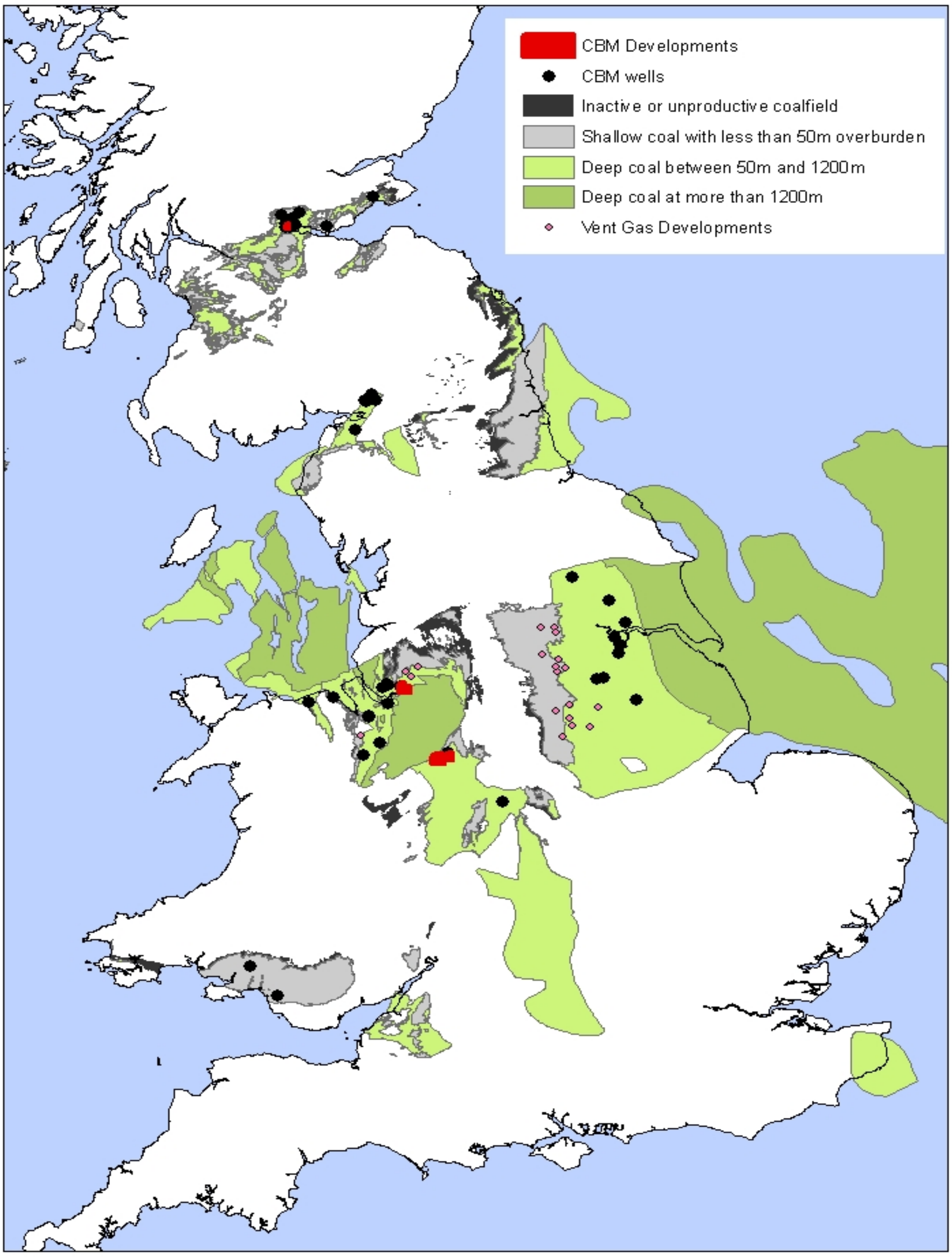
THE UNCONVENTIONAL HYDROCARBON RESOURCES OF BRITAIN'S ONSHORE BASINS - COALBED METHANE (CBM)



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Foreword

This report has been produced under contract by the British Geological Survey (BGS). It is based on recent analysis, together with published data and interpretations.

Additional information is available at the Department of Energy and Climate Change (DECC) website. https://www.og.decc.gov.uk/information/onshore.htm. 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. The 9th to 11th Landward licensing round data should be included by the end of 2010. 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/upstream/licensing/relinqlics/index.htm

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1. Overview

This document will review previous studies, factors of importance in UK coalbed methane (CBM) exploration, the geology of key CBM regions, and their comparison to US productive basins and preliminary resource estimates. However, the document's content is limited by the lack of released well logs, core studies and test data, and the resource estimates are speculative, due to the early stage of UK CBM development.

Gas is bound within coal by a process known as adsorption, where the gas molecules adhere to the surfaces within the coal. As pressure is reduced, gas is released from the coal surfaces, diffuses through the coal matrix and flows through the fracture system of the coal. Coalbed methane production can be subdivided into three categories: coal mine methane (CMM), abandoned mine methane (AMM) and coalbed methane (CBM) produced via boreholes from virgin coal seams. Methane trapped in coal and surrounding strata are released as a result of mining, and because this gas can be explosive when mixed with air, there is a history of tragic accidents caused by this gas, known as firedamp in the mining industry. Aside from safety concerns, venting this gas is destructive to the environment because methane is an important greenhouse gas, 23 times more powerful than carbon dioxide on a mass basis.

In CBM production, a well is drilled into the coal seam and water is pumped out to lower the pressure in the seam. This allows methane to desorb from the internal surfaces of the coal and diffuse into the cleat, where it is able to flow, either as free gas or dissolved in water, towards the production well. Permeability (imparted mainly by the cleat) is necessary to achieve CBM production. The natural permeability of coal seams can be low, so some CBM wells are stimulated (hydrofractured) to improve connectivity between the borehole and the cleat system. Wells may have many subsurface horizontal or multilateral sidetracks drilled from one surface location to penetrate more coal.

Licensing and activity

A UK Petroleum Exploration and Development licence (PEDL) allows a company to pursue a range of oil and gas exploration activities, subject to necessary drilling/development consents and planning permission. Alongside conventional onshore oil and gas exploration and development, the licence covers exploration and development of CBM, mine vent gas, oil shale, shale gas and gas storage in a previous gas field. A PEDL licence does not allow for underground coal gasification (UGC) or CO_2 sequestration. Until 1996, the UK Government issued a sequence of separate licences for each stage of an onshore field's life (Exploration Licences (XL or EXL), Production Licences (PL), Appraisal Licences (AL) and Development Licences (DL) and a number of them, and of even older Mining Licences (ML) are still in force, but have all been converted to the same terms as a PEDL. There are currently 334 Landward licences (Fig. 1).

Methane drained from abandoned mines (AMM) is obtained by applying suction to the workings. Mine vent gas consists primarily of methane desorbed from seams surrounding the mined seams, which have been de-stressed and fractured by the collapse of overlying and underlying strata into the void left by the extracted coal. Currently there are 26 UK coal mine vent developments in operation. The methane-rich gas is used for electricity generation or supplied to local industry for use in boilers and kilns.

DECC also grants methane drainage licences (MDL), permission to get coal mine methane (CMM) "in the course of operations for making and keeping safe mines whether or not disused". An MDL grants no exclusive rights and can overlap geographically with PEDLs. Each MDL typically covers one mine, although the Coal Authority holds a licence that covers the whole country. There are currently 20 UK MDL Licences.

Licensees wishing to drill into coal seams for vent gas or CBM extraction must also seek the permission of the Coal Authority, and planning consent must be granted by the local authority.

