THE HYDROCARBON PROSPECTIVITY OF BRITAIN'S ONSHORE BASINS

Department
of Energy &
Climate Change

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Foreword

This report has been produced under contract by the British Geological Survey (BGS). It is based partly on BGS confidential reports compiled for the Department of Energy (now Department of Energy and Climate Change) during the 1980s and partly on more recent analysis, together with published data and interpretations.

Additional information is available at the Department of Energy and Climate Change (DECC) website. https://www.gov.uk/oil-and-gas-onshore-exploration-and-production#resumption-of-shale-gas-exploration.   This includes licensing regulations, maps, monthly production figures, basic well data and where to view and purchase released well and seismic data.

Onshore seismic data and stratigraphic tops for wells are available at www.ukogl.org.uk

DECC has now published the technical reports etc acquired or produced for Landward licences following the expiration of the confidentiality period provided for by the licence together with the "Appendix B" licence application documents submitted for the 1st to 8th Landward licensing rounds. Also now available are Field Development Plans and Annual Field Reports for fields where the confidentiality period provided for by the relevant licence has expired. This information can be purchased from Mosaic Information Solutions on behalf of the DECC. If you require more information please contact: Ian Picton, Mosaic Information Solutions (email: ian@mosaicis.com). Relinquishment reports for some Landward licences can be found on the DECC website for download free of charge at

https://www.og.decc.gov.uk/web_files/relinqs/relinqs.htm

A glossary of terms used and equivalences is tabled at the end of the report.

Acknowledgements

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The seven photographs (Figs. 2.5, 2.6, 2.7, 4.1, 7.5, 7.6 and 8.1) were supplied by the British Geological Survey and are the copyright of the Natural Environment Research Council, NERC.

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Abbreviations and equivalences used in report.

1 Geological overview

This section provides a general synopsis of the petroleum systems of the United Kingdom's onshore basins. Unconventional energy systems are not considered. The following sections provide basic data for each basin or area. The coverage begins with Mesozoic petroleum systems in the south of England (Fig. 1.1), followed by late Palaeozoic petroleum systems in central England, northern England and southern Scotland. Section 9 suggests some future, untested plays. The concluding section describes concisely the state of exploration and prospectivity. The reference section is a comprehensive bibliography relating to onshore exploration and development.
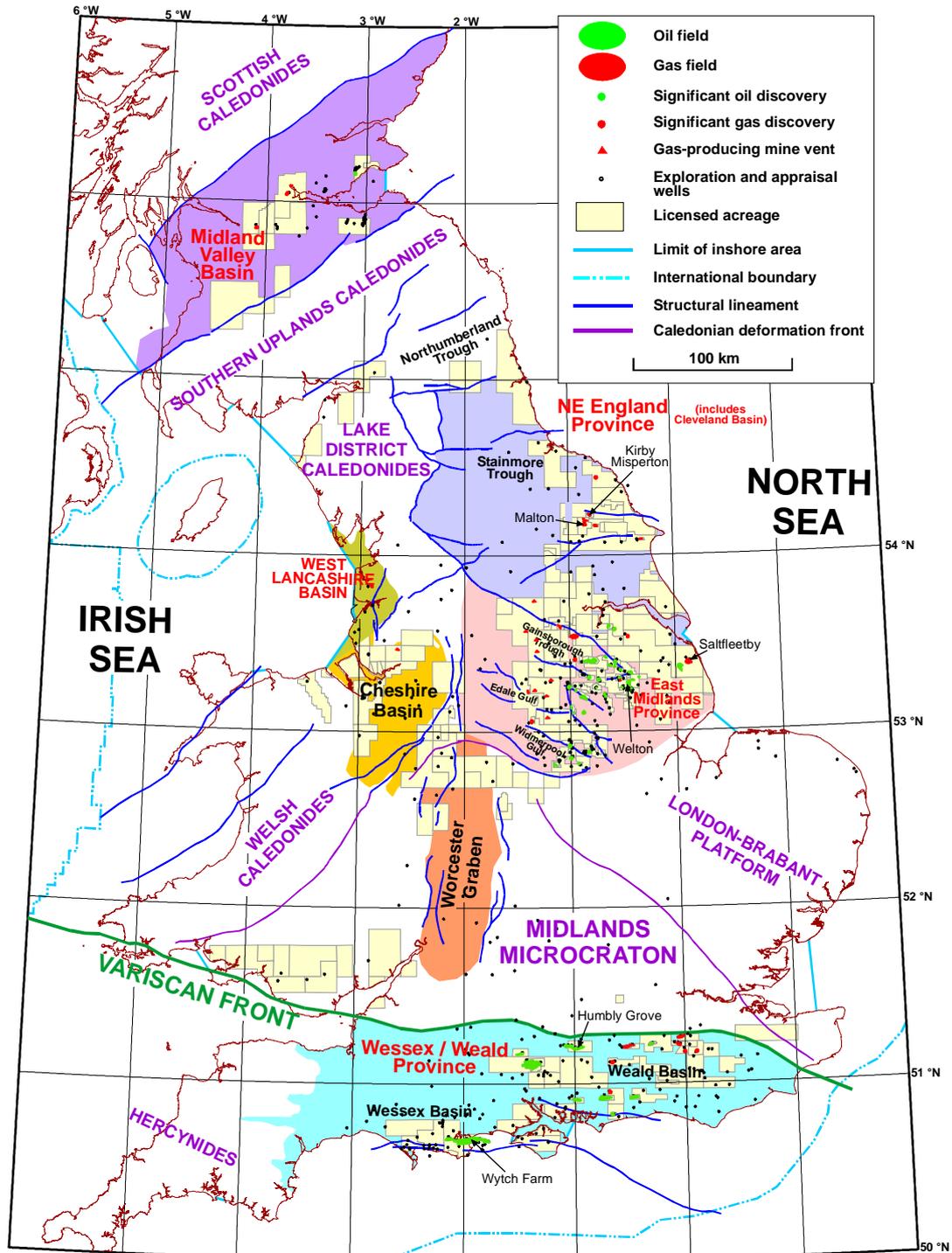
Fig. 1.1   Principal UK Onshore Hydrocarbon Provinces

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The Department of Energy and Climate Change's (DECC) onshore licence area includes some offshore areas, specifically estuaries e.g. in the Solway and seas between islands e.g. the Minch between the inner and outer Hebrides, NW of Scotland (Fig. 1.1). Geographical coordinates of these areas may be found here. A map showing the current onshore licensing situation is available here. Northern Ireland issues its own Licences to cover its onshore area, contact the Department of Enterprise, Trade and Investment's Energy Division, tel: 028 9052 9900 for more details.

For the purposes of describing hydrocarbon prospectivity, the onshore United Kingdom can be divided into productive basins, potentially productive basins and those where the prospectivity is less attractive. On figure 1.1 productive basin names and provinces are shown in red, potentially productive in blue and adjacent offshore basins in black. The productive or historically productive basins are: Wessex (section 2), Weald (3), West Lancashire (5), Cleveland (6), the East Midlands oil province (7, also known as Carboniferous Pennine Basin) and the Midland Valley of Scotland (8). The potentially productive basin reviewed is the Cheshire Basin (4). The Wessex and Weald basins both extend offshore into the English Channel, but only their onshore components are described. Similarly, the West Lancashire Basin is the eastern, onshore margin of the more extensive East Irish Sea Basin, and the Cleveland Basin is essentially the onshore extension of the Southern North Sea gas basin.

The productive basins have been explored for about 100 years and are now essentially at a mature stage of exploration. The average oilfield size is 2.1 million barrels (excluding Wytch Farm Oilfield, Fig. 1.2). Saltfleetby is the largest producing gas field, with recoverable reserves of 2.08 bcm (Fig. 1.3). Detailed statistics for producing fields are available here.
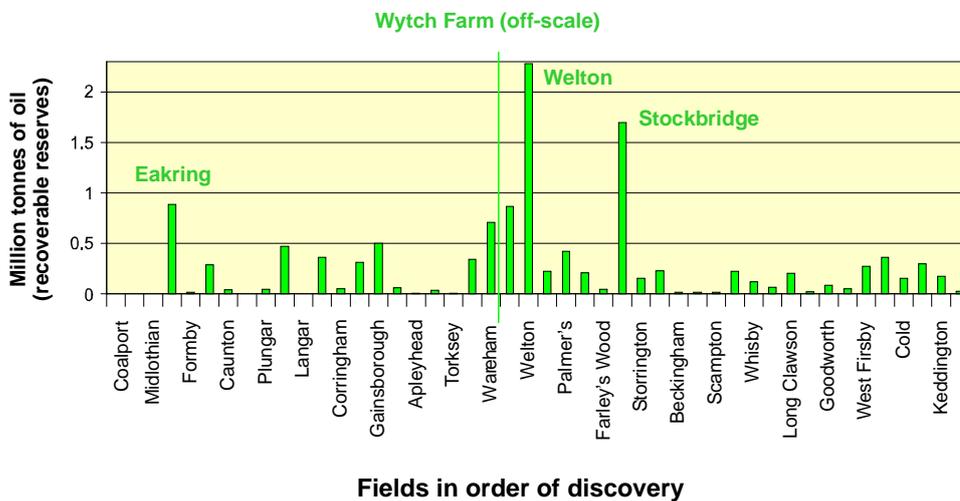
Fig. 1.2 Discovery sequence and operators' estimates of recoverable reserves in UK onshore oil fields
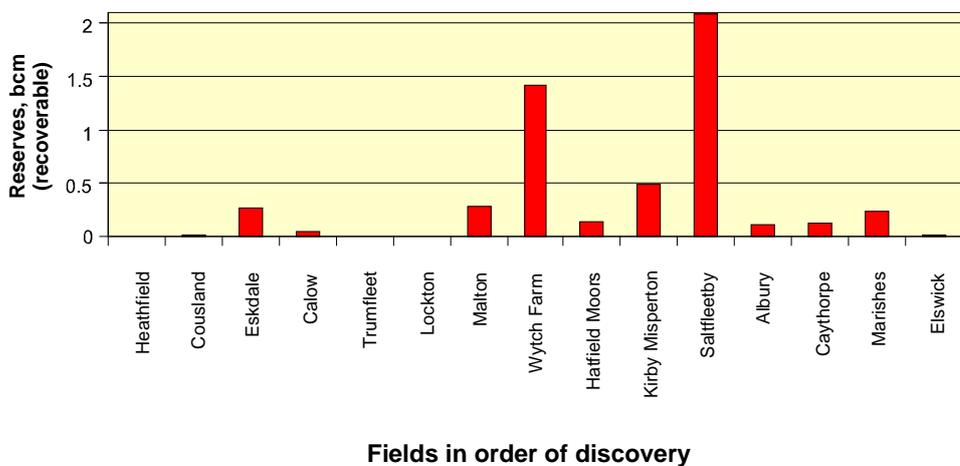
Fig. 1.3 Discovery sequence and operators' estimates of recoverable reserves in UK onshore gas fields

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Potentially prospective open acreage is currently available in the north of the East Midlands province (based on a hydrocarbon model) and in the Weald where small, possibly forgotten discoveries exist. The northern margin of the Cleveland Basin, in NE England, is under-explored, with unlicensed areas and an old oil discovery (BP's Fordon 1) that has not been followed up in recent years.

Of the potentially productive areas with good hydrocarbon shows, the Cheshire Basin offers the best prospects and has unlicensed acreage. This conclusion is based on the application of the East Midlands petroleum system to the Carboniferous underlying the Cheshire Basin. Recent exploration here concentrated on the overlying Triassic Helsby Sandstone play at shallow depths. There are two other Carboniferous plays near Edgmond and between Manchester and Buxton, which have not been tested adequately. Additional seismic reflection data is required in these areas. The Palaeozoic play of the Midland Microcraton (Fig. 1.1) is hypothetical at present. Limited exploration data make this a far higher risk venture, though some operators are currently pursuing this play.

DATA SOURCES

The onshore section of DECC's website provides comprehensive data and information on exploration and development.

Both well and seismic data are released after 5 years (or earlier if the operator concerned agrees).

Released seismic reflection data is available through the United Kingdom Onshore Geophysical Library (UKOGL), whose website shows the coverage available and details of how to obtain data.

Released well data is available from IHS Energy Group. Details on how to view or obtain well data can be found here.

Additional geological information is available from Nigel Smith at the British Geological Survey or the British Geological Survey website.

HISTORY

Onshore exploration has been episodic. Each of six principal phases of exploration has yielded some success (Evans 1990).

1 Up to early 1900s: two small companies actively exploring in geographically small areas and rare opportunistic drilling in other areas; limited oil production from accidental discoveries in coal workings (e.g. Coalport Tar Tunnel),

2 1919-1922: American-advised exploration on surface anticlines in Carboniferous rocks in northern England and Scotland,

3 1936-1960s: BP (then called D'Arcy) and Esso (Anglo-American) dominated exploration,

4 1960s-1980: a period of increased drilling, but sometimes without seismic control e.g. wells drilled on North Sea coast and East Anglia,

5 1980-1991: modern seismic-based exploration with BP, Shell, Amoco, Conoco and some smaller companies,

6 1991-present: BP sold off its smaller production and data and other large companies pulled out; smaller companies now dominate exploration.

A few important lessons can be learnt from these exploration efforts and the build up to them. In at least two instances, fields have been discovered by drilling deeper than previous shallow oil exploration wells. J Ford predicted the discovery of the East Midlands oilfields in discussion of a pessimistic paper (Dalton 1918), but he failed to convince backers to drill again at Kelham. The Formby oil seeps, known about in the 17th century and referred to in the 19th century, were forgotten until Cope remapped them, leading to the discovery of the very shallow Formby Oilfield in 1939. BP had abandoned the Weald Basin twice already, when in the early 1980s Carless made the key breakthrough by using seismic reflection data to resolve the migration paths in the basin, and by targeting pre-Cretaceous faulted blocks on the margins of the basin, rather than drilling the surface Tertiary (Alpine) anticlines.

Occasionally the very large structure in a licence has been drilled, rather than the productive targets in a nearby discovery, and the main attributes of this discovery are lost sight of, or not appreciated by adjacent licence holders.

There is attractive acreage in the Carboniferous Pennine Basin between the East Midlands oil province and the East Irish Sea discoveries where no hydrocarbon discoveries have been made. This observation offers hope for new discoveries.

PETROLEUM SYSTEMS

There are two main petroleum systems in the UK onshore - a wholly Mesozoic petroleum system in southern England (Fig.1.4), and a northern England petroleum system involving long-lived generation from mid- to late Carboniferous source rocks and migration into reservoirs of Carboniferous to Triassic age (Fig. 1.5). In Scotland, an older Carboniferous source rock has supplied hydrocarbons, retained within Dinantian (Lower Carboniferous) reservoirs.
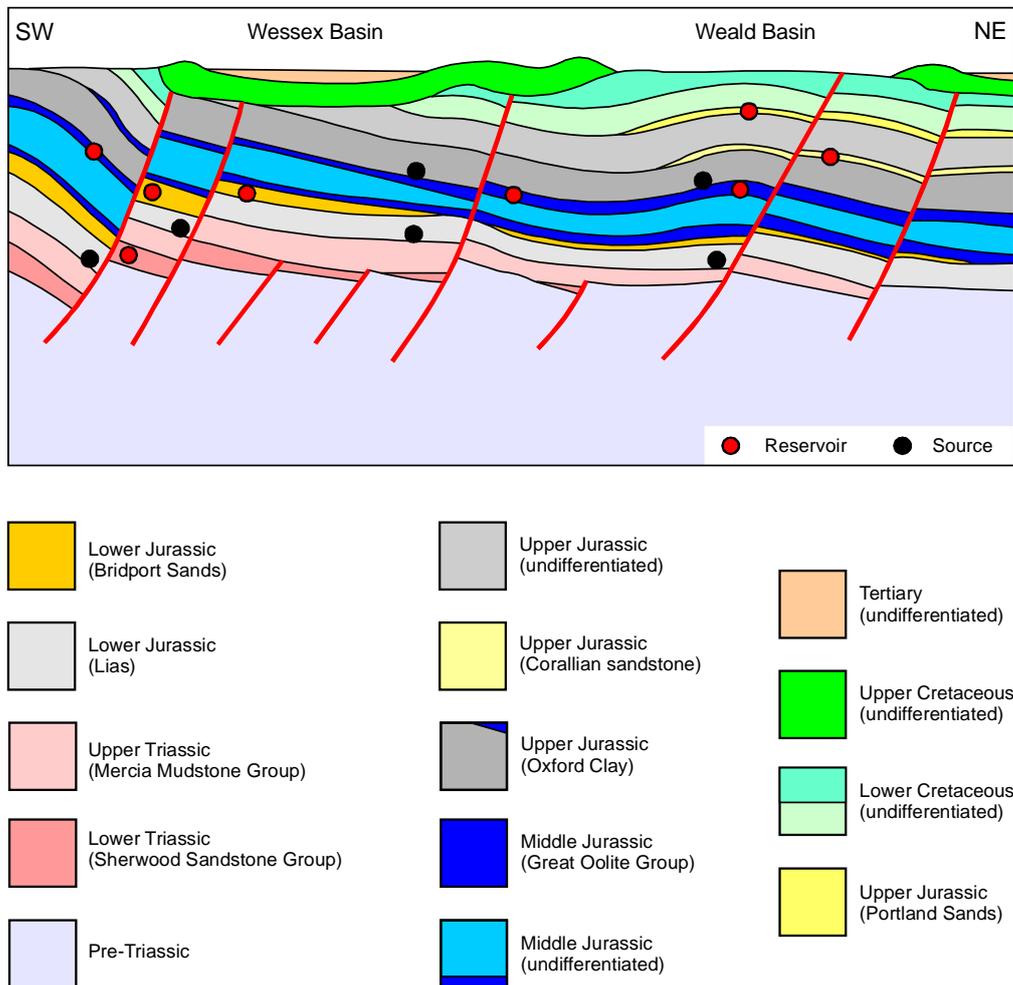
Fig. 1.4   Summary of southern England petroleum system

Southern England petroleum system (see Fig. 1.4)

Early Jurassic shales in southern England have matured to generate oil and some gas in the Wessex and Weald basins. Migration has occurred largely within Jurassic strata to the margins of both basins into carbonate reservoirs. Younger immature shales provide the seals to these reservoirs and very few shows are present above the Cimmerian (early Cretaceous) unconformity. Alpine inversion was the more intense in the Wessex Basin, juxtaposing older (early Jurassic and Triassic) clastic reservoirs against the early Jurassic source rocks. The producing fields are located on Jurassic-early Cretaceous palaeo-highs concealed by post-Cimmerian unconformity strata. Some later migration of hydrocarbons into Alpine structures has occurred, but many of the surface anticlines are dry. Surface shows are limited to where erosion has exposed Jurassic-early Cretaceous strata.

Northern England petroleum system
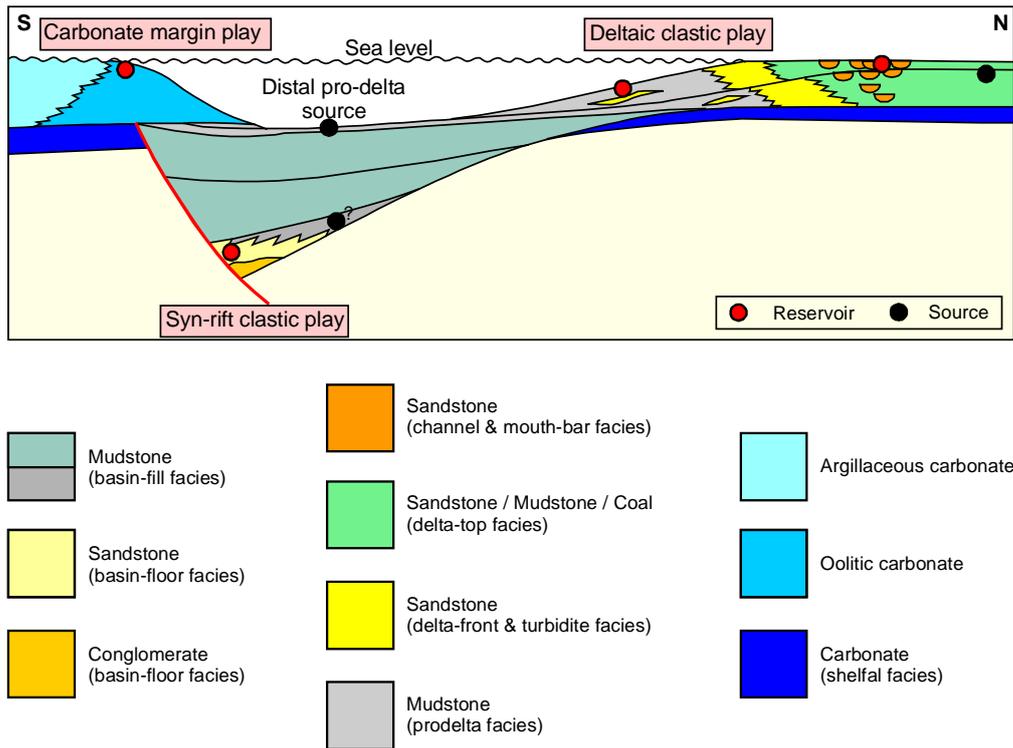
Fig. 1.5 Summary of the Carboniferous petroleum system in the East Midlands province

Northern England is dominated topographically by the N-S orientated Pennine Hills. The southern part of this line of hills contains the inverted Pennine Basin, which is part of a major Carboniferous basin extending from eastern Europe to Ireland. In the Pennine Basin, there are oil-prone source rocks in early Namurian shales, and gas-prone source rocks include Westphalian coals. The latter source rocks have supplied gas to reservoirs in most NW European countries. Maturation of both these source rock intervals began in Carboniferous times, before uplift caused by the end-Carboniferous, Variscan Orogeny. In the East Midlands province, maturation resumed in Permian and later times caused by 0-2000 m burial. In the west of the Pennines extensive Permo-Triassic faulting led to greater burial of Carboniferous strata (>4000m in some places). Maturation of its source rocks has progressively extended to the southern margins of the original Carboniferous Pennine Basin.

Oil shows are almost wholly restricted to Carboniferous strata in the East Midlands. Farther north and with greater burial oil has migrated into Triassic reservoirs (Formby Oilfield, West Lancashire Basin), where shows are present in Mesozoic strata. Gas has been generated in the areas of greatest end-Carboniferous Variscan inversion, probably from source rocks older than Westphalian (Cleveland and West Lancashire basins). This gas has been mainly trapped in Permian reservoirs in an extension of the Southern Gas Basin of the North Sea and the East Irish Sea Basin respectively.

In the Scottish Midland Valley, a slightly different petroleum system is based on Dinantian oil shale source rocks and interbedded clastic reservoirs. Upper Carboniferous coals are immature for gas generation here, except at the base of the sequence. Migration has occurred into the adjacent anticlines, which are reverse-fault controlled. There are no overlying Mesozoic strata.

2 Wessex Basin

INTRODUCTION

The Wessex Basin is one of two productive basins in southern England (Fig. 1.1), with oil and some gas production from Jurassic and Triassic reservoirs. Its producing fields include Wytch Farm, Wareham and Kimmeridge. Its petroleum system (Fig. 1.5) comprises Lower Jurassic source rocks, with migration from the Portland-Wight (or Channel) Sub-basin into Lower Jurassic and Triassic clastic reservoirs on the basin margin, beneath a Tertiary syncline.

The Wessex and Weald basins are separated by the Hampshire-Dieppe High (Fig. 2.1), although the boundary between the two is not precise, and at times they probably formed a single depositional basin (Scott & Colter, 1987). The basins display many similarities in tectonic and stratigraphic evolution through early Triassic to Tertiary times, similarities reflecting the regional influences of Atlantic margin rift-subsidence processes and subsequent Tertiary (Alpine) inversion tectonics. The basin-fills and stratigraphy illustrate the close similarities in their evolution (Fig. 2.2). However, differences are seen in the Permian and early Triassic fills both between and within basins. The Triassic Sherwood Sandstone Group is thicker in the Wessex Basin, especially in troughs or graben, but it also thins and onlaps onto palaeo-highs such as the Cranborne-Fordingbridge High (e.g. Bristow *et al*. 1995). In contrast, there is limited evidence for Permo-Triassic deposition in the Weald Basin (Penn *et al*. 1987; Scott & Colter 1987; Hawkes *et al*. 1998). Subsequent basin evolution was more closely linked, with thick Mesozoic sequences developed in extensional grabens.
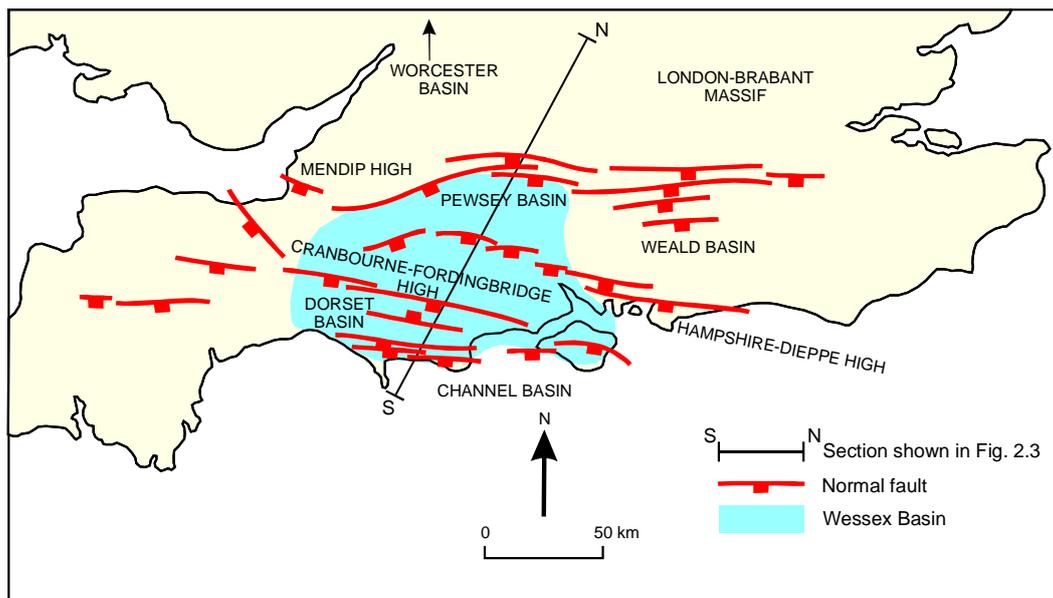
Fig. 2.1   Principal structural features of the Wessex Basin

In gross terms, the two basins show that the extensional graben depocentres, initiated in Permo-Triassic times, underlie regional upwarps that were formed by bulk shortening of the graben-fill. The overall effect (Fig. 2.3) has been to convert the former Mesozoic depocentres into structural highs (e.g. the Weald Anticline overlies the Weald Basin, the Portland-Wight High overlies the Portland-Wight Sub-basin) and the former highs now form the Tertiary basins (e.g. the London and Hampshire-Dieppe basins overlie the London Platform and Hampshire-Dieppe highs respectively). Therefore, they illustrate perfectly the principle of structural inversion with the association of structural features of opposite polarity (Cooper & Williams 1989; Hamblin *et al*. 1992; Chadwick 1993). Superimposed upon and delimiting these regional upwarps are more or less linear trending *en echelon* inversion structures. They lie above the main basin controlling normal faults, which suffered reversal of movement during Tertiary compression, the folds typically having the form of monoclinal or periclinal flexures.

TERTIARY			Eroded due to Tertiary Inversion and / or Late Tilting	UNDIFFERENTIATED	
CRETACEOUS	UPPER	CAMPANIAN		UPPER	CHALK
		SANTONIAN			
		CONIACIAN			
		TURONIAN		MIDDLE	
		CENOMANIAN		LOWER	
	LOWER	ALBIAN		UPPER GREENSAND	
		APTIAN		UPPER CIMMERIAN UNCONFORMITY — GAULT / LOWER GREENSAND	
		BARREMIAN - VALANGINIAN	ERODED PRIOR TO GAULT TRANSGRESSION	WEALDEN	
		RYAZANIAN		DURLSTON FORMATION	PURBECK GROUP
JURASSIC	UPPER	PORTLANDIAN		LULWORTH FORMATION	
		VOLGIAN		PORTLAND GROUP	
		KIMMERIDGIAN		KIMMERIDGE CLAY (immature)	
		OXFORDIAN		CORALLIAN	
		CALLOVIAN		OXFORD CLAY AND KELLAWAY BEDS (immature)	
	MIDDLE	BATHONIAN		CORNBRASH / FOREST MARBLE / FROME CLAY / FULLERS EARTH	GREAT OOLITE SERIES
		BAJOCIAN		INFERIOR OOLITE	
	LOWER	TOARCIAN		BRIDPORT SANDS	UPPER LIAS
		PLEINSBACHIAN		THORNCOMBE SANDS / EYPE CLAY	
		SINEMURIAN		LOWER LIAS CLAYS	
		HETTANGIAN			
TRIASSIC		RHAETIAN		PENARTH GROUP	
		NORIAN		UPPER RED MARL	MERCIA MUDSTONE GROUP
		CARNIAN		EVAPORITE SERIES	
		LADINIAN		LOWER RED MARL	
		ANISIAN		SHERWOOD SANDSTONE GROUP	
		SCYTHIAN	NON DEPOSITION		
PERMIAN				AYLESBEARE GROUP AND SILVERTON BRECCIA	
DEVONIAN - CARBONIFEROUS				VARISCAN UNCONFORMITY — VARISCAN BASEMENT	

Depth scale: 500m, 1000m, 1500m, 2000m, 2500m

Fig. 2.2 Stratigraphic position of the principal source rocks and reservoirs of the Wessex Basin

Petroleum production occurs from Jurassic and Triassic reservoirs. Source rock potential exists in the Liassic clays, Oxford Clay and Kimmeridge Clay, all Jurassic, with maximum maturity achieved along the axes of the sub-basins (Fig. 1.5). The critical relationship between the timing of oil generation, migration from the source rock, local structural development and the sometimes-transient continuity of migration pathways cannot be overemphasized. Proper evaluation of all these factors can often lead to an understanding of why not all the adjacent, seemingly identical structures are oil-bearing. Modelling the subsidence history of these basins is, however, difficult and complex due to the effects of Tertiary inversion, erosion and uncertainty in the geothermal gradient.
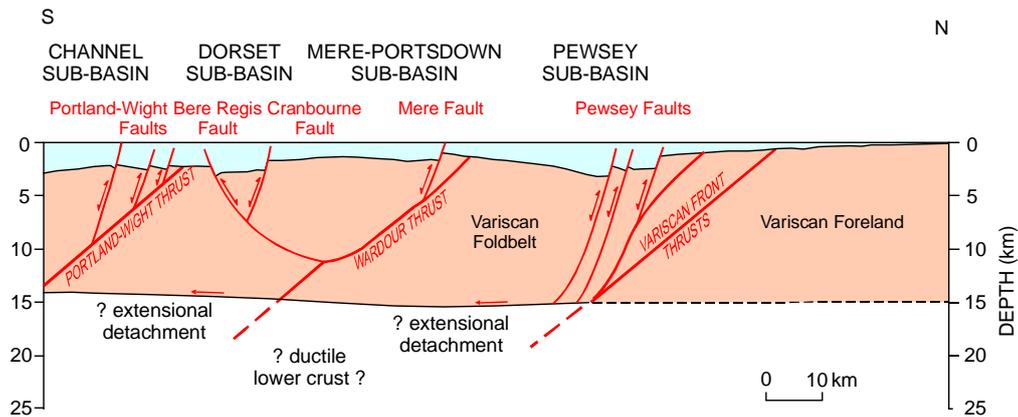
Fig. 2.3   Crustal section across the Wessex Basin, illustrating the influence of extensional reactivation of Variscan thrusts

Despite considerable lateral variations in subsurface temperatures (Gale *et al*., 1984), Butler & Pullan (1990) estimated, from bottom-hole temperatures and drill stem tests, that the present average geothermal gradient is 33° C/km. A larger 48° C/ km average geothermal gradient had been estimated for the basins by Ebukanson & Kinghorn (1986a). Diagenetic studies of the Great Oolite (Middle Jurassic) led Sellwood *et al*. (1989) to suggest that the geothermal gradient in southern England could have been higher than this during the late Jurassic and early Cretaceous.

EXPLORATION HISTORY

The Wessex-Channel Basin is a classic area of British geology, studied by generations of geologists. It incorporates the Wessex Basin (sensu Kent, 1949), which is the main oil-producing basin of onshore Britain, plus its offshore extension in the central and eastern parts of the English Channel. It occupies an area of over 40,000 km^2 (Fig. 2.1) and contains Permian to Tertiary sediments that are locally over 3 km thick (Penn *et al*. 1987). The deeper concealed parts of the basin have been drilled for stratigraphical, coal, oil, gas, and geothermal energy purposes. Each successive exploration programme was followed by an overview of part or all of the basin (e.g. Lamplugh & Kitchen 1911; Strahan 1913; Lamplugh *et al*. 1923; Arkell 1933; Kent 1949; Terris & Bullerwell 1965; Shephard-Thorn *et al*. 1972; Stoneley 1982). Early investigations of its hydrocarbon prospectivity have been described by Lees & Cox (1937), Lees & Taitt (1946) and Falcon & Kent (1960).

Following the award of the first prospecting licences under the 1934 Petroleum Production Act, drilling was carried out in 1936-1937 at Broadbench, in Kimmeridge Bay, with traces of live oil noted on joints in grey sandstones in the Upper Jurassic Corallian (Sandsfoot Grit) at a depth of about 825 feet (250 m). The well was plugged and abandoned at 943 feet (287 m), still in the Corallian (Osmington Oolite) as the limit of the rig had been reached (Brunstrom, 1963). Twenty -two years elapsed before the full significance of this 'discovery' was appreciated. In 1958, shows of oil in Upper Lias (Lower Jurassic) sandstones from a well to the west at Radipole, near Weymouth, led to renewed interest in Kimmeridge Bay. Three wells were drilled as part of a programme. Broadbench 2 (subsequently renamed Kimmeridge 1) was drilled in 1959, ENE of Broadbench 1 and encountered oil at a depth of 1880 ft (570 m) in the Cornbrash Limestone, i.e. top of the Middle Jurassic. Core oozed oil from partially leached calcite veins, and a series of production tests and acid treatments yielded between 30 and 4300 bopd. The well was completed as a producer in the Cornbrash (Evans *et al*. 1998). Two other wells were drilled to the producing horizon to the east (Kimmeridge 2) and southwest (Kimmeridge 3), proving the extent of the oilfield. Kimmeridge 4 was an appraisal well, drilled in 1960, to further test the geological structure, but it was terminated due to mechanical difficulties. The field began producing in 1961 (Evans *et al*. 1998) and, following the discovery and successful appraisal of the Wytch Farm Oilfield, there was renewed interest in the prospectivity of deeper reservoirs in the area. In 1980, Kimmeridge 5 was drilled as an exploration well to test the deeper potential of the Kimmeridge structure at Sherwood Sandstone (Lower Triassic) level, with the Bridport Sands (Lower Jurassic) as a secondary target. Weak gas shows and minor fluorescence were recorded throughout the Jurassic. The Sherwood Sandstone, encountered deeper than prognosed, had weak oil shows but reservoir quality was significantly poorer than at Wytch Farm (Evans *et al*. 1998).

Elsewhere in the basin, the first exploration well, Poxwell 1, was drilled by D'Arcy in 1937. Subsequent wells were drilled during the 1950s and 1960s at surface anticlines often associated with major faults, with variable and limited

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success. The drilling by BP in 1963 of the Lulworth Banks 1 well was a milestone in the British exploration industry, being the first offshore well drilled in the United Kingdom Continental Shelf (UKCS). Only relatively shallow Jurassic targets were tested in a broad open structure (Buchanan 1998; Hawkes *et al.* 1998), and minor gas shows were encountered in the Inferior Oolite.

The hydrocarbon exploration and production of the Wessex Basin has been dominated by the discovery, in 1973, of the Wytch Farm Oilfield (Fig. 2.4) in eastern Dorset. This oilfield, the largest onshore UK by several orders of magnitude, was discovered after a phase of seismic reflection surveying in 1970 and early 1971 had demonstrated the presence of an anticlinal structure. Even this exceptionally successful field had a chequered exploration history according to Hurst & Colter (1998), illustrating an underlying exploration pessimism, which the authors were trying to dispel. It has reserves estimated to be in excess of 380 mmbbls (Colter & Havard 1981; Bowman *et al.* 1993). Recent long-reach drilling from onshore sites and existing production locations has identified offshore extensions to the oilfield (McClure *et al.* 1995), increasing reserves to an estimated 500 mmbbls and putting the Wytch Farm Oilfield in the top ten UK fields, including the North Sea.
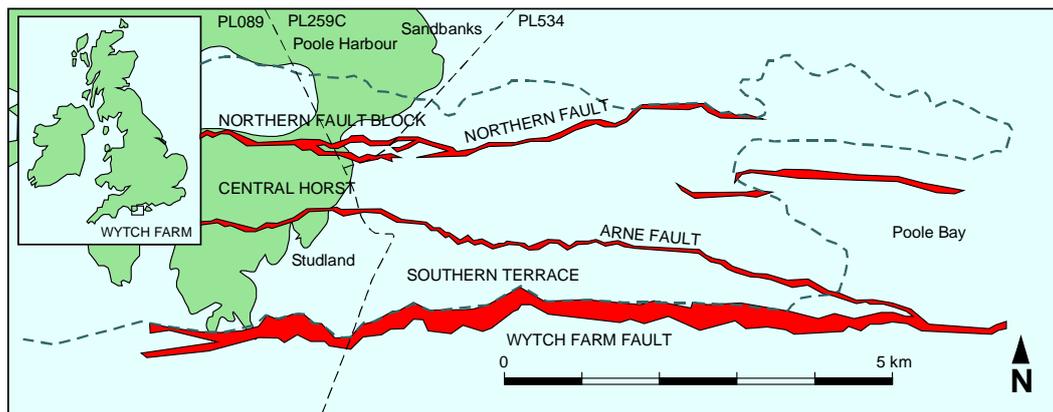
Fig. 2.4 Location of UK's largest onshore oilfield and its offshore extension at Wytch Farm, Wessex Basin (Hogg *et al.* 1999)

BASIN STRUCTURE

The Wessex Basin comprises four north-dipping (and with northward thickening sediments) half graben sub-basins (Fig. 2.3), and all four were controlled by south-dipping normal faults (Chadwick 1993). The Pewsey Sub-basin in the north structurally belongs with, but is located west of, the Weald Basin. The Mere or Vale of Wardour Sub-basin is controlled by the outcropping Mere Fault (or Wardour-Portsdown Fault), which was inverted during the Tertiary. The Dorset Sub-basin (Winterbourne Kingston Trough) is controlled by the concealed Cranborne Fault, which was not inverted. The southernmost sub-basin (named Channel or Portland-Wight) is located along the line of hills and the spectacular folds that crop out along the Dorset coast (see Figs 2.5, 2.6). The controlling Purbeck-Isle of Wight (or Portland-Wight) Fault has been inverted by Alpine deformation. This southernmost sub-basin has proved the only viable petroleum system so far. Its inversion history was a critical element in the discovery of Wytch Farm Oilfield (Hurst & Colter 1998).

STRATIGRAPHY

The stratigraphy of the Wessex Basin is summarised in Fig. 2.2. Permian red bed strata with mudstones, subordinate sandstones and basal breccias unconformably overlie deformed Variscan basement (Carboniferous-Devonian). Triassic strata comprise red bed sandstones and subordinate conglomerates in the lower part and mudstones with halites in the upper part. The Jurassic comprises an alternating mudstone and carbonate sequence, with subordinate sandstones. Early Cretaceous strata are preserved only in a few basinal areas. The Permian to early Cretaceous sequence essentially dips east beneath an unconformable cover of mid-late Cretaceous (including Chalk) and Tertiary strata.

Figure 2.5 Stair Hole, Dorset, south coast of England, showing deformation associated with reverse movement on the Purbeck-Isle of Wight Fault (© NERC).

Figure 2.6 Durdle Door, Wessex Basin on the south coast of England, west of the Kimmeridge Oilfield (© NERC).

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PETROLEUM SYSTEMS

Source rocks

The Lias clays, Oxford Clay and Kimmeridge Clay, all Jurassic, are the formations with the greatest potential for generating hydrocarbons in the Wessex-Channel Basin. Plays involving Westphalian (Carboniferous) coals as a source are considered a high risk, their presence or preservation being very localised and difficult to predict (Taylor 1986, Smith 1993). Other formations not considered here are either too strongly oxidized (e.g. those of the Triassic Mercia Mudstone Group), or are considered too thin (e.g. other Jurassic sequences) to yield substantial volumes of hydrocarbons (Penn *et al*. 1987). Cretaceous mudstones are known to be insufficiently mature.

All three principal source rock formations contain kerogens of Types II, III and II/III (Ebukanson & Kinghorn 1985). Type II is mostly unorganized amorphous sapropelic kerogen derived from algal material with good potential for oil and gas generation. Type III is finely dispersed, gas-prone material derived from allochthonous higher terrestrial plant material, and Type II/III is a mixed source or degraded Type II material. Although all have source potential, their maturity is highly variable, having been controlled by the complex structural evolution of the basins.

It is now well established that the source of most of the oil to the south of the Purbeck-Isle of Wight Monocline is from the basal Jurassic Lower Lias (Ebukanson & Kinghorn 1986a&b). Possible minor additions may have been derived from the Oxford Clay in the same area, and elsewhere in the Wessex Basin from higher in the Lias e.g. in the Winterborne Kingston Trough and the small accumulations in the vicinity of Wareham (Selley & Stoneley 1987).

