological Society, London.

Scotese, C. R. & W. S. McKerrow 1990. Revised world maps and introduction. In *Palaeozoic palaeogeography and biogeography*, W. S. McKerrow & C. R. Scotese (eds), 1–21. Memoir 12, Geological Society, London.

Scott, A. C. 1998. The legacy of Charles Lyell: advances in our knowledge of coal and coal-bearing strata. In *Lyell: the past is the key to the present*, D. J. Blundell & A. C. Scott (eds), 243–60. Special Publication 143, Geological Society, London.

Smith, D. B. 1979. Rapid marine transgressions and regressions of the Upper Permian Zechstein Sea. *Geological Society of London, Journal* 136, 155–6.

Stemmerik, L., J. R. Ineson, J. G. Mitchell 2000. Stratigraphy of the Rotliegend Group in the Danish part of the Northern Basin, North Sea. *Geological Society of London, Journal* 157, 1127–36.

Torsvik, T. H., M. A. Smethurst, J. C. Briden, B. A. Sturt 1990. A review of palaeomagnetic data from Europe and their palaeogeographical implications. In *Palaeozoic palaeogeography and biogeography*, W. S. McKerrow & C. R. Scotese (eds), 25–41. Memoir 12, Geological Society, London.

Torsvik, T. H., M. A. Smethurst, J. G.Meert, R. van der Voo, W. S. McKerrow, M. D. Brasier, B. A. Sturt, H. J. Walderhaug 1996. Continental breakup and collision in the Neoproterozoic and Palaeozoic – a tale of Baltica and Laurentia. *Earth Science Review* 40, 229–58.

Trewin, N. H. & M. G. Bramwell 1991. The Auk field, block 30/16, UK North Sea. In *United Kingdom oil and gasfields, 25 years commemorative volume*, I. L. Abbotts (ed.), 227–36. Memoir 14, Geological Society, London.

UNESCO 2002. *International stratigraphic chart*. International Commission on Stratigraphy.

Van Staal, C. R., J. F. Dewey, C. MacNiocaill, W. S. McKerrow 1998. The Cambrian–Silurian tectonic evolution of the northern Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of Iapetus. In *Lyell: the past is the key to the present*, D. J. Blundell & A. C. Scott (eds), 199–242. Special Publication 143, Geological Society, London.

Van Wijhe, D. H., M. Lutz, J. P. H. Kaasschieter 1980. The Rotliegend in the Netherlands and its gas accumulations. *Geologie en Mijnbouw* 59, 3–24.

Vejbaek, O. V. 1997. Dybe structurer I danske sedimentaere bassiner. *Geologisk Tidsskrift* 4, 1–31.

Wardlaw, B. R. 2000. Notes from the SPS Chair. *Permophiles* 36, 1– 3.

Watson, J. & F. W. Dunning 1979. Basement–cover relations in the British Caledonides. In *The Caledonides of the British Isles – reviewed*, A. L. Harris, C. H. Holland, B. E. Leake (eds), 67–91. Special Publication 8, Geological Society, London.

Ziegler, P. A. 1987. *Evolution of the Arctic–North Atlantic and the western Tethys*. Memoir 43, American Association of Petroleum Geologists, Tulsa.

Ziegler, P. A. 1990. *Geological atlas of western and central Europe* (2nd edn). Rotterdam: Shell Internationale Petroleum Maatschappij BV.

Retrieved from
'http://earthwise.bgs.ac.uk/index.php?title=Regional_tectonics_in_relation_to_Permo-Carboniferous_hydrocarbon_potential,_Southern_North_Sea_Basin&oldid=45606'
Category:

- Carboniferous hydrocarbon resources: the southern North Sea and surrounding onshore areas

Navigation menu

Personal tools

- Not logged in
- Talk

- Contributions
- Log in
- Request account

Namespaces

- Page
- Discussion

☐

Variants

Views

- Read
- Edit
- View history
- PDF Export

☐

More

Search

Search Go

Navigation

- Main page
- Recent changes
- Random page
- Help about MediaWiki

Tools

- What links here
- Related changes
- Special pages
- Permanent link
- Page information
- Cite this page
- Browse properties

- This page was last modified on 11 May 2020, at 11:13.

- Privacy policy
- About Earthwise