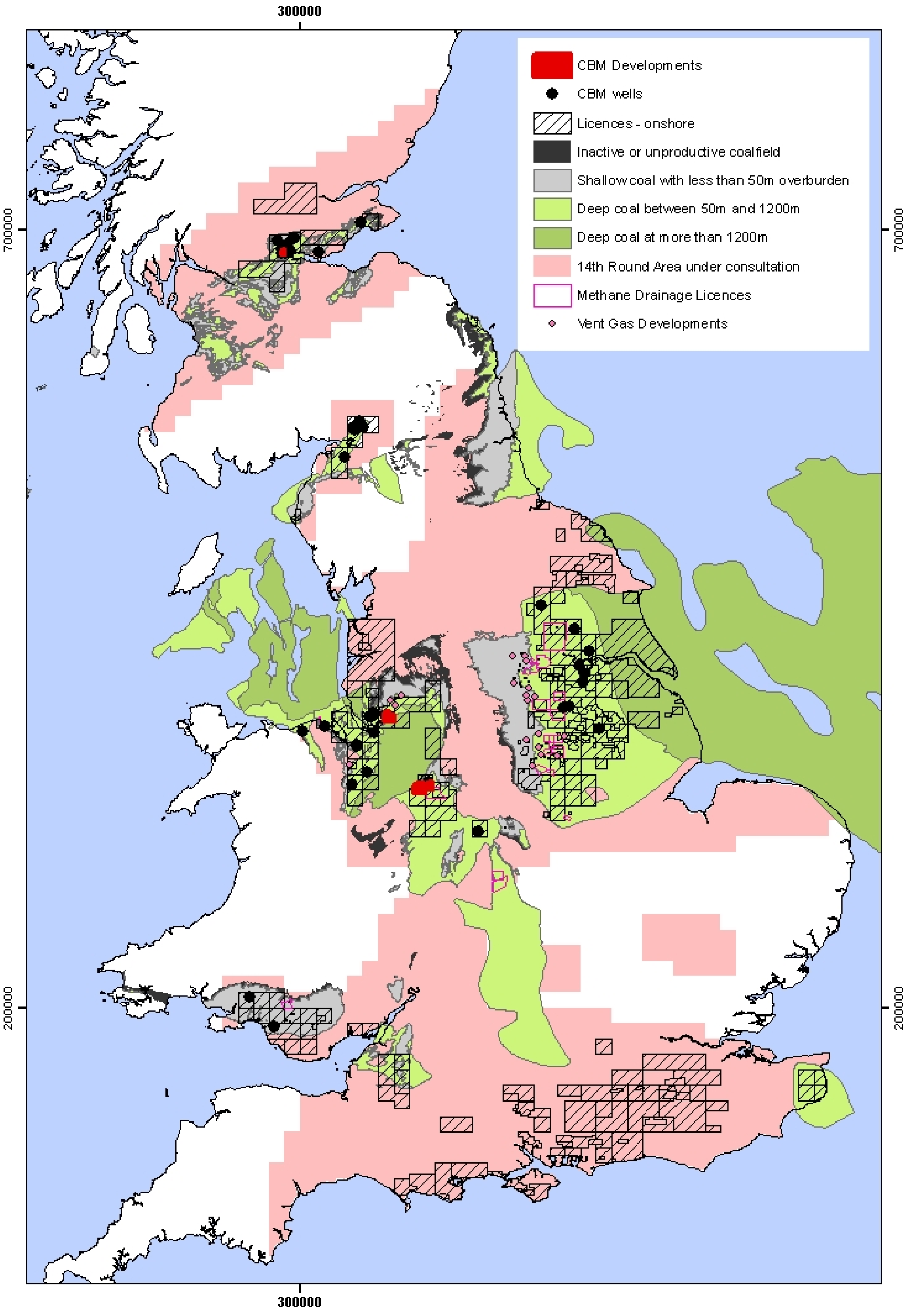

Fig.1 Current UK Petroleum Exploration and Development Licences (and methane drainage areas), CBM wells, CBM developments, vent developments and areas under consultation currently which may be offered in the 14th onshore Oil and Gas Licensing Round.

The UK CBM industry received a major impetus in 2008 with the award of 55 new licences covering more than 7,000 km^2 in the 13th Onshore Licence Round. Three CBM development plans have been approved by DECC, but as yet no full scale developments have been constructed. In the last 5 years over 40 CBM exploration and appraisal wells and 12 pilot production development wells have been drilled. IGAS and Nexen are generating electricity from CBM production, a first for the UK, at their Doe Green development, near Warrington (Dean 2010) and are currently drilling in Staffordshire at Keele Park as part of the Potteries CBM development. In Scotland, Composite Energy drilled 18 multi-lateral wells in their Airth CBM development, which is currently suspended, but produced water and gas in 2008 and 2009.

In July 2010 DECC published a Strategic Environmental Assessment (SEA) for the 14th UK Onshore Licensing Round on its website for a twelve-week consultation period. DECC will then consider the responses received, and plans to issue a Government Response about one month later.

Subject to the outcome of the SEA process DECC should then be in a position to request the translation and publication of a Notice for the Official Journal of European Union detailing the announcement of the UK's 14th onshore Oil and Gas Licensing Round. This usually takes around 6 - 8 weeks to complete. This would suggest the opening of the 14th Round for a 90 day application period starting in or around February 2011. The exact areas to be available in the Round and the timing are subject to the conclusions of the SEA and Ministerial decision.

Resource and reserve estimates

The BGS has estimated that the total CBM resource in the UK is 2,900 bcm (Jones 2004), the conclusion of a study which delineated the coals with the right depth, thickness, gas content and adequate separation from underground mine workings. This compares with a previous estimate of 2,450 bcm (Creedy 1999). Although this CBM resource potential is large, commercial production has yet to take place, and so there is a far greater degree of uncertainty in UK potential reserves - the resources that are economically viable to produce.

The BGS 2004 study estimated that as little as 1% of this resource could be recovered, because of perceived widespread low seam permeability, low gas content, resource density and planning constraints. However, US analogous CBM developments have now been proven to achieve recovery of 30-40% in some fields. If 10% of the UK CBM resource potential could be developed, the produced 290 bcm would correspond to over three years of UK natural gas supply (annual UK natural gas consumption in 2009 was approximately 86 bcm).

Once commercial UK CBM developments are established, a more reliable reserve estimate can be made, taking into consideration firm data - coal permeability, gas content, gas saturation from cores, achievable well density, landowner permit costing, environmental studies and mitigation costs, production profiles, costs of drilling, fracture stimulation, and the cost of access to the National Grid.

Previous CBM Studies

A wealth of knowledge has accumulated during firedamp precautionary work (*e.g.* Mostyn 1677, Hedley & Leck 1898, Briggs 1921, Williams *et al.* 1944, Frazer 1945, Bromilow 1952, Charlton 1952, Rhydderch and Yates 1964, Oldroyd *et al.* 1971, Creedy *et al.* 1982, Creedy 1983a, 1983b, 1989). Obtaining gas from anthracites is likely with significantly larger rewards than low maturity coals – outbursts were common during anthracite-mining, with soft coal in areas of anthracite being thought to be related to geological faults or other abnormalities, for example thinning of the seams. Low maturity, low gas content seams have been ignored to date. These might have some prospectivity value because the natural permeability is likely to be higher, though water production may be a problem.

The extent of coals in the UK subsurface was mapped by the British Geological Survey (1999) for the national Coal Authority – their extent was based on the published pre-Permian subcrop map (Smith 1985) as the top surface, with borehole and seismic data defining their base. Notable features of this map (Fig. 2) are the absence of coal beneath the Mesozoic Weald and Wessex basins in southern England. However, the information from subsequently-drilled boreholes has served to confirm the theory used by Godwin Austen (1855) to predict the existence of the Kent Coalfield and Berkshire (Coal) Basin, based on the reactivation of Carboniferous structures during Mesozoic and Tertiary times. Recent mapping by the British Geological Survey east of Bath suggests that thin Coal Measures are present here also, but other possible extensions have not been proved (*e.g.* north of Strat A1 borehole).

Within England south of the Stainmore-Cleveland Basin coals are largely confined to strata of Westphalian (late Pennsylvanian) age. Farther north and in Scotland a large number of coals also occur in Namurian (Mississippian to Pennsylvanian) and Dinantian (early Mississippian) strata.

Neither the pre-Permian subcrop map nor the coal mapping attempted to predict areas of possible Coal Measures beneath Variscan thrusts in southern Britain. The areas where this is a possibility include beneath Warlingham borehole in the Weald Basin, south of the Berkshire Syncline, the Mendips, where a small thrust slice outcrop of Westphalian Coal Measures occurs to the south (Ebbor), and SW Pembrokeshire, particularly where Precambrian rocks are thrust north over Westphalian strata along the Johnston Thrust. A different coal-bearing facies of similar Westphalian age crops out in SW England (Bude and Bideford formations) that contains a few anthracite seams, which were mined up to 1969. No modern drilling or logging has taken place here.

CBM resource estimates were made in a report carried out by the BGS under contract, as part of the DTI Cleaner Coal Technology Transfer Programme (Jones et al. 2004). A Coal Resources Map was produced, in which the coalfields were divided into their energy potential for underground coal gasification, CBM exploration and sequestration of carbon dioxide.