In much of southern England, the Kimmeridge Clay consists of rhythmic alternations of shales (plus some oil shales), more or less calcareous mudstones, interbedded micritic limestones, and thin sandstones/ siltstones. It is largely immature (Ebukanson & Kinghorn 1985, 1986; Penn et al. 1987), but may be marginally so at Kimmeridge (Selley & Stoneley 1987). Some controversy still surrounds the mode of formation of the organic-rich beds (Gallois 1976; Tyson et al. 1979; Irwin 1979; Farrimond et al. 1984). There is some resemblance to the Lower Jurassic, but total organic carbon (TOC) values are much higher, with some black shales up to 20 wt per cent TOC (Penn et al. 1987). Most of the kerogen in the laminated shales was deposited in oxygen deficient bottom waters and is of Type II, although mixed Type II/III is present. Basin modelling (TTI) predicts that the base of the Kimmeridge Clay has entered the oil generation window perhaps only in the northernmost axial part of the Wessex-Channel Basin (Penn et al. 1987), the majority of the formation having not attained the peak of oil generation.

The Upper Jurassic Oxford Clay consists mainly of more or less bituminous shales and mudstones in its lower part and calcareous mudstones, siltstones and thin limestones in its middle and upper parts. A stratigraphical variation in kerogen types was noted by Ebukanson & Kinghorn (1986a). The lower part is enriched in Type II sapropelic kerogen whereas Types II/III, III and IV become more abundant higher in the sequence. This may be a result of bottom waters having become increasingly oxygenated with time, or to variation in the supply of organic material (or both) during deposition. Shales of the Lower and Middle Oxford Clay have up to 12% TOC, mudstones of the upper part containing 1-2% less. Basin modelling (TTI) suggests that the Oxford Clay again falls in the oil generation window in the northern part of the Wessex-Channel Basin (Penn *et al*. 1987). An organic maturity (vitrinite reflectance, VR%) value of 0.56 from the Arreton 2 well in the Basin (Ebukanson & Kinghorn 1986a) supports this interpretation. Elsewhere, the Oxford Clay is insufficiently mature to have generated oil.

The Lower Jurassic Lias consists of cyclically interbedded shales, mudstones, marls and micritic limestones. The shales were deposited in oxygen-deficient bottom waters with low benthic faunal activity, and are rich in organic material (Hallam 1960). Some Lower Lias shales may contain up to 7 wt per cent TOC (Ebukanson & Kinghorn 1985). Basin modelling (TTI) for the Lias predicts that it falls within the zone of oil generation over much of the Wessex-Channel Basin, being overmature in its deepest axial parts (Penn *et al*. 1987). In the Pewsey Sub-Basin, the Lower Lias is marginally mature, but it is perhaps immature over the Hampshire Dieppe High (Penn *et al*. 1987). VR% values for the Lias in Arreton 2 well vary between 0.8-0.9 (Ebukanson, & Kinghorn 1986a) and support the maturity predictions. Oil generation from Lias source rocks probably began during deposition of Lower Cretaceous sediments and peaked at about the mid-Cretaceous (Penn *et al*. 1987).

Reservoir rocks

Two primary reservoirs exist in the Wessex Basin (Fig. 2.2), consisting of the Triassic Sherwood Sandstone Group and the Lower Jurassic Bridport Sandstone Formation (Upper Lias), respectively. Other Jurassic reservoirs locally include limestones of the Great Oolite Group (Frome Clay limestone), and the Corallian Beds and Portland Sands.

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The areal extent of these rocks and where they are likely to form effective reservoirs for hydrocarbons has been summarised by Penn *et al*. (1987).

The Sherwood Sandstone Group comprises a 100-300 m thick red-bed succession deposited in semi-arid conditions in a complex variety of alluvial-fluvial, lacustrine and aeolian environments (Holloway *et al*. 1989; McKie *et al*. 1998). Three facies associations are common - channel sandstones (with the best reservoir properties), sheetflood and playa/floodplain. A few wells have encountered oil or gas, but it is so far productive only at Wytch Farm, although oil shows were encountered at Kimmeridge Bay and offshore on the Central Channel High (well 98/22-2). At Wytch Farm, the Sherwood Sandstone Group shows an evolutionary trend from perennial braidplain through ephemeral sheetflood systems to ephemeral lacustrine conditions (McKie *et al*. 1998). This trend culminated in the deposition of the Mercia Mudstone Group, reflecting a long-term waning of sand supply. Within these broad overall trends are lower 2nd and 3rd order cycles. Second order cycles represent episodic reductions in fluvial sediment supply and rising base level during more humid climatic conditions. Third order cycles comprise thin, areally widespread floodplain and lacustrine horizons in the upper half of the Sherwood section. The sandstones between these horizons are aeolian and sheetflood deposits, and these are incised by coarse-grained, multistorey-multilateral channel deposits. These incisions are thought to represent fluvial erosion during dry climatic conditions, when lake levels fell and the alluvial plain was de-vegetated (McKie *et al*., 1998). The relative paucity of discoveries could be due to the special structural conditions required to allow migration from Jurassic rocks into the stratigraphically much lower Sherwood Sandstone (cf. Colter & Havard 1981; Penn *et al*. 1987). Porosity and permeability values are often high, arising from dissolution of anhydrite cement following the main compaction phase, and they have been further enhanced by dissolution of feldspar grains. Calcrete horizons can and do, however, reduce the vertical permeability (Bowman *et al*. 1993). The Mercia Mudstone Group (Middle to Upper Triassic) provides an adequate seal to the Sherwood Sandstone reservoir.

The Lower Jurassic Bridport Sands (Fig. 2.7), between 25 and 100+ m thick, consist of very fine to medium grained sandstones deposited under shallow marine conditions. They form the upper reservoir in the Wytch Farm field and, with the exception of the Kimmeridge Oilfield, provide the main reservoir in the smaller discoveries in the county of Dorset. Reservoir quality is the major risk on the Bridport Sands play. The best reservoir characteristics are found in the western part of the basin where the unit is dominated by siliciclastic sediments, though the distribution of sands is unfortunately not clearly related to the presence of local topographic highs. The sands pass laterally in the east into ferruginous, slightly arenaceous limestones, siltstones and shales. Downgrading of the siliciclastic reservoir can occur due to well-cemented layers ('doggers'), which form permeability barriers to hydrocarbons (Kantorowicz *et al*. 1987; Bryant *et al*. 1988; Bjorkum & Waldehaug 1993). The effective permeability can also be reduced by increased burial diagenesis, which occludes porosity. The thickly developed mudstones of the Middle Jurassic Fuller's Earth Formation provide the top seal for hydrocarbons reservoired in the Bridport Sands.

The limestones of the Middle Jurassic Great Oolite Formation form the main reservoir in the Humbly Grove Oilfield and in a number of other discoveries in the Weald Basin (Sellwood *et al*. 1989). However, when traced southwest into the Wessex-Channel Basin, the limestones pass laterally into the Frome Clay, with a resultant change in reservoir characteristics. Sandhills well, located towards the far east of the Wessex Basin had some oil indications in the Great Oolite.

Oil shows are encountered in the Middle Jurassic Cornbrash and Forest Marble in wells from the south of the basin (e.g. Bushey Farm and Sandhills), but these beds do not form predictable reservoirs (Colter & Havard 1981; Penn *et al*. 1987). The Kimmeridge Oilfield produces from a fissure system in the Cornbrash, which is almost impermeable (Brunstrom 1963).

The Corallian can be divided into a lower, dominantly limestone unit and an upper, dominantly sandstone unit, separated by a mudstone unit. The upper sandstone unit is not developed in the main southerly part of the Wessex-Channel Basin, but it may form an effective reservoir along the northwestern extension of the Hampshire-Dieppe High.

The Upper Jurassic Portland Beds are largely represented by limestones in the Wessex-Channel Basin. They have minor shows in the Arreton wells on the Isle of Wight.

Figure 2.7 The Bridport Sands reservoir forming a Dorset coastal cliff outcrop west of Wytch Farm, Wessex Basin (© NERC).

Seals

Regionally developed mudstones overlie both main reservoirs, providing effective seals. Above the Sherwood Sandstone Group are the red-bed mudstones of the Mercia Mudstone Group. At Kimmeridge Oilfield, a thick unit of plastic Kimmeridge Clay perhaps forms an effective seal to the producing fracture system, thereby preserving the hydrocarbon accumulation intact (Penn *et al*. 1987).

Traps

Structural closures in the Wessex-Channel Basin fall into two main categories. The most prospective are the upfaulted tilt-blocks and horsts (Fig. 1.5), commonly initiated in Triassic times, which formed in the active extensional phases of basin subsidence during the Jurassic and early Cretaceous. These are covered by a thick blanket of largely unfaulted Upper Cretaceous and Lower Tertiary sediments deposited during a prolonged spell of regional subsidence. Those structures formed during the Jurassic to early Cretaceous, and which remained unmodified by later Tertiary inversion events, are considered the most prospective. The beds within the horsts are tectonically undisturbed and sealing horizons remain unbreached. Importantly, reservoirs will also have been protected from the flow of meteoric groundwater. Prospective tilt-blocks and horsts can and may occur anywhere within the Wessex-Channel Basin.

The second type of structural closure is found within the major mid-Tertiary inversion structures, which developed by reversal of earlier normal faults. These features have essentially monoclinal form, but periclinal closures, some of considerable areal extent, are also common. The most important inversion structures lie in linear zones above the older, basin controlling faults such as the Portland-Wight Faults (Stoneley 1982; Penn *et al*. 1987). In these structures, the beds within the cores of the inversion structures are cut through by reverse faults, which, as is often the case, may reach the surface, and adversely affect prospectivity. Hydrocarbons may migrate up the fracture system and/or meteoric water may invade from surface, flushing the structures and degrading the hydrocarbons. Additionally, at shallower levels, extensional joint and fracture systems are often developed (Bevan 1985), again permitting the ingress of meteoric waters. Perhaps significantly, in the Wessex-Channel Basin the only currently producing hydrocarbon accumulation (Kimmeridge Oilfield) that occupies an inversion-related feature has atypical reservoir-seal relationships and, initially, was considered as having been replenished from another unidentified accumulation.

Other minor structural traps may exist within rollover anticlines developed against basin-controlling faults. These are difficult to identify due to the overprinting by the Tertiary inversion phase. The effects of the latter may be crucial in the prospectivity of these structures. If oil migrated during the Cretaceous, a Jurassic-Cretaceous rollover could be prospective, whereas a Tertiary structure would not be. Tertiary inversion could also have disturbed any hydrocarbon accumulations in these early rollover traps.

Stratigraphic pinch-out has not been demonstrated as a mechanism of hydrocarbon entrapment in the Wessex-Channel Basin. Such closures are likely to be small, and they must represent high-risk targets.

Generation and migration

The oil in the proven oilfields of the Wessex-Channel Basin was preserved in place during the Tertiary inversion phase. It seems inconceivable that other accumulations were not present in other fault blocks and structures, but in many places they were lost to surface during this inversion. The Osmington/Bran Point-Lulworth Cove-Mupe Bay-Worbarrow Bay area, on the south coast of county Dorset, is now seen as the site of a former large oilfield, perhaps the size of Wytch Farm, which was uplifted, eroded and breached during the Tertiary compression (Miles *et al*. 1993). Many of the former accumulations could have also lost hydrocarbons through fractures in the Chalk (Selley & Stoneley 1987).

The Dorset Sub-basin (Fig. 2.1) north of the South-Dorset High (Mid-Dorset High of Scott & Colter 1987) is both remote and structurally lower than the high and was probably so throughout the Mesozoic (Scott & Colter 1987). Consequently, unless saddles in the structure existed, it is unlikely that oil migrating from the south reached further north in the Wessex Basin than this high. The Dorset Sub-basin has also not had the thickness of Lower Cretaceous strata developed as in the south, and thus any source rocks in the area will not have been sufficiently buried to promote hydrocarbon generation.

The drilling of a number of dry holes testifies to the remoteness and immaturity of the Mesozoic in the northern sub-basins of the Wessex Basin. Any plays developed in this area require the development of Palaeozoic source rocks (Scott & Colter 1987) or Lias source rocks buried to sufficient depth, north of the Mere Fault.

Accumulations

SURFACE INDICATIONS

Onshore petroleum seepages in south Dorset were first described by Lees & Cox (1937). These occur in the Bencliffe Grit (Oxfordian) at Osmington Mills, and sporadically in the Lower Cretaceous along strike from Durdle Door in the west (Fig. 2.6) to Worbarrow Bay in the east. Traces of oil were obtained, by analysis, from the Upper Jurassic Portland Limestone on Portland Island, Dorset (Lees & Cox 1937) and veins of bitumen, in the Black Ven Marls, Belemnite Marls and Blue Lias. Traces of oil have also been described from as far west as Charmouth and Lyme Regis in Dorset (Lees & Cox 1937; Selley 1992). Petroleum is reported to have been extracted at Charmouth from the fibrous calcite veins ('beef') within the Lias shales (Stoneley in Selley 1992). Significantly, many of the seeps in the east occur where northerly-dipping beds crop out a short distance to the south of major faults (Selley & Stoneley 1987) and there are several anticlinal structures near to these seepages, most of which had been drilled prior to 1958 (Brunstrom, 1963). Gas has been discovered bubbling on the sea bed between Durlston Head and Anvil Point (Power 1978; Selley & Stoneley 1987).

The most significant seep is that at Mupe Bay. The story of the Mupe Bay boulder bed and the fossil oil seep has assumed almost mythical proportions in the British oil industry, but it does provide critical evidence towards unravelling the generation and migration of petroleum in south Dorset. A number of interpretations involve active seeps at the time of deposition, suggesting the Lias source rocks offshore to the south had entered the oil window during early Cretaceous times (e.g. Selley & Stoneley 1987). Early results from studies of the oil chemistry were interpreted as showing a maturity difference between the oils from the clasts and the host sandstone (Cornford *et al*. 1988), and supported the old suggestion of the origin of the clasts by contemporaneous oil cementation. Subsequently, it has been shown that no significant differences exist in the maturity or source of the oils, any differences being related to such processes as biodegradation (Miles *et al*. 1993). These findings remove the constraint of early Cretaceous generation of oil imposed by earlier studies. Thus the Mupe Bay seeps are now seen as the remnants of a former larger accumulation or oilfield, perhaps the size of Wytch Farm, which was uplifted and breached during erosion, following Tertiary compression and inversion (Miles *et al*. 1993).

SUBSURFACE INDICATIONS

Shallow drilling on most surface structures, such as the Poxwell Anticline, has proved them to be barren but Broadbench 1 had a minor oil show. Subsequently, many wells have been drilled in subsurface structures in the onshore and offshore parts of the Wessex-Channel Basin with numerous shows or indications, and oil and gas discoveries have been made in offshore block 98/11 (Buchanan 1998).

KIMMERIDGE OILFIELD

The Kimmeridge Oilfield lies in Kimmeridge Bay on the South Dorset coast and comprises a shallow accumulation within a faulted inversion anticline (the Purbeck Anticline). The field is located immediately south of the main Purbeck Disturbance, (Fig. 2. 1) which constitutes the most important structural feature in the area (Stoneley 1982; Underhill & Patterson 1998; Underhill & Stoneley 1998) and has a proven extent on land of approximately 1.5 km (Brunstrom 1963; Evans *et al*. 1998).

Production over the last 30 years totals over 3 mmbbls, at an average production of 370 bopd, including a single well production of 100 bopd (Evans *et al*. 1998), which declined to 70-80 bopd in 2001 (Anon 2001). It was thought that the field had produced more oil than the assessed volume of the structure (Ebukanson & Kinghorn 1985), indicating either continued migration into the structure from the Liassic source or migration from another leaking structure, downdip or at a deeper level in the succession. Brief references are found in Brunstrom (1963), Selley & Stoneley (1987) and Miles *et al*. (1993), with the most recent synthesis being that of Evans *et al*. (1998), who considered that the declining production history does not support replenishment. Gluyas *et al*. (2003) estimate the field's STOIIP as between 10-25 mmbo.

The oil is fully saturated with gas and occurs in a fissure system provided by fractured Middle Jurassic Cornbrash Limestone, the Cornbrash itself being almost impermeable at Kimmeridge (Brunstrom 1963). The fissures are not confined to the Cornbrash, but pass upwards into the overlying Kellaways Sand and the Oxford Clay. Kimmeridge 2 well encountered oil in fissures in the Oxford Clay 130 ft (40 m) above the Cornbrash.

Core analysis data indicate an average porosity of 1% and virtually zero permeability (Evans *et al*. 1998). Additionally, the Cornbrash reservoir is characterized by abnormally low reservoir pressures, well below hydrostatic -

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at pressures that would be expected in a reservoir several hundred metres shallower. This may be a result of a fracture system enlarged or 'opened' further during Miocene folding (Brunstrom 1963).

In common with the Wytch Farm and Wareham fields, the oil is probably sourced from the Lower Lias. Associated gas has been previously vented (450t per year), but permission was given for gas generation in 2001 (Anon 2001).

WAREHAM OILFIELD

Wareham Oilfield was discovered by BP in 1964. The discovery well produced 20 bopd from the Middle Jurassic Inferior Oolite and the top part of the Lower Jurassic Bridport Sandstone. It was re-entered in 1970, producing 100 bopd with a steadily increasing water-cut (Hurst & Colter 1998). Field production began in 1970, and had reached 79,770 bbl up to when it was transferred to British Gas ownership in1982 (Huxley 1983).

WYTCH FARM OILFIELD

The Wytch Farm Oilfield (Figs. 2.4, 2.8) started life as a modest discovery (30 mmbbl) in 1973, but later drilling identified deeper target horizons and it is now the largest onshore UK oilfield. It extends offshore, and present technology permits greater reserves to be exploited from existing onshore production sites by drilling up to 10 km long horizontal wells offshore.

At Wytch Farm the surface rocks are Tertiary in age and synclinal in structure (Fig. 2.8). The mature source rocks lie offshore to the south, within the Channel Sub-basin, where inversion and erosion have been concentrated. This structural relationship reveals the importance of the inversion to hydrocarbon migration. The palaeohigh at Wytch Farm has less disturbed and better quality reservoirs than the basinal areas to the south.

Much has been published on the Wytch Farm Oilfield, with Colter & Havard (1981), Dranfield *et al.* (1987) and Bowman *et al.* (1993) providing good general introductions. The discovery well, Wytch Farm 1, was drilled to test an east-west trending subsurface anticline identified from seismic interpretation. It encountered light oil in the Lower Jurassic Bridport Sands, tested at 660 bopd. Shows were also found in the Middle Jurassic Cornbrash, though no commercial production was established from this formation. The Lower Lias in the region of the field was found to be not particularly organic-rich, and immature. However, geochemical studies following the drilling of Arreton 2 well (south of the Isle of Wight monocline), indicated that not only do the Kimmeridge Clay, Oxford Clay and the Lias contain rich potential source rocks there, but that they are at or close to maturity. It was realized that any hydrocarbons generated from these sources probably migrated northwards across the Purbeck structure into the Wytch Farm area, and that the Triassic Sherwood Sandstone in the Wytch Farm structure could be higher than the Lower Lias source rocks south of the Purbeck monocline. Consequently, the Wytch Farm D5 well, was drilled in 1977, and found light oil in the Triassic reservoir.

The discovery of the Sherwood reservoir vastly increased the reserves of the field. Subsequently, an eastward extension of the field offshore beneath Poole Bay (Fig. 2.4) has been proved by extended reach drilling and reserves now stand at around 500 mmbbl of recoverable oil. Approximately half of the field reserves are thus held in an offshore extension, with over 90% or some 397 mmbbls of recoverable oil estimated in the Sherwood reservoir (Underhill & Stoneley, 1998), putting the Wytch Farm field in the top ten UK fields, including the North Sea. The field was on plateau in 1998, when it delivered about 110,000 bopd, 17.6 mcf of gas and 725 tonnes of liquefied petroleum gases (LPG) per day (McKie *et al*. 1998).

The original field limits were located within a large east-west trending fault block to the north of the Purbeck-Wight Disturbance (Fig. 2.1), closure being formed by dip and minor faults in the east, north and west and on the southern boundary by a down-to-the-south normal fault (Colter & Havard 1981). The present understanding is that the field comprises a series of northerly dipping fault blocks formed during early Cretaceous extension.
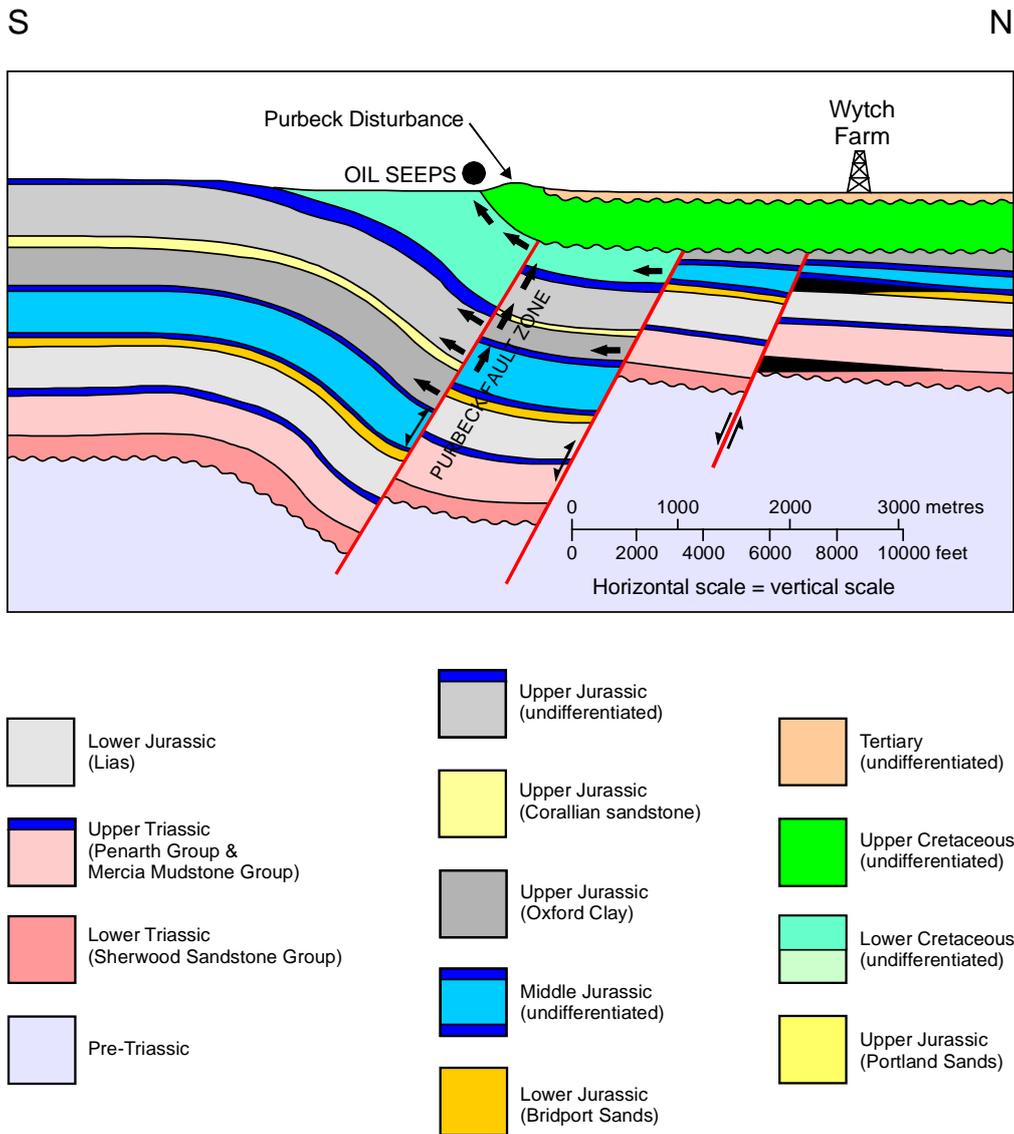
Fig. 2.8 N-S section across the Wytch Farm Oilfield, Wessex Basin (Underhill & Stoneley 1994) Essential factors in the southern England petroleum system include the influence of Jurassic faults defining palaeo-highs, reactivation of the Purbeck Fault with its thickened mature source rock hanging wall succession from which the oil was derived, and the undisturbed Cimmerian unconformity (beneath the Chalk)

CONCLUSIONS

The Wessex Basin is dominated by Wytch Farm Oilfield. The other fields, however, show that the more likely undiscovered field size is much smaller. The discrepancy between the production and field size of Kimmeridge Oilfield suggests that a nearby accumulation may exist, which is augmenting the field, although this is disputed in a recent paper (Evans *et al.* 1998). There may be undiscovered potential on the Isle of Wight to the south of the monocline, with oil shows in Arreton well suggesting that hydrocarbon generation and migration has occurred locally amid a mature source. In contrast, although the northwest Isle of Wight is located along strike of Wytch Farm field, several wells indicate that equivalent reservoirs are absent or poorly developed there.

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3 Weald Basin

INTRODUCTION

The Weald Basin is one of two productive basins in southern England (Fig. 1.1), with oil and some gas production from Jurassic and Triassic reservoirs. It lies to the northeast of the Wessex-Channel Basin and has oil field production from Brockham, Goodworth, Horndean, Humbly Grove, Palmers Wood, Singleton, Stockbridge and Storrington, and gas production from Albury.

The Weald Basin occupies an area that includes parts of the counties of East and West Sussex, Kent and Hampshire. It is bounded to the north by the London-Brabant Massif (Fig. 3.1), and is separated from the Central Channel Basin and the Paris Basin by a regional arch, the Hampshire-Dieppe High, also known as the Portsdown-Paris Plage Ridge (Butler & Pullan 1990) or the Regnenses Hinge (Hancock & Mithern 1987). The majority of outcrop in the basin is of Lower Cretaceous age, but Upper Cretaceous Chalk crops out around the basin margins, and there are extensive areas of Tertiary crop in the London Basin to the north and the Hampshire Basin to the south. As with the Wessex-Channel Basin, Tertiary inversion has modified greatly the structural relationships in the basin. A summary of the geological evolution is provided in Butler & Pullan (1990).
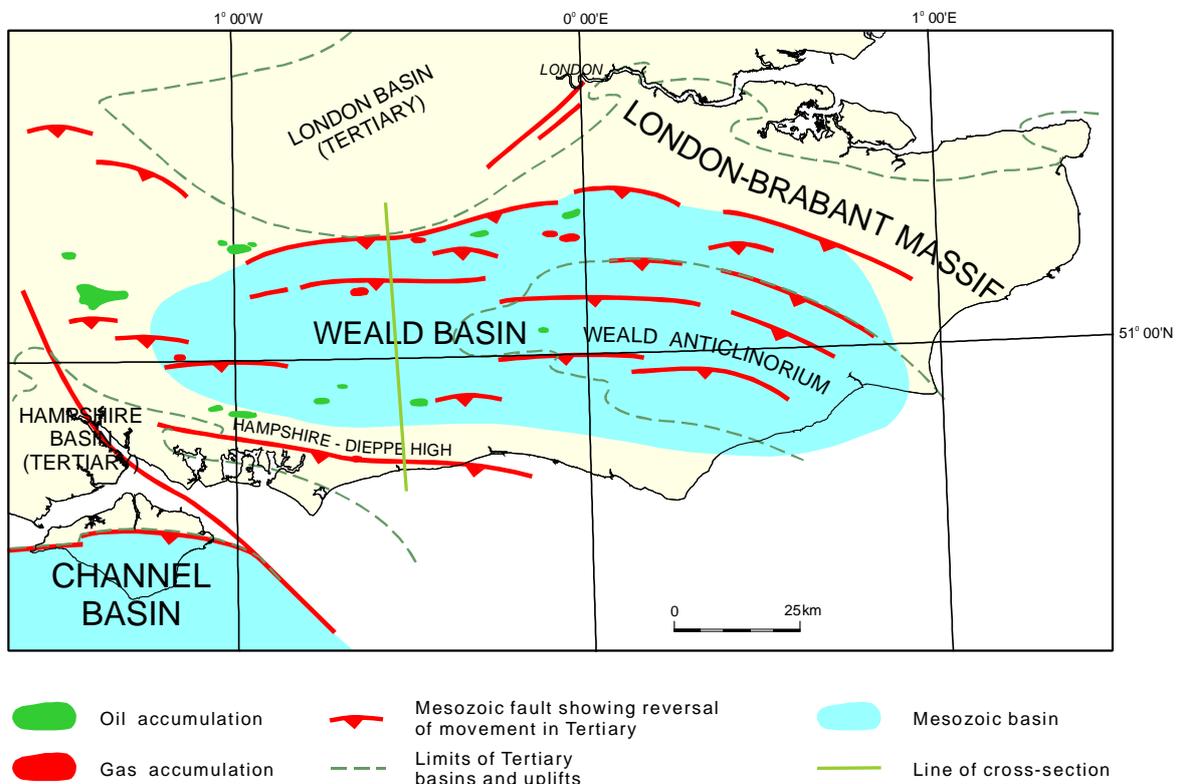
Fig. 3.1 Principal structural features of the Weald Basin (after Butler and Pullen 1990)

EXPLORATION HISTORY

Earliest reports of hydrocarbons in southern England come from the Sussex area, with gas detected in water wells in 1836 and 1875 (Dawson 1898; Pearson, 1903; Adcock 1963). Wells drilled subsequently in 1895 and 1896 at Heathfield in Sussex, to provide water for a hotel and railway station, also encountered gas (Strahan 1920; Adcock 1963; Hawkes *et al*. 1998). The railway station well reached Kimmeridgian strata, with a strong gas odour noted. On ignition, it produced a 5 m high flare. The well subsequently became Britain's first natural gas well, with production of 1000 cfd, used to provide gaslight for the station.

Hydrocarbon exploration of the Weald entered its first major phase between the 1930s and the 1960s. During this period, a number of wells were drilled on the basis of surface mapping, gravity and some seismic reflection data (Lees & Taitt 1946, Falcon & Kent 1960, Kent 1985). The first well was at Portsdown, on a prominent surface anticline

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forming Portsdown Hill (Taitt & Kent 1958). This was followed by boreholes at Henfield and Kingsclere on similar surface anticlines. Two other wells were drilled at about this time, at Penshurst (by Gulf Oil) and Grove Hill at Hellingly, Sussex (by Anglo-American Oil Company).

The discovery of the Wytch Farm Oilfield in 1973 in the adjacent Wessex-Channel Basin led to a resurgence of interest and activity in the Weald Basin. At this time, the introduction of new seismic techniques re-illustrated how the subsurface geology differed to that of the surface geology. The main realisation was that the compressional features at crop represented a Tertiary overprint on a Jurassic to Cretaceous extensional basin and, most importantly, that because of inversion, the surface structures were offset from deeper closures (Butler & Pullan 1990). Consequently, exploration activity in the late 1970s and early 1980s was concentrated on the older fault blocks of Jurassic and early Cretaceous age, leading to the discovery of a number of oil accumulations in the Weald Basin. The more recent discoveries are also illustrating that structures that were formed or strongly modified as a result of Tertiary movements still present important exploration objectives in not just the Weald Basin, but southern Britain in general.

BASIN STRUCTURE
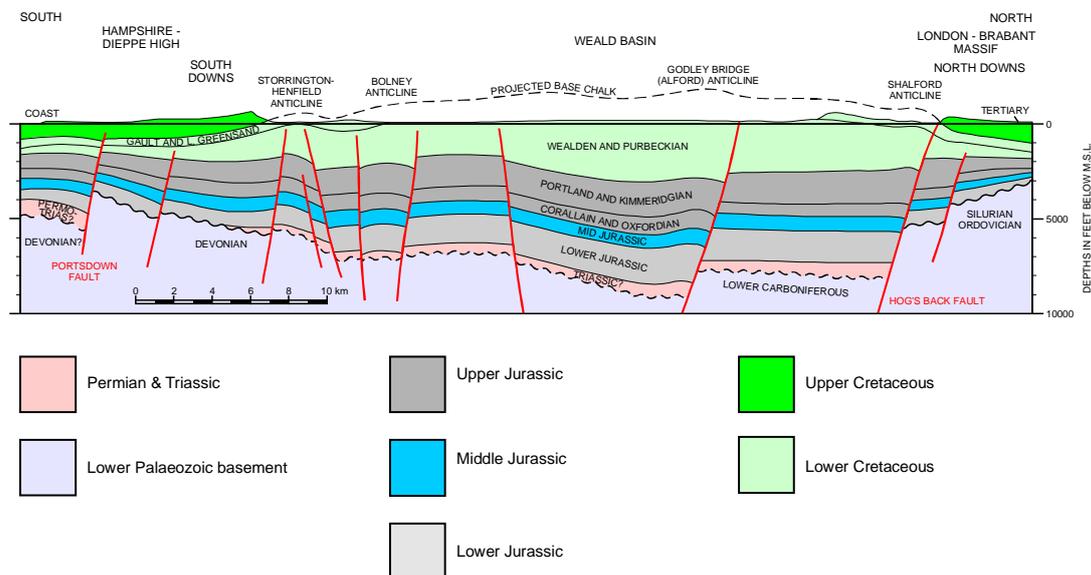
Fig. 3.2   Simplified north-south geological section through the central Weald Basin (after Butler and Pullen 1990)

In brief, prior to Tertiary uplift, the Weald Basin was an asymmetric, E-W trending basin (Figs. 3.1, 3.2), which became a major depocentre early in the Jurassic when it became separated from the Wessex-Channel Basin by a saddle, the Hampshire-Dieppe High, along a line from Southampton to Salisbury. In the east, Permian and Triassic sediments are absent; whilst to the west, some local Triassic deposition of both Sherwood Sandstone and Mercia Mudstone groups took place. The northern margin of the basin is defined by a series of down-to-the-south normal faults in the Hog's Back area, becoming less well defined to the east. A series of major E-W oriented faults developed within the basin, strongly influencing sedimentation. Its southern margin was formed by a gentle dip slope, cut by a series of antithetic faults. During the Tertiary, Alpine earth movements caused progressive uplift of the Weald Basin, leading to the major inversion feature termed the 'Wealden Anticlinorium', a gentle regional surface feature (Fig. 3.2), which in the eastern part of the basin may have amounted to more than 5000 feet amplitude (1525 m). This composite structure is 140 km long and 60 km wide, covering an area of 4500 km^2, running from Petersfield in the west out into the English Channel at Hastings. Superimposed upon this regional structure were local intense uplifts controlled by the reversal of movement on underlying faults that had propagated with normal movements in Jurassic and Cretaceous times. At crop, the inversion is manifested as a series of E-W trending, generally northerly facing periclinal structures, developed along the southern margin of the London-Brabant Platform and identical to those seen in the Wessex-Channel Basin. Such structures vary in width and amplitude depending upon their position within the basin, with more gentle folds found in the deeper parts of the basin. Between these uplifts are extensive zones, averaging 20 km wide, which have remained relatively undisturbed. Associated with NW-SE trending faults are tight

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folds with wavelengths of 2 km and amplitudes in the order of 150 m. They appear to have arisen during significant transpression and reversal of movement on the faults.

STRATIGRAPHY

The Weald Basin formed in Triassic times (Fig. 3.3) on the eastern margin of a major Permo-Triassic depocentre (Wessex Basin and Worcester Graben). Late Triassic strata are represented by a transgression that led to sustained marine deposition during the Jurassic in a cyclical limestone-mudstone succession. Syn-sedimentary growth faulting controlled deposition and led to thinner sediment accumulation on footwall regions. This tectonic control continued during earliest Cretaceous times as the basin filled up and non-marine sequences accumulated. Faulting then ceased and a regional thermal subsidence took over when the Biscay-Labrador Atlantic Ocean began spreading, forming the late Cimmerian unconformity. Initial deposition of clastic sediments was followed by Upper Cretaceous Chalk. An unconformity at the base of the Tertiary was caused by a compresssional event related to tectonism in the Alps. A larger uplift in Miocene times terminated regional deposition in the basin. No prospects or shows exist in the post-Cimmerian sediments.

PETROLEUM SYSTEMS

Source rocks

As with the Wessex-Channel Basin, the Lias clays, Oxford Clay and Kimmeridge Clay are the formations with the greatest potential for the generation of hydrocarbons in the Weald Basin, with other formations not considered (e.g. those of the Triassic Mercia Mudstone Group and other Jurassic strata). Again, all three principal source rock formations contain kerogens of Types II, III and II/III (Ebukanson & Kinghorn 1985). Although all have source potential, their maturity is highly variable, having been controlled by the complex structural evolution of the basin. The application of the vitrinite reflectance method as a maturity indicator for the Weald Basin appears to give low estimates. However, the presence and widespread occurrences of hydrocarbons, combined with other indicators of maturity, clearly indicate that oil and gas generation has occurred. Low vitrinite reflectance estimates could be related to the type of organic material present in the sediments.

The Upper Jurassic Kimmeridge Clay is considered an extremely rich oil-prone source, with TOC in excess of 10% (Butler & Pullan 1990), perhaps in some black shales reaching up to 20 wt per cent TOC (Penn *et al*. 1987). However, it is thought to be immature throughout much of southern England including much of the Weald Basin (Ebukanson & Kinghorn 1985, 1986; Penn *et al*. 1987). Basin modelling (TTI) and maturity studies predict that the base of the Kimmeridge Clay has entered the oil window in the axial part of the Weald Basin (Penn *et al*. 1987; Butler & Pullan 1990).

The Upper Jurassic Oxford Clay consists mainly of more or less bituminous shales and mudstones. Shales of the Lower and Middle Oxford Clay have up to 12 per cent TOC, values for the basal parts of the Oxford Clay being up to 5% (Butler & Pullan, 1990). Basin modelling (TTI) suggests that the Oxford Clay falls in the oil generation window, and is likely to have reached peak maturity for oil generation (Penn *et al*., 1987). Organic maturity (VR%) values of 0.74 for the Oxford Clay at Penshurst in the centre of the Weald Basin (Ebukanson & Kinghorn 1986) support this interpretation. Elsewhere, the Oxford Clay may at best be marginally mature or insufficiently mature enough to have generated oil. Burial history diagrams indicate that oil generation from the Oxford Clay may have begun in the early Cretaceous and continued throughout the Cenozoic period (Penn *et al*. 1987).

The Lower Jurassic Lias rocks, particularly the Lower Lias, are rich in organic material (Hallam 1960), with TOC in the range of 0.5 % to 2.1% (Butler & Pullan 1990). Some shales contain up to 7 wt per cent TOC (Ebukanson & Kinghorn 1985). The interval does show considerable vertical and lateral variation in richness, deteriorating in quality in the eastern part of the Weald Basin. Basin modelling (TTI) predicts that the Lias falls within the zone of oil generation over much of the Weald Basin, being perhaps overmature in the deepest parts of the basin (Penn *et al*., 1987). The Lower Lias is probably immature over the Hampshire Dieppe High (Penn *et al*., 1987). VR values for the Lias at Penshurst in the centre of the basin vary between 0.8-0.9% (Ebukanson, & Kinghorn, 1986), being in the main phase of oil generation and supporting the maturity predictions. The same authors show that the Lower Lias is marginally mature at Henfield, Warlingham and Winchester, around the periphery of the basin. Oil generation from Lias source rocks probably began during deposition of Lower Cretaceous sediments and peaked at about the middle of the Cretaceous (Penn *et al*. 1987).

Studies of the geothermal gradients (and thus levels of maturation) associated with the Variscan thrust belt show that in places they are low enough for older strata to have retained some prospectivity (Smith 1993). Carboniferous sediments, perhaps containing humic kerogen from the Westphalian Coal Measures, could also form a secondary source of gas in parts of the Weald Basin (Taylor 1986; Butler & Pullan 1990). However, they can only be present beneath allochthonous basement, because the youngest basement rocks drilled are Dinantian in age (Smith 1985).

All the Jurassic oils studied from the Weald Basin are light crudes, with API gravities in the range of 35^0 - 42^0, and they are isotopically similar (Butler & Pullan 1990). The closest match between oils and source rocks is with the Lower Liassic shales, but the results suggest a degree of mixing is evident, with contributions from more than one source interval. The gas is dry and its source enigmatic, with the majority of gas being found in Upper Jurassic and Cretaceous reservoirs and only in structures of Tertiary age (Butler & Pullan 1990). It may have its origins in release from pore waters at shallow depths, or it may have originated in deeper reservoirs, preferentially migrating to higher levels than oil during the Tertiary uplift.

Reservoir rocks

The Weald Basin contains a number of potential clastic and carbonate reservoirs (Fig. 3.3), and wells should therefore be planned with multiple objectives (Butler & Pullan 1990).

Subcrop maps illustrate that the Sherwood Sandstone (a major Triassic reservoir in the Wessex Basin) probably has limited distribution within the Weald Basin (Penn *et al*. 1987; Scott & Colter 1987). Within its Triassic, only Rhaetic strata have so far proved productive in the Humbly Grove Oilfield, but some potential remains for the Sherwood Sandstone Group, particularly in the west, where it is sealed by the Triassic Mercia Mudstone Group and the Lower Jurassic Lias (Butler & Pullan 1990).

The main reservoir in the Weald Basin is the Middle Jurassic (Bathonian) Great Oolite Group, and particularly the Great Oolite Limestone (Butler & Pullan 1990), within which oil was discovered in Storrington 1 well by Conoco in 1986. The main reservoir is also the Great Oolite at the Humbly Grove, Horndean, Goodworth, Singleton and Stockbridge oilfields and Baxter's Copse and Lidsey discoveries, though some other units also contain hydrocarbons. Oil production is from wells in the western half of the basin, as the quality of the reservoir decreases to the east due to facies variation and less favourable diagenetic history (McLimans & Videtich 1987, Scott & Colter 1987).

Few data are available on reservoir quality. The best primary intergranular porosity in the Great Oolite Limestone is developed in well-sorted, oolitic and skeletal grainstones and relatively clean packstones (McLimans & Videtich 1987). Similar lithologies have porosities ranging from less than 5% to in excess of 20% in Storrington 1 well (McLimans & Videtich 1987). The variation in porosity occlusion by cementation is dependent upon the residence time in the freshwater diagenetic environment. Short residence times provided some cementation that also provided support and protection during subsequent burial and compaction, whilst long residence times significantly reduced porosities. These variations are illustrated by the porosities of 11-13 % in Baxter's Copse and Palmers Wood wells, whilst nearly all Great Oolite Limestone porosity in Normandy 1 and Bordon 1 wells is occluded by early fringe cements (McLimans & Videtich 1987). The best porosity recorded to 1987 was that in Storrington 1 well, in which the reservoir interval has little cement, yet underwent little compaction.

Three principal phases of cementation are reported (Sellwood *et al*. 1989). Early calcite rim cements were followed by later 'saddle' dolomite and associated sphalerite and finally, mildly ferran calcite. The latter forms a pervasive cement throughout the Great Oolite and appears to have been the main cause of porosity reduction in the Weald Basin. Globules of oil were trapped between the early calcite cement and the saddle dolomite and numerous inclusions containing oil, gas, or both, are noted in the ferran calcite cement (Butler & Pullan 1990). However, ferran cement appears to have been inhibited from forming in some older structures due to the presence of migrated hydrocarbons (Hancock & Mithern 1987; Sellwood *et al*. 1989). The first phase of migration was probably associated with expulsion of fluids from Lower Jurassic shales during latest Jurassic to early Cretaceous times. The timing of the second phase of migration and remigration, with associated precipitation of ferran calcite, is more difficult to determine. It was inhibited from forming in the crests of pre-Tertiary structures, but seems to occur in the crests of structures of Tertiary age.

Due to the depositional environments prevalent at the time, most of the Jurassic reservoirs are of better quality around the margins of the Weald Basin, with significant deterioration in quality towards its centre (Penn *et al*. 1987; Butler & Pullan 1990). The majority of its Jurassic sediments were deposited in low energy, wave-dominated environments,

with no significant clastic source. It is thought that the Lower Jurassic Bridport Sands and the Middle Jurassic Corallian Beds may only have marginal prospectivity over much of the basin. The Bridport Sands are poorly developed here, and there does not appear to be an effective seal developed between these and the Middle Jurassic Inferior Oolite and Great Oolite. The Inferior Oolite has had interesting shows. The Lower Corallian Beds may provide an effective reservoir in the northern and eastern parts of the basin, where carbonates form the reservoir in the Bletchingley gas discovery. Similarly, the Upper Corallian Beds have their greatest potential in an E-W belt just south of the London-Brabant Platform, where the thickest sands are developed, with Palmers Wood (oil) having established the Corallian sand as a major reservoir. The Warlingham borehole, south of London, has also proved oil and gas in the uppermost Corallian Beds limestones. Production tests by BP established a daily production rate of 5 to 10 gallons of oil and 35000 scf gas (Worssam & Ivimey-Cook 1971). The Upper Jurassic Portland Beds may be developed in reservoir facies, although the formation passes laterally into mudstones towards the southeast Weald Basin (Penn *et al*. 1987). It has been proved productive of gas at Godley Bridge, where the Purbeck anhydrite forms an effective seal (Butler & Pullan 1990). Sands within the overlying Upper Jurassic Purbeck sequence form a gas reservoir at Albury. All of these sands of Corallian and Portlandian age clearly suggest the existence of a good northern clastic source on the London Platform towards the end of the Jurassic.

Secondary, less predictable reservoirs include the sands of the Lower Cretaceous Wealden Beds, with numerous shows of oil and gas, including at Bolney 1 and Heathfield wells. Enhancement of reservoir characteristics by fractures (and perhaps diagenesis) may also provide additional or improved reservoirs.

Seals

At the Godley Bridge well, the Purbeck anhydrite forms an effective seal to the Upper Jurassic Portland Beds (Butler & Pullan 1990). Upper Jurassic Corallian reservoirs are sealed by overlying thick Kimmeridgian shales and Great Oolite reservoirs are sealed by the Oxford Clay.

Significantly, no real overpressures exist in the Weald Basin, and it seems likely that its faults may provide a pressure release mechanism and are not therefore, in general sealing.

Traps

As in the Wessex-Channel Basin, structural closures fall into two main categories: upfaulted tilt-blocks and horsts, and major mid-Tertiary inversion structures, as developed by reversal of earlier normal faults. Prospective tilt-blocks and horsts can occur anywhere, but are probably best developed around the northern, western and southern margins of the Weald Basin and the southern margin of the Hampshire-Dieppe High. The most important inversion structures occur along the Pewsey-London Platform and Wardour-Portsdown structures. Again, their prospectivity is dependent upon the levels of structural disturbance during Tertiary inversion.

The first phase of oil migration (late Jurassic to early Cretaceous) led to the accumulation of oil in structures of pre-Late Cretaceous age (Butler & Pullan 1990). Such structures include those forming the Palmers Wood and Humbly Grove oilfields. Other traps were also formed by tilted fault blocks, on which syndepositional fault movements had occurred throughout the Jurassic and Early Cretaceous. Those around the margin have probably remained relatively undisturbed through the Tertiary uplift/inversion, although they must have suffered some regional tilting. However, Tertiary inversion affected in particular the centre of the Weald Basin, where many accumulations were probably destroyed or breached during the Tertiary (Butler & Pullan 1990). The second phase of hydrocarbon generation and migration, probably in the early Tertiary, led to the modification or breaching of existing traps and accumulation in new traps. An example of a modified existing trap is the Storrington Oilfield, where gas break-out may have occurred during Tertiary uplift and tilting leading to the formation of gas caps. Although the Godley Bridge field contains a minor oil phase, it represents a gas accumulation, the trap origins for which lie in the Tertiary movements (Butler & Pullan 1990).

Other minor structural traps may exist within rollover anticlines developed against basin controlling faults. These anticlinal traps may have been modified ('tightened') during Tertiary movements or tightened in association with reverse movements on NW-SE trending faults, such as at Detention well in Kent. However, no commercial accumulations have yet been found in structures associated with these intense local inversion movements, which perhaps is a result of no closure at depth, or sealing problems along faults. Stratigraphic pinch-out has not been demonstrated as a mechanism of hydrocarbon entrapment in the Weald Basin.

Generation and migration

Hydrocarbon generation from the Lower Jurassic Lias shales probably began in the deepest parts of the Weald Basin in early Cretaceous times (Penn *et al*. 1987), with peak generation in the mid- to late Cretaceous. Upper Jurassic Oxford Clay maturity was reached in the deepest parts of the basin in latest Cretaceous times, and it is probable that the Kimmeridge Clay also reached maturity in the very centre of the basin at about this time (Penn *et al*. 1987; Butler & Pullan 1990). The Lower Lias shales may have entered the gas generation window in deepest part of the Weald Basin in Late Cretaceous times. Tertiary uplift progressively lifted the source rocks out of the temperatures and pressures required for hydrocarbon generation, such that it was effectively halted by Miocene times, although it may have continued into the Tertiary in the less disturbed western areas. The uplift gave rise to an important second phase of oil migration and remigration of both oil and gas as the result of tilting of pathways and destruction of many earlier traps. Two phases of migration are supported by the fact that ferroan cements appear to have been inhibited by the presence of hydrocarbons in some early-formed structures.

Migration pathways in the Weald Basin were influenced by both sedimentary and tectonic factors (Fig. 1.5). The presence of three major widespread shale/clay sections created three vertically separated fluid regimes in reservoir intervals within the Triassic, the Middle Jurassic and the Upper Jurassic. The Middle Jurassic Great Oolite is the best studied and documented of these pathways. Lateral migration along this unit permitted movement well away from the mature source area, although its effectiveness would have been reduced with time as progressive cementation took effect. As an example, Stockbridge and Goodworth fields lie 30 km from the postulated limit of maturity in the Weald Basin (also demonstrating the effectiveness of the Oxford Clay seal (Butler & Pullan 1990)). Tectonic controls on migration were provided by faults. A clear relationship exists between major faults and the occurrence of multiple reservoir horizons with hydrocarbons at both shallow and deeper levels, with hydrocarbons distributed throughout the stratigraphic column in areas strongly affected by Tertiary inversion. Movement along faults seems likely as reservoir-reservoir juxtapositions are otherwise not common, and hydrocarbons are often encountered when drilling through fault planes (Butler & Pullan 1990).

Accumulations

SURFACE INDICATIONS

Surface indications and oil seepages in the Weald Basin are less frequent than in the Wessex Basin, being virtually unknown in the Jurassic and only rare in the Lower Cretaceous. The first documented discovery of gas bubbling up in groundwater was in 1836, during the digging of a water well at Hawkhurst in West Sussex (Pearson 1903; Strahan 1920). Workmen dug a pit by lantern light to 98 ft, and then deepened the hole by auger bit. Some 50 feet below this point in Wealden Beds, the auger suddenly disappeared into a cavity and was followed by a rush of gas, the result being two workmen burned to death. Subsequently, gas was reported in water wells in 1875, 1884, 1895 and 1896 (see below).

That combustible gas was sometimes released from the ground in West Sussex was a fact well known to local residents in the 19th century (Hirst 1985). Surface seepages are recorded at a number of localities around the Weald Basin (see Selley 1993). These include a small seepage from the Wadhurst Clay (Cretaceous) at Mark Cross, with 'thin oil films on water' (Reeves, 1948). Three localities in Sussex have what were described as oil seepages in the Tunbridge Wells Sand (Lower Cretaceous), but for which no details are given, although faulting is thought to be associated with most (Lees & Cox 1937; Reeves 1948). These are at Down Ash, Hailsham Cemetery, and 'sands from an old quarry near Hailsham', giving a colour using chloroform (Reeves 1948). At Hastings, Sussex colour indicating the presence of petroleum was obtained from samples of the Hastings Beds (Lower Cretaceous) when using chloroform (Lees & Cox, 1937). An oil seepage was also recorded from Tunbridge Wells Sands at The Horns, Sussex, although details other than it being associated with faulting (Reeves 1948) are unavailable.

Important oil shows are also found in the Wealden (Lower Cretaceous) exposures of Kent and Sussex at Chilley, near Pevensey. Here, in a drainage trench, a bituminous and richly oil impregnated sand in the Tunbridge Wells Group is reported to have contained 15.4% bitumen. It yielded 12% by weight (25% by volume) of black viscous oil with a specific gravity of 0.995 and a sulphur content of 0.66% (Mantell 1833; Lees & Cox 1937; Lovely 1946; Reeves 1948). The uppermost Jurassic Purbeck inliers of the Weald Basin were also reported to have indications of hydrocarbons, with an oil shale from crop yielding, on distillation, 20 gallons of oil per ton with a specific gravity of 0.878, setting point at 77° F and low sulphur content (Lees & Cox 1937).

BLETCHINGLEY GASFIELD

Four wells were drilled on the Bletchingley structure on the northern margin of the Weald Basin, Surrey during 1965-1966. Wells 1, 2 and 3 tested gas from the Upper Jurassic Corallian Limestone, but well 4 was dry since the reservoir section was found to be absent due to faulting (Trueman 2003). The Corallian Limestone is reported to be 130 ft thick, characteristically massive carbonate, occasionally oolitic, reefal in places with vugular and leached intergranular porosity.

HUMBLY GROVE OILFIELD

The Humbly Grove Oilfield is located in northeast Hampshire, on the northern margin of the Weald Basin. The geology and development of the oilfield have been summarised by Sellwood *et al*. (1985) and Hancock & Mithern (1987). The Herriard and Hesters Copse discoveries are in two closely related satellite structures. The original licence PL116 was awarded in 1969 and following relinquishments in 1975, PL116B was retained. Farm-ins, assignments of interest and acquisitions have led to a series of partners (see Hancock & Mithern 1987). Seismic reflection surveys totalling 72 km were acquired in 1977, 1978 and 1979, and their interpretation revealed the existence of an E-W trending horst, fault closed to the north and south and dip closed to the east and west, with 1250 acres (50 hectares) areal closure and 60 msecs TWTT of vertical closure. Geochemical analyses suggest that the principal source rock interval is probably basal Jurassic shales of the Lower Lias. Tertiary inversion had little effect on the Humbly Grove structure, but terminated hydrocarbon generation from its source rocks.

The discovery well, Humbly Grove 1 (HG1-X1), was drilled in May 1980. It encountered 136 ft (41 m) of hydrocarbon-bearing reservoir in Great Oolite Group (Bathonian) limestones (Hancock & Mithern 1987), and tested 39° API oil at 72 bopd. Further seismic data totalling 136 km were acquired between 1980 and 1982, further delineating the structure and providing sites for three appraisal wells. Spudded in 1982, HG2-A1 well was drilled on the structural crest. It encountered a gas cap and a sharp permeability interface, separating the Great Oolite reservoir into an upper zone of relatively high permeability (20-200 mD) and an underlying low permeability zone (0.5-2 mD). Drill stem testing confirmed high productivity of 750 bopd from the oil reservoir. The well also encountered gas in the Upper Triassic Rhaetic Formation, which was tested at 1.09 mmcfd gas with condensate – this formation had been water-bearing in HG1-X1 well. Following the appraisal programme, proven and probable reserves in the Great Oolite limestones were estimated at 13 mmbbl of 39° API oil, with a gas cap of 3 bcf. Development of the field commenced in two phases. In 1984, Phase I began production from the high-permeability reservoir, whilst appraising the low-permeability and Rhaetic reservoirs. Phase II, commencing in 1988, covered the development of the low-permeability reservoir. Field development has shown the Great Oolite to have a 75 ft (23 m) gas column and a 70 ft (21 m) oil column within the higher permeability reservoir, and a low permeability reservoir containing a long transition zone of 295 ft (90 m) of increasing water saturations. Development well HG-X4 subsequently also found oil in the previously discovered Rhaetic gas accumulation, which on test flowed 1469 bopd of 49° API oil (Hancock & Mithern 1987). A gathering station, pipelines, and a rail export terminal have been constructed. During 2005, four horizontal wells were drilled into the Great Oolite reservoir gas cap, then two further horizontal wells were drilled into the Rhaetic for gas storage purposes. Gas storage commenced during November 2005, and the field is currently operating as a gas store with 10 bcf working gas capacity whilst continuing to produce oil (Hurren & Hancock 2009). From gas storage start-up until February 2009, total gas imports and exports amounted to some 95 bcf.

HORNDEAN OILFIELD

The Horndean Oilfield lies on the southern margin of the Weald Basin, with the Middle Jurassic Great Oolite Group forming its producing reservoir. It was discovered during early 1983. A development well drilled in 1990 was the first horizontal well to be drilled in the Great Oolite Group in southern England. The field is an E-W elongate tilted fault block. With an original estimated STOIIP of 37 mmbo, Trueman (2003) recorded a cumulative production of 1.6 mmbo.

PALMERS WOOD OILFIELD

Discovered in 1983, the Palmers Wood Oilfield lies on the northern margin of the Weald Basin, south of London, and produces from Upper Jurassic Corallian sands. Trueman (2003) estimated the field's STOIIP as 11.73 mmbo, and recorded a cumulative production of 2.82 mmbo.

HERRIARD OILFIELD

The Herriard Oilfield lies within the Humbly Grove Development area, with the Middle Jurassic Great Oolite Group forming its producing reservoir. Discovered in 1983 with an estimated STOIIP of 6 mmbo, the field's cumulative production is 0.34 mmbo (Trueman 2003). The field has now ceased production.

STOCKBRIDGE OILFIELD

This field was also referred to as Larkwhistle Farm in some DECC publications. Discovered during 1984, the Stockbridge Oilfield lies on the south-western margin of the Weald Basin in Hampshire, and produces mainly from the Great Oolite Group. Its structure is formed by a broad E-W elongated dome, divided into two major fault blocks by an E-W oriented fault (Trueman 2003). Estimated STOIIP is 171 mmbo.

STORRINGTON OILFIELD

The Storrington field was discovered in March 1986 and its reservoir is the Great Oolite Group. It lies on the southern margin of the Weald Basin in West Sussex, on trend with the nearby Horndean and Singleton oilfields. The trap is located on an E-W trending horst with dip closure to the east and west (Trueman 2003).

ALBURY GAS FIELD

The Albury Gas Field lies on the northern margin of the Weald Basin, in Surrey, and has sands and limestones within the uppermost Jurassic Purbeck Group as its main producing horizon. It was found in 1987 in a broad E-W trending inversion anticline in the hanging-wall of the Hogs Back fault system (Trueman 2003). Modelled GIIP varies between 7 bcf (based upon the Albury 1 well) and up to 22 bcf (down to the structural spill point).

GOODWORTH OILFIELD

The Goodworth Oilfield lies on the northern margin of the Weald Basin, in Hampshire, close to the north-west of Stockbridge Oilfield. Oil production is from the Great Oolite Group (Trueman 2003).

SINGLETON OILFIELD

Discovered in 1989, the Singleton Oilfield lies on the southern margin of the Weald Basin, east of Horndean. Its main producing horizon is the Middle Jurassic Great Oolite Group.

CONCLUSIONS

Discoveries in the Weald Basin essentially show that migration has occurred towards its northern and southern margins, resulting in two parallel lines of fields following the structural strike of the basin. Higher risk is envisaged for acreage on the Hampshire Dieppe High between the Wessex-Channel and Weald basins, because this structure is generally beyond the limits of hydrocarbon migration from the main hydrocarbon kitchen. Nevertheless, a discovery at Lidsey shows that local generation in a small sub-basin on the High has occurred.

4 Cheshire Basin

INTRODUCTION

The Cheshire Basin (Fig. 1.1) is not a proven petroleum province, but it possesses similarities to both the productive offshore East Irish Sea Basin and the East Midlands hydrocarbon province. Some of the early drilling was focused on multiple reservoirs. Drilling in the 1980s featured some deep Carboniferous tests, mainly in the west of the basin. Later drilling has concentrated, unsuccessfully, on the shallow Triassic Helsby Sandstone reservoir. The main factors for the failures will be summarised here, which should lead to better-defined targets.

EXPLORATION HISTORY

Exploration for hydrocarbons in the Cheshire Basin was carried out in several phases. The First World War gave impetus to the first systematic search. Long before this time, hydrocarbon seeps in coalmines, houses, and at the surface had frightened householders and miners, arousing scientific curiosity (Robinson & Grayson 1990). One gas seep near Broseley was an early tourist attraction (Hopton 1711) and, when it ceased, exploration was conducted again, eventually proving successful (Mason 1747). The Coalport Tar Tunnel seep from sandstones in the Westphalian (Upper Carboniferous) Halesowen Formation (Fig. 4.1), discovered in 1786, is now part of the Ironbridge Gorge tourist site (Brown & Trinder 1979). This was exploited as a mined oilfield for about 50 years. Cannel coals and oil shales were also exploited during the mid-1800s, representing the earliest phase of hydrocarbon exploration. In the Flint district, a rich oil-bearing shale 4-10 inches (0.1-0.25 m) thick forms the roof to the Cannel Coal. This shale was used for the distillation of paraffin oil at Leeswood Green (Wedd & King 1924).

Figure 4.1 Coalport Tar Tunnel- one of the collection pits of a small, mined field in the Carboniferous Halesowen reservoir, exploited in the 18th century. The tunnel was opened up to bring out coal from below ground to the Severn River in Coalbrookdale, Shropshire (© NERC).

TECTONIC SETTING

The Cheshire Basin (Fig. 1.1) lies within a NNW-SSE trending Permo-Triassic rift that extends from the Wessex Basin to the Scottish Inner Hebrides. It also includes the south-western part of the Carboniferous Pennine Basin, and in turn overlies a northeastward extension of the Lower Palaeozoic Welsh Basin.

BASIN STRUCTURE

There are three superimposed basins. The oldest, Lower Palaeozoic basin is overmature for hydrocarbon generation. Overlying this, Carboniferous sub-basins developed in the foreland of the Variscan Orogen; these sub-basins were controlled by NE-SW trending faults. An E-W trending landmass (St George's Land) limited Carboniferous deposition to the south of the Cheshire Basin. Early Carboniferous carbonate and shale facies variations were controlled by differential subsidence of the rift phase. Fault-controlled subsidence then terminated as an extensive delta system prograded from the north in mid-Carboniferous times. Regional thermal subsidence created depocentres to the north and east of the present-day Cheshire Basin, in which deltaic and paralic sequences accumulated, including the main clastic reservoirs of the adjacent East Midlands province (Section 7). End Carboniferous tectonism, related to the Variscan Orogeny to the south, inverted the Pennine Basin about an axis centred along the present-day Pennine Hills of Derbyshire, Yorkshire and Lancashire.
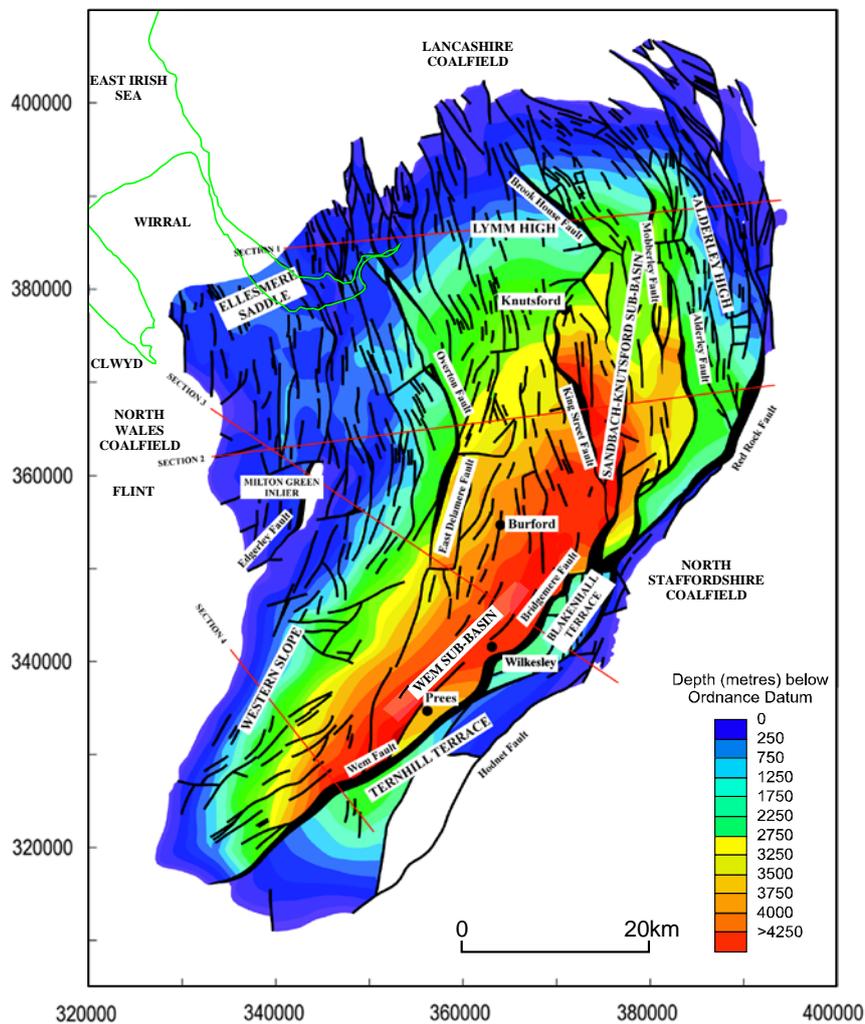
Figure 4.2 Depth to the base of the Permo-Trias in the Cheshire Basin

In Permian times, extension led to the formation of a regional N-S rift, in which the Cheshire Basin formed a west-offset depocentre controlled by the older NE-SW trending Carboniferous faults (Figs. 4.2, 4.3). Rifting continued

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until mid-Triassic times, when regional thermal subsidence became dominant. Only small, fault-controlled remnants of Lower Jurassic strata (the youngest preserved) occur in the basin, illustrating an inversion, common to many parts of the rift, which occurred in Tertiary times.
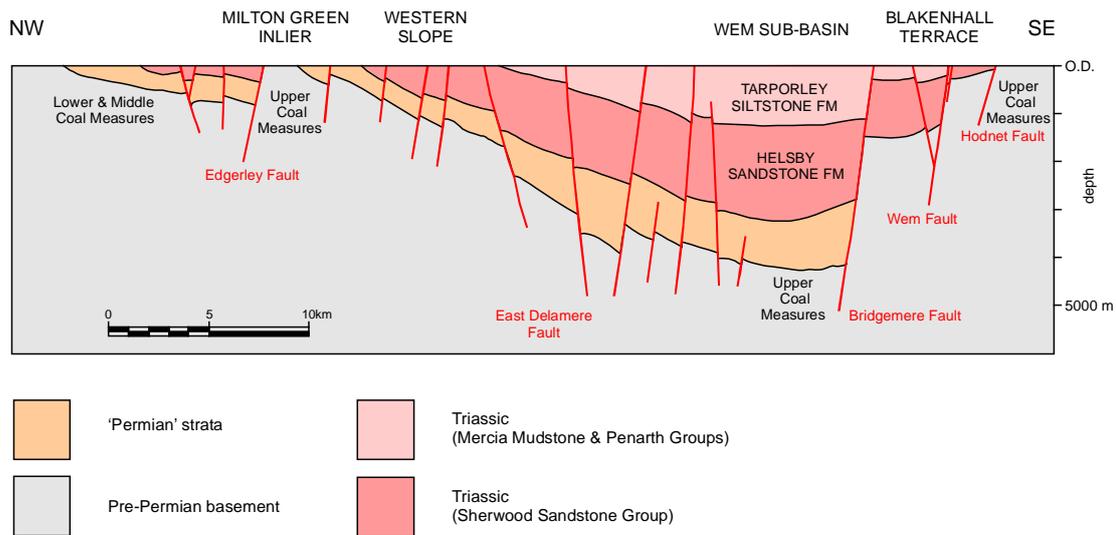
Fig. 4.3   NW-SE geological section through the central Cheshire Basin (after Plant et al. 1999)

STRATIGRAPHY

The stratigraphy of the Carboniferous and Permo-Triassic basins is shown in Figure 4.4. Punctuating the stratigraphy are important unconformities at the base and top of the Carboniferous; the latter is termed the Variscan Unconformity in Britain.

PETROLEUM SYSTEMS

Source rocks

Carboniferous source rocks (Fig. 4.4) include Dinantian (Brigantian) basinal shales and shaly ramp carbonates, early Namurian shales (Holywell Shales), Westphalian oil shales and cannel coals (oil-prone) and bituminous coals (gas-prone), which outcrop on the periphery of the Cheshire Basin. Early Namurian shales (Edale Shales and Holywell Shales respectively) are considered to be the source rocks of the East Midlands and East Irish Sea oilfields. Formby Oilfield, in the adjacent West Lancashire Basin (section 6), overlies the Bowland Shales (also of early Namurian age).

HOLYWELL SHALES (NAMURIAN)

These shales, of Pendleian to Yeadonian age, crop out in Clwyd (North Wales) adjacent to its coalfield, and are probably represented by oily shales between depths of 950-985 m in the Heswall Borehole on the Wirral Peninsula. TOC values range up to 5%. δC of saturated hydrocarbon fractions in the shale varies from -30‰ in the lower part to -27‰ in the upper part. The more depleted values are interpreted to result from a distal fluvio-deltaic environment, and are a fair match for the oils at the Douglas and Lennox oilfields in the offshore East Irish Sea Basin. Westphalian coals have δC values of -25‰ to -24‰ (Armstrong *et al*. 1997). Mikkelsen & Floodpage (1997) suggested that these source rocks are absent from the southern part of the Cheshire Basin subsurface, but this may not be the case.

WESTPHALIAN CANNEL COALS

Cannel coals are present in all the northern coalfields, and these and oil shales are found at several horizons in the Flint district (Wedd & King 1924). They are probably immature, as reasonable amounts of oil can be obtained by distillation. Oil shales were also reported in the Norton and Kidsgrove areas of the Potteries Coalfield by Gibson (1905). The volumes of oil obtainable vary from 20-80 gallons per ton. Oil has been produced at Leeswood by heating the oil shales and cannel coals. In the Flint district, curly cannel yielded 80 gallons per ton, smooth cannel 35 gallons, and oil-shale 33 gallons (Wedd & King 1924). Cannel at Clanway Colliery (N Staffordshire Coalfield) yielded 60-70 gallons of oil per ton (Gibson 1925). Shales and oil shales within the Upper Coal Measures of the Potteries Coalfield in Staffordshire have been used for oil production (Rees & Wilson 1998).
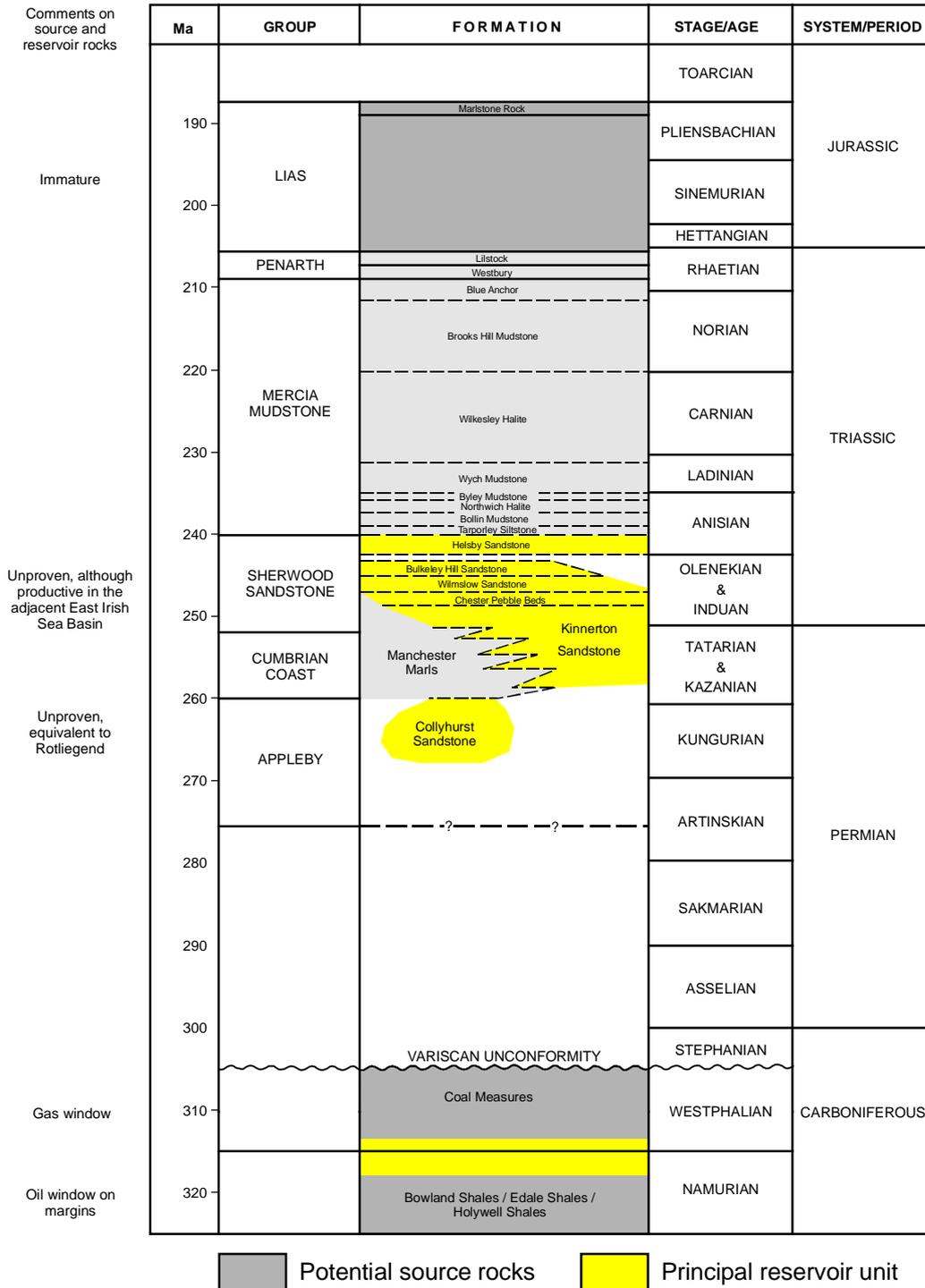
Fig. 4.4 Stratigraphic position of the principal source rocks and reservoirs of the Cheshire Basin

These source rocks can reasonably be expected to underlie the Cheshire Basin between the North Staffordshire, Lancashire and North Wales coalfields, although Mikkelsen & Floodpage (1997) have suggested a different view. Such terrestrial coaly source rocks provide waxy oils and could conceivably be the source of the Hem Heath and Coalport oil, which can be visualized as having migrated SW towards the margin of the (Carboniferous) Cheshire Basin.

WESTPHALIAN OIL SHALES

Oil shales are known at Aston Hall in Lower Coal Measures, in the roof of the Premier Coal (Fig. 4.1), and in the roof of the Yard or Cannel coal at Leeswood and Aston Hall (Wedd & King 1924).

Maturity of source rocks

Maturity depends on burial history and geothermal gradients. Erosion after the end-Carboniferous Variscan Orogeny presents the greatest obstacle to a definitive burial plot. Maturity of the post-Carboniferous section is more straightforward. Peak subsurface temperatures were reached in early Paleocene times, with the deepest parts of the Triassic Mercia Mudstone Group and all underlying Permo-Triassic strata lying within the oil window. The destruction of garnets in the Cheshire Basin is evidence that temperatures were once higher than 80°C, whereas their presence in the Little Hay Borehole indicates that the South Staffordshire Block did not reach this temperature (A. Morton - personal communication). This is an independent confirmation of the structural, burial and temperature history.

Geothermal gradient

The present day geothermal gradient of the Cheshire Basin is about 20°C/ km (Burley *et al.* 1984). Temperatures in the Lancashire coal mines gave an average of 20°-22° C/ km, although Rose Bridge Colliery was higher at 38°C/ km (Graham 1922, Verma 1981). This value is possibly influenced by proximity to an influx of saline water (De Rance 1886), although the temperature of this water is not known. The geothermal gradient in the North Staffordshire Coalfield is also higher, being 37°C/ km (Verma 1981).

Carboniferous palaeogeothermal gradient

Discussion of the Carboniferous geothermal gradient in central England was initiated by Suggate (1981) and Creaney (1981). Ewbank *et al.* (1995) modelled the late Carboniferous geothermal gradient in the Edale and Widmerpool sub-basins of the East Midlands province as 45-55°C /km, and found that the model fitted the vitrinite reflectance data, indicating that maturity was achieved by the end of the Carboniferous (Kirby *et al.* 1987). In contrast, Fraser *et al.* (1990) and Pearson & Russell (2000) found no change in maturity gradient at the end-Carboniferous Variscan Unconformity, suggesting that maturity had not been achieved until Cretaceous or Tertiary times.

To test these contrasting results, downhole vitrinite reflectance data were plotted for a number of hydrocarbon wells in the region. The maturity gradients within the Carboniferous section are higher than those in Mesozoic and Permian strata, where sufficient penetration has been made and the borehole fully sampled. Burial by sediments alone cannot reproduce the maturity gradients. Comparison of the results with areas where maturity and geothermal gradients are known e.g. Rhine Graben (Teichmuller 1987) and Cerro Prieto (Barker 1983) indicates that most of the wells probably experienced Carboniferous geothermal gradients of 35-60°C/ km. Some wells had higher values. By comparison with present day fold belts and forelands these values are not excessive.

From the coal rank maturity data, it is apparent that during late Carboniferous (Westphalian) times North Staffordshire had a higher palaeogeothermal gradient than Lancashire and the East Midlands coalfields. The reason may be proximity to late Carboniferous volcanism. Because of the varying thermal conductivity of different lithologies, the heat flow may not have been high.

Millot *et al*. (1946) assessed maturity from coal rank data in Keele 1 well, drilled in the Potteries Coalfield on the margin of the Cheshire Basin. Their depth-maturity plot reveals that the geothermal gradient in Keele 1 may have been as high as 81° C/ km in early Westphalian times, declining to 29-45° C/ km in late Westphalian times. Depending on the geothermal gradient, an uplift of 800 to 1300 m is indicated, most of which can be assigned to Tertiary rather than end-Carboniferous Variscan uplift (J Rowley personal communication).

From the same well, Suggate (1981) derived a rank gradient of 900 kcal/kg/km. This compares with Nottinghamshire-Yorkshire coalfield values of between 600-1000 kcal/kg/km and Tertiary coals at Taranaki, New Zealand of 500 kcal/kg/km. Taranaki coals (0.9 VR%; 8300 kcal/kg) were buried about 5 km deep, and the geothermal gradient there is 30°C/ km. Suggate (op. cit.) interpreted these relative values to indicate burial of the English coals to about half the depth of the Taranaki coals.

Differences in maturity have been found between late Westphalian rocks in the Knutsford and Keele boreholes using published equivalents between volatile matter percentages and vitrinite reflectance. Recently published vitrinite reflectance data (Pearson & Russell 2000), from Westphalian strata at the surface and at Knutsford borehole (depth about 3 km), also suggest that the difference in maturity can be attributed to a Permian to present day geothermal gradient of 34°C/ km and 3 km of additional burial.

Reservoir rocks

Potential reservoirs are from the top downwards (Fig. 4.4): Helsby Sandstone Formation, Wilmslow Sandstone Formation (both Triassic), Kinnerton Sandstone Formation, Collyhurst Sandstone Formation (Permian), Coal Measures, Millstone Grit sandstones and Dinantian sandstones (all Carboniferous). Many of the Upper Carboniferous sandstones in the Milton Green and Blacon East wells are thin, but thicker equivalents were found in the Erbistock well.

SHERWOOD SANDSTONE GROUP AND COLLYHURST SANDSTONE

Many of the Triassic and Permian sandstones are porous, with oversized pores indicating the dissolution of an earlier diagenetic cement of anhydrite and halite (Plant *et al*. 1999). This is a characteristic feature of other UK Permo-Triassic basins (Milodowski *et al*. 1986), and the timing of this secondary porosity is no older than latest Triassic (Milodowski personal communication). In the offshore East Irish Sea Basin, other authors (Burley 1984, Bushell 1986) have attributed secondary porosity development as due to leaching of carbonate and feldspar phases, which then allowed entry of hydrocarbons.

Lovelock (1977) analysed Triassic and Permian porosities and permeabilities in four boreholes from south of the Wem Fault, two from the Vale of Clwyd, and an unspecified number from other boreholes. In the upper part of the Permian Collyhurst Sandstone, porosities are 10-15% and permeabilities up to 20 mD, but in the lower part they reach above 25% and up to 18000 mD respectively. Downing & Gray (1985) reported an average porosity of 13% from geophysical logs for this unit. At outcrop, cemented parts of the Triassic Chester Pebble Beds have porosities up to 14% and low permeability, whereas coarse clean Triassic sands have average porosities of 22% and permeabilities up to 2500 mD. These values are probably not representative of subsurface properties, since geophysical logs indicate subsurface porosity of about 11% for these units. Geophysical logs give an average of 13% porosity for the Triassic Wilmslow Sandstone (Downing & Gray 1985).

By computing porosity values from density logs and obtaining theoretical values, Rowley (in Plant *et al*. 1999) showed that porosity decreases with depth in the Triassic Sherwood Sandstone Group and the Permian Collyhurst Sandstone. Early hydrocarbon migration is essentially required to forestall the decrease of porosity due to burial. In the main part of the Cheshire Basin, there is no evidence for such an early migration.

Isopachs of the Helsby Sandstone Formation and other Triassic formations show that the main thickening is east of a line between Prees and Knutsford wells. Thinning is apparent north of the Knutsford well and along the Red Rock Fault, and particularly to the west, so that at their western outcrop, the formations are considerably thinner than in the depocentre, which encompasses the Prees well, the northeast part of the Wem Fault and the King Street Fault, as far north as Knutsford. A probable connection with the offshore East Irish Sea Basin through the Mersey Estuary to the area between Knutsford and Ashton boreholes is indicated by the Permian isopachs. All of the isopach maps reinforce the structural pattern gained from the seismic reflection data, that there are four migration directions within Permo-Triassic strata:

1 towards the north from the Mersey depocentre

2 NE from the King Street depocentre

3 towards the west from the Wem depocentre

4 SW from the Mersey depocentre

Most of the drilling so far has concentrated on the area of thickest known Triassic Sherwood Sandstone Group. The Helsby Sandstone Formation (top of Sherwood Sandstone Group) is about 100 m thick along the western outcrop, but all the wells have encountered a thickness of more than 200 m. The overlying Tarporley Siltstone Formation is just in excess of 50 m thick along the western outcrop, but is greater that 150 m thick in all of the wells. None of the wells to date were drilled on Triassic palaeo-highs.

WESTPHALIAN RESERVOIRS

Laboratory tests on Westphalian sandstones in core from three British Coal boreholes gave porosities less than 15% and permeabilities less than 1.6 mD (Downing & Gray 1985, p 91). In the East Midlands oilfields, equivalent sandstones have porosities of 7-20%, averaging 12%. Late Westphalian sandstones, which are not productive, have higher porosities from 12-19%. Permeabilities are 0.06-37 mD, locally 400 mD for mid Westphalian sandstones, and 2-160 mD for the late Westphalian sandstones (Downing & Gray 1986).

Reddening of upper Westphalian sandstones has occurred during Permian and Triassic times in the Potteries Coalfield, along with enhancement in the porosity and permeability of the sandstones there (Rees & Wilson 1998).

NAMURIAN RESERVOIRS

Geophysical log analysis of Alrewas well revealed Namurian porosities ranging from 6 to 18%, but mainly less than 12%. At Ranton well, porosities of up to 10% are indicated by the sonic log, but zones with porosities up to 14% (perhaps suggesting the presence of fractures) are indicated by the neutron and density logs. Repeat formation tests at both wells were dry. In the East Midlands, Namurian porosities average 12%, with permeabilities a few tens of millidarcys only. A northerly decrease in porosity and permeability has been noted in the East Midlands oilfields, which is interpreted to be a Carboniferous burial effect. Similar northward loss of porosity and permeability is envisaged for the Cheshire Basin.