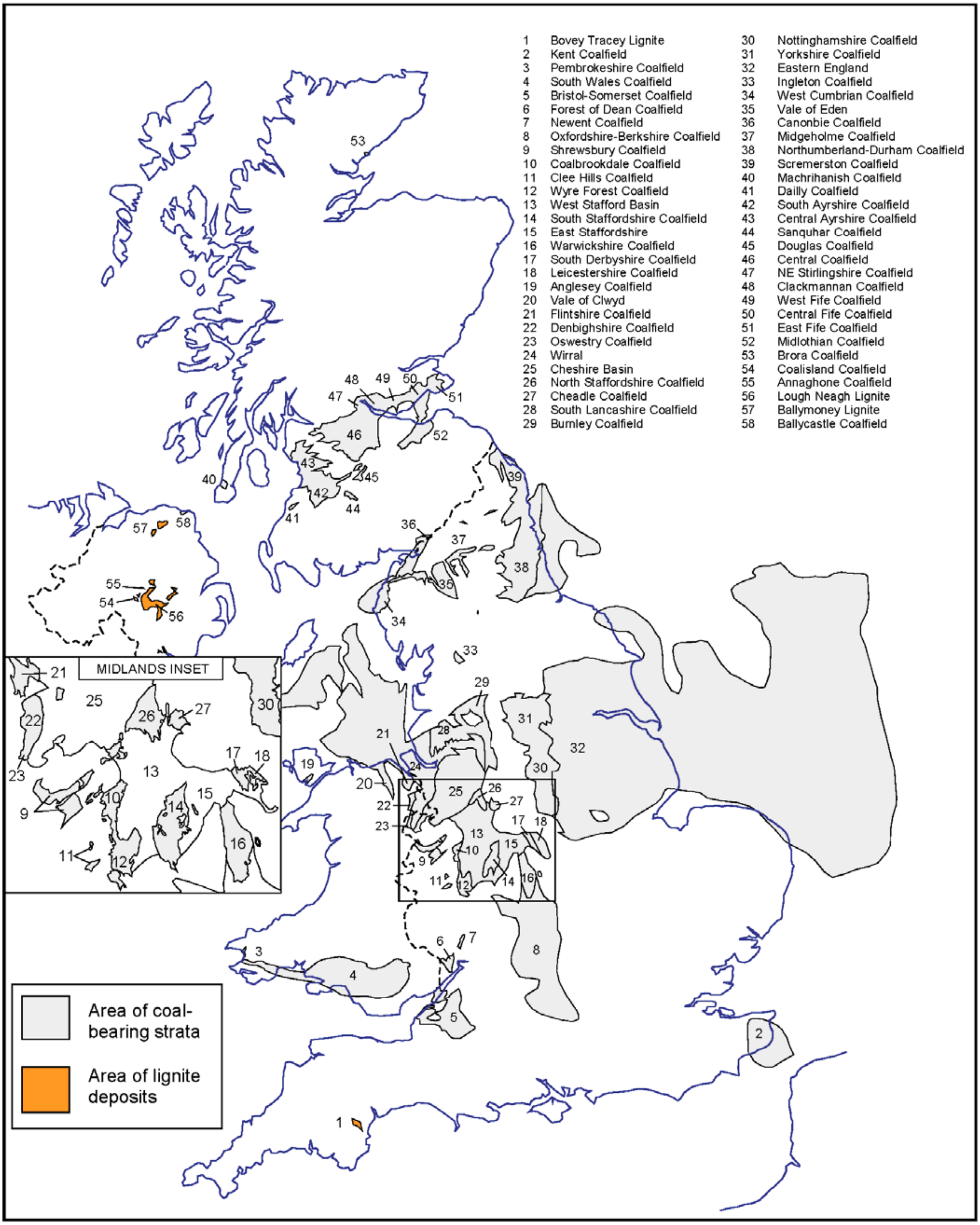

Fig. 2 Principal UK onshore coal basins

Fig. 3 Boreholes referred to in this report

2. CBM Data

The UK's National Coal Board (NCB) had a programme of measuring the gas content of coals, which began in the early 1980s. Geographically and stratigraphically extensive borehole-retrieved coals were analysed for methane and ethane, but not for higher hydrocarbon or non-hydrocarbon gases. Propane contents were measured in a few other boreholes. The NCB programme was initially in response to the need to make plans for methane drainage from coal mines, because prior extraction of CBM would make subsequent coal-mining safer. The typical gas composition of CBM or firedamp is methane (80-95%), ethane (0-8%), propane and higher alkanes (0-4%), nitrogen (2-8%) and carbon dioxide (0.2-6%), together with traces of argon, helium and hydrogen (Creedy 1991).

The data from the NCB programme now form the source rock database for a search for commercially viable CBM reserves in the UK. Very little systematic reservoir data has been collected with which to make an assessment of the reservoir qualities of UK coals, and the data acquired by CBM exploration has generally not been released into the public domain yet.

Additional data on gas produced during mining of coal seams was accumulated by coal companies and the Inspector of Mines, prior to nationalisation of the UK coal mining industry in 1947.

While amassing UK data on coal, it is useful to compare these with data from successfully producing areas of the world. However, some of the American and Australian coals are younger, very much thicker, and they contain other significant differences to the UK's Carboniferous coals.

American analogues

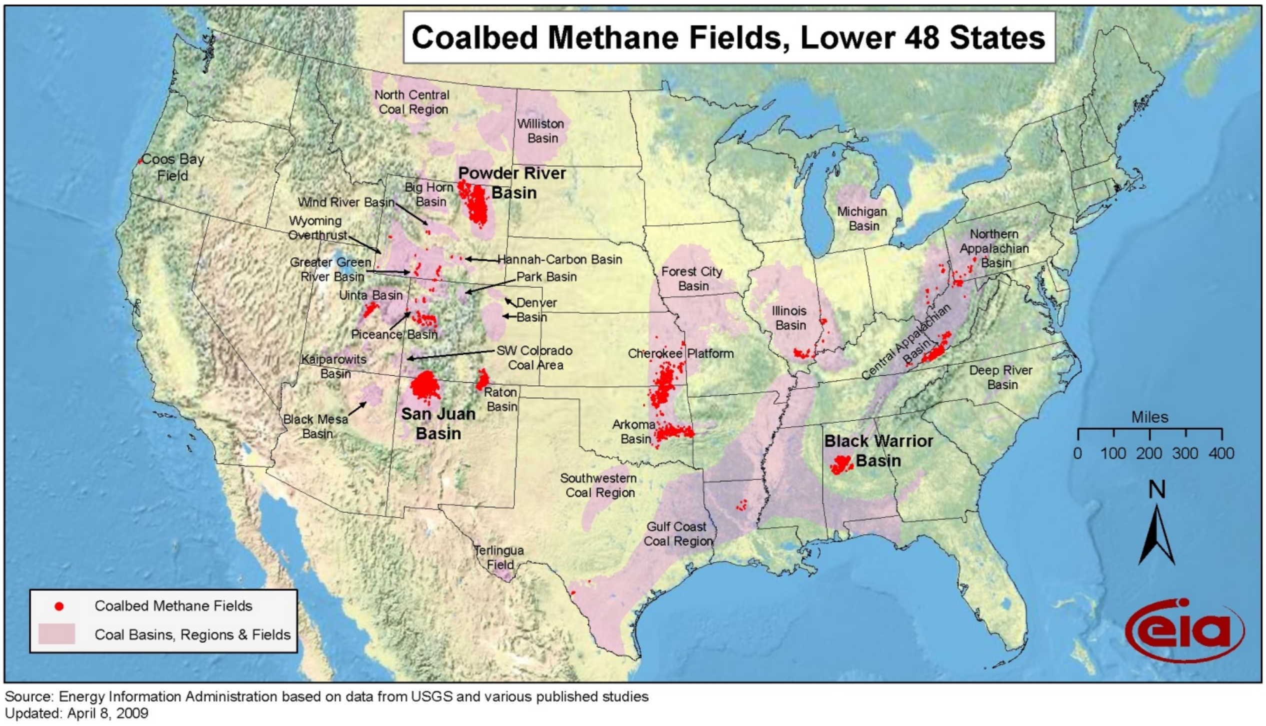

Fig. 4 US CBM producing basins, US Energy Information Administration www.eia.gov

CBM exploration began, and is more successful in America than anywhere else in the world (Fig. 4). In addition to Carboniferous coals which can be directly compared to contemporary UK coals (Sparks *et* al. 1993, Fig. 6) CBM has been produced from Cretaceous and Tertiary coals in the Rocky Mountain foreland basin. These latter coals have different characteristics to most UK Carboniferous coals (see Fig. 15). The Black Warrior Basin in Alabama has CBM production from Westphalian coals (*e.g.* from the Cedar Cove field), and the Appalachian foreland basin has close analogues for UK coals. Here the anthracites occur close to the Appalachian fold belt (Fig 4), although in South Wales the anthracites occur on the northern side of the coalfield, away from the Variscan fold belt. The US Black Warrior Basin CBM fields lie within an area where the vitrinite reflectance puts them within the oil window (Winston 1990, fig. 8 and tables).

Creedy (1994) compared the gassiness of UK and US coals. He noted that the Alabama (Black Warrior Basin) coals contain 12-17 m^3/t, and are thus comparable to North Staffordshire-Lancashire coals (Fig. 7). Illinois No 6 and Pittsburgh coals are less gassy. The Alabama CBM fields were initially productive from vertical wells.

Factors of importance in CBM exploration

A number of characteristics of coals and coal measures need to be assessed during exploration. These include the gas content, depth, maturity and thickness. The permeability of coals needs to be ascertained, which in turn depends on the maturity, the cleat system and its degree of openness or mineralization. The effects of depositional and tectonic structures, including uplift on coal and coal sequences need to be considered. Previous reviews of UK CBM prospects include those by Ayers *et al*. (1993) and Baily *et al*. (1995).

Gas contents

A database of more than 400 boreholes and some coalface samples was maintained until privatisation of the National Coal Board (NCB). Seams in South Staffordshire and the South Midlands contain 3 m^3/t or less, East Midlands coals reach 9 m^3/t, South Lancashire coals reach 11 m^3/t, North Staffordshire coals reach 15 m^3/t and West Wales anthracites hold about 20 m^3/t. (Creedy 1983). These values show that coals in the western UK have relatively high methane values. This matches an NCB coal rank (maturity) map based on the fixed carbon ratio of analysed coals (Mohafez undated), which also shows a western bias in high values. In South Wales the effect of the Variscan Front is perhaps masked by a westward increase in ranks, approximately coincident with the Westphalian Coal Measures / Warwickshire Group depocentre to the west and the low ranks related to the Usk Uplift in the east. NE Wales and south Lancashire also have high methane contents, whereas the main Pennine Basin depocentre lies to the east (Calver 1968).