DINANTIAN RESERVOIRS

Amongst the Lower Carboniferous, Dinantian reservoirs are the Onecote Sandstone (productive at Nooks Farm), sandstones in S Clwyd county (Minera Formation) and at Coalbrookdale and Lilleshall in Shropshire. Some of these sandstones have high porosities (N Riley personal communication).

Seals

Halites and mudstones of the Middle to Upper Triassic Mercia Mudstone Group are excellent seals, where sufficiently thick. At Formby Oilfield in Lancashire, there is no halite and the Mercia Mudstone is thin, resulting in a very leaky oilfield there.

There are no other significant mudstone beds within the Triassic. The Upper Permian Manchester Marl can be considered a reasonable seal, where it is composed of mudstone and halite. Halite is known only in the Cheshire Basin from a thin bed in the Heswall well, but it could be developed more extensively in the deep parts of the basin, in the area east of Knutsford and Prees wells. The Manchester Marl becomes sandy in the south, and westwards in the north of the Cheshire Basin, and is a poor seal there.

In the East Midlands, only a very small percentage of hydrocarbon shows occurs in post-Carboniferous rocks. Although hydrocarbons continued to be generated during Permian and Mesozoic times, there is no significant evidence of migration into post-Carboniferous rocks there. Similarly, in the Cheshire Basin there are relatively few cases of hydrocarbons in Permo-Triassic rocks in water wells, salt mines or other boreholes. There are commercial oil and gas accumulations offshore in the East Irish Sea Basin and at Formby oilfield in Lancashire, and oilsands occur in the Triassic of the adjacent Needwood Basin. Shows are commonplace in Carboniferous rocks surrounding the Cheshire Basin and in British Coal (formerly National Coal Board) boreholes in the subcropping Carboniferous so far reached by drilling. It is possible that, at the margins of the basin, hydrocarbons could have migrated from the Carboniferous into Permo-Triassic rocks, but no such indications are known from the basin itself, although they clearly occur in the smaller Needwood Basin. The latter has a much thinner Permo-Triassic cover than the Cheshire Basin, and it would be easier for hydrocarbons to migrate vertically there.

Although gas is normally more difficult to retain, the small gasfields in the East Midlands (e.g. Calow) have not required the presence of Permian or Triassic evaporites to maintain their seal. Carboniferous shales may therefore be adequate to seal hydrocarbons beneath the Permian unconformity, particularly where the shale-prone late Carboniferous Etruria Formation is present.

The active Permo-Triassic tectonics in the Cheshire Basin contrasts with the relatively slow accumulation of equivalent sediments on the gently shelving margin to the onshore continuation of the Southern North Sea Basin, in the East Midlands. However, as was shown above, the sub-basins of the Cheshire Basin are relatively simple structures, compared to the chaotic faulting in the offshore East Irish Sea Basin (Jackson *et al*. 1987). In a study of fault displacements and fault zone widths, Knott (1994) suggested that sealing is likely to be greater on wide faults of large displacement, which have correspondingly thicker zones of reduced permeability and porosity. Pinfold (1958) pointed out that faults dipping at 40-50°, as are common in the Lancashire Coalfield area, are likely to be sealing because of the weight of the rock column on the hanging wall.

Overburden

The eroded ovrburden, calculated from density and sonic velocity logs, varies between 450-2780 m for marginal and basin-centre wells respectively. The eroded strata are presumed to have been Jurassic-Lower Cretaceous, overlain unconformably by Upper Cretaceous Chalk (Plant *et al*. 1999).

Traps

Mikkelsen & Floodpage (1997) described fault-bounded structures near to the Permo-Triassic depocentres, but these have all proved to be dry. Faulted palaeo-high traps in Permo-Triassic reservoirs have not been specifically targeted.

The Carboniferous rocks underlying the Permo-Triassic Cheshire Basin are expected to show a similar combination of structural, stratigraphic and sedimentological trapping as in equivalent strata on the eastern limb of the Pennine Basin (East Midlands province, Section 7). Dinantian apron reefs may be expected to occur in the subsurface, and Dinantian sub-basins have been tentatively identified from seismic reflection profiles. Westphalian rocks overlap these Dinantian strata to the south of the basin in an undrilled area. Namurian strata are present everywhere else, except in a small inversion area associated with the Wem Fault (Plant *et al*. 1999). The late Carboniferous strata thin towards the south and west margins of the Cheshire Basin (St George's Land).

Generation and migration

TIMING OF GENERATION

In the Carboniferous Pennine Basin, outside of and in the NE of the Cheshire Basin, generation of hydrocarbons began from Dinantian and Namurian oil-prone rocks before Permo-Triassic burial (Kirby *et al*. 1987). Westphalian rocks were probably immature prior to later Permian and Mesozoic burial.

Additionally, new oil was probably generated in Permo-Triassic and later times during subsidence controlled by the Wem-Red Rock fault system, which would have generated hydrocarbons from the underlying Carboniferous rocks in the main part of the Cheshire Basin. The present day geothermal gradient is low, and there is little evidence for much higher values in Permian to Tertiary times, resulting in a deep-lying oil window.

MIGRATION WITHIN CARBONIFEROUS ROCKS

During Carboniferous times, migration was probably southwestwards from the Pennine Basin depocentre into the area now comprising the Cheshire Basin. This marginal area to St George's Land had thinner sediments and better reservoir sands than in the Pennine Basin. During the end Carboniferous Variscan Orogeny, inversion of the Pennine Basin produced the N-S Pennine Anticline and Derbyshire Dome and other highs that were formerly basins, causing some of the hydrocarbons to migrate northeastwards, away from the Cheshire Basin. This is calculated to amount to about half of the drainage area of the basin. Preferential erosion removed about 5-6 km of strata including probable reservoirs here, destroying a large proportion of these hydrocarbons. These migration directions are analogous (mirror image) to those in the East Midlands (see Section 7).

Migration of hydrocarbons since Carboniferous times may also have been largely within the Carboniferous section, if its seals were not breached. Since the Carboniferous, Permo-Triassic syn-sedimentary faulting has modified the migration directions. The large faults produced sub-basins, which will have had their own migration directions. For example in the main part of the basin, migration was probably up-dip towards Milton Green. The most prospective area for this oil is undoubtedly to the southeast of the Milton Green inlier (Plant *et al*. 1999), because there is probably no seal where the Carboniferous is at crop in a small inlier surrounding the Milton Green well. Hydrocarbon shows were recorded in the uppermost Carboniferous red beds in the Churton Borehole also drilled in this inlier.

The large amounts of Permo-Triassic subsidence in the Cheshire Basin and the East Irish Sea Basin contrast with the gentle contemporary subsidence on the margins of the North Sea Basin affecting the East Midlands oilfields. The fate of Carboniferous generated oil is difficult to predict. The mature oil of the East Irish Sea Basin migrated in post-Triassic times into Triassic reservoirs, whereas in the East Midlands, Mesozoic and younger migration was largely confined to within the Carboniferous strata.

MIGRATION INTO PERMO-TRIASSIC ROCKS

The carbon isotope characteristics of a late carbonate cement (late Triassic age) in the northwest of the Cheshire Basin reflect precipitation from fluids derived from thermal maturation and decarboxylation of organic matter. In this part of

the basin, fluid inclusion data indicates a different fluid composition from Alderley Edge (Plant *et al*. 1999). This is evidence of fluid migration from Carboniferous to Permo-Triassic rocks at the southern margin of the Lancashire Coalfield and in the West Lancashire Basin (Plant *et al*. 1999). The migration pathway for these fluids is probably not the main north-south trending, inclined normal faults which, with large displacements, are probably sealing (Knott 1994). Sub-vertical, east-west transfer faults may have formed better pathways for upward migration of fluids from Carboniferous rocks (Plant *et al*. 1999).

Small hydrocarbons shows in Permo-Triassic strata in boreholes at Ashton and Mickle Trafford and at outcrop at Burton Point suggest that trace amounts of hydrocarbons, reservoired at depth, may be migrating into Triassic Chester Pebble Beds and Permian Collyhurst Sandstone in the north-west of the basin.

Migration of uraniferous bitumen into the Ty Gwyn Copper Mine in N Wales is dated by 207Pb/206Pb as 248 +/-21 Ma (Early Triassic) (Parnell & Swainbank 1990). The source of the bitumen was probably Namurian Holywell Shales in the offshore East Irish Sea Basin.

In the West Lancashire Basin, the oil at Formby is 37° API, whereas the East Irish Sea oils are 44° API. Whether this latter difference represents two phases of generation in these basins is not known.

Accumulations

COALPORT TAR TUNNEL

The accidental discovery of oil in 1787 during construction of an underground coal removal tunnel (Fig. 4.1) led to production for about 50 years. The tunnel lies in the Coalbrookdale Coalfield, south of the Cheshire Basin. The reservoir is in late Carboniferous Halesowen Formation sandstones. The source rocks are presumably Namurian shales, which pinch out to the northeast of the tunnel.

NOOKS FARM DISCOVERY

The only discovery, made by Shell, is located at Nooks Farm east of the Cheshire Basin on outcropping Millstone Grit. Nooks Farm 1 discovery well tested 16.4 ft^3 gas from the Onecote Sandstone (late Dinantian). Its re-drill, Nooks Farm 1A, tested gas at 1.3 mmcfd from an interval at 433-466 m depth, at a reservoir pressure of 475 psi. Core from the well revealed medium and coarse-grained sandstones, with minor mudstones and conglomerates, which were cracked and fissured. Bitumen was noted on one surface and initial gas bleeding was reported. Porosity was dominantly 8-10% and permeability ranged up to 10 mD. An extended production test showed a reservoir pressure decline to 429 psi after producing 38 mmcf. Shell calculated a GIIP of 0.37 bcf .

OTHER SHOWS

There are several other geographical and geological locations where oil seepage has occurred. Carboniferous rocks in all the coalfields surrounding the Cheshire Basin have fair to good shows of hydrocarbons, with live oil, comparable to oil in the Nottinghamshire-Yorkshire Coalfield (Kent 1954, Challinor 1990). Late Westphalian sandstones in Shropshire have yielded oil at several localities. The base metal mines of the Shelve and Longmynd have bitumen stains on the ore.

Many of the coal seams are gassy, attracting drilling on three UK coal-bed methane exploration licences. In the Flintshire Coalfield at Point of Ayr Colliery, a methane drainage scheme was required to remove gas from underground workings. Similarly at Parkside Colliery in the Lancashire Coalfield, gas was drained and sold to a Warrington factory. At Wolstanton Colliery in the North Staffordshire Coalfield, excess methane was sold to local potteries.

Live oil has been encountered in the Coalbrookdale, Lancashire and North Staffordshire coalfields (Strahan 1920). In some instances this may be interpreted as migrating oil intercepted by mining, although oil-bearing sandstones are also known for example in the Coalbrookdale area. This oil has a probable local cannel coal source, and has migrated to the extremity of the Carboniferous basin (Longmynd-Shelve area). If there are similar sources beneath the Cheshire Basin, migration northwestwards from Wem-Wilkesley and northeast from Crewe-Knutsford would be expected.

A few oil shows are known from Triassic strata, mainly near the Wirral Peninsula, but these are less impressive than the Carboniferous shows.

CONCLUSIONS

Two oil provinces are contiguous with the Cheshire Basin. To the west and offshore is the East Irish Sea Basin province, in which Namurian shales (probably Holywell Shales) are the source and the Triassic Helsby (Ormskirk) Sandstone Formation is the reservoir. The Formby Oilfield in West Lancashire is an onshore field in this province, discovered in 1939. To the east of the Cheshire Basin is the East Midlands province (see Section 7), in which Namurian and Dinantian shales are the source rocks, and reservoirs are predominantly early Westphalian and late Namurian sandstones, with subordinate early Namurian and Dinantian reservoirs. The East Midlands hydrocarbon province is sourced and reservoired exclusively in the Pennine Carboniferous Basin, which also extends westwards beneath the Permo-Triassic Cheshire Basin.

There are no significant shows in Permian and younger strata. The most modern exploration focussed on the Triassic Helsby reservoir, whereas exploration in Carboniferous strata is recommended as potentially more fruitful. At least two areas with different plays look promising.

5 Cleveland Basin

INTRODUCTION

The Cleveland Basin is situated in northeast England (Fig. 1.1), where it forms an onshore component of the Southern North Sea Gas Basin, specifically of the Sole Pit Trough. The basin has been inverted, and it forms significant topography in the North York Moors (this is unusual for Mesozoic rocks in the UK).

In Late Permian times, the Cleveland Basin lay at the western margin of the Zechstein Sea, and its sediments thicken gradually eastwards across it. In Triassic times a similar, though largely non-marine basin prevailed, in which eastward thickening of strata is less obvious.

EXPLORATION HISTORY

Exploration for gas in the Cleveland Basin began near Middlesbrough in 1891, and followed blow out of a salt borehole. The gas in this borehole contained H_2S (Anon 1891), and others nearby contain high N_2 content.

One of the first hydrocarbon prospectivity reports for the basin (Kendall 1921) came into the files of BP (Kent 1976), who eventually drilled the recommended prospect at Robin Hood's Bay in 1957. The most likely reservoirs were identified as Permian carbonates, with some gas produced on test. A second prospect was identified by BP and drilled successfully at Eskdale in 1937.

Exploration was aided by a search for potash minerals by ICI, Fisons and RTZ, but the next discovery was made by Home Oil of Canada in 1966 at Lockton, where BP had drilled an earlier shallow well. Eskdale and Lockton fields produced for 7 and 3 years respectively, before water cut increased.

A further influx of newer operators and improved seismic reflection profiling has led to further prospects being drilled along the southern faulted margin to the basin. Exploration by Taylor Woodrow was successful at Kirby Misperton, where Namurian sandstones have proved productive.

BASIN STRUCTURE
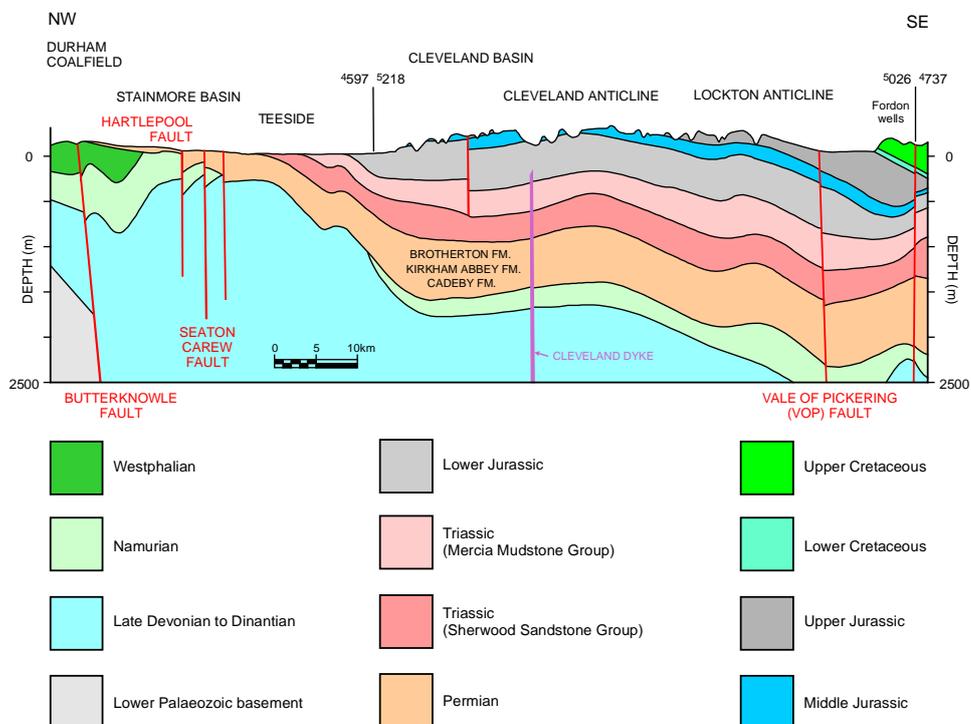
Fig. 5.1 NW-SE geological section through the central Cleveland Basin

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The Cleveland Basin is a Jurassic to early Cretaceous basin (Fig. 5.1), which was inverted during the Tertiary Alpine Orogeny. It overlies a Carboniferous basin (Fig. 7.1), which itself was also inverted by the end-Carboniferous Variscan Orogeny (Kent 1980). Both its northern margin, near Teeside, and its southern margin are extensively faulted. The southern margin faults are called the Vale of Pickering-Flamborough Head Fault Zone (VOPFHFZ; Kirby & Swallow 1987). To its south, at Market Weighton, is postulated a concealed granite (Fig. 7.1), which was buoyant during Early Carboniferous and Jurassic synrift subsidence. Thinning of Jurassic strata over the 'Market Weighton axis' can be seen on geological maps of all scales. The VOPFHFZ has been the focus of most of the recent gas discoveries made by Taylor Woodrow.

It is likely that in both phases of Early Carboniferous and Early Jurassic extension, faults on the northern margin were dominant. The most important was probably the south-dipping Butterknowle Fault, which reaches the North Sea coast north of Hartlepool (Fig. 7.1). This fault also controlled the development of the Carboniferous Stainmore Basin half graben to the west of the Cleveland Basin (Chadwick *et al.* 1995). This and related faults separate the outcropping Northumberland and Durham Coalfield to the north from the concealed Carboniferous of the Cleveland Basin. The faults were reactivated as reverse faults during the end-Carboniferous Variscan inversion. There are some shows in deep boreholes in Teeside, encouraging the belief that hydrocarbons may be trapped there by the faulting. Most of these boreholes were not drilled as hydrocarbon wells.

Many of the faults along the VOPFHFZ also dip south (Fig. 5.1), and may have caused major subsidence in late Jurassic and early Cretaceous times. These faults, which were not reactivated as reverse faults, separate the Carboniferous Cleveland Basin (inverted Namurian and older strata) from the concealed Selby Coalfield to the south. Westphalian Coal Measures were removed from most of the inverted area (Smith 1985).

STRATIGRAPHY

Early to mid-Carboniferous, Dinantian and Namurian strata subcrop the end-Carboniferous Variscan unconformity across the region (Fig. 5.2). Westphalian strata are restricted to some outliers, but they are more extensive both to the south (Selby Coalfield) and north (Durham Coalfield) of the Cleveland Basin (BGS Coal Map 1999). This has been the effect of the Variscan inversion (Kent 1980).

Permian and Triassic strata were deposited in an E-W trending basin, which was not fault controlled. Carboniferous faults on the northern margin of the Cleveland Basin were rejuvenated in Jurassic to early Cretaceous times and, together with antithetic faults on the southern margin, formed a major depocentre (Figs. 5.1, Fig. 5.3). Mid-Cretaceous strata were formerly present, until eroded after Tertiary Alpine inversion (Kent 1980). High maturity, high sonic velocity and other effects have been noted in the basin's sediments by Hemingway & Riddler (1982).

PETROLEUM SYSTEMS

Source rocks

Maturity of the exposed rocks of the Cleveland Basin is very high. Hemingway & Riddler (1982) reported Middle Jurassic coals with vitrinite reflectance values of 0.82-0.87%, whereas even Westphalian coals in the Durham Coalfield to the north have values of only about 0.4%, and Namurian shales at Richmond, 0.7%. Lower Jurassic shales lie within the oil window, which may account for the shows of oil in the basin. The Lower Jurassic Jet Rock may be the source of the oil shows in the Jurassic of Fordon 1 well and, less certainly, of the 30 bopd tested from the Namurian in this well. Several shallow wells and Fordon 2 were drilled here by BP (Falcon & Kent 1960), without success.

The Carboniferous rocks of the Cleveland Basin lie beyond the wet gas window. Westphalian source rocks are largely absent from the basin, except for the Robins Hood Bay borehole, where an offshore outlier trending NW-SE terminates nearby (BGS 1999). Westphalian strata north of the Cleveland Basin in Durham are immature for gas. South of the basin, beneath the Market Weighton area, and in its southern faulted zone the VOPFHFZ, Westphalian are likely to have been buried sufficiently to reach the gas window (Smith 1985).

Reservoir rocks

Hydrocarbons have been found in rocks of Namurian and Jurassic age. Gas is dominant (as in the adjacent Southern North Sea Basin). The main reservoirs (Figs. 5.2, 5.3) are Upper Permian (Zechstein) limestones, the basal Permian Rotliegend (Yellow Sandstone) and Namurian sandstones.
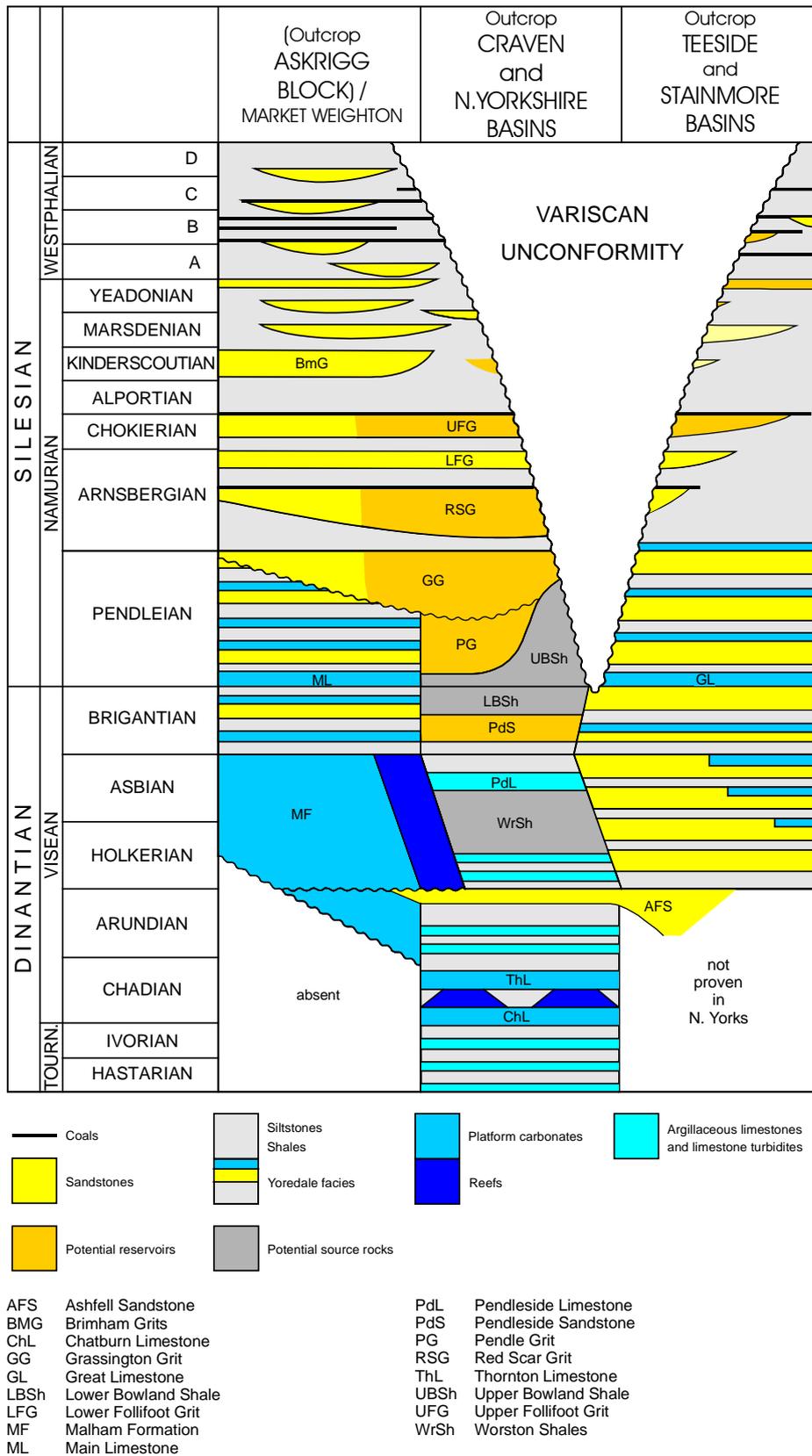
Fig. 5.2 Stratigraphic position of the principal Carboniferous source rocks and reservoirs of the Cleveland Basin
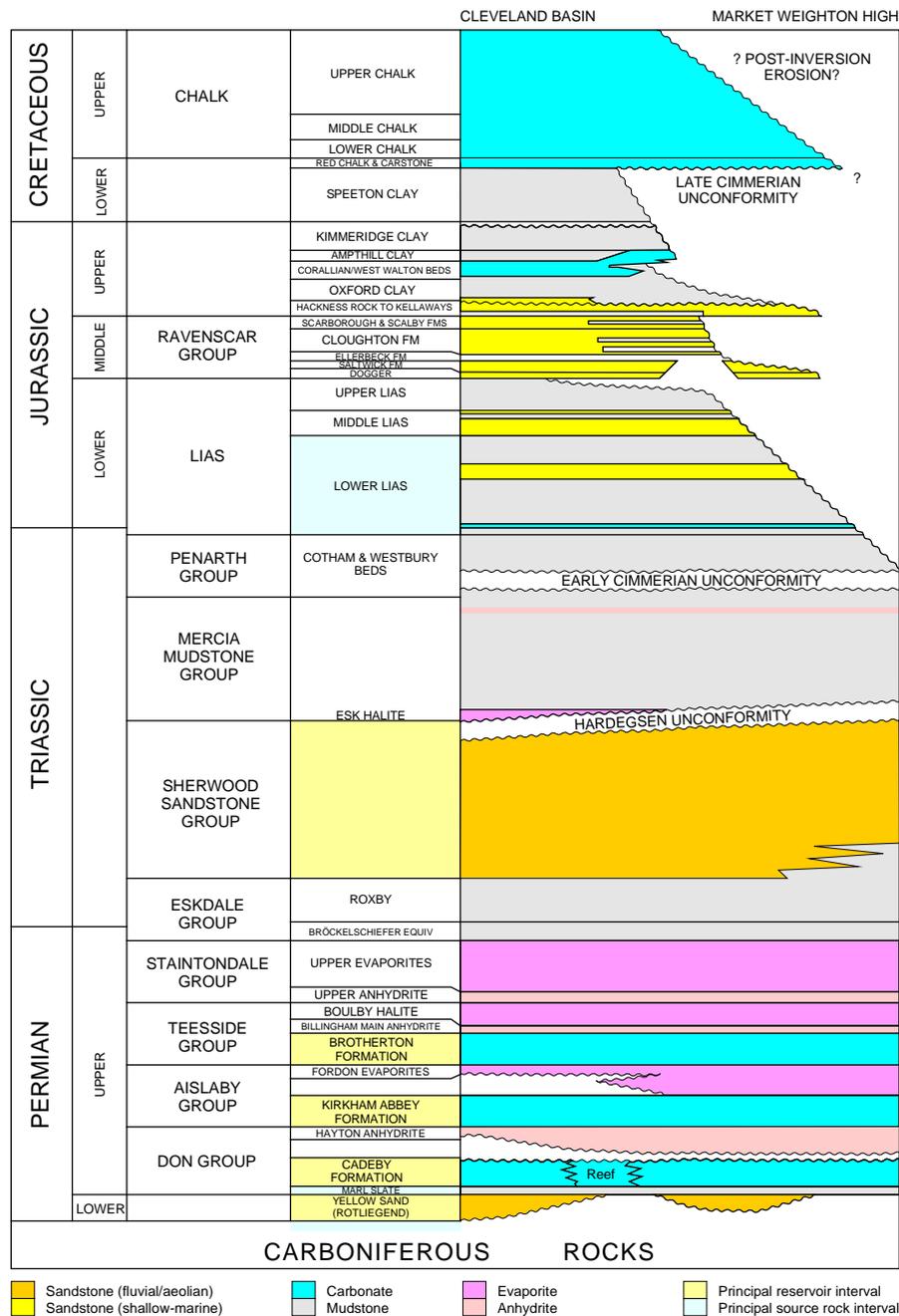
Fig. 5.3 Stratigraphic position of the principal post-Carboniferous source rocks and reservoirs of the Cleveland Basin

Traps

There are probably both stratigraphic and sedimentological elements to the Carboniferous traps (as in the East Midlands province – Section 7). The Carboniferous succession is less well imaged on seismic data than the overlying Permian and Mesozoic, and production from it is so far restricted to deeper levels in productive Permian wells. There are fault traps along the southern margin of the Cleveland Basin formed by E-W trending Jurassic to early Cretaceous syn-sedimentary faults. These faults cut across the N-S trending Upper Permian facies boundaries and isopachs. Yellow Sands (Lower Permian Rotliegend equivalent) are only greater than 10 m thick to the south of this line of faulting. Above the late Cimmerian unconformity, the Upper Cretaceous cover is relatively unfaulted, and a similar inversion history and trap configuration can be invoked for the remainder of the Cleveland Basin as in the Wessex and Weald basins (Sections 2, 3).

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The discoveries and recently developed fields (Malton, Kirby Misperton and Pickering) are concentrated along a N-S trend within fault blocks of the VOPFHFZ. Marishes field is within the same fault zone to the east of Malton. The Lockton and Eskdale fields lie within the Cleveland Basin itself, nearer to the coast.

Generation and migration

Carboniferous basins are interpreted to directly underlie large parts of the Jurassic Cleveland Basin. To the south of the Cleveland Basin, Westphalian coals are only marginally mature for gas generation. Therefore, the most likely source of gas within the basin is from deeply buried Namurian shales.

Jurassic and early Cretaceous migration of hydrocarbons was towards the southern margin of the basin, towards the high formed by the postulated Market Weighton Granite. Migration to the north was also possible. After Tertiary inversion, some re-migration may have taken place northwards towards the axis of the basin from its southern margin.

Accumulations

CAYTHORPE GASFIELD

Caythorpe was discovered in 1987 by Taylor Woodrow. Two horizons, the Upper Permian Kirkham Abbey Formation carbonates and the Lower Permian Rotliegend sandstones, are productive. There is only limited penetration of the Westphalian subcrop.

ESKDALE GASFIELD

In 1937, BP and ICI tested gas at 2.5 mmcfd from the Upper Permian Upper Magnesian Limestone. In 1940, Eskdale 2 well flowed at about 2 mmcfd, but it was shut in until developed in 1960 (Adcock 1963). This field is the furthest north within the Cleveland Basin. The gas from the wells was not used in chemical manufacture as anticipated, but in 1960 it was sold to Whitby Gasworks (BP Ltd. 1962). Eskdale 10 well produced gas from the Upper Permian Lower Magnesian Limestone, but attempts to increase production by pumping brine and hydrochloric acid into the fissures led to an increasing water cut (Adcock 1963). Production lasted about seven years, before the water cut became too great and the field was abandoned. It was relicensed to Candecca in and then sold to Star Energy who drilled a further well although production has not recommenced.

KIRBY MISPERTON GASFIELD

Kirby Misperton was discovered by Taylor Woodrow in 1985. Sour gas is reservoired in the Upper Permian Kirkham Abbey Formation, and gas is also produced from the Follifoot Grits (Namurian). Deep penetration of the subcrop formations reached what is probably the Ash Fell Sandstone (Lower Carboniferous).

LOCKTON GASFIELD

Lockton Gasfield was discovered in 1966, by Home Oil, near a previous BP well, that was drilled only as deep as the Lower Jurassic. Production began in 1971, but rapid water cut forced closure in 1974 (Huxley 1983).

MALTON GASFIELD

Malton Gasfield was discovered in 1970 by Candecca. Gas was obtained from four zones in the Upper Permian carbonates (Zechstein) and two within the Namurian. Taylor Woodrow drilled two appraisal wells in the 1980s.

MARISHES GASFIELD

Marishes was discovered in 1988 by Taylor Woodrow. Two zones in the Upper Permian carbonates had gas shows (Brotherton Formation and Kirkham Abbey Formation). Two DSTs (Brotherton Fm and lower Namurian, Arnsbergian sandstones) were performed but the results are not on record.

PICKERING

Discovered in 1992 by Kelt, Pickering is located on the footwall of the Vale of Pickering Fault. Gasfields 2-5 inclusive are known as the Ryedale Gasfields and the gas is sold to ScottishPower at the nearby Knapton Power Station. Tullow now owns these fields.

CONCLUSIONS

The prospective nature of the southern margin of the Cleveland Basin is clearly shown by the presence of producing gas fields, and many blocks are licensed along this faulted margin. It is clear from all Jurassic isopach maps that its southern margin represents an antithetic structural component to the basin. This is not universally acknowledged, because some of the E-W faults on this margin dip south and the northern part of the basin lies offshore. The Cleveland Basin's productive southern margin is the structural equivalent of the southern margin of the Weald Basin (Section 3). By analogy with the latter, prospects on the northern faulted margin of the Cleveland Basin might also be worth pursuing.

Encouraged by oil shows in Fordon 1 well, drilling near to where Bowland Shales (Namurian) source rocks form the pre-Permian subcrop might lead to successful Carboniferous plays in the Cleveland Basin.

6 West Lancashire Basin

INTRODUCTION

This Permo-Triassic sub-basin forms the onshore part of the East Irish Sea Basin (Fig. 6.1). Formby and Elswick are two onshore fields that complete a line of fields in the southern part of this important hydrocarbon-producing basin. The petroleum system has a Carboniferous source, Mesozoic generation at least in part, Permian faulted structures, Triassic (and Pleistocene sand) reservoirs and seals, and some recent migration.
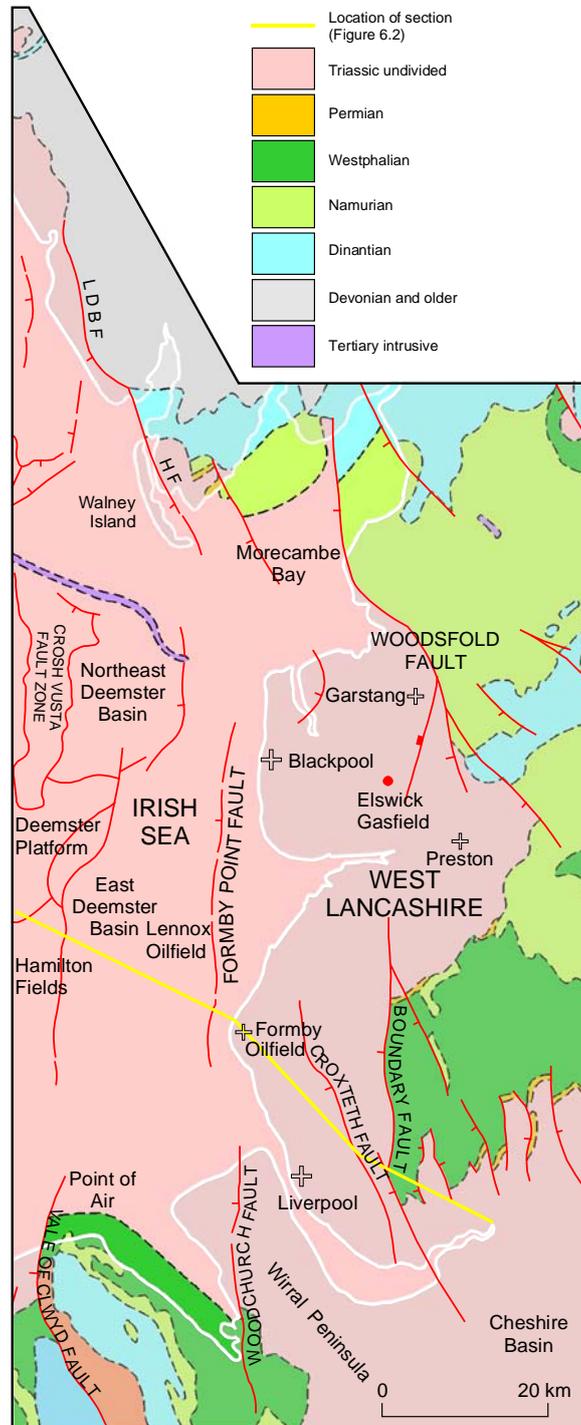
Fig. 6.1 Simplified geological map of the West Lancashire Basin

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EXPLORATION HISTORY

The oil shows near Formby Oilfield were known in the 17th century. These were overlooked by a drilling campaign inspired by the First World War, but new geological surveying (Cope 1939) prompted drilling by BP before the Second World War. After this war, a more exhaustive, but unsuccessful search was made for Carboniferous accumulations. This search did not include the use of seismic reflection data. Steel Bros. held a licence east of BP's, where all the main oil shows are found in Westphalian Coal Measures (Pinfold 1958).

The magnitude of the end-Carboniferous Variscan unconformity at Formby, proved by biostratigraphic dating, indicates that this oil field overlies a buried extension to the Dinantian-Namurian Craven Basin. At one time, this great unconformity was considered to downgrade Carboniferous prospects, but wells sited on more complete successions were all dry (Pinfold 1958).

Subsequent exploration aided by seismic reflection data has added one further gasfield, at Elswick, also overlying the buried extension to the Craven Basin. A number of other wells drilled have been dry.

TECTONIC SETTING

The East Irish Sea Basin forms part of a NNW-SSE trending Permo-Triassic rift system, which extends from beyond the Wessex Basin in the south to the Hebrides, off NW Scotland. This rift system truncates NE-SW trending Carboniferous structures; the structural grain in the latter was inherited from the Lower Palaeozoic substrata.

Fig. 6.2   NW-SE geological section from the East Irish Sea Basin through the West Lancashire Basin to the Cheshire Basin

BASIN STRUCTURE

The West Lancashire Basin *sensu stricto* forms a sub-basin on the eastern margin of the productive, offshore East Irish Sea Basin. It is dissected by a series of NNW-SSE trending faults that bound Westphalian strata of the Lancashire Coalfield in the south, and the Dinantian-Namurian Craven Basin in the north (Fig. 6.1). At Formby oilfield, Lower Permian Collyhurst Sandstone thickens against syn-sedimentary faults (Fig. 6.2). In the East Irish Sea Basin, Permo-Triassic extension continued at least until mid-Triassic times, when thermal subsidence took over during the cyclical deposition of halites and mudstones (Jackson & Mulholland 1993). Some of these halites extend onshore into the Lancashire Basin.

STRATIGRAPHY

Carboniferous strata of the West Lancashire Basin (Fig. 6.3) can be divided geographically into those occurring within a southern block and a northern basin. The northern basin (Craven) has a thick, partly carbonate and partly clastic Dinantian and Namurian fill, and has been inverted, removing all overlying Westphalian strata except in a few synclinal outliers. The Craven Basin shares these characteristics with the offshore East Irish Sea Basin. The southern block (Rossendale-Llyn) is characterised by thin Dinantian, thinner Namurian and more complete Westphalian strata.

Lower Permian Collyhurst Sandstone (Fig. 6.3) is locally absent, but thickens towards syn-sedimentary growth faults where present. Upper Permian Manchester Marl unconformably overlies Carboniferous strata in some areas. Lower Triassic Sherwood Sandstone is a potential reservoir sealed by Middle to Upper Triassic Mercia Mudstone, which contains interbedded halite units in the north. No strata of Jurassic to Tertiary age are present.

One of the reservoirs of the Formby Oilfield, the Shirdley Hill Sand is of Late Pleistocene age, being interbedded with Boulder Clay and overlain by Holocene peat deposits.

PETROLEUM SYSTEMS

The petroleum system in this basin features Carboniferous source rocks, Triassic and Pleistocene sand reservoirs, a leaky oilfield, and possibly an unproved deeper Carboniferous reservoir. The age of the reservoir at Elswick Gasfield is problematic.

Source rocks

The southern gas and oil fields of the East Irish Sea Basin have been sourced from the mid-Carboniferous (Namurian) Holywell Shale. Of Pendleian to Yeadonian age, this unit crops out in Clwyd (N Wales) adjacent to its coalfield, and is probably also represented by oily shales between depths of 950-985 m in the Heswall Borehole on the Wirral Peninsula (Armstrong *et al*. 1997). Its shales extend in the subsurface northeast to the Craven Basin, where they are called Bowland Shales and Sabden Shales. The Bowland Shales are considered the principal source rocks there (Lawrence *et al*. 1987). They subcrop the end-Carboniferous Variscan unconformity in an area surrounding the Dinantian, northeast of Formby and abutting the Pendle Fault to the southeast.

Reservoir rocks

The most unlikely and youngest rocks are reservoirs at Formby Oilfield. These include the Triassic Tarporley Siltstone Formation and the Pleistocene Shirdley Hill Sandstone. The reservoir at Elswick Gasfield could be the Lower Permian Collyhurst Sandstone, or may be Triassic in age. Namurian and Westphalian sandstones are also potential reservoirs.

Seals

The Middle to Upper Triassic Mercia Mudstone Group (Fig. 6.3) forms the main seal to the Lower Triassic Helsby Sandstone and Tarporley Siltstone reservoirs, but is thin and commonly lacks halite in this basin-marginal position. Migration of hydrocarbons up the N-S faults has occurred in recent times, forming accumulations in the overlying Pleistocene Shirdley Sandstone at Formby Oilfield. This accumulation is partially sealed by overlying Upper Pleistocene boulder clay and Holocene peat.

Overburden

Presumed overburden here, now removed, would have included Jurassic to Cretaceous strata. These are estimated to have been between 1-2 km thick over the West Lancashire Basin, and perhaps even thicker offshore in the East Irish Sea Basin.