Gas content increase with depth

An increase in gas content with depth is seen in the majority of boreholes, although Creedy (1988) showed six other variations. The increase in gas with depth can be explained as the consequence of Hilt's Law which predicts an increase in maturity with depth. A corollary of this observation and law is that coals of younger age have lower gas contents than older coals. This is apparent in the low gas contents of the coals in the Warwickshire Group, of Westphalian C-D age. However exceptions occur in the South Wales and Kent coalfields. Although there is an increase in gas content with depth in the South Wales Coalfield, there is a much larger increase in gas content towards the north-west. This might suggest that non-burial factors are controlling this, but the depocentre of Westphalian sediments (and therefore probably those subsequently removed by erosion) lies in the west of the coalfield. The north-westward increase in gas content also mirrors the coal rank and vitrinite reflectance data (Mohafez undated, Gill *et al*. 1979). Coals of anthracitic rank show a relatively slow increase in maturity and gas content with depth (*e.g.* Five Roads borehole, Creedy 1988, Fig. 3) because they have almost reached the limit of the scales.

Bituminous coals of the Birch borehole in North Staffordshire Coalfield (Creedy 1988, Fig. 5) have increasing methane contents down to the Rowhurst Rider seam at 790 m, but the Burnwood seam (829 m) and those beneath it have much lower methane contents, whereas the ethane content continues to rise. This may suggest that still higher hydrocarbons (not measured by the National Coal Board) are also increasing downhole.

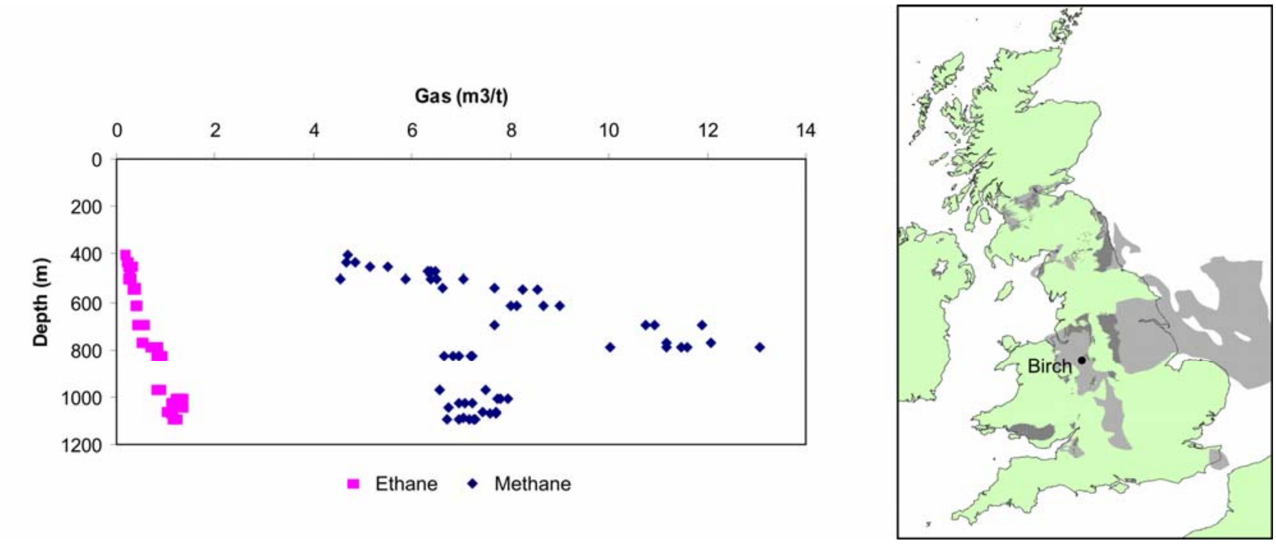

Fig. 5 Methane and ethane content in the Birch borehole, as measured and recorded in the National Coal Board database. Coals below 800 m have lower than expected methane contents (about 4m^3/t lower), which are partially offset by the more rapid increase in ethane content below this depth.

Gas content increase with increasing maturity

Maturity of coals is measured by vitrinite reflectance and, in older analyses, volatile matter percentage (or carbon content). Volatile matter percentage plotted against depth shows a degree of variation between low maturity and high maturity profiles (Fig. 6), but a general increase in maturity with depth. Peat coals are immature. The Keele borehole shows the most complete downhole section in England, and is largely within the oil window. The Mardy and Gwendraeth sections (South Wales) are in anthracitic coals. Jurassic coals from the Cleveland Basin and Dinantian coals have been uplifted by basin inversions. The oil window is indicated on Figure 6, and the Cedar Cove CBM field data from the Black Warrior Basin, Appalachian foreland in Alabama, USA are included for comparison. Meissner (1984) has derived a formula to estimate the volume of gas from the volatile matter percentage: Volume of methane = -325.6 x log (VM%/37.8).

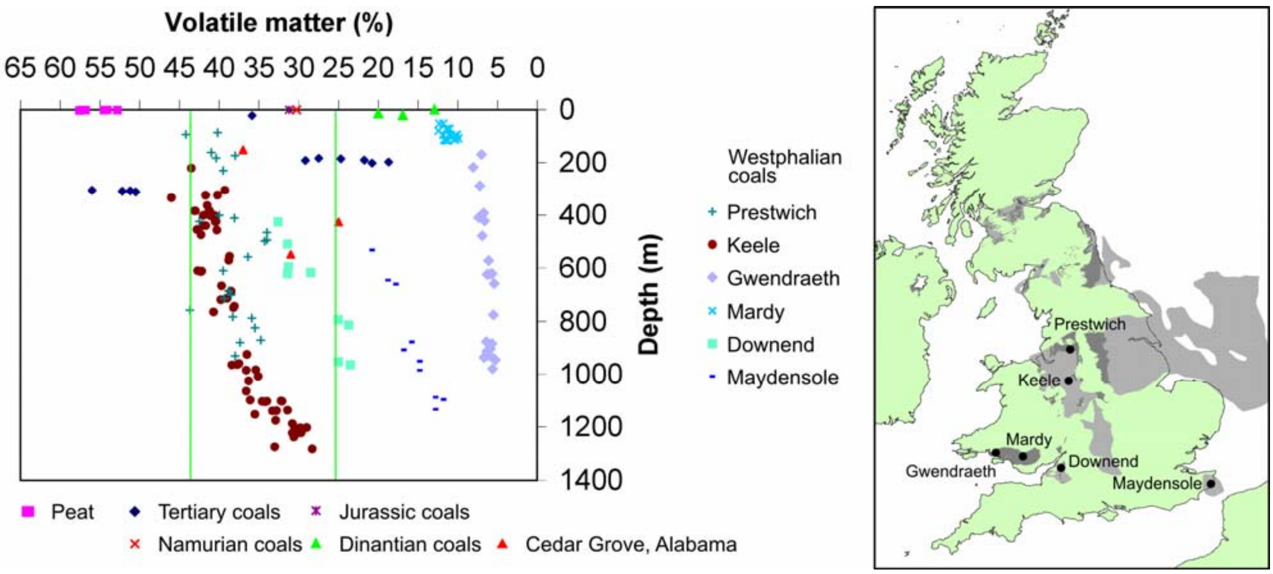

Fig. 6 Some UK Volatile Matter-depth plots compared to the Cedar Cove CBM field, US Black Warrior Basin, in the Alabama Appalachian foreland basin. The green box represents the oil window.

The presence of igneous intrusions causes perturbations of the normal downhole increase in maturity (*e.g.* Ridd *et al*. 1970). The variation in the rate of increase in maturity with depth is probably caused by variable geothermal gradients. These variations can be distinguished where the observed values exceed the rate of increase applicable to burial. England's western coalfields contain coals of higher maturity than those coals east of the Pennines, although they were formerly part of the same Pennine Basin. These western coalfields contain the gassy coals of the former coal mines and the highest measured gas content values of coals in the National Coal Board boreholes.

There is a progressive increase in gas contents (Fig. 7) northwards from Oxfordshire, on the Wales-Brabant Massif, towards the Pennine Basin margin (Warwickshire & South Staffordshire) and its depocentre (Lancashire). A slight increase also occurs southwards from Oxfordshire into South Wales (not shown on Fig. 7), into the foreland basin in Kent, and probably also into Somerset, although this basin lacks data. But A northwestwards increase in rank of the Nine Foot (Westphalian B) coal in South Wales is seen, from 32% to 6% Volatile Matter, accompanied by an increase in gas content from 5 to 20 m^3/t (Creedy 1988).

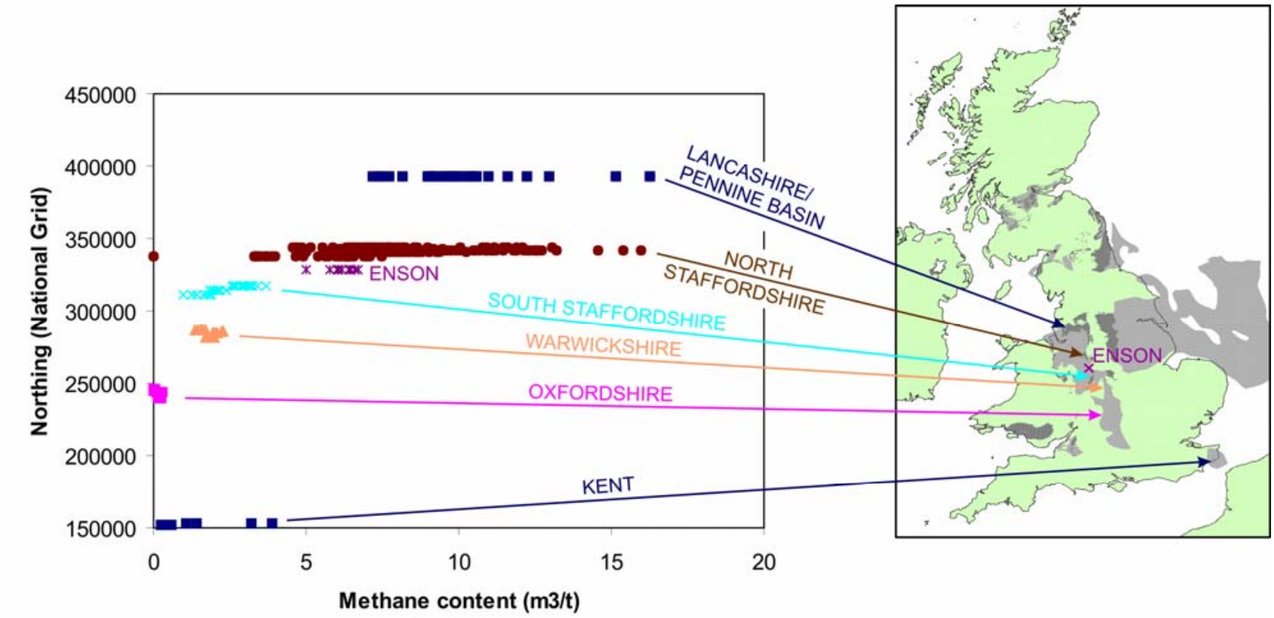

Fig.7 Northward increase in Methane content in coals by coalfield. The range of gas contents is shown. Enson is a borehole on the Mesozoic ridge between the South and North Staffordshire coalfields. Kent and South Wales (not shown) coalfields in the Variscan foredeep have higher values than those of the foreland but Kent's are lower than would be expected from their maturity.

The gas content gradients vary from 0.002 m^3/t per 100 m (in NE England) to 0.03 m^3/t per 100 m (Yorkshire) and 0.09 m^3/t per 100 m (Lancashire and North Staffordshire). In South Wales they reach 0.1 m^3/t per 100 m (Creedy 1988). This reflects the Westphalian Coal Measures depocentres, because for example the Top Hard seam gas content decreases from the NW, where it crops out, towards the SSE near the basin edge and Creedy thought that lower values of gas content occur close to the Variscan unconformity. Although this reflects the common decrease in gas content uphole, in some European coalfields there is an enhancement just below the unconformity (Freudenberg *et al*. 1996), which may result from an impermeable cover, whereas a permeable cover (*e.g.* Rotliegendes) may result in more complete degassing.

Creedy mapped an enhancement of ethane relative to methane near the Top Hard coal subcrop beneath the Variscan unconformity in the Witham prospect. Methane migration by diffusion is more rapid because its molecules are smaller in size. In the UK coalfields (with underlying Coal Measures) seams within the Westphalian C-D Warwickshire Group were rarely measured, so any enhancement cannot be resolved. There is also the added problem of an unconformity (aka Symon Fault) at the base of the Warwickshire Group in the SW Pennine area (Smith *et al*. 2005) and elsewhere, particularly on the basin margins of the underlying Westphalian A-B Coal Measures.

Gas content increase with increasing Coal Measures thickness

The Coal Measures depocentres can be identified by compiling isopachs of the Westphalian B age interval, defined between the *Aegiranium* and *Vanderbeckei* marine bands. This interval has been the most often drilled and dated, for coal and other exploration boreholes in the depocentres of the Pennines, southern part of the Kent Coalfield and western part of the South Wales Coalfield.

Isopachs of the overlying Warwickshire Group are located in different places *e.g.* Warwickshire-Oxfordshire, SW Pennines (Smith *et al*. 2005) and show different trends (NW-SE trend in Kent). This was shown diagrammatically by Smith *et al*. (2005) between the Pennine Basin depocentre in the north and the unconformable Warwickshire Group eroding down onto Precambrian rocks of St. George's Land in the south. The gas content of coals is greater in North Staffordshire, Lancashire and NE Wales compared to South Staffordshire, and is higher in the anthracitic part of the South Wales Coalfield which coincides with thicker Coal Measures.

Bacterial methanogenesis

The USA Black Warrior CBM fields have experienced uplift and freshwater flushing with bacteria (Pitman *et al*. 2003) in an analogous way to the Antrim Shale gas. The USA Powder River Basin coals also contain biogenic gas (Shurr & Ridgley 2002).

Water has been a problem for coal mining in a number of UK coalfields, but there is no evidence that earlier episodes of water flushing could have led to enhanced gas contents. Deep circulation of meteoric water has occurred within Carboniferous limestone in several basins north of the Variscan Front and in the east Pennines, leading to warm water emergence during Holocene times, but there is no evidence that the water rose into Westphalian strata. In Kent some downward contribution from Jurassic and Cretaceous aquifers into Westphalian strata has occurred, but it is not known whether this preceded mining operations. Water that is more saline and probably older occurs at greater depths in Snowdown and Tilmanstone collieries (Plumptre 1959). Gas was only a problem at Betteshanger (Plumptre 1959), but warm methane-rich water was encountered in one of the Dover shafts. Uplift and unconformities (particularly in Kent, where thinning Jurassic on the Weald Basin margin has resulted in several periods of erosion) have been viewed hitherto as detrimental to CBM prospects (Creedy 1994).

Degasification of coal samples before analysis

The problem of degasification of coal samples prior to analysis provoked debate during the first phase of CBM exploration in the UK (early 1990s). Hillfarm Coal Company managed to get their coal samples into canisters within 10 minutes after drilling ceased (Bacon 1995). American coals in CBM prospects are quickly analysed after collection to minimise losses of gas, whereas the National Coal Board (NCB) was accustomed to taking its time with samples before analysing them. Ayers *et al.* (1993) stated that an average delay of 9.7 hours occurred by the NCB method. This value and other data published by C Haynes have been plotted on Fig. 8, although Creedy (1991) believed the gas loss for NCB samples was less than half those recorded in the US.

NCB samples were crushed to measure the gas content, whereas Victorian scientists (*e.g.* Thomas 1875) subjected their samples to heating.

Coal comprises 3 principal organic constituents – vitrinite, exinite and inertinite. The latter group includes fusinite, which appears to be responsible for faster degassing rates, possibly because fusinite fractures more readily along bedding planes (Creedy 1983a). NCB sampling appears to have attempted to avoid the fusinite-rich coals (Creedy 1986, p 142). For a fusinite content of 20% about 16% methane was desorbed within 10 hours (Creedy 1991), which plots between C Haynes and Creedy (1991) data (Fig. 8).

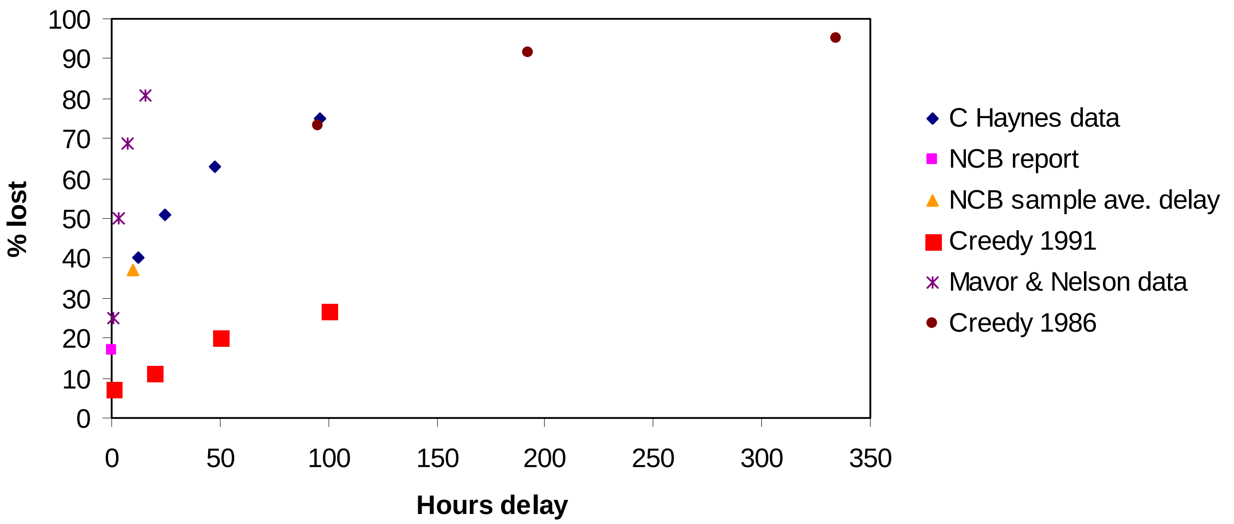

Figure 8 Gas desorption (degasification) of coal samples with time

The Upper Cretaceous Fruitland coals of the US San Juan Basin desorbed 69% of their measurable gas content in an average of 7 hours (Mavor & Nelson data in Donovan 2007), far higher than Haynes's data. This faster desorption is probably caused by their higher permeability (see Section 4).

Coal mining, and in particular the order of seam extraction, affects the methane content of return airways and of coal samples (Dawson 1954), indicating either that methane migrates from a mined coal to higher seams or surrounding seams lose methane during mining of seams. This is related to the de-stressing of rocks during mining and could be used as a model for horizontal and multilateral completions in recent CBM wells.