PERIOD	Series	STAGE		West Lancashire Basin
TRIASSIC		NORIAN		
		?		
		CARNIAN		
		?		Breckells Mudstones
		LADINIAN		Kirkham Mudstones
		?		
		ANISIAN		Singleton Mudstones
				Hambleton Mudstones
		?		Ormskirk/Helsby Sandstone
		SCYTHIAN		Sherwood Sandstone
		?		
PERMIAN	Upper			Manchester Marls
	Lower			Collyhurst Sandstone
			VARISCAN UNCONFORMITY	
CARBONIFEROUS		WESTPHALIAN (largely eroded except in south)		Coal Measures
		e.g. Pendle Grit NAMURIAN		Millstone Grit Sabden Shale Bowland Shale
		DINANTIAN		Carboniferous Limestone

Fig. 6.3 Stratigraphic position of the principal source rocks and reservoirs of the West Lancashire Basin

Traps

Most traps in the East Lancashire Basin are formed by N-S trending Permian and later faults, particularly where these intersect the margin of the underlying Carboniferous Craven Basin (Kirby *et al.* 2000). The Elswick Gasfield is within a surface dome formed between the Thistleton and Woodsfold faults (Aitkenhead *et al.* 1992, Figs. 6.4, 6.5).
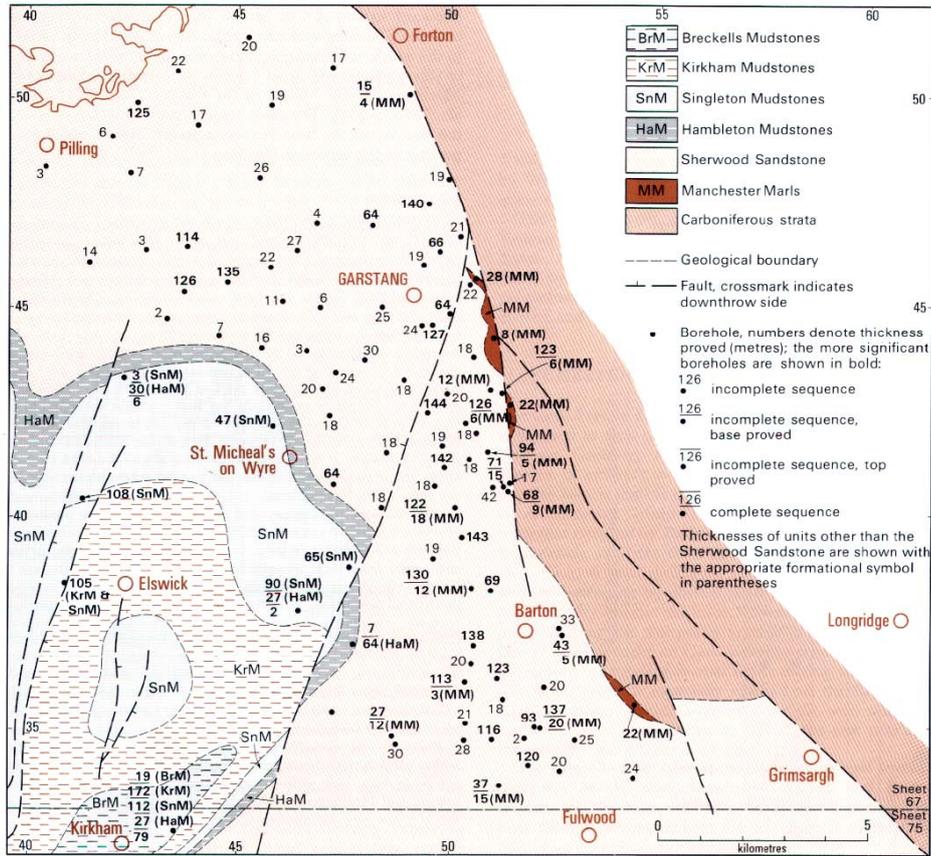
Figure 6.4 Geological map in the vicinity of the Elswick Gasfield showing the dome south of Elswick village above a subsurface graben and the Carboniferous outcrop (Aitkenhead *et al*. 1992).
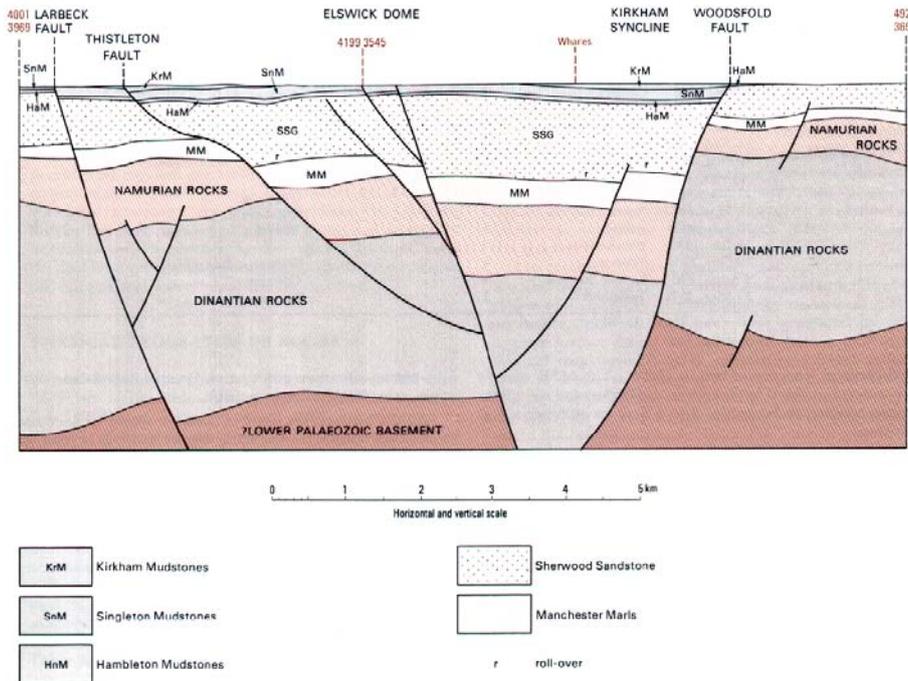

Figure 6.5 NW-SE section across the Elswick Dome, West Lancashire Basin (Aitkenhead *et al*. 1992)

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Migration

Duncan *et al*. (1998) suggested that the Formby Oilfield was charged from the (offshore) downdip Lennox trap (Fig. 6.1). This seems unlikely in view of the 25 km distance involved. Instead, northwestward migration of oil towards the Formby field could be envisaged from the onshore subcrop of the Namurian Bowland Shales. The Carboniferous Craven Basin's depocentre against the Pendle Fault probably formed the oil kitchen, rather than somewhere to the north as suggested by Falcon & Kent (1960), or migration from west of the Formby Point Fault. It seems likely that several N-S Permo-Triassic faults have tapped the migrating oil and, with a very thin Mercia Mudstone seal, seepage to the surface has occurred here.

Accumulations

There are two productive fields in this basin, Formby Oilfield (now abandoned) and Elswick Gasfield.

FORMBY OILFIELD

Formby Oilfield was discovered in 1939 and is a breached structure, with oil seeps at the surface. It lies on the southeastern margin of the East Irish Sea Basin (Fig. 6.1), and is on the same E-W trend as the offshore East Irish Sea Basin oilfields, discovered by Hamilton (now BHP; Yaliz 1997, Haig *et al*. 1997). One of these, the Lennox Oilfield, is about 25 km to the northwest and has been in production since 1996. The Formby Oilfield is a NE-SW trending faulted anticline, plunging to the SW. Its bounding N-S trending Ince-Blundell Fault throws down about 80-90 m to the east (Rowley 1987). The seal to the accumulation is the Upper Pleistocene Boulder Clay and overlying Holocene deposits, although oil has also migrated into sands within the Boulder Clay and Holocene peat. One well produced 200 gallons/day from the Boulder Clay sands (Lees & Taitt 1946). Formby G2 was the discovery well, which produced from the Triassic Tarporley Siltstones at 38 m depth at a rate of 1440 gallons/day (Lees & Taitt 1946). The reservoirs, therefore, are amongst the most unlikely and unreliable in the UK.

Its API (37°) is comparable with East Midlands' oils, but is lower than in the East Irish Sea fields (44°). The recent migration, the poor sealing of the Triassic reservoir and the probable Carboniferous oil generation suggest that a primary Carboniferous reservoir may have been tapped by the Permo-Triassic and later faulting. This primary trap was searched for, unsuccessfully, by BP (Falcon & Kent 1960).

Shallow drilling was carried out at four sites, Flea Moss, Freshfield, Barton Moss and Formby, after oil seeps were reported by Cope (1939). The Formby Oilfield was developed rapidly during the Second World War. Formby G11 well encountered gas, which blew out from the Triassic Variegated Beds at 100' (30 m). Many other shallow wells encountered oil shows in the Pleistocene Shirdley Hill Sand, Triassic Tarporley Siltstone Formation (of the Mercia Mudstone Group) and Lower Triassic Helsby or Ormskirk Sandstone Formation. Production was obtained from these reservoirs at, or above, 50 m depth (Rowley 1987).

The success of Hamilton's offshore discoveries can be attributed, in part, to the subcrop of Namurian basal mudstone source rocks, without intervening Upper Namurian deltaic sandstones or Westphalian Coal Measures, a characteristic shared by Formby Oilfield. From the details released by Hamilton, the oil maturity window of the Holywell Shales at the offshore oilfields was attained by Mesozoic burial. The rate of increase of maturity within the Mesozoic and Permian section is very low. Carboniferous maturity gradients are considerably higher both onshore and in the East Irish Sea Basin.

Formby produced 71,560 barrels of oil. This oilfield could be considered the first discovery in the East Irish Sea Basin, and highlights how the interplay between Carboniferous subcrop and source rock maturity, Triassic reservoirs, seals and faulting is the key to further successes in the West Lancashire Basin.

ELSWICK GASFIELD

This one-well field was discovered by British Gas in 1990 and brought into production by Independent Energy in 1996. The surface dome structure is shown in the British Geological Survey's Garstang memoir (Aitkenhead *et al*. 1992; Figs. 6.4, 6.5). Like at Formby and in offshore Lennox and Douglas fields, Westphalian Coal Measures are absent below the end-Carboniferous Variscan Unconformity. The reservoir is said to be Lower Permian Collyhurst Sandstone or upper Permian sandstone (composite log for Elswick, Brooks *et al*. 2001) but this is questionable based on seismic reflection, well correlation and facies grounds. A Triassic age for the reservoir is more likely.

CONCLUSIONS

There may be some potential for a Carboniferous-reservoired discovery in the West Lancashire Basin. Detailed comparisons with the East Irish Sea discoveries and estimations of timing of maturity attainment and migration directions are required. The main generation and migration from the Namurian Holywell Shales offshore is interpreted to be Jurassic or early Cretaceous (e. g. Yaliz 1997, Duncan *et al.* 1998). The offshore Douglas and Lennox fields lie close to the North Wales coast. The Llyn-Rossendale Ridge (Jackson & Mulholland 1993) extends NE-SW from Lancashire to North Wales, passing through the Wirral Peninsula: this ridge separated the Cheshire and East Irish Sea/West Lancashire basins in Mesozoic times and was a Carboniferous high.

In contrast, the Carboniferous Craven Basin source rocks to the north will have undergone significant hydrocarbon generation by late Carboniferous times. The continuation of this basin southwest beneath Elswick and Formby is certain (Kirby *et al.* 1999), but its position beneath the East Irish Sea Basin is not yet known. It probably lies north of the Lennox and Douglas fields.

The Carboniferous structures (NE-SW) are intersected by Mesozoic and Permian N-S faults. A favourable position for a new exploration well would be between the Craven Basin succession proved in Formby 1 and 4 wells and the western extension of the Lancashire Coalfield. The postulated continuation of the Pendle Fault forming the SE boundary to the Craven Basin passes south of Formby Oilfield; it is possible that Carboniferous reservoired oil is present to the south of this fault. A seismic profile depicting the Pendle Fault, farther east was published by Fraser & Gawthorpe (1990). The westward continuity of the Pendle Fault across the West Lancashire Basin is difficult to follow because of the subsequent N-S Permian faulting.

The Croxteth wells farther south had oil shows mostly in the basal Namurian and the top of underlying Carboniferous Limestone strata (Magraw & Ramsbottom 1956). There are oil seeps to the surface in Permo-Triassic strata at a railway cutting near Croxteth. Plant *et al.* (1999) reported oil shows in Triassic sandstones in Thornton and Saughall Massie boreholes (Wirral Peninsula). Shows of oil were also reported by Harriman & Miles (1995) from the Wirral and Liverpool. These shows are isotopically heavier than at the Formby Oilfield, which is linked to a Namurian Holywell Shales source. There may be potential in these areas, where oil seems to be migrating successfully from the Namurian (or Westphalian) to Triassic strata, and also further north in the Fylde Peninsula where halites within the Mercia Mudstone Group provide a good seal above the Lower Triassic Ormskirk (Helsby) Sandstone.

7 East Midlands province

INTRODUCTION

The East Midlands hydrocarbon province (Fig. 1.1) comprises several concealed Carboniferous sub-basins, trending NW-SE (Fig. 7.1). To the west is the Pennine Anticline (and Derbyshire Dome), where the Carboniferous rocks crop out along the main end-Carboniferous inversion. Thirty-three fields have been discovered in this Carboniferous petroleum system, mostly with Upper Carboniferous reservoirs, in a swathe extending 110 km (70 miles) from near Loughborough (Leicestershire) to Saltfleetby on the Lincolnshire North Sea coast.
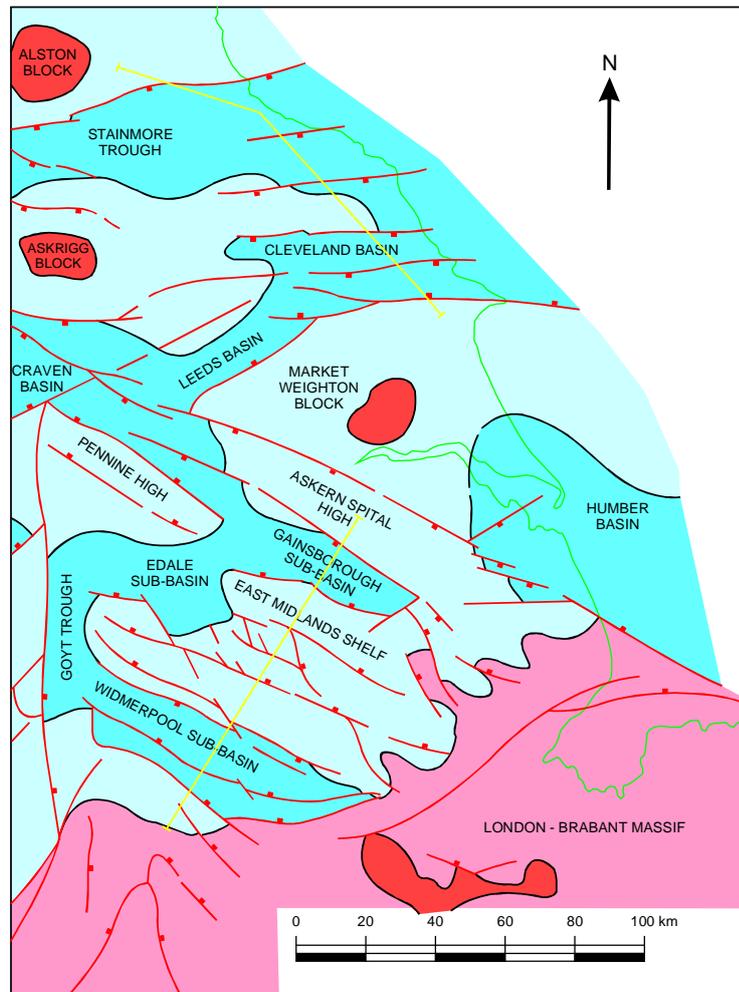
Fig. 7.1   Carboniferous basins of eastern England including the Cleveland Basin and East Midlands province

EXPLORATION HISTORY

The region has been one of active hydrocarbon exploration since the latter days of the First World War. Significant quantities of oil were first encountered at Hardstoft in 1919. A major exploration effort was begun just before the Second World War resulting in the discovery of the Eakring-Duke's Wood, Caunton and Kelham Hills oilfields in the years 1939-43.

Exploration continued at a reduced level after the War. After the 1940s, BP had an agreement with the National Coal Board (NCB) in the East Midlands province whereby they located new wells based on NCB evidence of shows, and meanwhile deepened, tested and cored favourable coal exploration boreholes. There is no doubt that the shows in the coal mines are closely linked to the oilfields. An October 1995 fatal mining accident was caused by an influx of hydrocarbons at Thoresby Colliery, and occurred where the coal exploration was nearest to the Bothamsall Oilfield.

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Further important discoveries were made at Plungar (1953), Egmanton (1955), Bothamsall and Corringham (1958), Beckingham and Gainsborough (1959), Apleyhead and South Leverton (1960), Glentworth (1961), Torksey (1962) as well as numerous other minor finds (e.g. Langar and Nocton) and shows. Exploration activity virtually ceased in the late 1960s, but was renewed following the oil price rises resulting from the 1973 Middle East war. Further significant discoveries were made, such as Welton (1981; the UK's second largest onshore field) and Farley's Wood (1983), as well as several minor accumulations, e.g. Brigg, which were not developed. Much of the early exploration was carried out by BP (and predecessors) and partners, but in the last fifteen years an increasing number of other companies and consortia have been attracted to the area by its steady proven success rate. BP pulled out of the area after an unfavourable internal company report on remaining Carboniferous prospects (Fraser *et al.* 1990).

Several smaller companies have bought fields and data from BP. Among these companies, Pentex (also known briefly as Sibir) have conducted a campaign of appraisal drilling and seismic acquisition on these fields. Candecca, Altaquest and Cirque have recently developed new fields. Saltfleetby Gasfield was briefly held by Morrison Middlefield Resources Ltd, now taken over by Roc Oil, and is the UK's largest onshore gasfield, with reserves of 73 bcf and 2 mmbbl of ngl (DECC website).

With minor, local exceptions, the oil and gas found to date in the East Midlands province have been in Upper Carboniferous strata. However, the original discovery at Hardstoft was made in an exposed anticlinal structure, with a Dinantian, Carboniferous Limestone reservoir. Other boreholes on surface-mapped structures have achieved only limited success. The main producing oilfields are in anticlinal structures within Carboniferous rocks that are concealed by a gently east-dipping, largely undeformed cover of Permian to Cretaceous rocks (Smith 1985). The earlier discovered fields were found by combining the results of geophysical surveys with structural data gathered from deep mining of coal. The same methods cannot be employed today, as much of the exploration is in the east of the region beyond the limits of coal working. Underground coal mining has declined since 1980s privatisation of the National Coal Board.

TECTONIC SETTING

The Carboniferous Pennine Basin is part of a larger E-W trending rift near the southern margin of the Laurentian-Scandinavian craton. This rift extends into Denmark, Germany and Poland in the east and Ireland in the west. It is separated from the Variscan Fold Belt to the south by a landmass called either St. George's Land or Wales-Brabant.

BASIN STRUCTURE

Beginning in the late Devonian and extending throughout much of early Carboniferous times, the East Midlands region was subject to N-S tension in response to the onset of subduction in the Variscan Fold-Belt to the south (Leeder 1982, Bott *et al.* 1984). Extensional movements resulting from this period of tension were taken up on pre-existing structures, principally with north-westerly, but also north-easterly, trends.

Many pre-existing Caledonian structures, including thrusts as well as higher-angle faults, were reactivated during early Carboniferous sedimentation as syn-sedimentary growth faults. Movement on these resulted in the formation of a number of tilted blocks or half-graben structures (Smith *et al*. 1985, Fraser & Gawthorpe 1990; Fig. 7.2). The largest tilted blocks are cored by Lower Palaeozoic granites, e.g. to the NW of the Pennine Basin (Fig. 7.1)and probably also in the Market Weighton-Hornsea area of Yorkshire (separating East Midlands province and Cleveland Basin, Section 5). Although fault movement and block tilting were fairly continuous, there appear to have been periods of more intense activity. Some faults seem to have been active for only a limited period, growth being taken up on other structures at other times.

Kent (1966) applied the classic 'block and basin' structural pattern of northern England to the East Midlands region, deducing that thin incomplete Lower Carboniferous sequences occur on uplifted blocks, whereas the equivalent succession is generally thicker and more complete in the basins. The blocks and basins were thought to have been relatively fixed in position throughout Carboniferous time, but in practice, their boundaries were drawn largely on Namurian isopach maps. This view is now seen to be an over-simplification, the blocks and basins recognised by Kent (1966), e.g. Gainsborough and Edale sub-basins, being essentially late Dinantian to early Westphalian features which overlie a different early Dinantian tilt-block system.

Although some subsidence continued in the sub-basins into the Westphalian, the Dinantian tilt-blocks were buried by Upper Carboniferous sediments. During the late Namurian and Westphalian the whole region can be regarded as having formed part of a single more widespread basin (Pennine Basin) covering much of northern England between St. George's Land to the south and the Craven Faults to the north.
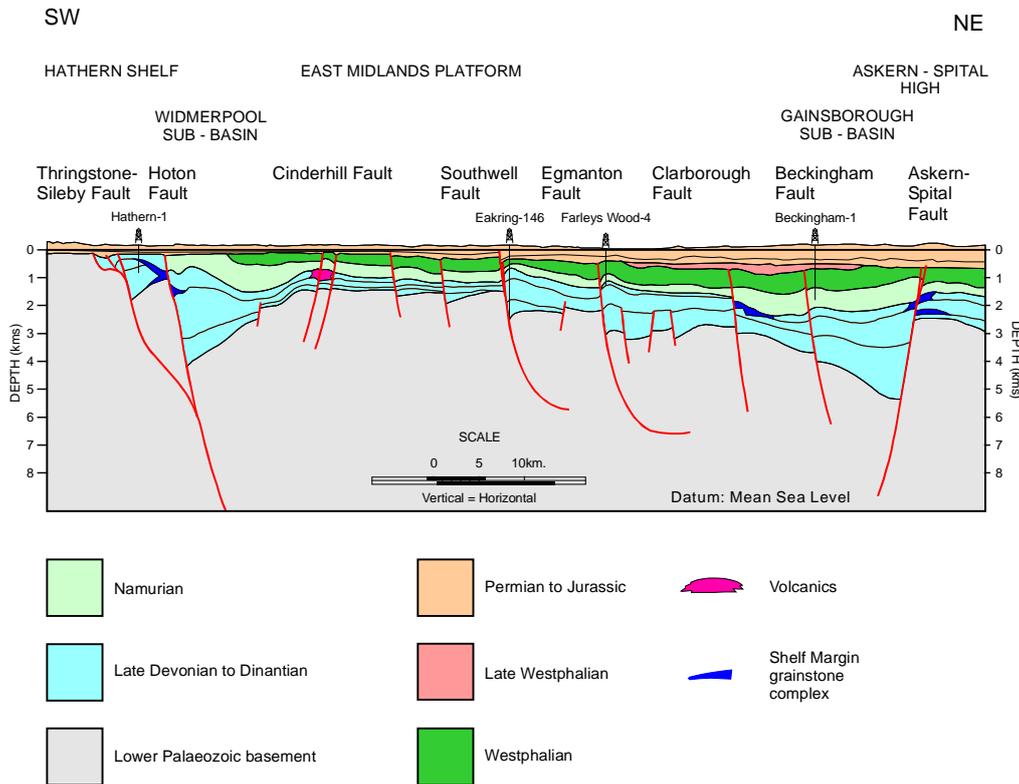
Fig. 7.2 SW-NE geological section through the East Midlands province

Leeder (1982) related the Dinantian rifting and tilt-block formation to crustal thinning brought about by the extensional tectonic regime. He suggested that the more widespread successor Pennine Basin is a 'sag basin' resulting from cooling of the aesthenosphere following the earlier phase of crustal thinning. Upper Carboniferous isopachs conform to this model of evolution towards a more regional basin. Seismic refraction experiments elsewhere in northern England have found no evidence for a shallow Moho, so subsequent events have overprinted any early Carboniferous crustal thinning.

The East Midlands province was then subjected to a major E-W compressional phase in late Carboniferous and earliest Permian times (Variscan Orogeny) that led to inversion of the Carboniferous rocks. This uplift created the Pennine Hills that border the East Midlands province to the west. Other uplifted structures formed by reactivation of the syn-sedimentary faults.

An easterly regional tilt was then imposed by Permian and Mesozoic subsidence in the Southern North Sea. Further minor phases of extension and of Mesozoic uplift and erosion, that control prospectivity in the Mesozoic basins elsewhere in England (Sections 1-5), also affected the East Midlands province. A more important period of uplift and erosion began in the Tertiary period, and erosion continues to the present day.

The structure of the region is best known in the area worked for Westphalian coal. Generally, the Top Hard or Barnsley Seam has been the most extensively worked coal, and where present it has been taken as the main datum for structure contours. The structure in the coalfields shows a strong NW-SE grain. There are numerous asymmetrical anticlines of this trend, some of which have proved to be oil-bearing (e.g. Eakring, Hardstoft). In some cases, seismic reflection data show that development of these anticlines was related to reactivation of north-easterly dipping reverse faults (believed to be reactivated 'basement' thrusts). In other cases, normal faults are associated with the folds. Throws on the NW-SE trending faults are commonly less than 25 m, but they locally exceed 100 m. North-easterly trending faults are less numerous and generally have modest throws. Notable exceptions to this rule do occur, however, where NW trending faults are terminated by larger NE trending structures e.g. the Don Monocline.

To the west of the coalfields, the structure of the Carboniferous strata is well known from surface mapping, with faults and folds of similar NW-SE trend and magnitude. Farther east, towards the east of the coalfield, the folds are more open and their axes are more variable in orientation and less well defined. This pattern appears to continue eastwards of the coalfields, where seismic reflection data indicate only small, low-amplitude folds with no common

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orientation between NW-SE trending faults. Faults with a NE-SW orientation are either uncommon here, or their throws are too small to be detected from the seismic data.

For the most part, the Permian and later movements have imparted a simple easterly tilt to the Carboniferous structures, and reactivated both NW and NE trending faults to only a limited degree. Jurassic strata thin northwards along their outcrop towards the Market Weighton area (from where they thicken northwards also, Section 5), showing this area to be a palaeo-high. There was a shallow Jurassic basin near the Wash, in Lincolnshire. One general result of the Mesozoic tilt has been to reduce the area of closures in the Carboniferous traps. Folding of the Permian and Mesozoic rocks is so gentle that they contain only a few shallow closures.

STRATIGRAPHY

The large volume of borehole and geophysical data, supplemented by details of coal workings, and a long history of academic research, has resulted in a large scientific literature relating to the region. The broad aspects of the stratigraphy are well known, and are locally known in immense detail. The following account can only briefly summarise this work, and draws heavily on previous work. The main data sources are British Geological Survey memoirs of Wray *et al.* (1930), Bromehead *et al.* (1933), Edwards *et al.* (1940), Mitchell *et al.* (1947), Edwards (1951, 1967), Eden *et al.* (1957), Smith *et al.* (1967, 1973), Stevenson & Gaunt (1971) and Frost & Smart (1979). Hydrocarbon-related publications include Lees & Taitt (1946), Falcon & Kent (1960), Howitt & Brunstrom (1966), Kent (1967) and Downing & Howitt (1969). More modern seismic stratigraphic concepts are found in Fraser *et al.* (1990) and Fraser & Gawthorpe (1990). Extensive bibliographies are to be found in these publications and in George *et al.* (1976) and Ramsbottom *et al.* (1978). The most recent comprehensive review is by Kent (1966).

PETROLEUM SYSTEMS

Source rocks

Source rocks are present in late Dinantian shales (Lower Bowland Shales, Widmerpool Formation) and limestones (e.g. Bee Low Limestone). These rocks encroach southeastwards onto St. George's Land in the sub-basins and troughs of Gainsborough, Edale and Widmerpool. The existence of two other less well-defined sub-basins, Louth and Humber is suggested by a combination of borehole and seismic interpretation.

The sub-basins probably contain mid-Dinantian shales (e.g. Long Eaton well), and some limestones at outcrop may also be classed as source rocks (e. g. Milldale Limestones). These sub-basins also contain thick early Namurian shales (Sabden, Upper Bowland shales and equivalents). It is these distal pro-delta shales that have been identified as the principal source rocks for the East Midlands province (Fraser *et al.* 1990), the East Irish Sea oilfields, and probably Formby Oilfield (Armstrong *et al.* 1997). Ewbank *et al.* (1995) interpreted an early Namurian mudstone source, typified by type II kerogen, in the Edale Sub-basin for the bitumens in the South Pennine Orefield. Equivalent distal pro-delta shales are absent further north in England in shallower water deltas of Northumberland, Solway and Stainmore (Fraser *et al.* 1990).

Probably two different oil sources are represented. The most abundant carbon isotope of the oil is the δC -30‰, correlated with the pro-delta Namurian shales (Fraser *et al.* 1990). An isotopically heavier oil (-27‰) is found in Caunton and Kelham Hills fields and Newark discovery (Fraser *et al.* 1990), all more distant from the basin sources, and the authors interpret this oil as being derived from marine bands and interdistributary mudstones. Similar oils are found at Parkhill and Cherry Willingham in the East Midlands and in the Cheshire Basin (Harriman & Miles 1995).

Hydrocarbon source rocks must reach a vitrinite reflectance value of about 0.6% to begin generating oil, with the oil window extending to about 1.3%. Very few vitrinite reflectance data have been published from hydrocarbon wells in the East Midlands. The time at which generation occurs depends on the geothermal gradient and the depth of burial. The maturity gradient chosen for the data is also important. Kirby *et al.* (1987) gave evidence for Carboniferous generation of hydrocarbons, particularly in the west of the basin (west of the main oilfields). Fraser *et al.* (1990) have published data for the Bardney well, which is located east of the main oilfields, near to the margin of St. George's Land and therefore not near the source kitchen. Their maturity profile shows no change in gradient at the end-Carboniferous Variscan Unconformity. However, this may be incorrect, since nearly all wells show that maturity gradients are higher in the Carboniferous, with the exception of upper Westphalian strata, and there is a rapid maturity increase below the unconformity. This increase can be attributed to both erosion of Carboniferous strata, after the uplift caused by the Variscan Orogeny, and higher geothermal gradients in Carboniferous times.

There are three factors to consider. The Carboniferous Pennine Basin was buried sufficiently deep, and with high geothermal gradients began generating hydrocarbons in late Carboniferous times (Kirby *et al*. 1987). Inversion of the basin along the Pennine Uplift may have prevented more source rocks becoming mature and led to erosion of Upper Carboniferous strata. The effect of later subsidence toward the North Sea Basin, in Permian and Mesozoic times, has been to extend the area of oil generation eastwards. The combined effects of the latter two events produced a synclinal area between the Pennine Uplift and St George's Land, west of the oilfield swathe, where hydrocarbons continued to generate. This produced two probable migration directions: to the southeast towards the East Midlands oilfields and to the west (Hardstoft and gas field line).

The NW-SE trending Carboniferous sub-basins (Gainsborough, Widmerpool, Edale) extended tongues of generating potential toward the St George's Land basin margin.

Reservoir rocks

Potential reservoir rocks abound in the (probable) late Devonian to Carboniferous succession. In practice, the main reservoirs in the oilfields found to date have been the Namurian sandstones of the Millstone Grit (Fig. 7.3) and the Westphalian Lower and Middle Coal Measures (Fig. 7.4). Small quantities of oil have also been produced from the top of the Dinantian Carboniferous Limestone. These and other potential reservoirs are considered below in an account based on Gale *et al*. (1984).

LATE DEVONIAN AND BASAL CARBONIFEROUS

The main potential reservoirs of this age are the rocks of Old Red Sandstone facies, which are believed to be extensive beneath the Triassic Needwood Basin (e. g. Caldon Low borehole). They have been drilled at Eakring 146 well, and were probably deposited on the hanging walls of synsedimentary faults. No hydrocarbon shows are known in rocks of this facies within the East Midlands province or adjacent areas, and no core analyses or drill stem test results are available.

DINANTIAN CARBONIFEROUS LIMESTONE

Small quantities of oil have been produced from a few fields (Hardstoft, Eakring, Duke's Wood, Plungar, Nocton) and lesser amounts proved in a number of boreholes (e.g. Bingham, Nettleton 2), in every case in fractures at the top of the limestone, immediately below the contact with the overlying rocks.

Prior to lithification, many of the deposits that now make up the Carboniferous Limestone are likely to have had high porosity and permeability. However, the results of burial (meteoric) diagenesis on these rocks has produced limestone with high sonic velocities, uniformly very low value hydraulic properties and negligible intergranular flow, both at outcrop and in the subsurface. Total replacement of calcite by dolomite results in a maximum volume reduction of 12%, so that dolomitic rocks can be expected to have a greater porosity than their parent limestones. At outcrop in the Derbyshire Dome (Figs 7.5, 7.6), this is commonly found to be the case where coarse sucrosic dolomite replaces limestones of several different kinds, obliterating earlier fabrics. Dolomitisation of late Dinantian Asbian and Brigantian rocks is relatively superficial and relates to the former presence of nearby unconformably overlying Permian rocks. More extensive, but still local and patchy, dolomitisation is found in the Woo Dale Limestones (Holkerian age) and in their subsurface equivalents. Petrographical work and chemical analysis show that dolomitisation is rarely complete and, given the very low porosity of the parent limestone, the maximum porosity of dolomitised rocks is likely to be in the range 10-12%. Bearing in mind the patchy irregular nature of the dolomitisation, it is possible that significant reservoir rocks could be produced in this way, notably in those of Chadian to Holkerian age. Core examination suggests that sporadic sub-vertical fractures are present in more deeply buried limestones. In an attempt to evaluate the extent of such fractures, Evans & Brereton (1990) interpreted a number of Fracture Identification Logs and open-hole Variable Density Logs. This work has shown that high angle fractures, trending at 240^0, occur in pre-Carboniferous, Carboniferous (including Carboniferous Limestone) and Permian formations. From the limited data, there is no indication of any stratigraphic control on the presence or absence of fractures in the limestone.

A karst system, seen in the present day outcrops in Derbyshire, is probably of relatively recent origin, dating from the exposure of the Carboniferous Limestone at the surface in Tertiary times. It is unlikely that this modern karstifaction has had any effects on the concealed limestone of the East Midlands. The buried shelf limestones, however, have been exposed previously at several periods in their history, notably during the Dinantian itself, during early Namurian times, and in the southeast during the whole of Namurian times. It is here at Nocton that production from the

Carboniferous Limestone was sustained for a short time. In addition, small areas were exposed in the early Permian. Palaeokarst phenomena, attributable to these periods, can be detected at outcrop and in the subsurface rocks, both within the limestone and at its junction with the overlying late Namurian Millstone Grit or Westphalian Coal Measures. Cavern and fissure formation has been reported at this boundary in Derbyshire outcrops by Simpson and Broadhurst (1969), but the cavities so formed are in-filled by calcite and fluorite. Some of the wells in the East Midlands e.g. Nettleham have encountered karstification in the top of the Carboniferous Limestone.

Since fissure flow predominates, porosities and permeabilities determined from core analysis are largely meaningless in relation to the flow characteristics or to reservoir properties. Thus, the aquifer properties of the Carboniferous Limestone are difficult to define or predict. Drill-stem tests have been carried out at approximately 30 sites, but very few can be interpreted beyond providing a water sample, a pressure reading and a temperature reading. The large majority of DSTs produced a small amount of water, indicating low permeability but providing insufficient data for a quantitative estimate. Rarely, some "high flow rates" have been reported. Zones of mud loss have also been noted, indicating the presence of open fractures. It is commonly observed that the limestone is fractured just below its contact with the Namurian Millstone Grit, but the presence of these fractures does not always cause any appreciable increase in permeability. In the Plungar Oilfield, the top part of the limestone has an average porosity of 10%, being permeable where tested. A few core analyses carried out gave a mean permeability value of 3 mD, but as has been pointed out these values are meaningless if fractures are the conduits of flow. Similarly, core analyses on samples of Lower Carboniferous limestone and sandstone at Eakring Oilfield gave a porosity of 5.6% and a permeability of 0.2 mD. At Nettleham 1 well, core analyses on a 10 m interval of limestone gave a mean porosity of 5.3% and a mean permeability of 1.3 mD (0.04 to 5.4 mD). The core showed abundant hairline fractures in addition to a larger fracture system and intergranular pores. The limestone was found to be fractured over a 29 m interval which, when tested by DST, indicated a permeability of 1.1 mD and a transmissivity of 0.03 Dm, which is in very good agreement with the core analysis results. Core analyses from subsequent drilling at Nettleham 2 well, over 52 m, showed a range of porosity from 10.8 to 19.5% (mean of 15.2%) and the mean permeability of the most permeable section to be 3.3 mD. The transmissivity of the whole section is calculated to be 0.1 Dm. Core analyses from another borehole, Grove 3, indicate a porosity of 7.8%, a vertical and horizontal permeability of 0.07 and 0.56 mD respectively, and an estimated transmissivity of 0.006 Dm.

To summarise, the potential of the Carboniferous Limestone as a hydrocarbon reservoir has not been realised to date. Apart from zones of dolomitisation, intergranular flow is negligible. The extent to which fissure systems, whether of tectonic, diagenetic or palaeokarst origins, occur in the limestone of the subsurface will determine whether significant hydrocarbon reservoirs exist. The potential might be greater to the west where the typical East Midlands province Upper Carboniferous reservoirs are absent. This western area might extend from the Hardstoft field to the numerous shows along the eastern margin of the Pennines to the Derbyshire Dome (e.g. Windy Knoll, near Castleton). A search for the concealed extension to the late Dinantian Asbian apron reefs is a possible play. Evidence of hot H_2S water in some boreholes suggests that deep circulation has occurred.

NAMURIAN MILLSTONE GRIT

Namurian fluviodeltaic and turbiditic sandstones of the Millstone Grit (Fig. 7.3) are producing reservoirs in a number of oilfields, e.g. Eakring-Duke's Wood, Gainsborough-Beckingham and Bothamsall. In addition, non-economic quantities of oil and gas have been observed in Namurian sandstones in many boreholes. Although the thickness of individual sandstone reservoirs varies, wherever Millstone Grit rocks are present there is always a significant proportion of sandstone in their upper part.

Individual sandstone beds of the Millstone Grit normally act as discrete aquifers due to the presence of intervening thick mudstones and shales. Flow is either intergranular or fissure, but the latter dominates even where the formation is at shallow depths. Studies of wells and tunnels show that water flow decreases dramatically with depth as the numbers of fissures are reduced. Fluvio-deltaic Millstone Grit sandstones have been extensively drilled and tested in the East Midlands oilfields, but there are few data relating to the laterally equivalent turbiditic facies that occur in some of the sub-basins. The latter forms fans of limited extent; grain-size of the turbidite sandstones ranges from very fine to very coarse, the coarsest varieties occurring within submarine channels and the finest in the outer fan and between channels. The turbiditic sandstones are commonly poorly sorted, feldspathic and, outside the channels, thinly interbedded with shales. Porosities and permeabilities are therefore likely to be very low. It was thought unlikely that this facies could form a good reservoir, until Rempstone Oilfield was discovered. The deltaic facies includes clay, mudstones and siltstones, crevasse-splay sandstones and large, braided, sand-filled fluvial channels that are often mutually erosive and combine to form sheet-like sand bodies.
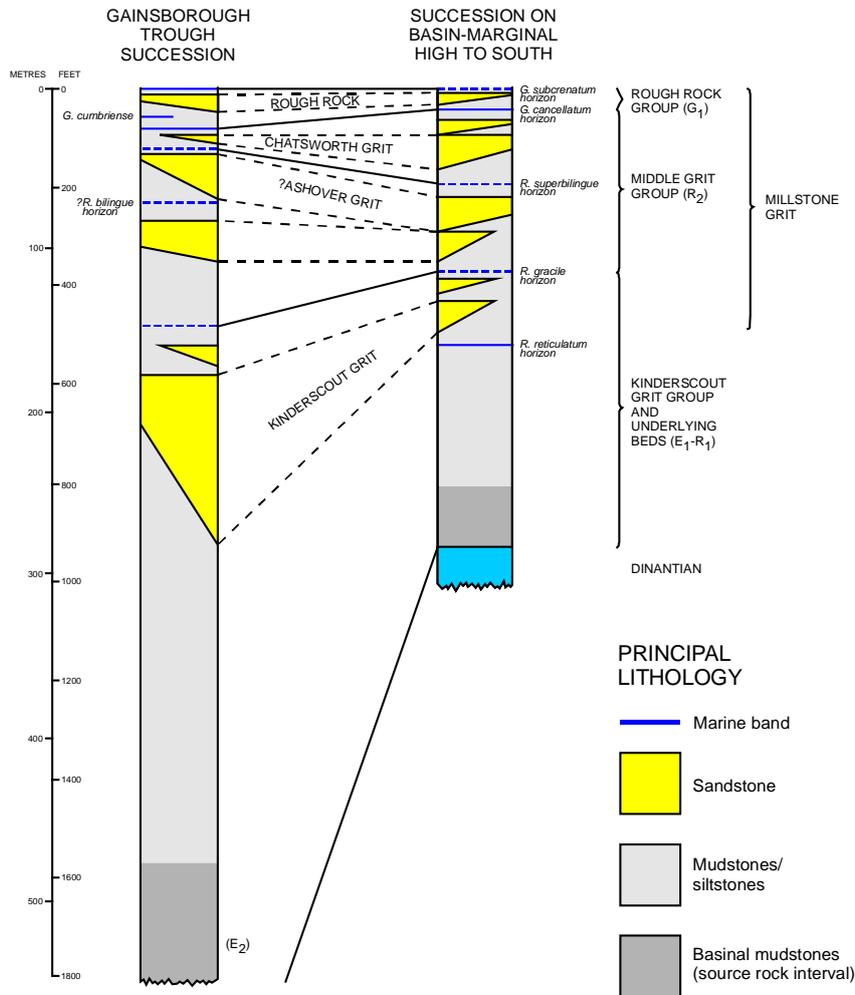
Fig. 7.3 Comparison of the Namurian (Upper Carboniferous) successions in the Gainsborough Trough and on the basin-marginal high to the south

These sandstones are commonly pebbly, the coarser fraction being subrounded to rounded and their finer fraction varying between subrounded and subangular. They are mostly feldspathic. Pressure solution of quartz grains, kaolinisation and sericitisation of the feldspars, partial replacement by iron oxides, and some secondary silicification combined with the poorly sorted nature of these sandstones has led, in general, to very low intergranular porosities and permeabilities.

Poor reservoir properties have generally been confirmed by over a hundred drill-stem tests and many core analyses. Some improvement in reservoir properties can be caused by fracturing, which can be recognised in core and from log analysis (Evans & Brereton 1990). However, the majority of tests have been carried out in the most favourable sandstone sequences where aquifer properties would be expected to be highest, not only because of the grain size, presence of fractures and lack of cement, but also because the presence of hydrocarbons has been shown to restrict the diagenetic processes that tend to reduce permeability. There appears to be a general trend of decrease in reservoir properties in a northerly direction, with the exception of the Brigg 1 well, which shows anomalously high value results (mean permeability from cores of 31 mD) for its location. Mean porosity decreases from 16% near Newark northwards to between 7 and 11% in the Gainsborough area, and has an overall regional average of 12%. Similarly, mean values of permeability decrease from approximately 30 mD to the north of Newark to around 1 mD in the northern oilfields area. Mean values as low as 0.3 mD have been determined from cores taken at Scaftworth 2 well. Ignoring some locally high values (around 120 mD), the mean regional permeability is 14 mD. To the north of the main oilfield area, at Tetney Lock, two DSTs produced no water flow, indicating very low permeability.

Even allowing for fracture enhancement, the reservoir properties of the Millstone Grit sandstones are for the most part poor. However, as they have sustained small but commercial production over a number of years, sometimes assisted

by sand fracturing, one must judge the low permeability as being adequate. Therefore, these sandstones must be considered as having some reservoir potential wherever they occur.

WESTPHALIAN COAL MEASURES

The Westphalian Coal Measures sandstones form the major reservoirs of the East Midlands Oilfields, notably in such fields as Eakring-Duke's Wood, Gainsborough, Beckingham and Welton.

Compared with many other areas in Britain, the Lower and Middle Coal Measures (Fig. 7.4) of the East Midlands contain a relatively small percentage of sandstone (around 20%). The coarsest sandstones occur in channel fills, form narrow and generally thin, mostly discrete meandering bodies, and account for less than 1% of the total sequence. However, where channels are locally stacked upon each other, thicknesses of sandstone up to 100 m can be attained. The sandstones are quartz rich, with minor feldspar and accessory mica. Grain sizes range from very fine to coarse-grained. Other sandstones also occur, thinly interbedded with siltstones, in levee, distributary mouth bar and interdistributary bay deposits. These sandstones have a limited lateral extent and are generally more argillaceous than the channel sandstones. Diagenesis appears to be facies controlled (Hawkins 1978) with mixed layer illite/clay, ferroan-dolomite and ferroan-calcite cements in distributary mouth bars, quartz, ferroan-dolomite and kaolinite in channels, and quartz, ferroandolomite and siderite in levee and interdistributary bay deposits. Porosity retention is greatest in the coarsest sandstones in the axial regions of the channels, and is least in the fine-grained sandstones where quartz cementation predominates. Except where oil was emplaced early, however, porosities and permeabilities are generally poor.

Thicker, and perhaps more extensive sandstone bodies with greater porosity and permeability are found in the Upper Coal Measures. In the centre of the East Midlands around Lincoln, the lateral equivalents of the upper Middle Coal Measures and the overlying Upper Coal Measures contain numerous medium to coarse-grained, red, yellow or white, commonly poorly cemented quartz sandstones. Individual sandstones range up to 25 m thick, with a total thickness of up to around 130 m. These sandstones generally have the best reservoir characteristics of all Carboniferous rocks in the region, but no major hydrocarbon shows have been recorded yet from such strata in the East Midlands province.

Porosity and permeability of the sandstones have been determined from geophysical logs, core samples and *in situ* testing, usually by drill-stem tests. The presence of fractures has locally been detected by log analysis (Evans & Brereton 1990) and from core examination. Because of the varied nature of the sandstone bodies and the different methods of aquifer property determination, no trends can be derived. Mean sandstone porosity in the Lower and Middle Coal Measures ranges from 7.5 to 20%, the majority of values being around 12%. Mean permeability values show a similar variability, the Lower and Middle Coal Measures sandstones ranging from 0.06 to 37 mD, their mean value being approximately 13 mD. A section of exceptionally high porosity and permeability is found in the Westphalian Basal Sandstone in Welton 2 well. Here, the permeability determined from core analysis averages 400 mD, the porosity averages 19.5% and the calculated transmissivity is 4.9 Dm. Porosity increase in Westphalian reservoirs is usually accompanied by an increase in permeability from about 0.1 mD at 9% porosity to approximately 100 mD at 17% porosity. However, the main group of points plot between 0.2 and 10 mD permeability and between 8 and 15% porosity.

Because hydrocarbon discoveries are lacking in the Upper Coal Measures and in the local red bed equivalents of the Middle Coal Measures around Lincoln, there has been little detailed work carried out on their reservoir properties. However, the NCB discovered that in the area south from Lincoln to Newark, these rocks are relatively permeable, are water bearing, and pose a potential threat to future mining developments. In four boreholes studied by the NCB, mean core porosity ranges from 12 to 19% with an average of around 15%. The corresponding permeability values are 3 to 160 mD and around 80 mD. The only other physical property data available on Upper Coal Measures sandstones is from the Tetney Lock Borehole in the north of the province, where five core samples had a mean porosity of 13% and a mean permeability of 1.7 mD.

In summary, typical Coal Measures sandstones have low porosity and permeability, but perhaps slightly greater than those of the underlying Namurian Millstone Grit. However, such values have proved adequate reservoirs in a number of fields, commonly with the assistance of sand fracturing. The basal sandstones of the Coal Measures around Welton have much better properties locally. Potentially good aquifers also occur in the high Middle Coal Measures and Upper Coal Measures around Lincoln. The effect of burial on porosity of Namurian to early Westphalian channel sandstones was shown by Fraser *et al*. (1990) to decrease from about 18% at 2000 m to 10% at about 2500 m.
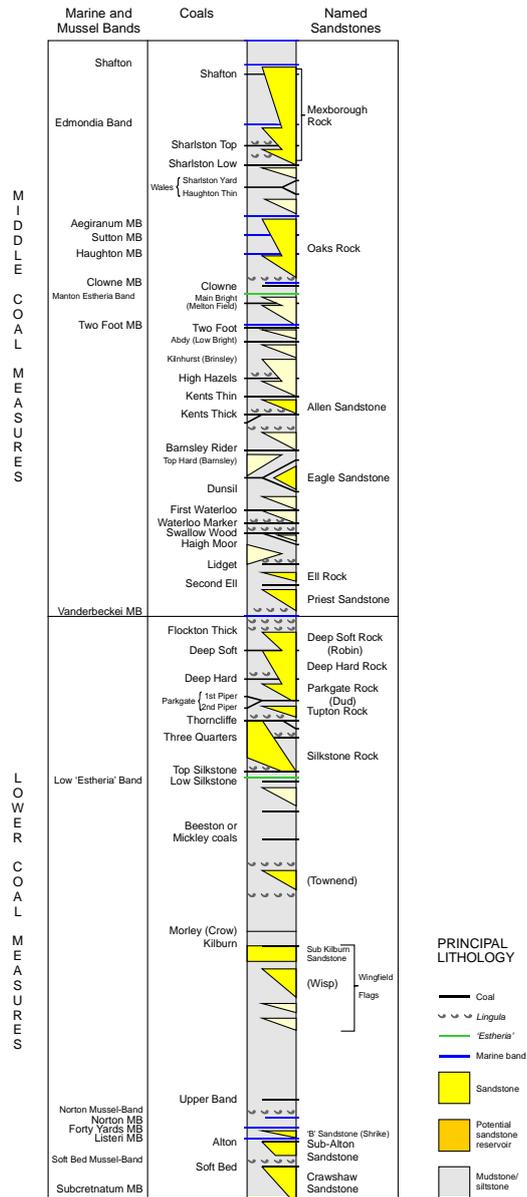
Fig. 7.4 Stratigraphy of the Westphalian (Upper Carboniferous) coal measures of the East Midlands province

PERMIAN

Very few occurrences of hydrocarbons (almost certainly sourced from Carboniferous rocks) have been reported in Permian and younger rocks. The most notable of these is a sizeable oil show at Nocton in Basal Permian Sands, which are thin and patchy in the East Midlands province, except locally. A continuous sandstone body is probably limited to the present east coastal area, where thicknesses in excess of 30 m have been noted. Porosity and permeability values far exceed most Carboniferous sandstones (Gale *et al*. 1983). A DST at Tetney Lock suggested an average permeability of 150 mD, and higher values (average 300 mD) have been recorded in core at Great Hatfield well, north of the Humber Estuary. Clearly, where such sandstones are sufficiently well developed, in closed structures into which Carboniferous-sourced oil or gas has leaked, they would provide an excellent reservoir rock. Where these sandstones are thin or absent, Upper Permian reservoirs commonly contain small amounts of gas, and these include the dolomites and dolomitic limestones of the Kirkham Abbey Formation and the Upper Magnesian Limestone. The reservoir potential of these rocks is largely dependent on the presence of fractures.

Seals

Argillaceous sediments are abundant in the Upper Carboniferous rocks, and form effective intraformational seals to hydrocarbon accumulations. The early Namurian shales form a seal to the limited oil occurrences at the top of the

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Carboniferous Limestone (Fig. 7.3). The generally argillaceous nature of the Westphalian Lower and Middle Coal Measures largely prevents escape both from isolated sandstones within them, and from underlying sandstones at the top of the Namurian Millstone Grit and the base of the Coal Measures. Indeed, it is likely that these argillaceous beds have prevented migration into the higher sandy Upper Coal Measures and, except in a few instances where pre-Permian erosion cuts deepest, into overlying Permian and Mesozoic strata. Evidence from the Gainsborough and Beckingham oilfields indicates that faults are presently sealed and there, at least, do not form active pathways for migration. Whether this was always true is uncertain. Particularly while the sediments remained only partially consolidated during the Carboniferous, and again during the tensional stresses of the Jurassic and Cretaceous, some migration along faults might be expected.

Overburden

The extent of Tertiary uplift and erosion in the East Midlands is controversial. Geological estimates need to be carefully balanced against those derived from depth of burial studies, AFTA (apatite fission track analysis) and maturity parameters. Whereas AFTA and sonic velocity studies appear to give over-estimates of former overburden (Green *et* al. 2001), Holliday (1999) has presented a consensus view that about 1200 m of latest Cretaceous-early Tertiary sediments have been removed.

Traps

Three key trapping elements have contributed to many of the fields.

STRUCTURAL

All known commercial hydrocarbon accumulations in the East Midlands province are held in anticlinal structures, although these are not simple structural traps. There is a wide range of closed structures in the region, falling into three main types, namely faulted anticlines (both symmetrical and asymmetrical), closed roll-overs against faults, and horst-blocks. The main period of formation of these structures was at the end of the Carboniferous, but many probably were initiated in early Carboniferous or even late Devonian times, and all have been modified by post-Permian movements and regional tilting towards the east and northeast. Oil generation within the region probably began in the Westphalian and continued until at least the end of the Cretaceous. Thus, at all times, there were closed structures into which this oil could migrate. Reconstruction of present-day structures to their pre-Permian appearance shows that the result of Mesozoic tilting was to reduce the area of individual closures or even to turn closed anticlines into unclosed noses. The tilting probably led to renewed migration, and even loss, of much early (Carboniferous) generated oil.

Oil generated in Jurassic and Cretaceous times would find the structures broadly as now disposed, and subsequent Cenozoic tilting can have had only minor effect on the size of accumulations.

SEDIMENTOLOGICAL

While a structural closure, on present evidence, seems to be a necessary prerequisite for hydrocarbon accumulation within the East Midlands province, it is clear that the traps are also often sedimentologically controlled. This is illustrated in the Gainsborough Oilfield, where many of its producing sandstone reservoirs are either discontinuous, lenticular bodies (shoestring sands), which do not occur everywhere on the structure (Coal Measures) or, if more sheet-like, are laterally variable in facies (Millstone Grit). This means that a borehole drilled on the highest point of a closure may prove dry, although the structure may otherwise prove productive down dip. Thus, sedimentological factors exert a strong influence on the position of oil or gas accumulations.

STRATIGRAPHIC

The fields and new discoveries lie on a NE-SW trend that extends from near Nottingham to Welton and Saltfleetby; between the latter two fields, relatively thin Westphalian Coal Measures overlap the Namurian onto Dinantian Carboniferous Limestone. Although these finds are, at least in part, structurally controlled, the overlap of Coal Measures sandstones onto tight limestone is one of the key trapping elements. Petroleum generated from all the source rocks of the early Namurian shales (the principal source rock), other shales and late Namurian marine bands would have found its simplest migration up-dip to the overlapping Westphalian Basal Sandstones reservoir. There are similar untested possibilities on the flanks of the Lincoln-Nocton Ridge, where Middle and probable Upper Coal Measures rest on the limestone, and again around the Grantham High. These plays may be too far from the source kitchens of the sub-basins, which have played a key role in the migration history.

Migration

Oil generated in the East Midlands during the Carboniferous, prior to the end-Carboniferous Variscan Orogeny, would have migrated up dip towards the surrounding basin-marginal areas. This general easterly migration would have been partially reversed following Variscan uplift of the Pennines inversion axis, particularly in the western half of the East Midlands. The bitumen of Windy Knoll and various lead mines on the eastern edge of the Derbyshire Dome represents the surface and near-surface extent of this migration.

In the western part of the East Midlands province (roughly corresponding to the Carboniferous outcrop), many of the once oil-bearing reservoirs have been eroded or breached during the uplift of the Pennines. Preservation of oil and gas at lower levels is a possibility, particularly since the first discovery Hardstoft well produced from the top of the Carboniferous Limestone. The Dinantian apron reefs would make an attractive target (Figs. 7.5, 7.6), if they can be located in the subsurface. Reservoirs containing gas are more common in the west (e.g. Calow, Ironville, Hatfield Moors and Everton).

Fig. 7.5 View of Dinantian reefs from Chrome Hill, Derbyshire, East Midlands province. Similar small reefs probably lie concealed in the subsurface (© NERC).

In the more intense structures in the east of the East Midlands province (Carboniferous subcrop area), some oil and gas could have survived the tilting and reversal of migration pathways.

In the Bothamsall Oilfield, Hawkins (1978) indicated that there had been two phases of migration. The first occurred during shallow to moderate burial of the Carboniferous strata, and a second phase followed the folding (trap formation) at the end of the Carboniferous. The obvious conclusion is that the onset of oil generation hereabouts must have been during the Carboniferous. The oil emplaced during the Carboniferous would have experienced further burial and temperature increase during the Mesozoic sediment loading. This would have allowed some thermal alteration of the surviving reservoired oil, producing a lighter oil (lower specific gravity, higher API) by cracking of heavier compounds together with an increase in gas content. Subsequent uplift and erosion would have allowed the biodegradation of some oils (e.g. Windy Knoll, Derbyshire) by the invasion of microbial-bearing meteoric waters.

Hydrocarbons generated during the Mesozoic would be expected generally to have migrated westwards, i.e. up dip, but because the Mesozoic strata generally contain no hydrocarbons, the effect of the tilting on Carboniferous structures needs to be considered. Because the Permian and Mesozoic cover thickens towards the northeast, the likelihood of gas generation increases in that direction. Upper Carboniferous strata also thicken in the same direction.

Fig. 7.6 View of Dinantian reefs at Glutton, Derbyshire, East Midlands province. Similar small reefs probably lie concealed in the subsurface (© NERC).

The generally argillaceous nature of the Coal Measures has largely prevented migration of hydrocarbons, of whatever age, from the Carboniferous into younger formations. Most or all of any hydrocarbons following such a path are likely to have been lost to surface. as there are so few structural closures in the overlying cover rocks, and stratigraphic traps, e.g. sealed isolated mounds of Basal Permian Sands, are believed to be rare.

Regional late Cretaceous-Tertiary uplift would have terminated oil generation in source rocks on the margin of St. George's Land, but source rocks at depth within the sub-basins, e.g. Widmerpool Sub-basin, still lie in the oil window. This uplift, however, may well have provided new opportunities for migration and/or the further loss of oil from the region.

Accumulations

A simplified account of the exploration history in the region is given in the introduction to this East Midlands section; more detailed accounts have been published by a number of authors e.g. Huxley (1983).

Minor occurrences of oil, tar and bitumen have been known in the Carboniferous Limestone of Derbyshire for many centuries, as have a number of oil seepages at, or close to, the junction of this limestone with the overlying Namurian shales of the Millstone Grit (Bromehead 1923). The earliest known commercial exploitation of hydrocarbons in the East Midlands was in 1847 from seepages in the Coal Measures at Riddings Colliery, Derbyshire. Other similar occurrences are recorded by Bromehead (1923) and Kent (1954). In recent years, oil has been extracted from Bevercotes Colliery close to the Bothamsall Oilfield.

HARDSTOFT OILFIELD

Hardstoft Oilfield was discovered by the first systematic, American-advised search for oil conducted during and after the First World War. On 3rd June 1918 (Strahan 1920), oil was encountered here at 938 m, at the top of the Carboniferous Limestone, in a faulted asymmetrical anticline. The Westphalian Coal Measures are at crop in this field. Hardstoft produced oil at 8-10 barrels per day initially. Production by October 1919 was 849 barrels from the single well. A number of later exploration wells failed to yield any significant oil, and the total production from the field was only around 26,000 barrels over a period of twenty-five years. Additional details are given by Bromehead (1923), Giffard (1923), Wade (1928), and Smith and others (1967).

This first discovery proved anomalous. The East Midlands oil province is situated farther east, and production has been from Westphalian and Namurian Millstone Grit reservoirs, concealed by Permian and Mesozoic strata. Indeed all the subsequent discoveries, except Calow, have been located beneath the Permian and Mesozoic strata. The subcrop and depth to this base Permian unconformity (Smith 1985a & b) reveal detail on the extent of some of these structures.

CALOW GASFIELD

This field's reservoirs are the lower Westphalian Crawshaw Sandstone and the Namurian Chatsworth Grit (Brunstrom 1966). There is no detailed information in Falcon & Kent (1960), and Adcock (1963) referred only to the wells as having been completed as commercial gas wells for the Gas Council. The seal is provided by shales within the Coal Measures, and there are no overlying Mesozoic or Permian strata. Fraser *et al*. (1990) published a map of the structure (Fig. 7.7), which has closure of more than 100 m, and reported a gas column of 30-40 m sealed at two reservoirs by delta-top shale and argillaceous sandstone. Fraser & Gawthorpe (1990) showed a seismic profile across the thrust-faulted anticline (Fig. 7.8), and reported production of 0.5 bcf of gas. Caribe operates the licence enclosing this field.
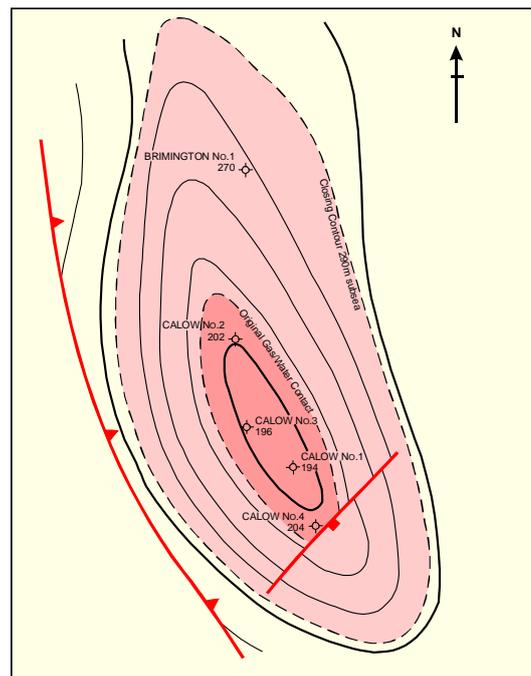
Fig. 7.7   Depth to top Chatsworth Grit at Calow Gasfield, East Midlands province (after Fraser & Gawthorpe 1990)

IRONVILLE GASFIELD

This field's reservoir is the Namurian Kinderscout Grit (Brunstrom 1966). Adcock (1963) stated that the Ironville 3 well was completed as a gas producer with a potential of 800,000 cfd production. Ironville 5 well was drilled to the top of the Lower Palaeozoic, with no shows in the Carboniferous Limestone.

EAKRING-DUKE'S WOOD OILFIELD

The first major oil discovery in the East Midlands was made at Eakring in 1939, closely followed by the satellite structure of Duke's Wood and nearby closures at Caunton and Kelham Hills. These traps can now be seen as culminating on a broad anticlinal ridge that brings Westphalian Middle Coal Measures, and locally Lower Coal Measures, to subcrop beneath the Permo-Triassic cover (Smith 1985a). A very full account of these oilfields was provided by Lees and Taitt (1946) with additional details by Falcon and Kent (1960), Edwards (1967), and Storey and Nash (1993). The Eakring and Duke's Wood oilfields are formed by a NNW trending anticline with a faulted western limb. Kirby *et al*. (1987) interpreted the western boundary as a reverse fault, dating from the end-Carboniferous Variscan Orogeny, which reactivated an early Dinantian syn-sedimentary growth fault. This structural style is shown in the seismic profile published by Fraser & Gawthorpe (1990).

The main reservoir, originally interpreted as the upper Namurian Rough Rock, is now identified as the lower Westphalian Crawshaw Sandstone (Lower Coal Measures), but production was also obtained in stratigraphically higher and lower sandstones and locally from the top of the Carboniferous Limestone. Analytical results indicate considerable differences between the crude oil in the four War-time fields and lesser differences between reservoirs within individual fields. Both Eakring and Duke's Wood fields are now abandoned, their final production figures being 2,104,630 barrels and 4,413,410 barrels respectively.
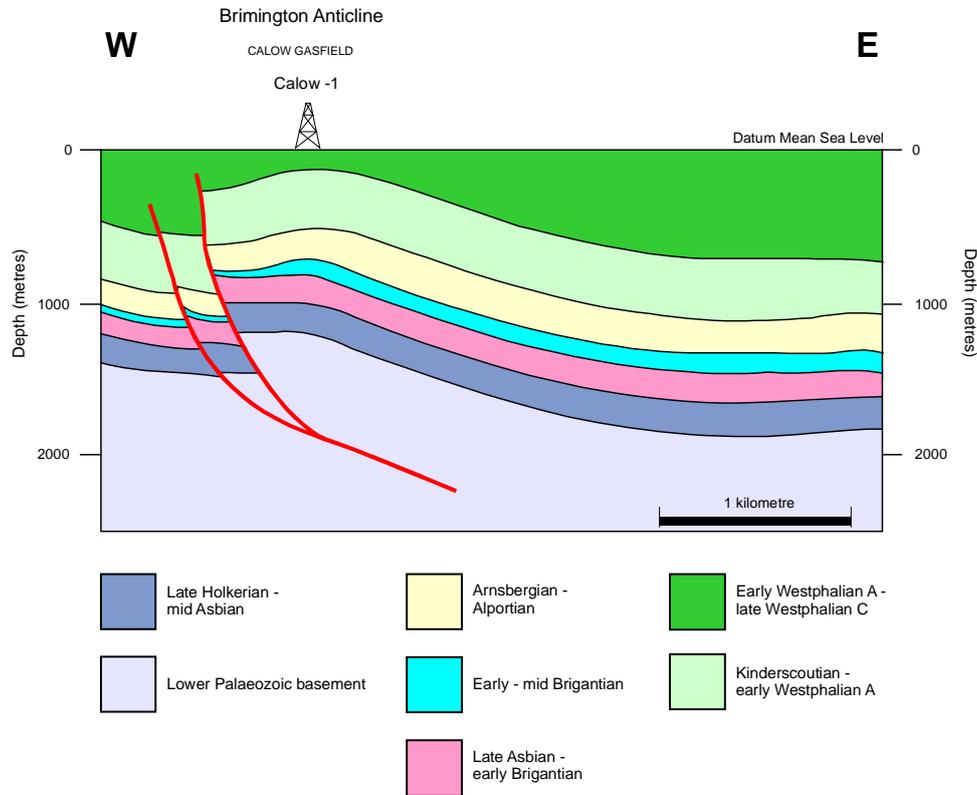
Fig. 7.8 Interpreted seismic reflection profile, showing west-directed reverse faulting producing
local inversion, Calow Gasfield, East Midlands province (after Fraser & Gawthorpe 1990)

The specific gravity of the oil varies from 0.837-0.853 at Eakring and 0.857-0.866 at Duke's Wood (Lees & Taitt 1946). The oils have a high wax content (Southwell 1945). The gas saturation pressure is low, at about 400 psi (BP 1962), and the original reservoir pressures were about 1000 psi (Dickie & Adcock 1954).

Brief production was achieved from the Carboniferous Limestone at one well, at a rate of 50 tons/day and two wells were producing from this reservoir (Lees & Taitt 1946). Secondary recovery of oil began in 1948 (Dickie & Adcock 1954).

The geothermal gradient at Eakring is significantly higher than at both Duke's Wood and Kelham Hills (Southwell 1945).

KELHAM HILLS OILFIELD

This field was discovered near the site of the Oilfields of England Ltd coal borehole at Kelham B, drilled in 1920, which had suggested to Ford (Dalton 1918) that oilfields would be discovered in the East Midlands. The original Kelham borehole obtained oil at a rate of 5-8 gallons/day. Kelham Hills Oilfield was discovered in 1941, and secondary recovery in the field began in 1951 (Dickie & Adcock 1954). The field produced a total of 2,077,880 barrels of oil. Specific gravity of its oils varies from 0.88 at 643 m (BOD) to 0.892 at 631 m (BOD). The gas saturation pressure is very low, at 100 psi (BP 1962).

CAUNTON OILFIELD

The Caunton field produced 268,940 barrels of oil from a basal Coal Measures sandstone and the Namurian Ashover Grit. Secondary recovery of oil began in 1954.

PLUNGAR OILFIELD

The Plungar Oilfield lies on the northern margin of the Widmerpool Sub-basin. Detailed accounts have been published by Falcon and Kent (1960) and Warman *et al.* (1956). The field's structure is a broad, gently faulted dome, about 1.5 km across, with a steeper southern edge. Production has been obtained from sandstones in both the Namurian Millstone Grit and Westphalian Lower Coal Measures, and locally from a 3-7 m oil column at the top of the underlying Carboniferous Limestone. Up to twelve sandstones are productive, but generally only two of these produce in any one well. The sandstones vary from less than 1 m thick to nearly 10 m. Permeability varies from 0.1-1000 mD, but is generally in the range 5-50 mD (Warman *et al.* 1956). Different sandstones have different oil-water contacts and contain oil of different character and specific gravity. Within the field, the specific gravity ranges from 0.85-0.9. Gas saturations vary, although all are very undersaturated (Warman *et al* 1956). The gas saturation pressure is very low, at 100 psi (BP 1962). Production, now ceased, totalled 306,070 barrels.

EGMANTON OILFIELD

The Egmanton Oilfield lies in a gentle WNW to ESE trending anticline, cut by several faults parallel to the fold axis (Fig. 7.9), and is 4.8 km long and 0.8 km wide (Falcon and Kent 1960). Oil occurs in several sandstones in the Lower Coal Measures and Millstone Grit. Again, the main producer is the lower Westphalian Crawshaw Sandstone (Edwards 1967) with some production from lower levels. Production totalled 3,327,270 barrels and the field is now exhausted. Experimental tertiary recovery methods were tried here with some success (Gair *et al*. 1980). A seismic profile across the field was published by Fraser & Gawthorpe (1990), showing Dinantian growth across the structure, similar to Eakring field. The gas saturation pressure is low, at about 400 psi (BP 1962).
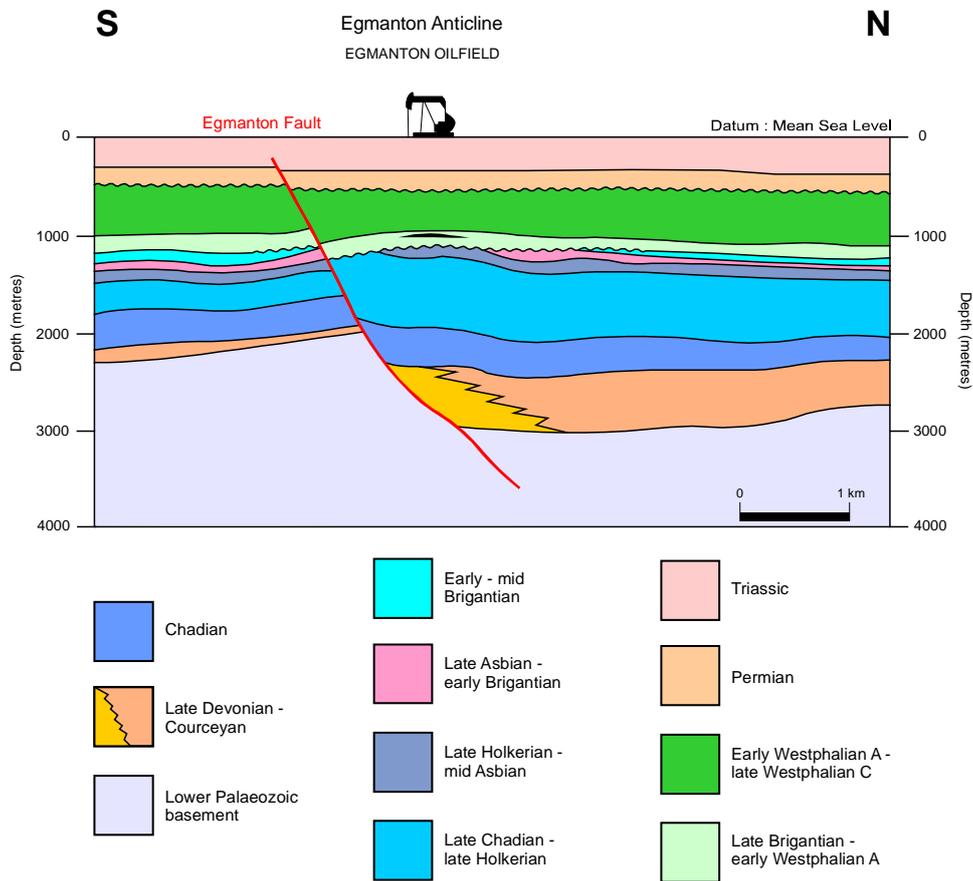
Fig. 7.9 N-S section across Egmanton Oilfield, East Midlands province (after Fraser & Gawthorpe 1990)

BOTHAMSALL OILFIELD

The Bothamsall Oilfield, a roughly circular structure of around 1 km radius, has been the subject of a detailed study by Hawkins (1978). From the Egmanton Oilfield extends a NW-trending fault, which controls Bothamsall's structure. Production here is from two sandstones, the lower Westphalian Sub-Alton (Lower Coal Measures) and the upper Namurian Rough Rock (top of Millstone Grit), which in part of the field is joined to a local development of the Crawshaw Sandstone (base of Coal Measures). Of particular interest is the evidence deduced by Hawkins (1978)

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relating depositional environment, diagenetic modifications of mineralogy and reservoir properties (porosity and permeability), affected by the early emplacement of oil. Production to the end of 1982 totalled 2,564,070 barrels. Tertiary recovery methods using surfactants have been tested here in recent years, but the field is now exhausted.

CORRINGHAM OILFIELD

There are few details available for the Corringham Oilfield, in a small fault-bounded anticline. Oil has been found at several levels in the Lower Coal Measures and in the Millstone Grit, three of which have given production. Total production to the end of 1982 was 361,520 barrels.

GAINSBOROUGH-BECKINGHAM OILFIELD

A notable feature of this combined field is the large number of oil- and gas-bearing sandstones, ranging in age from Namurian to Westphalian B. However, because of faulting and sedimentological variation, not all are present or hydrocarbon bearing in every well drilled. Much of the production of 3,584,710 barrels at Gainsborough and 2,493,720 barrels at Beckingham, to the end of 1982, has come from the 'Eagle' Sandstone of Westphalian B age. A contour map of the Top Hard Coal was published by Brunstrom (1966). Recoverable reserves were assessed at 13 mmbbl of oil and 6.5 bcf of associated gas.

SOUTH LEVERTON OILFIELD

The South Leverton Oilfield is in a shallow east-west trending anticline. Oil occurs at two levels in the Namurian Millstone Grit and one in the Westphalian Lower Coal Measures, but the only producing sandstone is the upper Namurian Rough Rock. Production to the end of 1982 was 402,970 barrels.

GLENTWORTH OILFIELD

The Glentworth Oilfield is part of a major anticlinal area into which the Hemswell and Spital boreholes were also drilled. Field production amounted to 211,550 barrels by the end of 1982. Shows were found throughout much of the Upper Carboniferous, but the production is limited to a sandstone bed near the top of the Westphalian Middle Coal Measures.

NOCTON DISCOVERY

Minor production (less than 100,000 barrels) has been obtained at Nocton, Langar and Apleyhead. Nocton 2 well produced briefly from the Dinantian Carboniferous Limestone, initially at 3 tons/day, declining as water production increased (Lees & Taitt 1946).

WELTON OILFIELD

Welton Oilfield was discovered in 1981, on a NW-SE trending anticline, and produced from a 68 m thick Westphalian Basal Sandstone. This sandstone was interpreted as comprising a series of channel fills, which were abandoned progressively southwards across the field (Rothwell & Quinn 1987). In their paper, (Rothwell & Quinn *op. cit.*) showed a seismic profile, structure map, wireline-palynological correlation, isopachs, and reservoir characteristics of the field. The Welton field overlies thick Dinantian limestones on the SE margin of the Gainsborough Sub-basin; a seismic profile (Fraser & Gawthorpe 1990) shows Dinantian growth on the fault controlling its position (Fig. 7.10). The Gainsborough Sub-basin is itself controlled by a SW-dipping synsedimentary fault, in contrast to the other sub-basins to the southwest, in the East Midlands, which are controlled by NE-dipping faults. The oil is a sour crude (Fraser *et al.* 1990) and recoverable reserves of oil are predicted to be 16.74 mmbbl (DECC Website). Production began in 1984.

NETTLEHAM OILFIELD

Nettleham well tested the Westphalian Basal Sandstone at 1060 bopd, and a probable karstic top to the underlying Carboniferous Limestone flowed at 12.9 bopd. A lower zone of interest in Nettleham 2 well could not be tested due to the large borehole diameter.
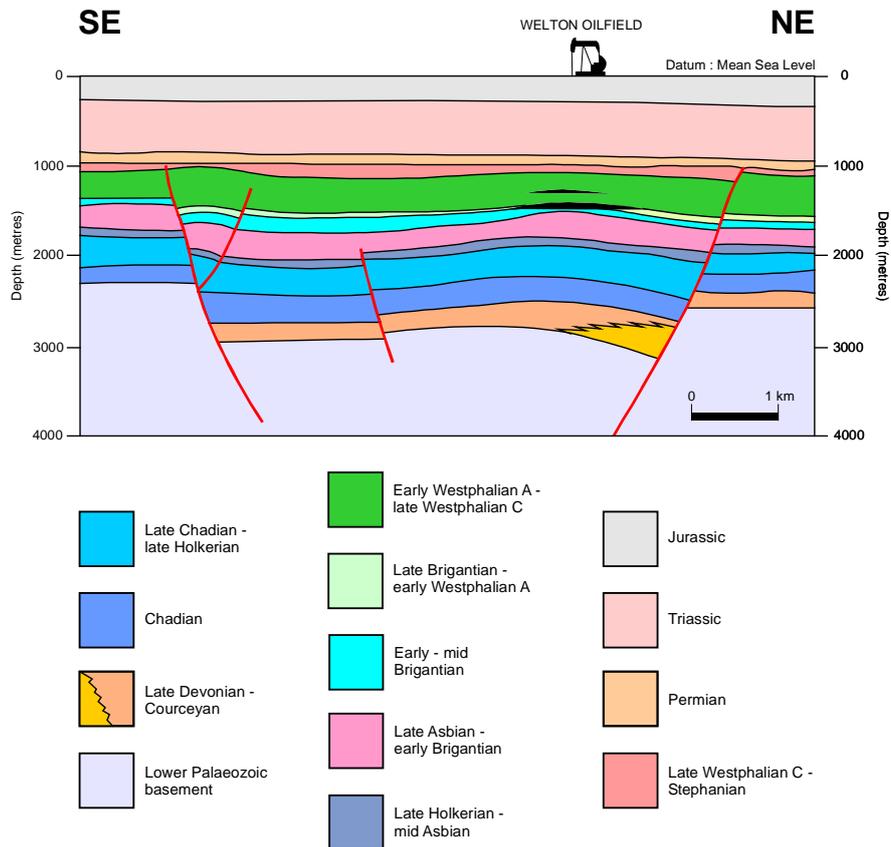
Fig. 7.10 Seismic reflection and depth converted section across Welton Oilfield, East Midlands province (after Fraser & Gawthorpe 1990)

WIDMERPOOL SUB-BASIN FIELDS AND DISCOVERIES (LANGAR, BELVOIR, LONG CLAWSON AND KINOULTON)

Several discoveries are located on the northern margin of the Widmerpool Sub-basin. Langar 1 well tested 198 bopd from near the top of the Namurian Millstone Grit, and subsequent boreholes had oil shows and produced water; production lasted only two years. Belvoir well tested 27 bopd from the Ashover Grit, but no production was obtained from the younger Namurian Chatsworth Grit.

Long Clawson and Kinoulton wells are nearer the basin depocentre. The first Long Clawson well was drilled in 1943; the second well tested 70 bopd from near the top of the Namurian Millstone Grit in 1986. Long Clawson field began production in 1991.

The Kinoulton discovery well tested oil at 9 bopd from the lower Westphalian Crawshaw Sandstone, but is now capped.

REMPSTONE OILFIELD

This field was the first discovery to be made just to the south of the Widmerpool Sub-basin, and it is also remarkable for having an early Namurian reservoir (Pendleian age turbidites named the Rempstone Formation). The structure is within the hanging wall, but close to the crop of the surface Normanton Hills Fault. The reservoir tested 21 bopd of 34.2° API oil in Rempstone 1 and similar amounts in 2z well. Subsequent nearby exploration wells tested different traps and were unsuccessful.

BECKINGHAM WEST OILFIELD

This field was discovered in 1985 by BP and produces from one well (Beckingham 37). Beckingham West lies west of the former mining licence awarded to exploit the original Beckingham field.

CROSBY WARREN OILFIELD

RTZ discovered this field in 1986 and tested three Namurian sandstones, the Rough Rock, Beacon Hill Flags and the Upper Kinderscout Grit. The flows are not available.

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EAST GLENTWORTH OILFIELD

East Glentworth was discovered by BP in 1987, testing about 5 bopd from the Mexborough Rock (Westphalian C) and also from the Namurian Chatsworth Grit. Production began in 1993.

FARLEY'S WOOD OILFIELD
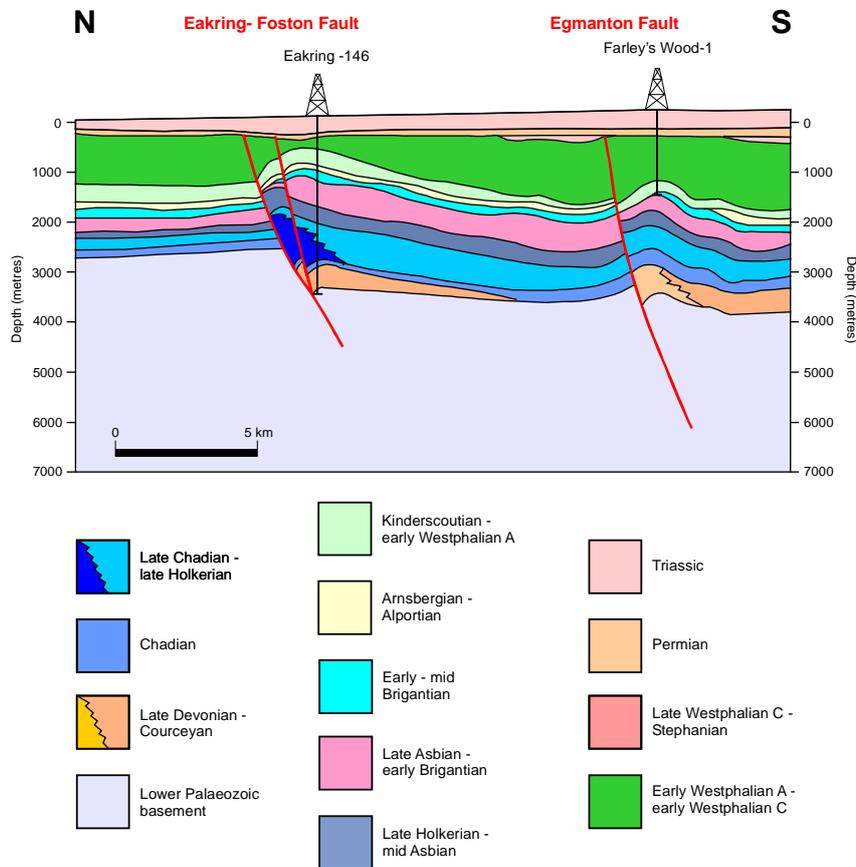
Fig. 7.11 N-S section through Farley's Wood Oilfield, East Midlands province (after Fraser & Gawthorpe 1990)

The first exploration well on this field (Fig. 7.11) was drilled in the 1940s, and two subsequent wells failed because the thick oil-soaked sandstones were too impermeable for production (Falcon & Kent 1960). Farley's Wood 4 well tested 1000 bopd, declining to 200 bopd after hydraulic fracturing. Onshore Oilfield Services Ltd operate the licence including this field.