3. Coal maturity

The initial work on UK coal maturity was based on coal rank (volatile matter percentages) or fixed carbon ratio (Mohafez 1966) in National Coal Board boreholes. Later work has used vitrinite reflectance (White 1991, Bevins *et al*. 1996). The equivalence of these parameters, relative to the oil and thermogenic windows and anthracites is shown on Figure 9. Gas is present in greatest amounts within anthracites, so the thermogenic gas floor, containing very dry gas lies to the left of the red window. The gas storage capacity at reservoir pressure is known for UK coals – and most are reported to be undersaturated within coalfield areas (Creedy 1994).

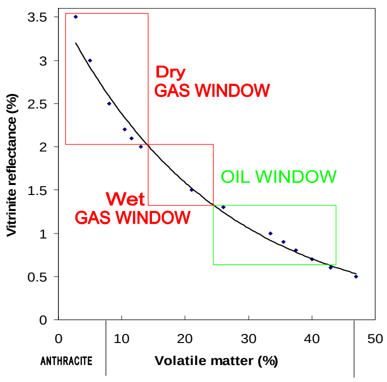

Fig. 9 Hydrocarbon maturity windows and main coal maturity indices. The oil window ranges from 25-43% volatile matter, and the wet gas window ranges from 14-25% volatile matter.

The USA Black Warrior Basin CBM fields occur within coals of the Pottsville Formation (Pennsylvanian age) lie in the oil window (Winston 1990).

Experience in different UK areas suggests that maturity was attained by the time of the Variscan orogeny and uplift at the end of Carboniferous times (Creedy 1988, Ayers *et al*. 1993), although Suggate (1976) preferred a Mesozoic age. The early coalification may have even occurred before the late Westphalian C unconformity (Symon Unconformity of the Welsh Borderland, Smith *et al*. 2005), seen in most coalfields. Mesozoic secondary coalification has probably occurred in the deep Mesozoic basins (Baily *et al*. 1995). Along strike variations in maturity near the Variscan Front were attributed by (Smith 1993) to thick and thin skinned tectonics and higher heat flow. There is also the likelihood that reactivated Caledonian structures were involved in this variation (near to the Caledonian Front in west Wales). Heat from underlying granites in NE England has enhanced maturity westwards from the Northumberland-Durham Coalfield. This has occurred even though the two granites here (Alston and Wensleydale) are known to have been emplaced in Early Devonian times. Elevated heat flow, comparable to that which still emanates today in Cornish Variscan granites, subjected unconformably overlying Carboniferous rocks to an increase in maturity (Creaney 1980, 1981, 1982). Concealed, undrilled postulated granites *e.g.* Market Weighton-Hornsea may also have had this affect elsewhere.

The Carboniferous maturity pattern and its effect on gas content and permeability has been modified subsequently by Variscan and later uplifts, which have led to degasification and migration of gas into conventional reservoirs. This has occurred in the Southern North Sea and Cleveland Basin, although a Westphalian source for other onshore gas fields and discoveries is not proven (DECC 2010). Subsequent re-burial in Permian and Mesozoic times has not produced equivalent burial depths, except in the Cheshire and Cleveland basins. The post-Carboniferous subsidence has preserved the gas content downhole gradients and the coal ranks because these are both related, unless methane has migrated back into coal seams subsequently. This seems unlikely, given the very low permeability of the coals, but it is more likely where mining has taken place. The gas contents of seams where no mining has taken place are likely to be higher. Dawson (1954) showed that in the Haig Mine, Cumberland, the gas content of the Bannock seam was between 3 to 7 times lower where the Main seam had been mined 37 m below, 8 years previously.

Volatile matter (%) and geothermal gradients

On a depth-volatile matter (VM) percentage plot (Section 2, Fig. 6) recent peats and Tertiary lignites plot to the left (lower VM) of the Carboniferous coals. The plot suggests that even the highest VM% Carboniferous coals have been uplifted by about 1 km. The older Carboniferous coals (Dinantian-Namurian) and the Kent and South Wales coals lie in the gas window and may have been uplifted by another 2 km. However, their gradient (increase of VM%) appears lower, which might signify a much higher geothermal gradient. US data from the US Cedar Cove CBM field, plots within the oil window (green frame), shadowed most closely by Downend borehole (Bristol Coalfield) of all the UK profiles. The anthracite field of South Wales has less than 8% VM, and it is not possible to attain values much lower than 4%. South Wales would require burial of more than 3 km relative to Keele to obtain the values shown.

In the South Wales Coalfield maturity increases gradually with depth, as expected by Hilt's Law, but it also increases more rapidly from SE to NW. Because of the configuration of the basin (Thomas 1974) it is unlikely that this maturity high in the NW is the result of burial alone. Bloxam & Owen (1985) suggested the cause was a post Carboniferous intrusion based on interpretation of an aeromagnetic anomaly (the nearest analogues are the Lundy Granite, a Tertiary intrusion, and minor post Carboniferous intrusions in Herefordshire). In the Appalachians Levine (1986) modelled 7-8 km of burial for anthracites but with palaeogeothermal gradients of less than 37˚C/km. A higher geothermal gradient is preferable for the South Wales anthracites (Gayer 1999), and the ultimate cause (atypical for a foreland basin) is either an underlying intrusion of post-Carboniferous age (Bloxam & Owen 1985, or retention of heat from an earlier emplacement, using the Weardale Granite model), or hot fluids derived from the Variscan fold belt (Gayer 1999), following the model of Oliver (1986) A higher geothermal gradient is likely, and it may have exceeded 100˚C /km by comparison with Tertiary gradients and maturity in the Rhine Graben, where crustal thinning has occurred. Bevins *et* al. (1996) suggested a high geothermal gradient of about 50˚C/km, based on fluid inclusion data at Wyndham Colliery. There is a topographic-driven meteoric hot water circulation system present today in Lower Carboniferous limestones in several areas, both along the Variscan Front and in Derbyshire, where karstic limestones allowed deep penetration of water in late Carboniferous times – this may have been driven by even higher topography within overlying Silesian sediments in the foreland synclines.

Using Rhine Graben data for comparison, most of the Midland and northern coalfields probably had higher geothermal gradients than the present day average, and even higher, over 100 ˚C /km at Beckermonds Scar and Raydale boreholes near the Wensleydale Granite. Carboniferous volcanism is widespread both at the surface (Derbyshire, South Staffordshire) and subsurface (Belvoir, East Midlands concealed area), which probably caused higher geothermal gradients in these areas.

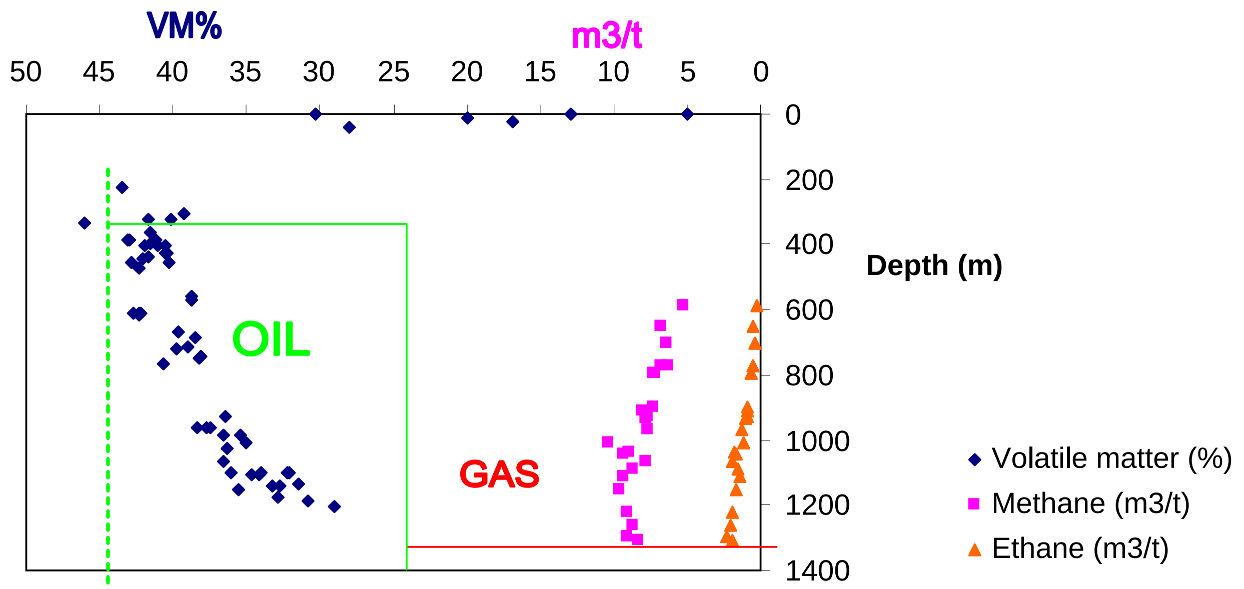

Fig. 10 A plot of volatile matter (VM) in the Keele borehole (Millot *et al.* 1947) and gas content of coals in the nearby Hobgoblin borehole (data in Creedy 1986). The range of coals analysed in both boreholes is broadly the same. The lowest coal (Winpenny) is 40 m deeper in Keele, whereas the highest coal (Great Row) is 70 m deeper in Hobgoblin. The oil window is defined as in Figure 9. The ethane content in coals rises below a depth of 550 m, indicating that wetter gases are being formed within the lower part of the oil window. Volatile matter values of less than 37% are considered the most favourable for gas generation, corresponding to the values in Cedar Cove CBM field.