HATFIELD MOORS (& HATFIELD WEST) GASFIELD

The Hatfield Moors discovery well blew out from the shallow Oaks Rock in 1981, and tested 15 mmcfd gas. The geophysical logs of Hatfield Moors 3 well, a re-drill of 1 well, clearly show this Westphalian B reservoir. The trap is a NE-SW oriented tilted anticlinal fault block, and the Oaks Rock reservoir is a 5-10 km wide fluvial channel that flowed from NE to SW (Ward *et al*. 2003). Hatfield West 1 found gas in the same reservoir with a higher GWC than Hatfield Moors in a separate closure across a NE-SW fault from the Hatfield Moors structure. GIIP at the Hatfield Moors and Hatfield West fields is estimated at 6.1 and 2.4 bcf respectively. During the 38 days attempting to control the discovery well's fiery blow-out, approximately 1 bcf of gas was lost. Recoverable reserves are estimated to be 4.27 bcf at Hatfield Moors and 1.68 bcf at Hatfield West. Following drilling of two horizontal wells in 1998 and 1999, Hatfield Moors has operated as a gas storage facility, and is the first such project onshore UK.

KIRKLINGTON OILFIELD

A coal exploration borehole in 1915 found gas in a fault near the eventual 1985 BP discovery well. An earlier 1948 BP well failed to produce on DST.

SCAMPTON OILFIELD

BP discovered this field in 1985 with the Westphalian Basal Sandstone reservoir testing 350 bopd. Production ceased in 1988.

SCAMPTON NORTH OILFIELD

Scampton North field was discovered by BP in 1985, testing 550 bopd from the Westphalian Basal Sandstone and the Upper Namurian Rough Rock.

STAINTON OILFIELD

Stainton field was discovered by BP in 1984, with 60 bopd tested from the Westphalian Basal Sandstone, which overlies thin late Namurian strata at this location.

WEST FIRSBY OILFIELD

Enterprise discovered this oilfield in 1987, testing the Westphalian Basal Sandstone at 864 bopd, with an oil-water contact within underlying Namurian strata, which are more than 166 m thick (base Namurian is below well TD). The trap is a subtle dip-closed structure located along strike from previously discovered oil fields (Corringham, Glentworth, East Glentworth) in the inverted hanging wall of the NW-SE trending Morley-Campsall (Askern-Spitall) Fault (Bailey 2003). Recoverable reserves are around 1.6 mmbo, but this is based on a recovery factor of approaching 12% in a four-well production scheme (Bailey, *op. cit.*).

WHISBY OILFIELD

Whisby was discovered in 1985 by BP, testing 147 bopd from a thin Westphalian Basal Sandstone. Production began in 1990.

TRUMFLEET GASFIELD

BP discovered gas in the Beacon Hill Flags of Namurian age in 1957 (Brunstrom 1966), with potential production then estimated to be 0.2 mmcfd. Trumfleet 2 well was dry, but Trumfleet 3 was capable of producing nearly 8 mmcfd (Adcock 1963). The Beacon Hill Flags comprise a gradational coarsening-upwards mouth bar unit, 10 m thick, overlying a 15 m fining-upwards channel unit (Cowan & Shaw 1991).

The Trumfleet field is a faulted dome on the Askern-Spital High, near its junction with the NE-SW trending South Don Fault. This field lies near the gas limit, with only oilfields to the southeast. Cowan & Shaw (1991) reported a vitrinite reflectance value of 1.02% from late Namurian shales in this field, and modelled the base Namurian as having entered the oil window in Carboniferous times.

Trumfleet field was brought into production by Edinburgh Oil & Gas and is now owned by Independent. About 0.2 bcf gas is present, and production began in 1998.

FISKERTON AIRFIELD OILFIELD

Discovered in 1998 by Cirque, this field is about 2 km southeast of Welton Oilfield. Production began in 1998.

TORKSEY OILFIELD

Torksey field produced about 50,000 bbl oil from 1963 until the 1980s (Huxley 1983). Torksey 4 well tested the lower Westphalian Crawshaw Sandstone and the Namurian Chatsworth Grit. From the logs, it appears that a deeper Namurian sandstone (probably Kinderscout Grit) should have been tested also.

SALTFLEETBY GASFIELD

Morrison Middlefield Resources Ltd submitted a plan to develop the Saltfleetby Gasfield (Fig. 7.12), discovered by Candecca in 1986. The proposal was to drill two more wells and produce 33 mmcfd of gas and 1500 bpd of natural gas liquids (Anon 1999). The field was then taken over by Roc Oil (UK) Ltd and production began in 1999. This is

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the UK's largest onshore gasfield, with estimated recoverable reserves of 73 bcf gas, with a GIIP of 114 bcf (Hodge, 2003). The full-to-spill trap is formed by a faulted four-way dip closure, and the reservoirs comprise stacked Late Namurian to Early Westphalian fluvio-deltaic sandstones.

COLD HANWORTH OILFIELD

Cold Hanworth 1 well was drilled in 1986 by Enterprise; Candecca made the field discovery with a second well. Star Energy now owns the field, which began production in 1998. Reserves of 1.13 mmbls oil were initially present, and production began in 1998.

NEWTON-ON-TRENT OILFIELD

AltaQuest discovered Newton-on-Trent field in 1998, when production started. Reserves of 0.18 mmbls oil were originally present (DECC website).
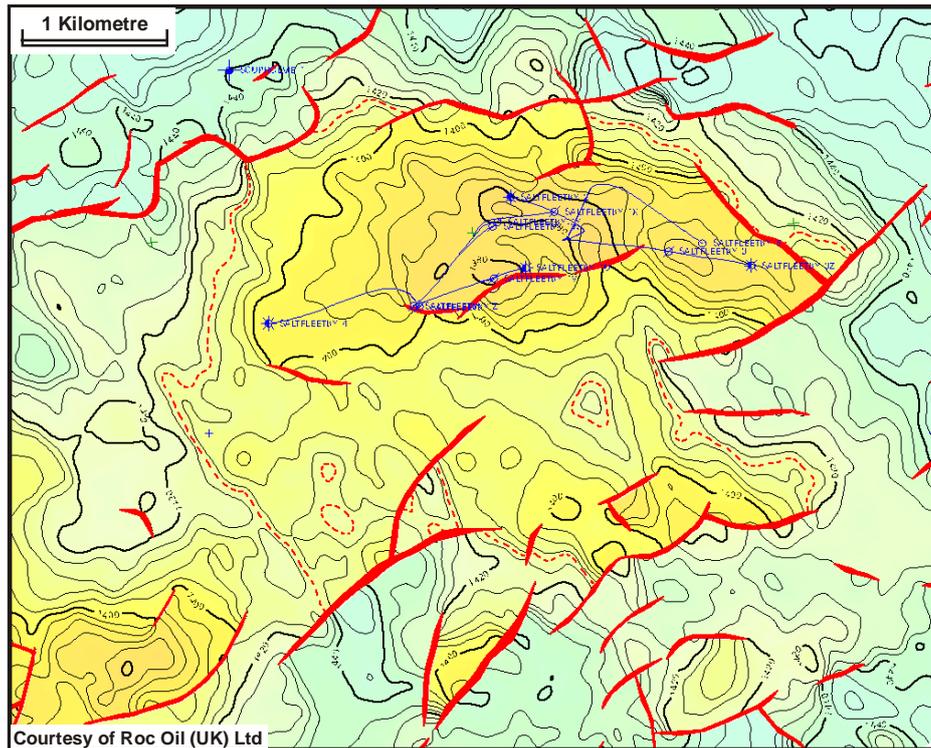
Figure 7.12 Two-way travel time to top basal Westphalian at Saltfleetby Gasfield, East Midlands province (courtesy of Roc Oil (UK) Ltd.

KEDDINGTON OILFIELD

Keddington field was discovered in 1998 by Candecca. Reserves of 1.27 mmbls oil were originally present, and production began in 1998.

OTHER SIGNIFICANT DISCOVERIES

The DECC website lists Broughton, Hemswell, Everton, Cropwell Butler 2, Reepham, Brigg, Belvoir and Kinoulton as significant discoveries. Broughton and Brigg lie on the Crosby Warren trend. Brigg 1 well tested 3.8 bopd and 62.8 bopd respectively from the lower Westphalian Kilburn and Crawshaw sandstones, but Brigg 2 well was not productive. Broughton well tested 40 bopd from the lower Westphalian Penistone Flags. Hemswell well, north of East Glentworth field, tested 10 bopd from the lower Westphalian Parkgate-Tupton-Deep Hard sandstones. Everton well, located west of the Beckingham field, tested 3 mmcfd gas and 20 bpd of condensate from Alportian (Namurian) sandstones.

CONCLUSIONS

1. Around seventy-five million barrels of recoverable oil and 27 bcf of recoverable gas had been discovered in the Carboniferous rocks of northern England by 1990 (Fraser & Gawthorpe 1990). Most of the oil is found in the East Midlands province. Oil or gas shows abound in boreholes, and oil seepages occur at outcrop and in former lead and coal mines.

2. The oilfields occur in a broad NE-SW trending swathe from south of Nottingham to the Humber Estuary. The southeast limit to this swathe is the basal Westphalian onlap onto the margin of St George's Land. A secondary line of mostly small gas fields extends N-S from Ironville to Hatfield Moors, nearer to the original Carboniferous basin's depocentre. Theoretically, this secondary line could be extended northeastwards, encircling the Askern-Spital High and extending back southeastwards to Saltfleetby Gasfield.

3. Potential source rocks are plentiful and mature throughout the Carboniferous. Thick sequences of oil-prone late Dinantian shales occur in the Widmerpool, Edale and Gainsborough sub-basins. Even more widely occurring are the thick early Namurian shales, while the marine bands and associated shales of the late Namurian and Westphalian, although thin, occur over the greater part of the region. The oils have variable APIs and high wax contents.

4. The timing of oil generation was probably spread over a considerable period. There is evidence for early oil generation (Carboniferous) in the Bothamsall Oilfield. Burial modelling indicates that some of the deeper, particularly Dinantian, source rocks could have become mature in late Westphalian times especially in the areas of thickest sedimentation, e.g. Widmerpool and Gainsborough sub-basins. Within the Carboniferous Pennine Basin to the west, source rocks also became mature for oil in late Carboniferous times (Kirby *et al.* 1987). Outside the Carboniferous depocentres, late Namurian to Westphalian source rocks and thin early Namurian sources probably became mature for oil in Jurassic and Cretaceous times.

5. Migration was primarily away from the Pennine Basin depocentre, southeast towards the East Midlands. Since the tilt-block structure is orientated NW-SE, local migration also had a secondary component of up-dip NE (or SW) migration, and the syn-sedimentary growth faulting often juxtaposed a thinner reservoir against a thicker source interval. The southeast margin of the Pennine Basin is marked by a thinning of the Namurian to zero, and here the Westphalian Basal Sandstone reservoir is productive.

6. The principal reservoir rocks are sandstones of late Namurian and Westphalian A and B age (Figs 7.3 and 7.4), although their reservoir characteristics are inferior to younger Westphalian (Upper Coal Measures) sandstones. In the Rempstone Oilfield, the reservoirs are early Namurian turbidite sandstones. Minor production has been obtained from the Dinantian Carboniferous Limestone. With a few local exceptions, the reservoirs have very low permeability, even where fractured, mean values being generally less than 15 mD. Other potential reservoirs include the Old Red Sandstone facies, dolomitised or karstified intervals within the Carboniferous Limestone, and Upper Coal Measures sandstones, but none of these have yet yielded a significant hydrocarbon show.

7. The oils vary in composition from field to field and even within a reservoir, and there appear to be two isotopically distinct oils. Limited geochemical data support the source being predominantly early Namurian shales. However, given the compositional variation, great stratigraphic range of potentially mature source rocks, the long interval over which oil generation is to be expected, and the close proximity of the reservoirs to potential sources, it is concluded that the oils were derived from more than one relatively local source over a long period of time. It is reasonable to expect that some oils are mixtures from two or more sources, and that oils were modified by re-burial after their initial accumulation.

8. The oil is trapped in anticlinal structures that were in place at the end of the Carboniferous, but most were probably initiated much earlier. Minor post-Carboniferous (Mesozoic and Tertiary) movements also affected these structures, and the whole region was tilted to the east and northeast. The effect of this tilting has been to reduce the area of closure in many traps, and it may have caused the loss of some oil.

9. For the most part the reservoirs are not continuous sandstone bodies. They are laterally very variable and, in the Westphalian Coal Measures particularly, commonly have a 'shoe-string' form. Individual reservoirs in many cases are not continuous over a whole closure, and the oil-bearing structures are thus in part stratigraphic traps.

10. Oil has been discovered in two main structural positions relative to original Carboniferous depositional features. The minor fields occur on antithetically faulted horsts, located down-flank from the crest of a tilt-block. The more important fields are located on the roll-over and reverse-faulted anticlines. Gainsborough and Beckingham fields fall within the Gainsborough Sub-basin with Glentworth and Corringham fields on its faulted northern margin, and

Torksey and South Leverton fields on its gradational southern margin. Plungar, Langar, Belvoir and the recently re-drilled structure at Cropwell Butler, being on the gradational northern margin of the Widmerpool Sub-basin, are in an analogous position to Torksey-South Leverton relative to the Gainsborough Sub-basin. Bothamsall, Farley's Wood and Egmanton fields are on the same *en echelon* structural line, shown to be a growth fault by Fraser & Gawthorpe (1990), and Eakring, Caunton and Kelham Hills fields all lie within a large area of uplift, caused by inversion along a controlling syn-sedimentary growth fault (Kirby *et al*. 1987) and antithetic faults.

The third main (stratigraphic) position is represented by Welton and Nettleham oilfields and recent discoveries towards Saltfleetby, located along the line of overlap of Namurian Millstone Grit by Westphalian Coal Measures. The Welton area is particularly prolific; it lies at the southeastern termination of the Gainsborough Sub-basin. Production also occurs where Coal Measures overlie thin uppermost Millstone Grit shales, further north towards the Pennine depocentre.

11. Because of the uncertainties regarding the position of potential reservoirs and their lack of continuity, low and variable permeability and porosity, it has been generally impossible to make detailed predictions about a closure prior to drilling, and indeed several wells have often been needed for a preliminary appraisal. 3D seismic reflection data and analysis and directional drilling should minimize these problems.

8 Midland Valley of Scotland

INTRODUCTION

A proven petroleum system exists in the Midland Valley, utilising Dinantian oil shales as source rocks and interbedded sandstones as reservoirs. The Carboniferous rocks are only marginally mature at the surface, but lie in the gas window at depth. Migration has been into adjacent end-Carboniferous Variscan anticlines, which were probably controlled by earlier Carboniferous syn-sedimentary faults.

EXPLORATION HISTORY

Commercial oil exploration in Scotland started with the realisation that Boghead coal was a richer, more reliable and larger source of oil than the various coals the Scotsman James Young had been experimenting on at Alfreton Colliery, England, during the mid 19th century. Earlier experiments and patents for distilling oil from coal and shale in Scotland by William Murdoch and Archibald Cochrane in the latter part of the 18th century had laid a foundation for Young's enterprise.

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Figure 8.1 D'Arcy well derrick in 1919, in East Lothian (Cousland-D'Arcy Anticline) in Midland Valley of Scotland (© NERC).

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Young opened a plant to distil the Boghead coal (torbanite) at Bathgate in 1851. Upon exhaustion of this source, the industry turned to the less productive oil shales (Dinantian Oil Shale Group), which are more widespread in Scotland. Young produced 500,000 barrels in 1878 at West Calder, with production peaking at 2.1 million barrels during the First World War. The industry was finally killed by the withdrawal of a tax concession in 1964. Hallet *et al.* (1985) estimated that 75 million barrels had been produced, and 37 million barrels of recoverable reserves remain (Cameron & McAdam 1978).

Conventional hydrocarbons were sought during the First World War, using American advice and personnel. The D'Arcy well (Fig. 8.1) in East Lothian (1919) discovered oil (50 barrels) and gas (300,000 cfd) on the southern part of the (later productive) Cousland Anticline (Fig. 8.2).
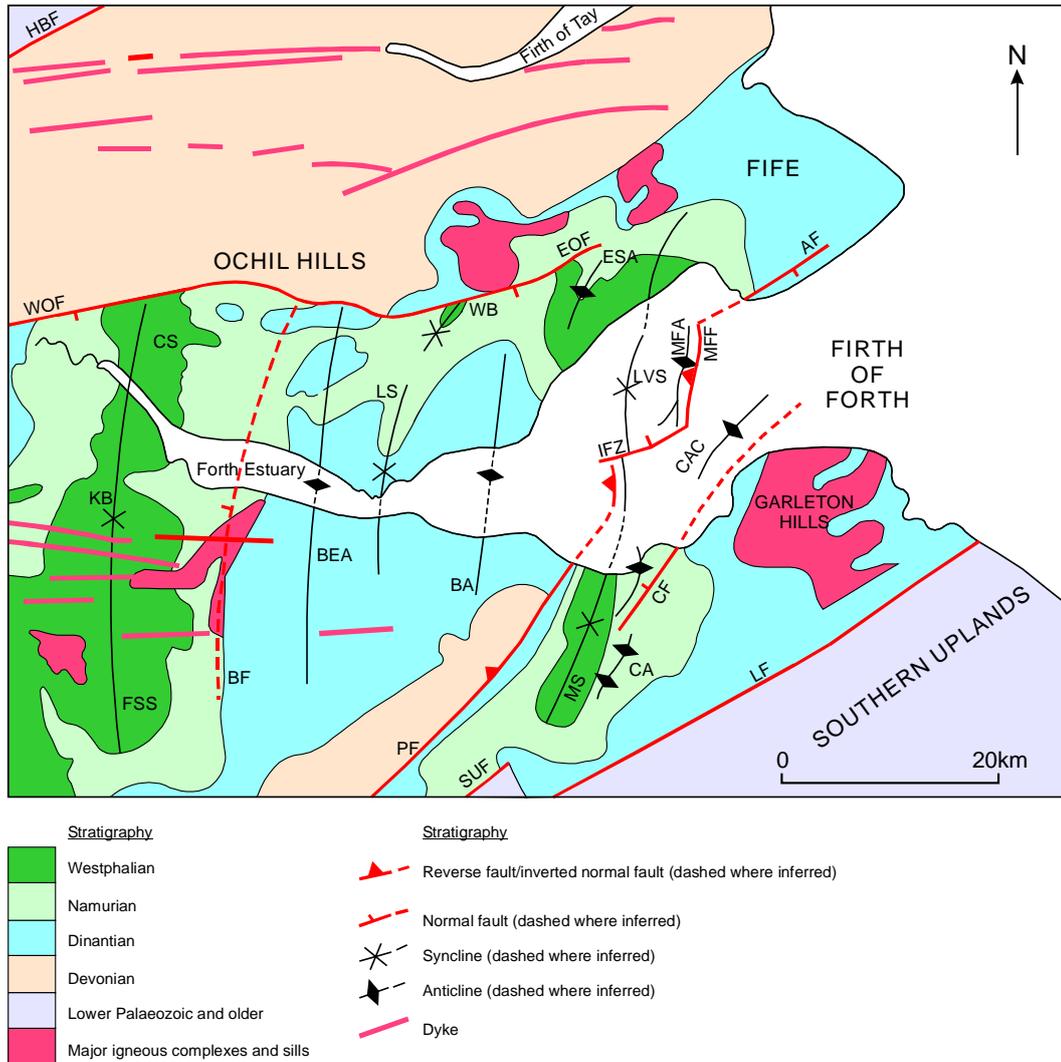
Figure 8.2 Major structures and generalised surface outcrop stratigraphy of the eastern Midland Valley of Scotland (modified after Rippon *et al.* 1996). AF, Ardross Fault; BA, Burntisland Anticline; BEA, Barmule Anticline; BF, Bo'ness Fault; CA, Cousland Anticline; CAC, Crossgatehall Anticlinal Complex; CF, Crossgatehall Fault; CS, Clackmannan Syncline; EOF, East Ochil Fault; ESA, Earl's Seat Anticline; FFS, Falkirk-Stane Syncline; HBF, Highland Boundary Fault; IFZ, Inchkeith Fault Zone; KB, Kincardine Basin; LF, Lammermuir Fault; LS, Lochore Syncline; LVS, Leven Syncline; MFA, Mid Forth Anticline; MFF, Mid Forth Fault; Midlothian Syncline; PF, Pentland Fault; SUF, Southern Upland Fault; WOF, West Ochil Fault; WB, Westfield Basin.

Anglo-American (later Esso or Exxon) discovered the Midlothian Oilfield, near D'Arcy, and this produced 30,000 barrels between discovery in 1946 and 1965 (Hallett *et al.* 1985). BP (then known as D'Arcy) discovered the

Cousland Gasfield, which produced 330 million cubic feet of gas for ten years and the gas was sold to Musselburgh Gasworks.

Modern exploration based on seismic reflection-defined targets has resulted in many wells with hydrocarbon shows but no new oilfields. Burmah made an oil discovery at Milton of Balgonie in Fife and Marinex made a small gas discovery at Bargeddie, in the Upper Oil Shale Group in 1989.

TECTONIC SETTING

The Midland Valley Carboniferous sub-basins lie within a NE-SW trending rift. This rift formed at the southern margin of the Caledonian high-grade metamorphic terranes and north of the Southern Uplands Lower Palaeozoic forearc prism (Fig. 1.1).

BASIN STRUCTURE

The early Carboniferous strata of the Midland Valley were deposited in a series of sub-basins, orientated NE-SW (Fig. 8.2). Among the basin-controlling faults are the Pentland, Ochil and Campsie faults. In the east, the Pentland and Crossgatehall faults were reactivated as reverse faults during the end-Carboniferous Variscan Orogeny. They extend into the offshore Firth of Forth (estuary), close to where Conoco drilled and abandoned well 25/26-1 in 1990. Southwest of Edinburgh, the Pentland Fault has been inverted, to a degree that Lower Palaeozoic basement rests at outcrop on Carboniferous strata. The greatest thicknesses of Namurian strata broadly follow Dinantian depocentres. Several anticlines display condensed sections (e.g. Burntisland and Balmule anticlines). The uppermost Dinantian (Limestone Coal Group) and the Namurian strata thicken towards the Ochil Fault. Westphalian strata, in contrast, appear to thicken southwards against the Southern Upland Fault.

STRATIGRAPHY

The Carboniferous lithostratigraphy of the Midland Valley (Fig. 8.3) is significantly different from that in the East Midlands province. Unlike in England, Dinantian strata are dominated by clastic reservoirs and oil shale source rocks rather than carbonates. Also unlike in England, Namurian strata include both significant limestones and coals. The latter are also numerous in the overlying Westphalian, in a sequence which lacks some of the English marine bands (Cameron & Stephenson 1985).

PETROLEUM SYSTEMS

Source rocks

Oil-prone source rocks include the oil shales of the Dinantian Calciferous Sandstone Measures (formerly Oil Shale Group; Fig. 8.3). The high land-plant content of these oil shales results in a very waxy oil. Gas-prone source rocks include coals, which range in age from late Dinantian to Westphalian.

Burial and igneous heating have led to an eastwards increase in maturity in the Midland Valley. The surface strata, where not affected by Dinantian volcanics and late Carboniferous intrusions, are immature for oil. Deeper boreholes show that beneath thick Upper Carboniferous cover, the Dinantian source rocks have reached the oil window (Murchison & Raymond 1989). Beneath the Leven and Midlothian synclines (Ritchie *et al*. 2003), where there are no wells, these source rocks have probably entered the gas window.

Reservoir rocks

Proven Dinantian reservoirs in the Midland Valley include the Binny, Dalmeny, Hermand, Hailes, Dunnet, Granton and Craiglieth sandstones, and these have porosities reaching up to 23% (Lees & Taitt 1946).

Seals

Carboniferous rocks crop out at the surface over much of the Midland Valley. Unconformably overlying rocks are found only in a small sub-basin near Glasgow. Shales within the Carboniferous strata have formed intraformational seals to the discovered hydrocarbons.

| SERIES	Stage (or Heerlen zones)	Goniatite zones	Miospore zones	Non-marine Bivalve zones	Marker Marine Bands	Lithostratigraphy	CENTRAL & EAST FIFE	SOUTH FIFE LOTHIAN	Lithology and environments of deposition
			XI	Tenuis		Upper Coal Measures			Sandstones, siltstones and mudstones, rare thin coals, a few freshwater limestones, one or two marine bands, soil profiles with cornstone, fluviodeltaic origin: secondary reddening in places.
WESTPHALIAN	D, C		X	Phillipsii	SKIPSEY'S Marine Band	Middle Coal Measures			
	B		IX	U. Similis-Pulchra					Cyclic development of sandstones, mudstones and seatearths, coals of workable thickness, fauna consists mainly of non marine bivalves, several marine bands: fluviodeltaic origin.
	A		VIII	L. Similis-Pulchra	QUEENSLIE Marine Band	Lower Coal Measures			
			VII	Modiolaris	LOWSTONE Marine Band				
			VI	Communis	SIX GROUP Marine Bands				
			SS	Lenisulcata	FIVE GROUP Marine Bands				
NAMURIAN	Yeadonian	G₁	FR		THREE GROUP Marine Bands	Passage Group			Mainly sandstones and mudstones, refractive clays of workable thickness, several marine bands including thin limestones: fluviodeltaic origin.
	Marsdenian	R₂	KV						
	Kinderscoutian	R₁							
	Alportian	H₂	SO		CASTLECARY LIMESTONE				
	Ckokierian	H₁							
	Arnsbergian	E₂	TK		CALMY LIMESTONE	Upper Limestone Group			Cyclic development of sandstones, siltstones, limestones and mudstones, rich marine fauna including bryozoa, brachiopods and molluscs, thin coals: marine shelf and fluviodeltaic origin
					ORCHARD LIMESTONE				
					INDEX LIMESTONE				
	Pendleian	E₁	NC		BLACK METALS Marine Bands	Limestone Coal Group			Cyclic development of sandstones, siltstones, mudstones and seatearths, coals of workable thickness, two prominent marine bands and numerous bands with Linguia and non-marine bivalves: mainly fluviodeltaic origin.
					TOP HOSIE LIMESTONE				
VISEAN	Brigantian	P₂	VF		NEILSON SHELL BED	Lower Limestone Group			Shales, mudstones, limestones and sandstones, rich fauna including corals, bryozoa, brachiopods and molluscs, some thin coals: marine shelf and fluviodeltaic origin.
					HURLET LIMESTONE		Pathhead Beds		
		P₁				Strathclyde Group	Sandy Craig Beds	Upper Oil-Shale Group	Mudstones and sandstones, several oil-shales of workable thickness, a few marine bands which vary in character laterally, algal limestones, some soil profiles with cornstones: mainly fluviodeltaic and lacustrine origin.
	Asbian		NM				Pittenweem Beds		
		B?	TC		MACGREGOR Marine Bands		Anstruther Beds	Lower Oil-Shale Group	Sandstones, mudstones, seatearths, marine and freshwater limestones, some oil-shales, bands with non-marine bivalves, ostracods and algal bodies and scarce marine bands: mainly fluviodeltaic and lacustrine origin.
	Holkerian						Fife Ness Beds		
	Arundian	Pu				Inverclyde Group	Balcomie Beds		
	Chadian						Bailagan Formation	Cementstone Group	Gray, green and red mudstones and sandstones, cementstone bands, sparsely fossiliferous with ostracods, fish and rare non-marine bivalves, algal limestones, some soil profiles with sornstone: fluvial lacustrine and lagoonal origin, perhaps also saokha.
TOURNAISIAN	Courceyan		CM				Kinnesswood Formation		
	?		?			Stratheden Group	Knox Pulpit Formation		Yellow sandstone of aeolian origin.
UPPER DEVONIAN / FAMENNIAN							Glenvale Formation	Upper Old Red Sandstone	Red sometimes yellow, sandstones and siltstones, conglomeratic especially near base, fossil fish (Bothnolepis and Holoptychius spp.): aeolian, fluvial and fan origin.
							Burnside Formation		

COALS

Fig. 8.3 Stratigraphic position of the principal Carboniferous source rocks and reservoirs of the Midland Valley of Scotland

Overburden

Namurian and Westphalian strata were probably deposited in a thermal sag basin, before end-Carboniferous Variscan inversion caused the beginning of basinwide erosion. The preserved Westphalian strata thin eastwards in East Lothian. Permian and later Mesozoic strata may have also been present in the Midland Valley; the former are now preserved only in a small basin south of Glasgow.

Traps

The principal hydrocarbon traps in the Midland Valley are reverse-faulted anticlines.

Generation and migration

Some local hydrocarbon generation probably commenced in late Carboniferous times near igneous intrusions. The main phase of generation in the Midland Valley is difficult to date, because nothing is known about the former extent or thickness of any Permian-Tertiary cover. Migration is speculated to have probably begun in Cretaceous times, possibly continuing through the Tertiary until the present day.

Accumulations

MIDLOTHIAN OILFIELD

The discovery well, D'Arcy (Fig. 8.1), was completed in 1922 by Government drilling, a legacy of the First World War. Anglo-American drilled the trap again in 1937, establishing the field limits.

COUSLAND GASFIELD

Cousland Gasfield was discovered in 1957, by BP. Gas was sold to Musselburgh Gasworks until its closure in 1965 (Huxley 1983). The supply peak was in 1961 (49 mmcf). Five sandstones in the Dinantian contained gas (probably including the Hailes and Craiglieth sandstones of the Lower Oil Shale Group), with two producing over 4 mmcfd gas on test (Lees & Taitt 1946).

CONCLUSIONS

There is lack of modern data with which to assess the future prospectivity of the Midland Valley. Subsurface data (Ritchie *et al*. 2003), shows that there are a number of prospects that could be drilled on the margins of the Leven and Midlothian synclines, including a large structure west of Conoco's Firth of Forth 1 well. This structure is perhaps more analogous to the productive Cousland Anticline than to the structure drilled by Conoco.

9 Overall Conclusions

1. Liberalisation of the gas market has rendered some small fields commercial, for example Calow (East Midlands province), which had been abandoned for a number of years by BP until revived by Caribe.

2. Some discoveries were originally discounted by surface obstructions. Technological advances in directional drilling could be applied to these locations.

3. Careful assessment of the characteristics of discoveries and fields needs to be applied to neighbouring licences. This has not always been evident in past exploration.

4. The Wessex Basin may have some potential west of Wareham and in the southern part of the Isle of Wight.

5. The Weald Basin has potential, particularly east of Storrington, east of Palmer's Wood, and perhaps on the eastern margin, north of Heathfield.

6. The East Midlands oilfields are intimately associated with the Dinantian sub-basins (often called troughs or gulfs in the literature). The recent confirmation of a Humber Sub-basin extends the prospective zone NE to the Humber Estuary. North of the Humber Estuary is a sparsely drilled area. The application of 3D seismic data should enable improved predictions about a closure prior to drilling.

7. In the Cheshire Basin, a revival of interest should be based on the search for similar Dinantian sub-basins and adjacent Upper Carboniferous reservoirs as in the East Midlands. Permian Collyhurst Sandstone or Triassic Sherwood Sandstone reservoirs should be viewed as secondary targets.

8. The West Lancashire Basin also has some potential, either at Triassic Sherwood Sandstone level or possibly in Carboniferous reservoirs.

9. The Midland Valley may harbour more discoveries, if exploration is based more closely on the two successful fields' characteristics.

10 Glossary

Unit abbreviation	Full name
API	American Petroleum Institute oil gravity unit
Bbl	barrels
Bcf	billion cubic feet (1,000,000,000)
Bopd	barrels of oil per day
BP	British Petroleum
Cfd	cubic feet of gas per day
$^{o}C/km$	degrees centigrade per kilometre
DST	drill stem test
GIIP	Gas Initially In Place
Kcal/kg/km	kilocalories per kilogram per kilometre
Km	kilometres
km^2	square kilometres
M	metres
Ma	million years before present
MD	millidarcy
mmcfd	million cubic feet of gas per day
Psi	pounds per square inch
Tcf	trillion cubic feet
TOC	total organic carbon
TTI	time-temperature index
VR%	vitrinite reflectance per cent

UK chronostratigraphy	North American chronostratigraphy
Westphalian	Pennsylvanian
Namurian	Late Mississippian to early Pennsylvanian
Dinantian	Mississippian

References

ADCOCK, C.M. 1963. Natural gas in Britain. *Gas World*, pages 266-268, 291-294 and 321-323.

ALDRIDGE, R.J. 1986. Conodont palaeobiogeography and thermal maturation in the Caledonides. *Journal of the Geological Society, London*, **143**, 177-184.

AITKENHEAD, N.A. 1977. The Duffield Borehole. *Bulletin of the Geological Survey*, **59**.

AITKENHEAD, N.A., CHISHOLM, J.I. & STEVENSON, I.P. 1985. Geology of the country around Buxton, Leek and Bakewell. *Memoir of the British Geological Survey,* **111**.

AITKENHEAD, N.A., BRIDGE, D.Mc., RILEY, N.J. & KIMBELL, S.F. 1992. Geology of the country around Garstang. *Memoir of the British Geological Survey*, **67**.

ALLEN, P.M. 1980. Copper Mineralization in Great Britain. In: Jankovic, S & Sillitoe, R.H. (Eds.) *European Copper Deposits.* Special Publication UNESCO-IGCP Project 169, 63, No. 1. 266-276.

ANDERSON, W. 1945. On the chloride waters of Great Britain. *Geological Magazine*, **82**, 267-273.

ANON. 1911. Coal boring at Calvert. *Iron and Coal Trades Review*, Sept 1st, 316-317.

ANON. 1974. *The oilfields of Britain*. BP Shield International Publication. 7p.

ANON. 1999. Exploration: United Kingdom. *Oil and Gas Journal,* Mar 8. p 87.

ANON. 2001. Gas recovery at Kimmeridge. *Mineral Planning*, **87**, p20.

ARKELL, W.J. 1933. The Jurassic System in Great Britain. Oxford University Press, London, 681pp

ARMSTRONG, J.P., SMITH, J., D'ELIA, V.A. A. & TRUEBLOOD, S.P. 1997. The occurrence and correlation of oils and Namurian source rocks in the Liverpool Bay-North Wales area. In: Meadows, N. S., Trueblood, S.P., Hardman, M. & Cowan, G. *Petroleum geology of the Irish Sea and adjacent areas*. Geological Society Special Publication No. 124, 195-211.

ARSCOTT, R.L. & HACKETT, P. 1969. The occurrence of gas outburst fractures in the East Midland Coalfield. *Quarterly Journal of Engineering Geology*, **2**, 89-101.

BAILEY, R. J. 2003. The West Firsby Oilfield, Development Licence 003, Lincolnshire. In: Gluyas, J. G. & Hichens, H. M. (eds) *United Kingdom Oil and Gas Fields, Commemorative Millennium Volume*, Geological Society, London, Memoir, **20**, 921-926.

BAYLIS, S.A. & CLAYTON, C.J. 1998. Characterisation of an outcropping reservoir- the oil seeps of Dorset.

BERGSTROM, S.M. 1980. Conodonts as paleotemperature tools in Ordovician rocks of the Caledonides and adjacent areas in Scandinavia and the British Isles. *Geologiska Foreningens i Stockholm Forhandlinger*, **102**, 377-392.

BEVAN, T.G. 1985. A reinterpretation of fault systems in the upper Cretaceous rocks of the Dorset coast, England. *Proceedings of the Geologists Association*, 96, 337-342.

BJORKUM, P.A. & WALDERHAUG, O. 1993. Isotopic composition of a calcite-cemented layer in the lower Jurassic Bridport Sands, southern England: implications for formation of laterally extensive calcite-cemented layers. *Journal of Sedimentology*, **63**, 678-682.

BOWMAN, M.B.J., McCLURE, N.M. & WILKINSON, D.W. 1993. Wytch Farm oilfield: deterministic reservoir description of the Triassic Sherwood Sandstone. In: Parker, J.R. (ed), *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*. The Geological Society, London, 1513-1518.

BP LTD. 1962. *The oilfields of Britain*. British Petroleum Company Ltd. 30 pp.

BRAITHWAITE, R.S.W. 1994. Mineralogy of the Alderley Edge-Mottram St. Andrew area, Cheshire, England. *Journal of the Russell Society*, **5**, 91-102.

BRIDGE, D.McC., CARNEY, J.N., LAWLEY, R.S. & RUSHTON, A.W.A. 1998. Geology of the country around Coventry and Nuneaton. *Memoir of the British Geological Survey*, **169**.

BRIGGS, H. 1921. Characteristics of outbursts of gas in mines. *Transactions of the Institution of Mining Engineers,* 61, 119-146.

BRISTOW, C.R., BARTON, C., FRESHNEY, E.C., WOOD, C.J., EVANS, D.J., COX, B.M., IVIMEY-COOK, H.C. & TAYLOR, R.T. 1995. Geology of the country around Shaftesbury. *Memoir of the British Geological Survey, Sheet 313 (England and Wales).* 182pp, 64 Figs, 13 Tables.

BRITISH GEOLOGICAL SURVEY 1999. Coal resources map of Britain. BGS & The Coal Authority.

BROMEHEAD, C.E.N. 1923. The oil horizons of England. *Geological Magazine*, **lx**, 297-307.

BROMEHEAD, C.E.N., EDWARDS, W., WRAY, D.A. AND STEPHENS, J.V. 1933. Geology of the country around Holmfirth and Glossop. *Memoir of the Geological Survey*, No. 86. 209 pp.

BROOKS, J.R.V., STOKER, S.J. & CAMERON, T.D.J. 2001. Hydrocarbon exploration opportunities in the 21st century in the UK. In: Downey, M.W., Threet, J.C. & Morgan, W.A. (eds) *Petroleum provinces of the Twenty-first century*. American Association of Petroleum Geologists Memoir, **74**, 167-200.

BROUGH, B.H. 1889. Outbursts of gas in metalliferous mines. *Transactions of the North of England Institution of Mining and Mechanical Engineers*, 38, 59-73.

BROWN, I. AND TRINDER, B. 1979. *The Tar Tunnel*. Ironbridge Gorge Museum Trust. 11 pp.

BRUNSTROM, R.G.W. 1963. Recently discovered oilfields in Britain. In: *Sixth World Petroleum Congress, Frankfurt June 1963, Section 1*, Paper 49, 1-10.

BRUNSTROM, R.G.W. 1966. Indigenous petroleum and natural gas in Britain. *Institute of Petroleum*, 5-27.

BRYANT, I.D., KANTOROWICZ, J.D. & LOVE, C.F. 1988. The origin and recognition of laterally continuous carbonate-cemented horizons in the Upper Lias Sands of southern England. *Marine and Petroleum Geology*, **5,** 108-133.

BUCHANAN, J.G. 1998. The exploration history and controls on hydrocarbon prospectivity in the Wessex basins, southern England, UK. In: Underhill, J.R. & Stoneley, R. (eds), *Development, Evolution and Petroleum Geology of the Wessex Basin,* Geological Society, London, Special Publications, **133,** 19-37.

BURLEY, A.J., EDMUNDS, W.M. & GALE, I.N. 1984. Catalogue of geothermal data for the land area of the United Kingdom. *Investigation of the Geothermal Potential of the UK*.

BURLEY, S.D. 1984. Patterns of diagenesis in the Sherwood Sandstone Group (Triassic), United Kingdom. *Clay Mineralogy*, **19**, 13-22.

BURTON, J.B. 1984. Colliery Methane utilisation schemes within the western area. *The Mining Engineer,* Sept 1984, 175-180.

BUSHELL. T.P. 1986. Reservoir geology of the Morecambe field. In Brooks, J., Goff, J.C. & Van Hoorn, B. (Eds). *Habitat of Palaeozoic gas in NW Europe*. Geological Society Special Publication No. 23. 189-208.

BUTLER, A.J., WOODCOCK, N.H. & STEWART, D.M. 1997. The Woolhope and Usk Basins: Silurian rift basins revealed by subsurface mapping of the southern Welsh Borderland. *Journal of the Geological Society, London,* **154**, 209-223.

BUTLER, M., & PULLAN, C.P. 1990. Tertiary structures and hydrocrbon entrapment in the Weald Basin of southern England. In: Hardman, R.F.P. & Brooks, J. (eds), *Tectonic Events Responsible for Britain's Oil and Gas Reserves*, Geological Society, London, Special Publications, 55, 371-391.

CALVER, M.A. 1968. Distribution of Westphalian marine faunas in Northern England and adjoining areas. *Proceedings of the Yorkshire Geological Society*, 37, 1-72

CANDY G.J. 1983. Petroleum exploration onshore U.K. In: Brooks, J. (ed) *Petroleum geochemistry and exploration of Europe,* Geological Society, London, Special Publication No. 12, 67-68.

CHADWICK, R.A. 1993. Aspects of basin inversion in southern Britain. *Journal of the Geological Society, London*, **150**, 311-322.

CHADWICK, R.A. 1997. Fault analysis of the Cheshire Basin, NW England. In: Meadows, N. S., Trueblood, S. P., Hardman, M. & Cowan, G. *Petroleum geology of the Irish Sea and adjacent areas*. Geological Society Special Publication No. 124, 297-313.

CHADWICK, R.A. & EVANS, D.J. 1995. The timing and direction of Permo-Triassic rifting in southern Britain. In: Boldy, S.R. (ed) *Permo-Triassic Rifting in the UK*, Geological Society, London, Special Publications, 91, 161-192.

CHADWICK, R.A., HOLLIDAY, D.W., HOLLOWAY, S. & HULBERT, A.G. 1995. The structure and evolution of the Northumberland-Solway Basin and adjacent areas. Subsurface *Memoir of the British Geological Survey*.

CHALLINOR, P.J. 1990. Oil ingress into mine workings. *The Mining Engineer*, August, 68-74.

CHISHOLM, J.I., CHARSLEY, T.J. & AITKENHEAD, N. 1988. Geology of the country around Ashbourne and Cheadle. *Memoir of the British Geological Survey*, **124**.

CLAYTON, C.J., FLEET, A.J. & MYERS, K.J. 1998. Depositional control of organic richness in Wessex Basin petroleum source rocks.