Stuffken (1960) determined that the maximum expulsion of gas from coal occurs between VM 23-28%. This straddles the oil-wet gas windows (Fig. 9), corresponding to a porosity range of sandstones in NW Germany of 10-16% (Bartenstein 1979), and coinciding with the porosity range of East Midlands province Carboniferous sandstones. The porosity of the sandstones increases more significantly with VM greater than 38%, nearer to the oil window onset. This increase may equate with a permeability increase noted for US coals above 300 m (Section 4, Fig. 16).

A plot of percentage volatile matter (VM) of the Westphalian C-D Warwickshire Group coals shows two populations of maturity (Fig. 11). The high volatile coals of the Warwickshire-Oxford coal basin contrast with the Kent Coalfield boreholes, where the lower seams are low volatile coals. The Forest of Dean and Newent (Lower House boreholes) samples plot near the oil window. Pyrite and ankerite are present in the cleat of the Steeple Aston and Withycombe Farm coals (Cope *et al*. 1977), but permeability may be higher in these coals, as gas is present in the interbedded sandstones in both boreholes (Poole 1977, 1978). The low maturity of these coals (near the onset of the oil window) might indicate biogenic methane here. The increase in permeability of Westphalian C-D Warwickshire Group coals in central England , however, is offset by the low gas content; none of the boreholes have values higher than 1 m^3/t (Fig. 7). The permeability of the interbedded sandstones is high, although low near to an igneous sill at about 600-775 m in Steeple Aston.

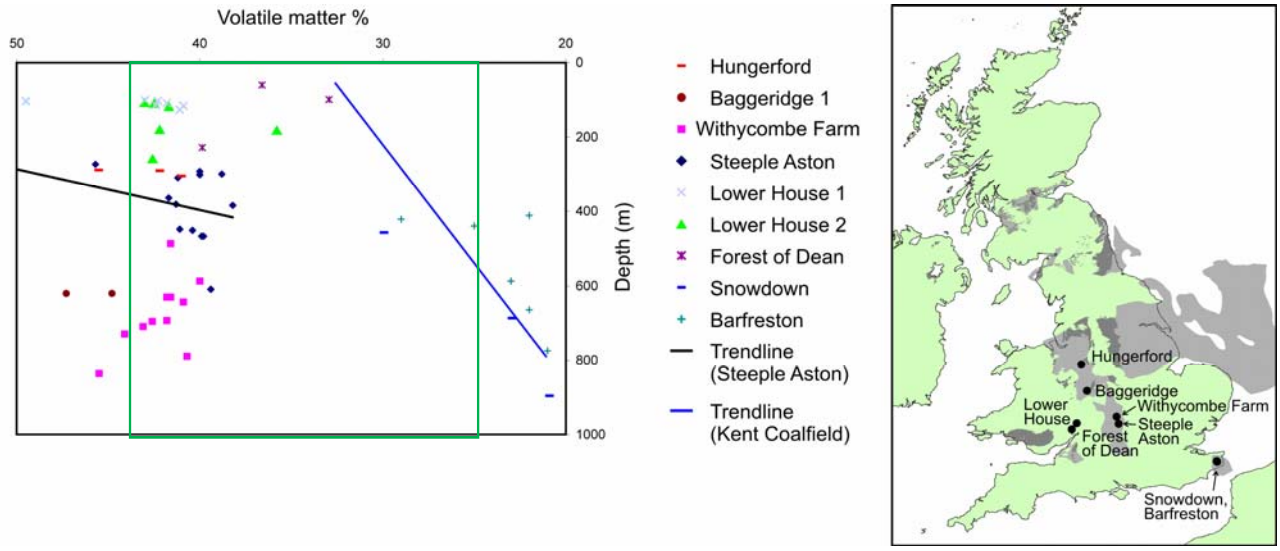

Fig. 11 Westphalian C-D Warwickshire Group seam maturity variability in the Warwickshire-Oxford coal basin, Kent Coalfield, and Staffordshire Coalfields with oil window highlighted in green.

The derived trendline for Steeple Aston is probably erroneous as it suggests a very high rate of VM decrease (50%/km) that boreholes outside Kent do not confirm. A VM gradient of 6%/km might be more appropriate for the non-Kent areas of relatively high volatile matter. The Kent boreholes (Snowdown and Hungerford), nearer the Variscan Front, show a VM decrease of about 18%/km depth, which might trend upwards to the shallower Forest of Dean values.

There is an increase in methane content with decreasing percentage volatile matter (Fig. 12, Creedy 1988). The threshold for significant gas generation at VM 37% results in a methane content of about 5 m^3/t east of the Pennines, whereas in North Staffordshire's Hobgoblin borehole (Fig. 3) the methane content at this same threshold is about 7 m^3/t.

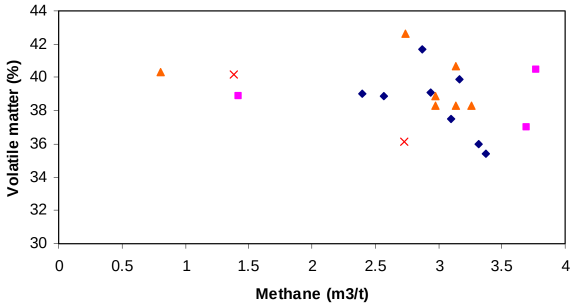

Fig. 12 Methane content plotted against percentage volatile matter (analyses of coals at approximately the same depths).

Moisture content

The moisture content is another indicator of maturity. On Figure 13 the oil window probably begins at about 5.5% moisture content and ends at about 1%. Presence of moisture causes swelling of the coal and reduces permeability (Lama & Bodziony 1998).

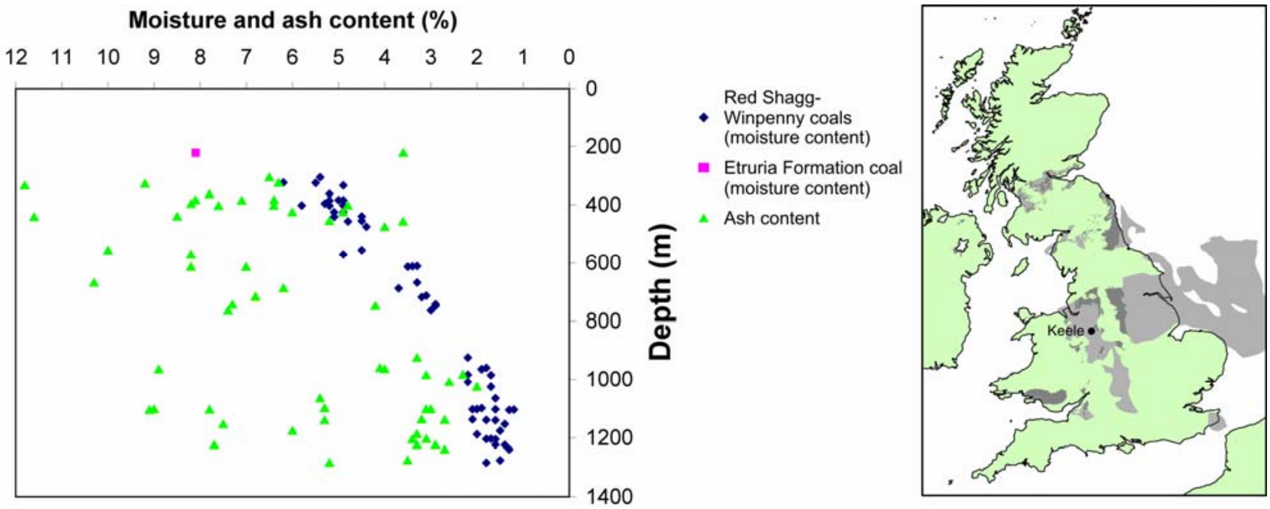

Fig. 13 Moisture and ash content of coals in Keele 1 borehole, showing a general decline in moisture with depth. Different samples of the same seam have moisture content differences of about 1% (Millott *et al.* 1946). Compare this with other maturity plots (Fig. 9, and of the same borehole Fig. 10).