COCKIN, G.M. 1911. On the Carboniferous Limestone of Fair Oak, Cannock Chase Coalfield. *Transactions of the Institution of Mining Engineers*, xli, 323-327.

COLLINSON, J.D. 1988. Controls on Namurian sedimentation in the Central Province basins of northern England. In: Besly, B. & Kelling, G. (Eds.) *Sedimentation in a synorogenic basin complex: the Upper Carboniferous of Northwest Europe*. Blackie, 85-100.

COLLINSON, J.D., JONES, C.M. & WILSON, A.A. 1977. The Marsdenian (Namurian R2) succession west of Blackburn: implications for the evolution of Pennine Delta Systems. *Geological Journal*, **12,** 1, 59-76.

COLTER, V.S. 1998. The East Irish Sea Basin - from caterpillar to butterfly, a thirty-year metamorphosis. In: Meadows, N.S., Trueblood, S.P., Hardman, M. & Cowan, G. *Petroleum geology of the Irish Sea and adjacent areas*. Geological Society Special Publication No. 124, 1-9.

COLTER, V.S. & BARR, K.W. 1975. Recent developments in the geology of the Irish Sea and Cheshire basins. In: Woodland, A.W. (Ed.) *Petroleum and the Continental Shelf of North-West Europe. Vol 1*. 61-73.

COLTER, V.S. & EBBERN. J. 1978. The petrography and reservoir properties of some Triassic sandstones from the northern Irish Sea Basin. *Journal of the Geological Society, London*, **135**, 57-62.

79

COLTER, V.S. & HAVARD, D.J. 1981. The Wytch Farm Oil Field, Dorset. In: Illing, L.V. & Hobson, G.D. (eds), *Petroleum Geology of the Continental Shelf of Northwest Europe*, Institute of Petroleum Geology, London, 494-503.

COOPER, M.A. & WILLIAMS, G.D. (eds) 1989. Inversion Tectonics. Geological Society, London, Special Publications, **44,** 375pp.

COPE, F. W. 1939. Oil occurrences in south-west Lancashire. *Bulletin of the Geological Survey of Great Britain*, **2**, 18-25.

CORFIELD, S.M., GAWTHORPE, R.L., GAGE, M., FRASER, A.J. & BESLY, B.M. 1996. Inversion tectonics of the Variscan foreland of the British Isles. *Journal of the Geological Society, London,* **153**, 17-32.

CORNFORD, C. 1986. The Bristol Channel Graben: organic geochemical limits on subsidence and speculation on the origin of inversion. *Proceedings of the Ussher Society*, **6**, 360-367.

CORNWELL, J.D., BUSBY, J.P., COLMAN, T.B., & NORTON, G.E. 1995. Exploration for carbonate-hosted base-metal mineralisation near Ashbourne, Derbyshire. BGS *Mineral Reconnaissance Report 139,* 57 pp.

CORNFORD, C., CHRISTIE, O., ENDRESEN, U, JENSEN, P. & MHYR, M. 1988. Source rock and oil seep maturity in Dorset, southern England. *Organic Geochemistry*, **13,** 399-409.

CORNFORD, C., YARNELL, L. & MURCHISON, DG. 1987. Initial vitrinite reflectance results from the Carboniferous of south Devon and north Cornwall. *Proceedings of the Ussher Society*, **6**, 461-467.

COWAN, G. & SHAW, H. 1991. Diagenesis of Namurian fluvio-deltaic sandstones from the Trumfleet field, South Yorkshire. *Marine and Petroleum Geology*, **8**, 212-224.

CREANEY, S. 1981. Coal ranks on the Alston Block, north-east England: a reply. *Proceedings of the Yorkshire Geological Society*, **43**, 453-455.

CREEDY, D.P. 1986. Methods for the evaluation of seam gas content from measurements on coal samples. *Mining Science and Technology*, **3**, 141-160.

CREEDY, D.P. 1988. Geological controls on the formation and distribution of gas in British Coal Measure strata. *International Journal of Coal Geology*, **10**, 1-31.

CREEDY, D.P. 1991. An introduction to geological aspects of methane occurrence and control in British deep coal mines. *Quarterly Journal of Engineering Geology*, **24**, 209-220.

DALTON, W.H. 1918. On the oil prospects of the British Isles. *Institution of Petroleum Technologists,* vol iv, 37-63.

DAVIES, A.M. & PRINGLE, J. 1913. On two deep borings at Calvert Station (North Buckinghamshire) and on the Palaeozoic floor north of the Thames. *Quarterly Journal of the Geological Society*, **69**, 308-342.

DAWSON, C. 1897. Discovery of a large supply of 'natural gas' at Waldron, Sussex. *Nature,* **57,** 150-151.

DAWSON, C. 1898. On the discovery of natural gas in East Sussex. *Quarterly Journal of the Geological Society, London,* LIV, 564-572.

DEPARTMENT OF TRADE & INDUSTRY (DTI), 1998. The Energy Report (known as "Brown Book"). HMSO.

DE RANCE, C. E. 1886. On the occurrence of brine in the Coal Measures. *Transactions of the Manchester Geological Society*, **18**, 61-81.

DICKIE, R.K. & ADCOCK, C.M. 1954. Oil production in the Nottinghamshire Oilfields. *Journal of the Institute of Petroleum*, **40**, 179-190.

DIDYK, B.M., SIMONEIT, B.R.T. & EGLINTON, G. 1983. Bitumen from the Coalport Tar Tunnel. *Organic Geochemistry,* **5,** 99-109.

DINES, H.G. 1958. The West Shropshire Mining Region. *Bulletin of the Geological Survey of Great Britain,* No. **14**, 1-43.

DOWNING, R.A. & GRAY, D. 1986. *Geothermal energy - the potential of the United Kingdom.* British Geological Survey. 187pp.

DOWNING, R.A. & HOWITT, F. 1969 (for 1968). Saline ground-waters in the Carboniferous rocks of the English Midlands in relation to the geology. *Quarterly Journal of Engineering Geology,* **1**, 241-269

DRANFIELD, P., BEGG, S.H. & CARTER, R.R. 1987. Wytch Farm Oilfield: reservoir characterisation of the Triassic Sherwood Sandstone for input into reservoir simulation studies. In: Brooks, J. & Glennie, K. (eds), *Petroleum Geology of North West Europe,* Graham & Trotman, London, 494-503.

DUNCAN, W.I., GREEN, P.F. & DUDDY, I.R. 1998. Source rock burial history and seal effectiveness: key facets to hydrocarbon exploration potential in the East and Central Irish Sea basins. *Bulletin of the American Association of Petroleum Geologists*, **82**, 7, 1401-1415.

EAKIN, P.A. 1989. Isotopic and petrographic studies of uraniferous hydrocarbons from around the Irish Sea Basin. *Journal of the Geological Society, London,* **146**, 663-673.

EARP, J.R. & TAYLOR, B.J. 1986. Geology of the country around Chester and Winsford. *Memoir of the British Geological Survey*, **109**.

EBBERN, J. 1981. The geology of the Morecambe Gas Field. In: Petroleum Geology of the Continental Shelf of NW Europe. 485-493.

EBUKANSON, E.J. & KINGHORN, R.R.F. 1985. Kerogen facies in the major Jurassic mudrock formations of southern England and the implication of the depositional environments of their precursors. *Journal of Petroleum Geology*, **8,** 435-462.

EBUKANSON, E.J. & KINGHORN, R.R.F. 1986a. Maturity of organic matter in the Jurassic of southern England and its relation to the burial history of the sediments. *Journal of Petroleum Geology*, **9,** 259-280.

EBUKANSON, E.J. & KINGHORN, R.R.F. 1986b. Oil and gas accumulations and their possible source rocks in southern England. *Journal of Petroleum Geology*, **9,** 413-428.

EDMUNDS, F.H. 1928. Wells and springs of Sussex. *Memoirs of the Geological Survey*, 263 pp.

EDMUNDS, W.M. 1996. Bromine geochemistry of British groundwaters. *Mineralogical Magazine*, **60**, 275-284.

EDWARDS, W.N. 1967. Geology of the country around Ollerton. *Memoir of the Geological Survey of Great Britain*. **113**.

EVANS, C.J. & BRERETON, R. 1990. In situ crustal stress in the UK from borehole breakouts. In: Hurst, A., Lovell. M. A. & Morton, A.C. (eds) *Geological Applications of wireline logs*. Geological Society, London Special Publication. 327-338.

EVANS, D.J., MENEILLY, A. & BROWN, G. 1992. Seismic facies analysis of the Westphalian of the southern North Sea. *Marine and Petroleum Geology*, **9**, 578-589.

EVANS, D.J., REES, J.G. & HOLLOWAY, S. 1993 The Permian to Jurassic stratigraphy and structural evolution of the central Cheshire Basin. *Journal of the Geological Society*, **150**, 857-870.

EVANS, D.J., REES, J.G., HOLLOWAY, S., SMITH, N.J.P. & CHADWICK, R.A. 1994. Discussion on the Permian to Jurassic stratigraphy and structural evolution of the central Cheshire Basin: reply. *Journal of the Geological Society, London,* **151,** 893-895.

EVANS, I. J., JENKINS, D. & GLUYAS, J. G. 1998. The Kimmeridge Bay oilfield: an enigma demystified. In: Underhill, J.R. & Stoneley, R. (eds), *Development, Evolution and Petroleum Geology of the Wessex Basin*, Geological Society, London, Special Publications, **133,** 407-413.

EVANS, W.B., WILSON, A.A., TAYLOR, B.J. & PRICE, D. 1968. Geology of the country around Macclesfield, Congleton, Crewe and Middlewich. *Memoir of the British Geology Survey*, **110**.

EVANS, W.E. 1990. Development of the petroleum exploration scene in the UK onshore area; a struggle over the last 75 years. In: Ala-M., Hatamian, H., Hobson, G.D., King, M.S. & Williamson, I. (eds). *Seventy-five years of progress in oil field science and technology.* A.A. Balkema, Rotterdam, 49-54.

EWBANK, G., MANNING, D.A.C. & ABBOTT, G.D. 1993. An organic geochemical study of bitumens and their potential source rocks from the South Pennine Orefield, central England. *Organic Geochemistry,* **20,** 579-598.

EWBANK, G., MANNING, D.A.C. & ABBOTT, G.D. 1995. The relationship between bitumens and mineralization in the South Pennine Orefield, central England. *Journal of the Geological Society, London,* **152**, 751-765.

FALCON, N.L. & KENT, P.E. 1960. Geological results of petroleum exploration in Britain 1945-1957. *Geological Society, London Memoir*, **2**. 56 pp.

FARRIMOND, P., CORNET, P., EGLINGTON, G. *et al*. 1984. Organic geochemical study of the Upper Kimmeridge Clay of the Dorset type area. *Marine and Petroleum Geology*, **1**, 340-354.

FEARNSIDES, W.G. & TEMPLEMAN, A. 1934. A boring through Edale Shales to Carboniferous Limestone and pillow lavas at Hope Cement Works, near Castleton, Derbyshire. 100-121.

FOX-STRANGWAYS, C. 1905. The geology of the country between Derby, Burton-on-Trent, Ashby-de-la-Zouch and Loughborough. *Memoir of the Geological Survey of Great Britain*.

FRASER, A.J., NASH, A.J., STEELE, R.P. & EBDON, C.C. 1990. A regional assessment of the intra-Carboniferous play of northern England. In: J. Brooks, J. (ed.) *Classic Petroleum Provinces.* Geological Society Special Publication No. 50, 417-440.

FRASER, A.J. & GAWTHORPE, R.L. 1990. Tectono-stratigraphic development and hydrocarbon habitat of the Carboniferous in northern England. In: Hardman, R.F.P. & Brooks, J. (eds). *Tectonic events responsible for Britain's Oil and Gas Reserves*. Geological Society Special Publication No. 55. 49-86.

FRASER, A.J. & GAWTHORPE, R.L. 2003. An atlas of Carboniferous basin evolution in Northern England. Geological Society Memoir **28**.

FYFE, J.A, LONG, D. & EVANS, D. 1993. The geology of the Malin-Hebrides sea area. *United Kingdom Offshore Regional Report*. British Geological Survey.

GAIR, D.J., GRIST, D.M. & MITCHELL, R.W. 1980. The East Midlands additional oil project. *Proceedings of the European Offshore Petroleum Conference*.

GALE, I., HOLLIDAY, D.W., KIRBY, G.A. & ARTHUR, M. 1984. The Carboniferous rocks of Lincolnshire, Nottinghamshire and southern Humberside. *Investigation of the Geothermal Potential of the United Kingdom*. British Geological Survey (unpublished).

GALE I., SMITH, I.F. & DOWNING, R.A. 1983. The post Carboniferous rocks of the E Yorkshire and Lincolnshire Basin. *Investigations of the Geothermal Potential of the UK*. British Geological Survey.

GALLOIS, R.W. 1976. Coccolith blooms in the Kimmeridge Clay and the origin of North Sea oil. *Nature,* **259**, 473-475.

GIBSON, W. 1905. The geology of the North Staffordshire Coalfields. *Memoir of the Geological Survey of England & Wales*. HMSO.

GIBSON, W. 1925. The geology of the country around Stoke-upon-Trent. *Memoir of the Geological Survey of England*. **113**.

GIFFARD, H.P.W. 1923. The recent search for oil in Great Britain. *Transactions of the Institution of Mining Engineers*, **65**, 221-250.

GLUYAS, J.G., Evans, I. J. & Richards, D. 2003. The Kimmeridge Bay Oilfield, Uk Onshore. In: Gluyas, J. G. & Hichens, H. M. (eds) *United Kingdom Oil and Gas Fields, Commemorative Millennium Volume*, **20**, 943-948.

GRAHAM, J.I. 1922. Rock temperatures in the Coal Measures of Great Britain. *Transactions of the Institution of Mining Engineers*, **63**, 343-399.

GRAYSON, R.F., OLDHAM, L. & CONNELL, S.A. 1990. Hydrogen sulphide springs in the Pennines and adjacent areas: a neglected hazard. Lecture to North West Group of Institution of Geologists. 10th April 1990.

HAIG, D.B., PICKERING, S.C. & PROBERT, R. 1998. The Lennox oil and gas field. In: Meadows, N.S., Trueblood, S.P., Hardman, M. & Cowan, G. (eds). *Petroleum Geology of the Irish Sea and adjacent areas*. Geological Society Special Publication no. 124, 417-436.

HALLAM, A. 1960. A sedimentary and faunal study of the Blue Lias of Dorset and Glamorgan. *Philosophical Transactions of the Royal Society of London,* **243,** 1-44.

HALLET, D., DURANT, G.P. & FARROW, G.E. 1985. Oil exploration and production in Scotland. *Scottish Journal of Geology*, **21**, 4, 547-570.

HAMBLIN, R.J.O & COPPACK, 1995. Geology of Telford and the Coalbrookdale Coalfield. *Memoir of the British Geological Survey*, **152-153**.

HAMBLIN, R.J.O., CROSBY, A., BALSON, P.S., JONES, S.M., CHADWICK, R.A., PENN, I.E. & ARTHUR, M.J. 1992. The geology of the English Channel. British Geological Survey, United Kingdom Offshore Regional Report Series, HMSO, London, 106pp.

HANCOCK, F.R.P. & MITHERN, D.P. 1987. The geology of the Humbly Grove Oilfield, Hampshire, UK. In: Brooks, J. & Glennie, K. (eds*), Petroleum Geology of North West Europe*, Graham & Trotman, London, 161-170.

HARDMAN, M., BUCHANAN, J., HERRINGTON, P. & CARR, A. 1993. Geochemical modelling of the East Irish Sea Basin: its influence on predicting hydrocarbon type and quality. In Parker, J. R. (ed.) *Petroleum geology of northwest Europe: proceedings of the 4th Conference*. 809-821.

HARRIMAN, G. & MILES, J. 1995. A new oil seep in the heart of Liverpool. *Petroleum Exploration Society of GB Newsletter*, July, 88-89.

HAWKES, P.W., FRASER, A.J. & EINCHCOMB, C.C.G. 1998. The tectonostratigraphic development and exploration history of the Weald and Wessex Basins, southern England. In: Underhill, J.R. & Stoneley, R. (eds), *Development, Evolution and Petroleum Geology of the Wessex Basin,* Geological Society, London, Special Publications, **133,** 39-65.

HAWKINS, P.J. 1978. Relationship between diagenesis, porosity reduction, and oil emplacement in late Carboniferous sandstone reservoirs, Bothamsall Oilfield, E Midlands. *Journal of the Geological Society, London,* **135**, 7-24.

HEASLEY, E.C.; WORDEN, R.H. & HENDRY, J.P. 2000. Cement distribution in a carbonate reservoir; recognition of a palaeo oil-water contact and its relationship to reservoir quality in the Humbly Grove Field, onshore, UK. *Marine and Petroleum Geology*, **17,** 639-654.

HEMINGWAY, J.E. & RIDDLER, G.P. 1982. Basin inversion in North Yorkshire. *Transactions of the Institute of Mining and Metallurgy* (Section B Applied Earth Science), **91**, 175-186.

HIRST, C. 1985. The last days of the first commercial gas find. *Petroleum Review*, June 1985, 24-25.

HOGG, A.J.C., EVANS, I.J., HARRISON, P.F., MELING, T., SMITH, G.S., THOMPSON, S.D. & WATTS, G.F.T. 1999. Reservoir management of the Wytch Farm oil field, Dorset, UK; providing options for growth into later field life. In: Fleet, A.J., Boldy, S.A.R. (eds). *Petroleum geology of Northwest Europe; proceedings of the 5th conference*. The Geological Society of London, 1157-1172.

HOLLIDAY, D.W. 1993. Mesozoic cover over northern England: interpretation of apatite fission track data. *Journal of the Geological Society, London*, **150**, 657-660.

HOPTON, R. 1711. An account of the eruption of a burning spring at Broseley, Shropshire. *Philisophical Transactions*, **27-28**, 475-476.

HURREN, C. & HANCOCK, I. 2009. Humbly Grove gas storage. Abstract, *PESGB Newsletter*, April 2009,12-15.

HURST, A. & COLTER, V.S. 1998. A history of events in the exploration for the Wytch Farm oilfield, southern England. *Petroleum Geoscience*, **4**, 377-379.

HUXLEY, J. 1983. *Britain's onshore oil industry*. Macmillan Publishers, London.

ICKES, E.L. 1923. Recent exploration for petroleum in the UK. *Transactions of the American Institute of Mining and Mechanical Engineers*, **70**, 1053-1075.

INESON, P.R. & FORD, T.D. 1982. The South Pennine Orefleld: its genetic theories and eastern extension. *Mercian Geologist*, **8**, 282-303.

IRWIN, H. 1979. On an environmental model for the type Kimmeridge clay. *Nature,* **279,** 819-820

JACKSON, D.I., MULHOLLAND, P., JONES, S.M. & WARRINGTON, G. 1987. The geological framework of the East Irish Sea Basin. In Brooks, J. & Glennie, K. W. (Eds) *Petroleum geology of North West Europe*. Graham & Trotman. 191-203.

JACKSON, D.I. & MULHOLLAND, P. 1993. Tectonic and stratigraphic aspects of the East Irish Sea Basin and adjacent areas: contrasts in their post-Carboniferous structural styles. In Parker, J.R. (Ed.) *Petroleum geology of northwest Europe: proceedings of the 4th Conference*. 791-808.

JEFFS, O.W. 1886. Note on the occurrence of copper in the Keuper Sandstone at the Peckforton Hills, Cheshire. *Proceedings of the Liverpool Geological Society*, **5**, 139-144.

JONES, R.C.B., TONKS, L.H. & WRIGHT, W.B. 1938. Geology of the Wigan District. *Memoir of the Geological Survey of Great Britain.*

JUKES, J.B. 1859. The South Staffordshire Coalfield. *Memoir of the Geological Survey of England & Wales*.

KANTOROWICZ, J.D., BRYANT, I.D. & DAWANS, J.M. 1987. Controls on the geometry and distribution of carbonate cements in Jurassic sandstones: Bridport Sands southern England and Viking Group, Troll Field, Norway. In: Marshall, J.D. (ed), *Diagenesis of Sedimentary Sequences*, Geological Society, London, Special Publications, **36,** 103-118.

KENT, P.E. 1948. A deep borehole at Formby, Lancashire. *Geological Magazine*, **135**, 253-264.

KENT, P.E. 1954. Oil occurrences in coal Measures in England. *Bulletin of the American Association of Petroleum Geologists*, **38**, 1699-1713.

KENT, P.E. 1966. The structure of the concealed Carboniferous rocks of north-eastern England. *Proceedings of the Yorkshire Geological Society,* **35**, 323-352.

KENT, P.E. 1980. Subsidence and uplift in East Yorkshire and Lincolnshire: a double inversion. *Proceedings of the Yorkshire Geological Society*, **42**, 505-524.

KENT, P.E. 1985. UK onshore oil exploration, 1930-1964. *Marine and Petroleum Geology*, **2,** 56-64.

KING, R.J. 1968. Mineralization. In: Sylvester-Bradley, P.C. & Ford, T.D. (eds.) *The Geology of the East Midlands.* Leicester UP. 112-132.

KIRBY, G.A., SMITH, K., SMITH, N.J.P. & SWALLOW, P.W. 1987. Oil and gas generation in eastern England. In: Brooks, J. & Glennie, K.W. (eds). *Petroleum geology of North West Europe*. Graham & Trotman, 171-180.

KIRBY, G.A. & SWALLOW, P. 1987. Tectonism and sedimentation in the Flamborough Head region of north-east England. *Proceedings of the Yorkshire Geological Society*, **46**, 301-309.

KIRBY, G.A., BAILY, H.E., CHADWICK, R.A., EVANS, D.J., HOLLIDAY, D.W., HOLLOWAY, S., HULBERT, A.G., PHARAOH, T.C., SMITH, N.J.P., AITKENHEAD, N. & BIRCH, B. 2000. The structure and evolution of the Craven Basin and adjacent areas. *Subsurface Memoir of the British Geological Survey*.

KNOTT, S.D. 1994. Fault zone thickness versus displacement in the Permo-Triassic sandstones of NW England. *Journal of the Geological Society, London*, **151**, 17-25.

LAMPLUGH, G.W. & KITCHIN, F.L. 1911. The Mesozoic rocks in some of the Coal Explorations in Kent. *Memoir of the Geological Survey*, 212pp.

LAMPLUGH, G.W., KITCHIN, F.L. & PRINGLE, J. 1923. The concealed Mesozoic rocks in Kent. *Memoir of the Geological Survey*, 248pp.

LANE, D.E. 1987. Point of Ayr Colliery. *Mining Magazine*, Sept. 1987, 226-237.

LAWRENCE, S.R., COSTER, P.W. & IRELAND, R.J. 1987. Structural development and petroleum potential of the northern flanks of the Bowland Basin (Carboniferous) Northwest England. In: Brooks, J. & Glennie, K. (eds). *Petroleum geology of north-west Europe*. Vol 1. Graham & Trotman. 225-233.

LEES, G.M. & COX, P.T. 1937. The geological basis of the present search for oil in the United Kingdom. *Quarterly Journal of the Geological Society*,

LEES, G.M. & TAITT, A.H. 1946. The geological results of the search for oilfields in Great Britain. *Quarterly Journal of the Geological Society*, **101**, 255-313.

LEWIS, C., GREEN, P.F. CARTER, A. & HURFORD, A.J. 1992. Elevated K/T palaeotemperatures throughout northern England: three kilometres of Tertiary erosion? *Earth and Science Planetary Letters*, **112**,131-145.

LOVELOCK. P.E.R. 1977. Aquifer properties of Permo-Triassic sandstones in the United Kingdom. *Bulletin of the British Geological Survey*, **56**, 49pp.

MacCARTHY, F.J., TISDALL, R.M. & AYERS, W.B. 1996. Geological controls on coalbed prospectivity in part of the North Staffordshire Coalfield, UK. In: Gayer, R. & Harris, L. (Eds) *Coalbed methane and coal geology*. Geological Society Special Publication No. 109, 27-42.

MAGRAW, D. & RAMSBOTTOM, W.H.C. 1956. A deep borehole for oil at Croxteth Park, near Liverpool. *Liverpool & Manchester Geological Journal*, **1**, 512-520.

MANTELL, G. 1833. *Geology of South-East England*. Spottiswoode, London, 415pp.

MASON. C. 1747. A letter concerning Spelter, melting iron with pit-coal and a burning well at Broseley. *Philisophical Transactions of the Royal Society,* **44, II,** 370-373.

McCLURE, N.M, WILKINSON, D.W., FROST, D.P. & GEEHAN, G.W. 1995. Planning extended reach wells in Wytch Farm Field, UK. *Petroleum Geoscience*, **1,** 115-127.

McKIE, T., AGGETT, J. & HOGG, A.J.C. 1998. Reservoir architecture of the upper Sherwood Sandstone, Wytch Farm field, southern England. In: Underhill, J.R. (Ed) *Development evolution and petroleum geology of the Wessex Basin*. Geological Society Special Publication, **133**, 399-406.

McLIMANS, R.K. & VIDETICH, P.E. 1987. Reservoir diagenesis and oil migration: Middle Jurassic Great Oolite Limestone, Wealden Basin, southern England. In: Brooks, J. & Glennie, K. (eds*), Petroleum Geology of North West Europe,* Graham & Trotman, London, 119-128.

MIKKELSEN, P.W. & FLOODPAGE, J.B. 1997. The hydrocarbon potential of the Cheshire Basin. In: Meadows, N.S., Trueblood, S.P., Hardman, M. & Cowan, G. (eds), *Petroleum geology of the Irish Sea and adjacent areas*. Geological Society Special Publication No. 124, 161-183.

MILES, J.A., DOWNES, C.J. & COOK, S.E. 1993. The fossil oil seep in Mupe Bay, Dorset: a myth investigated. *Marine and Petroleum Geology*, **10,** 58-70.

MILLOTT, J.O'N, COPE, F.W. & BERRY, H. 1946. The seams encountered in a boring at Pie Rough, near Keele, north Staffordshire. *Transactions of the Institution of Mining Engineers*, **cv**, 528-570.

MILODOWSKI, A.E., STRONG, G.E., WILSON, K.S., ALLEN, D.J., HOLLOWAY, S. & BATH, A.H. 1986. Diagenetic influences on the aquifer properties of the Sherwood Sandstone in the Wessex Basin. *Investigation of the Geothermal potential of the UK*. BGS.

MITCHELL, G.H. 1942. *The Geology of the Warwickshire coalfield*. Wartime pamphlet no. 25. 38 pp.

MOSER, M.R., RANKIN, A.H. & MILLEDGE, H.J. 1992. Hydrocarbon-bearing fluid inclusions in fluorite associated with the Windy Knoll bitumen deposit. *Geochimica Cosmochimica Acta*, **56**, 155-168.

NOONER, D.W., UPDEGROVE, W.S., FLORY, D.A. & MUELLER, G. 1973. Isotopic and chemical data of bitumens associated with hydrothermal veins from Windy Knoll, Derbyshire, England. *Chemical Geology,* **11,** 189-202.

OLIVER, G.J.H. 1988. Arenig to Wenlock regional metamorphism in the Paratectonic Caledonides of the British Isles: a review. In: Harris, A.L. & Fettes, D.J. (eds.) *The Caledonian-Appalachian Orogen.* Geological Society Special Publication No. 38, 347-363.

ORMEROD, G.W. 1848. Outline of the principal geological features of the salt field of Cheshire and the adjoining districts. *Quarterly Journal of the Geological Society*, **4**, 262-

OSWALD, D.H. 1996. Islip axis gas could support central England power generation. *Oil and Gas Journal*, Aug 5th, 55-57.

PARNELL, J. 1983. The distribution of hydrocarbon minerals in the Welsh Borderland and adjacent areas. *Geological Journal*, **18**, 129-139.

PARNELL, J. 1987. Secondary porosity in hydrocarbon-bearing transgressive sandstones on an unstable Lower Palaeozoic continental shelf, Welsh Borderland. In: Marshall, J.D. (ed.) *Diagenesis of sedimentary sequences*. Geological Society Special Publication No. 36. 297-312.

PATTRICK, R.A.D. & BOWELL, R.J. 1991. The genesis of the West Shropshire Orefield: evidence from fluid inclusions, sphalerite chemistry and sulphur isotopic ratios. *Geological Journal,* **26,** 101-115.

PEARSON, R. 1903. The discovery of natural gas in Sussex: Heathfield district. *Transactions of the Institute of Mining Engineers,* LXVI (26), 494-507.

PEASEGOOD, W.G. 1909. Discharge of inflammable oil in a coal-seam. *Transactions of the Institution of Mining Engineers*, **35**, 116-119.

PENN, I. E., CHADWICK, R. A., HOLLOWAY, S., ROBERTS, G., PHARAOH, T. C. & ALSOP, J. M. 1987. Principal features of the hydrocarbon prospectivity of the Wessex Channel Basin, UK. In: Brooks, J. & Glennie, K. W. (eds) Petroleum Geology of North West Europe. Graham and Trotman, London, 109-118.

PINFOLD, E.S. 1958. The search for oil in Lancashire. *Liverpool and Manchester Geological Journal,* **3,** 106-123.

PLANT, J.A., JONES, D.G. & HASLAM, H.W. (Eds). 1999. *The Cheshire Basin: Basin evolution, fluid movement and mineral resources in a Permo-Triassic rift setting*. British Geological Survey.

PLOT, R. 1686. *The natural history of Staffordshire*.

POCOCK, R.W., WHITEHEAD, T.H., WEDD, C.B. & ROBERTSON, T. 1938. *Shrewsbury District*. Memoir of the British Geological Survey, **152**.

POOLE, E. G. & WHITEMAN, A.J. 1966. *Geology of the country around Nantwich and Whitchurch. Memoir of the British Geological Survey*, **122**.

POWER, T.O. 1978. Gas seepages off Anvil Point. Triton, February No. 57.

RAISWELL, R. & BERNER, R.A. 1986. Pyrite and organic matter in Phanerozoic normal marine shales. *Geochimica et Cosmochimica Acta*, **50**, 1967-1976.

REDWOOD, Sir BOVERTON, 1922. *Treatise on Petroleum*. Charles Griffin, 3 vols.

REEVES, J.W. 1948. Surface problems in the search for oil in Sussex. *Proceedings of the Geologists Association*, **59**, 234-269.

RICHARDSON, L. 1931. Wells and springs of Leicestershire. *Memoir of the British Geological Survey.* 160 pp.

ROBERTS, D.G. 1989. Basin inversion in and around the British Isles. In: Cooper, M.A. & Williams, G.D. (eds) *Inversion Tectonics*. Geological Society Special Publication **44,** 131-150.

ROBINSON, N. & GRAYSON, R. 1990. Natural methane seepages in the Lancashire Coalfield. *Land and Minerals Surveying,* **8,** 333-340.

ROBINSON, N., BRASSELL, S.C. & EGLINTON, G. 1986. Molecular evaluation of hydrocarbons. In Bath, A.H. *et al*. (eds) *Deep source gases and hydrocarbons in the UK crust.* Report FLPU 86-2.

ROBSON, R.W., LINEY, A.D. & HIRST, D. 1990. Harworth Colliery. *Mining Magazine*, Nov 1990. 340-345.

ROTHWELL, N.R. & QUINN, P. 1987. The Welton Oilfield. In: Brooks, J. & Glennie, K. (eds.) *Petroleum Geology of North west Europe*. Graham & Trotman, 181-189.

ROWE, J. & BURLEY, S.D. 1997. Faulting and porosity modification in the Sherwood Sandstone at Alderley Edge, northeastern Cheshire: an exhumed example of fault-related diagenesis. In: Meadows, N.S., Trueblood, S.P., Hardman, M. & Cowan, G. (eds) *Petroleum geology of the Irish Sea and adjacent areas*. Geological Society Special Publication No. 124, 325-352.

ROWLEY, W.J. 1987. The Formby Oilfield. *(Unpublished) 7pp.*

RHYDDERCH, L.D. & YATES, D.C. 1964. Outbursts of firedamp in the North Staffordshire Coalfield. *Transactions of the Institution of Mining Engineers*, **124**, 168-184.

SCOTCHMAN, I.C. 1987. Relationship between clay and organic maturation in the Kimmeridge Clay Formation, onshore UK. *Petroleum geology of north west Europe.* Brooks, J. & Glennie K.W. (eds) Graham & Trotman. London, 251-262.

SCOTCHMAN, I.C. 1994. Maturity and burial history of the Kimmeridge Clay Formation, onshore UK; a biomarker study. *First Break*. **12**, 193-202.

SCOTT, J. & COLTER, V.S. 1987. Geological aspects of current onshore Great Britain exploration plays. In: Brooks, J. & Glennie, K. (eds), *Petroleum Geology of North West Europe*, Graham & Trotman, London, 95-107.

SELLEY, R.C. 1987. British shale gas potential scrutinized. *Oil and Gas Journal*, June 15th.62-64.

SELLEY, R.C. 1992. Petroleum seepages and impregnations in Great Britain. *Marine and Petroleum Geology*, **9**, 3, 226-244.

SELLWOOD, B.W.T., SCOTT, J., MIKKELSEN, P. & AKROYD, P. 1985. Stratigraphy and sedimentology of the Great Oolite Group in the Humbly Grove Oilfield, Hampshire. *Marine and Petroleum Geology*, **2,** 44-55.

SELLWOOD, B.W.T., SHEPHERD, T.J., EVANS, M.R. & JAMES, B. 1989. Origin of late cements in oolitic reservoir facies: a fluid inclusion and isotopic study (Mid-Jurassic, southern England). *Sedimentary Geology*, **61,** 1-15.

SELLEY, R.C. & STONELEY, R. 1987. Petroleum habitat in south Dorset. In: Brooks, J. & Glennie, K. (eds), *Petroleum Geology of North West Europe*, Graham & Trotman, London, 139-148.

SHEPHARD-THORN, E.R., LAKE, R.D. & ATITULLAH, E.A. 1972. Basement control of structures in the Mesozoic rocks in the Strait of Dover regio, and its reflection in certain features of the present land and submarine topography. *Philosophical Transactions of the Royal Society of London,* **A272,** 99-113.

SHERLOCK, R.L. 1921. Rock Salt and brine. *Memoir of the British Geological Survey Special Reports on the mineral resources of Great Britain*, **18**.

SMITH, E.G., RHYS, G.H. & EDEN, R.A. 1967. Geology of the country around Chesterfield, Matlock and Mansfield. *Memoir of the British Geological Survey*, **112**.

SMITH, K., SMITH, N.J.P. & HOLLIDAY, D.W. 1985. The deep structure of Derbyshire. *Geological Journal,* **20,** 215-225.

SMITH, N.J.P. (Compiler) 1985. *Map 1: Pre-Permian Geology of the United Kingdom (South).* British Geological Survey.

SMITH, N.J.P. 1987. The deep geology of central England: prospectivity of the Palaeozoic rocks. In: Brooks, J. & Glennie, K.W. (eds.) *Petroleum Geology of North West Europe.* Graham & Trotman. 217-224.

SMITH, N.J.P. 1993. The case for exploration of deep plays in the Variscan fold belt and its foreland. In: Parker, J.R. (ed.) *Petroleum geology of Northwest Europe: Proceedings of the 4th Conference*. Geological Society, London. 667-675.

SMITH, N.J.P. & RUSHTON, A.W.A. 1993. Cambrian and Ordovician stratigraphy related to structure and seismic profiles in the western part of the English Midlands. *Geological Magazine,* **130,** 665-671.

SMITH, S.F. 1982. The Parkside Colliery Methane Gas Disposal project. *The Mining Engineer,* May 1982, 663-665.

SOUTHWELL, C.A.P. 1945. Petroleum in England. *Journal of the Institute of Petroleum*, **31**, 27-39.

SPIRO, B. 1986. Stable isotope studies. In Bath, A.H. *et al.* (eds) *Deep source gases and hydrocarbons in the UK crust.* Report FLPU 86-2. British Geological Survey .

STEPHENS, J.V. 1929. Wells and Springs of Derbyshire. *Memoir* of *the Geological Survey England and Wales*. 155pp.

STEVENSON, I.P. & GAUNT, G.D. 1971. Geology of the country around Chapel en le Frith. *Memoir of the British Geological Survey*, **99**.

STOKES, A.H. 1878. Economic geology of Derbyshire. *Transactions of the Chesterfield Institute of Engineers,* **6**.

STOREY, M.W. & NASH, D.F. 1993. The Eakring Dukeswood oil field: an unconventional technique to describe a field's geology. In: Parker, J.R. (ed.) *Petroleum geology of Northwest Europe: Proceedings of the 4th Conference*. Geological Society, London. 1527-1537.

STRAHAN. A. 1920. *Mineral Oil, Kimmeridge Oil-Shale, Lignites, Jets, Cannel Coals etc.* 2nd Edition, vol. 7.

SUGGATE, R.P. 1981. Coal ranks on the Alston Block, north-east England: a discussion. *Proceedings of the Yorkshire Geological Society*, **43**, 451-453.

TAYLOR, J. C.M. 1986. Gas prospects in the Variscan Thrust Province of southern England. In: Brooks, J., Goff, J. C. & Van Hoorn, B (eds). *Habitat of Palaeozoic gas in N W Europe*. Geological Society Special Publication No. 23. 37-53.

TEICHMULLER, M. 1987. Recent advances in coalification studies and their application to geology. In: Scott, A.C. (ed.) *Coal and coal-bearing strata: recent advances*. Geological Society Special Publication No. 32, 127-169.

TERRIS, A.P. & BULLERWELL, W. 1960. Investigations into the underground structure of southern England. *Advancement of Science,* August, 232-252.

TREWIN. N.H. & HOLDSWORTH, B.K. 1973. Sedimentation in the Lower Namurian rocks of the North Staffordshire Basin. *Proceedings of the Yorkshire Geological Society*, **39**, 3, 371-408.

TRUEMAN, S. The Humbly Grove, Herriard, Storrington, Singleton, Stockbridge, Goodworth, Horndean, Palmers Wood, Bletchingly and Albury Fields, Hampshire, Surrey and Sussex, UK Onshore. In: Gluyas, J. G. & Hichens, H. M. (eds) *United Kingdom Oil and Gas Fields, Commemorative Millennium Volume*, **20**, 929-941.

TYSON, R.V., WILSON, R.C.L. & DOWNIE, C. 1979. A stratified water column environmental model for the type Kimmeridge Clay. *Nature,* **277**, 377-380.

UNDERHILL, J.R. & PATTERSON, S. 1998. Genesis of tectonic inversion structures: seismic evidence for the development of key structures along the Purbeck-Isle of Wight Disturbance. *Journal of the Geological Society, London*, **155**, 975-992.

UNDERHILL, J.R. & STONELEY, R. 1998. Introduction to the development, evolution and petroleum geology of the Wessex Basin. In: Underhill, J.R. & Stoneley, R. (eds), *Development, Evolution and Petroleum Geology of the Wessex Basin,* Geological Society, London, Special Publications, **133,** 1-18.

VERMA, Y.K. 1981. Studies in virgin strata temperatures with special reference to the NCB's Western Area mines. *The Mining Engineer,* **141,** 655-663.

WARD, J. 1997. Early Dinantian evaporites of the Easton 1 well, Solway Basin, onshore, Cumbria, England. In: Meadows, N.S., Trueblood, S.P., Hardman, M. & Cowan, G. (eds) *Petroleum geology of the Irish Sea and adjacent areas*. Geological Society Special Publications **124,** 277-296.

WARD, J., CHAN, A. & RAMSAY, B. 2003. The Hatfield Moors and Hatfield West Gas (Storage) Fields, South Yorkshire. In: Gluyas, J. G. & Hichens, H. M. (eds) *United Kingdom Oil and Gas Fields, Commemorative Millennium Volume*, Geological Society, London, Memoir, **20**, 905-910.

WARMAN, H.R., ROBERTS, K.H., BRUNSTROM, R.G.W. & ADCOCK, C.M. 1956. Report on oil and gas in the United Kingdom. In: *Symposium sobre yacimientos de petroleo y gas. XX International Geological Congress*. 317-351.

WATSON, D.F., FARRIMOND, P. & HINDLE, A.D. 1999. Hydrocarbon seeps of the Wessex Basin. In: Williams, B.J. (ed.) Geoscience in South-West England. *Proceedings of the Ussher Society,* **9,** 394.

WEDD, C.B. & KING, W.B.R. 1924. The geology of the country around Flint, Hawarden and Caergwrle. *Memoir of the British Geological Survey*, **108**.

WEDD, C.B., SMITH, B., KING, W.B.R. & WRAY, D.A. 1929. The country around Oswestry. *Memoir of the Geological Survey,* **137,** 234 pp.

WHITEHEAD, T.H. & EASTWOOD, 1927. Geology of the southern part of the South Staffordshire Coalfield. *Memoir of the Geological Survey.*

WILLETT, H. 1875. 13th Report of the Sub-Wealden Exploration Group.

WILLIAMS, P.F.V. 1986. Petroleum geochemistry of the Kimmeridge Clay of onshore southern and eastern England. *Marine and Petroleum Geology.* **3**, 258-281.

WILLS, L.J. 1956. *Concealed Coalfields.* Blackie & Son Ltd. Glasgow. 208pp.

WOODWARD, H.B. 1903. Notes on the occurrence of natural gas at Heathfield, Sussex. *Transactions of the Institute of Mining Engineers,* LXV (25), 717-723.

WORSSAM, B.C. & IVIMEY-COOK, H.C. 1971. The stratigraphy of the Geological Survey borehole at Warlingham, Surrey. *Bulletin of the Geological Survey of Great Britain*, **36**, 1-146.

YALIZ, A. M. 1997. The Douglas oil field. In: Meadows, N.S., Trueblood, S.P., Hardman, M. & Cowan, G. (eds). *Petroleum Geology of the Irish Sea and adjacent areas*. Geological Society Special Publication no. 124, 399-416.