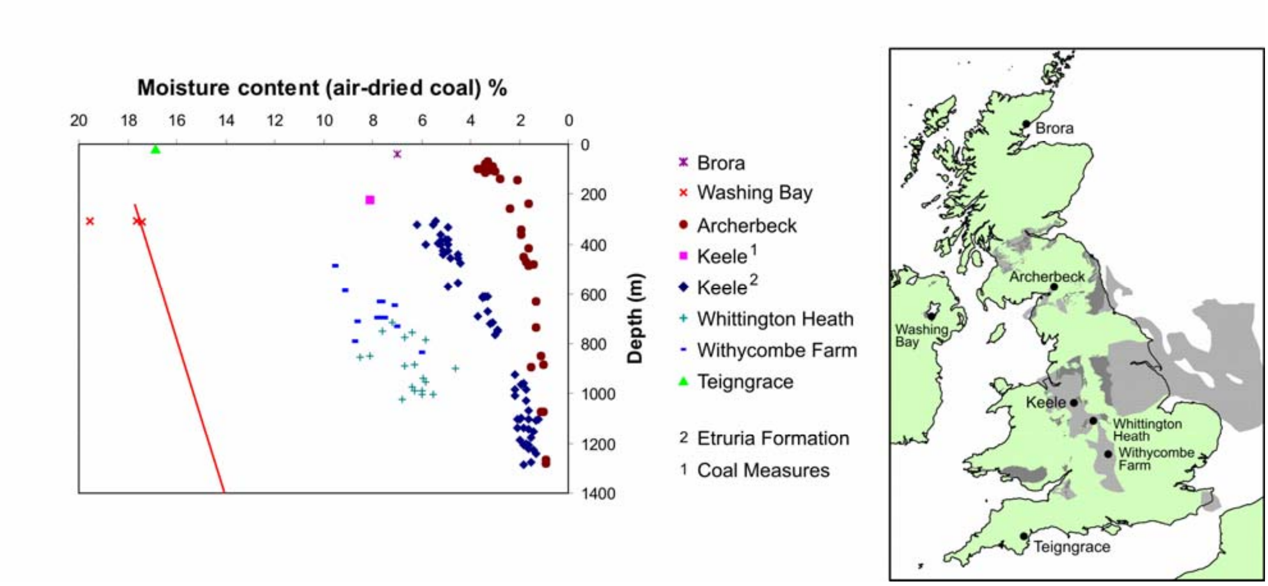

Fig. 14 Plots of moisture content of coals with depth

The decline in moisture content with depth (Figs 13 & 14) progresses from Tertiary lignites (15-20%, *e.g.* Washing Bay) to bituminous coals (less than 10%). The line on the left (Fig. 14) depicts the decrease in moisture accompanying burial in Tertiary lignites, extrapolated to depth. Plotting to the right of the graph, Whittington Heath, Withycombe Farm and Washing Bay boreholes contain coals which have not been significantly uplifted, whereas the coals plotting farther right have been uplifted. The Brora coal from northeast Scotland is of Jurassic age. Anthracites have moisture contents below 2%.

4. Permeability

The permeability and water content of Cretaceous-Tertiary US coals is radically different from its Carboniferous coals (Fig. 15).

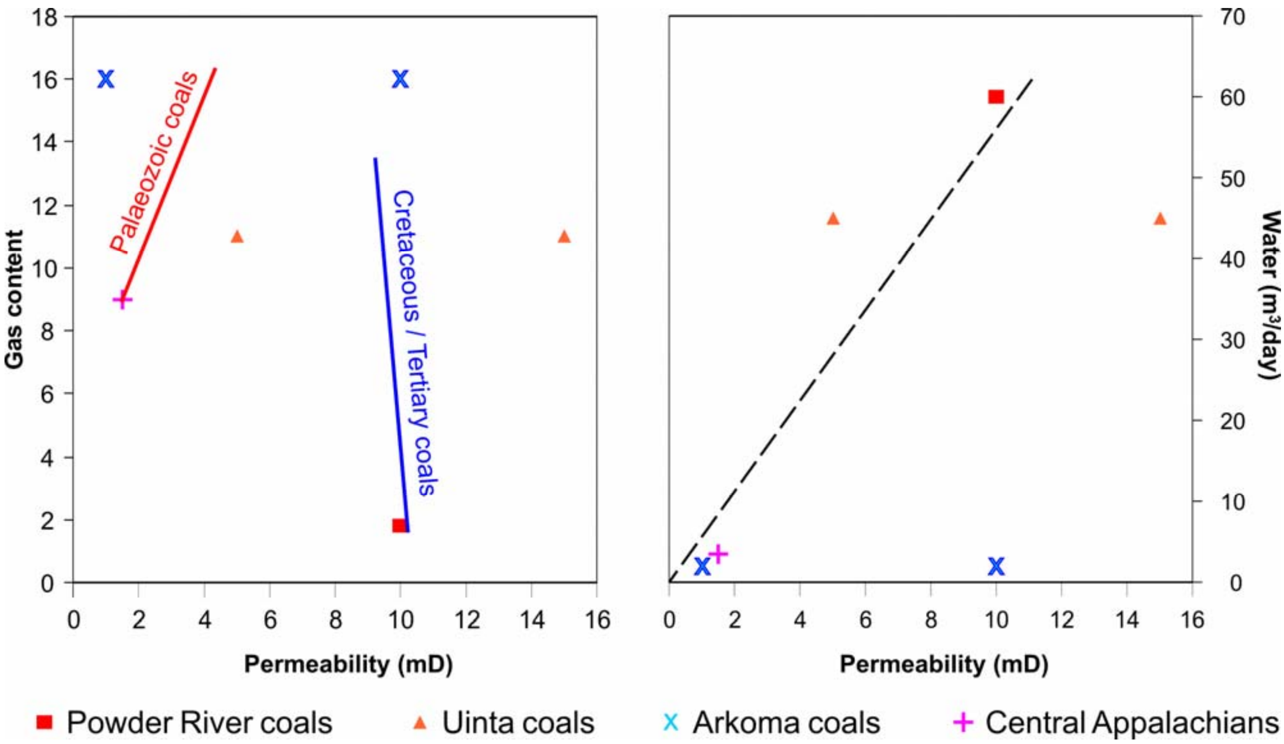

Fig. 15 A plot of permeability vs. gas content and water production for US coals. The water content is higher in the younger coals (Cretaceous-Tertiary age) of the Rocky Mountain foreland basin. The Appalachian foreland basin Carboniferous coals are more closely comparable with UK coals, but their permeabilities are still significantly higher.

There are few published coal permeability measurements for UK coals. On Figure 16 these are compared with US coals (modified from McKee *et al*. 1986), with the trendline following the lowest permeability coals in the USA. A permeability of about 5 mD, obtainable in US coals between 300-2,500 m depth (McKee *et* al. 1998) was said to be exceeded in the Aberavon well (Eden Energy recorded values of 18 mD and 44 mD above 250 m depth), and at Airth post-fracture values up to 25 mD have been recorded (Creedy 1999). The Great Row seam in North Staffordshire was estimated to have a permeability of 0.1-0.5 mD, whereas permeability of contemporary US Appalachian coals ranges from 0.1-27 mD and permeability of the US Black Warrior Basin coals from 2-30 mD (Creedy 1994). Durucan *et al*. (1995) recorded a permeability of 3 mD for a coal in an Evergreen-drilled well (Cheshire Basin area, possibly Sealand 1).

On Figure 16, the permeability values for Margam Forest (Enron) and Manvers Main Colliery (Oldroyd *et al*. 1971) coals are typical for the UK - very low, plotting on the lowest US coal trend (Flores 1998, McKee *et al*. 1986). The higher values at Aberavon 1 borehole (Eden Energy website 2008) may reflect the less deeply buried coals measured there, because the US coals show a rapid improvement in values above about 300 m depth. The Airth coal value was tested after a hydrofracturing (Creedy 1999), which puts it in the realm of an average US coal (but pre-fracturing).

Coal seams with permeability less than 5 mD are prone to outbursts, and a gas content of more than 8 m3/t is an equivalent trigger according to Lama & Bodziony (1998).

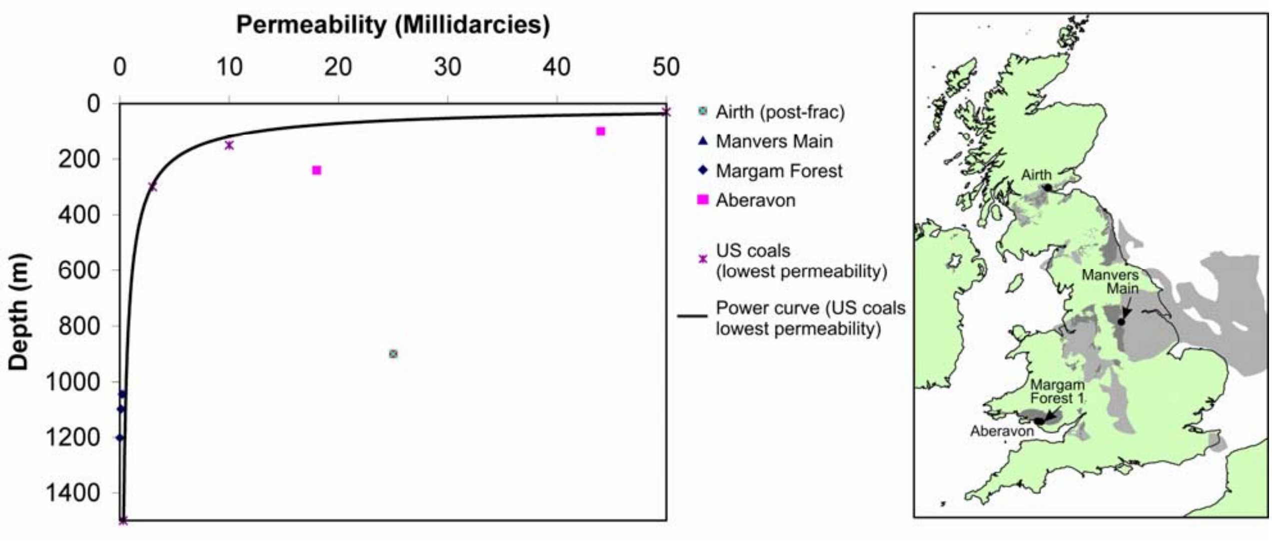

Fig. 16 A plot of UK coal permeability and the lowest permeability values of US coals vs. depth.

The permeability of interbedded sandstones, some of which had gas shows derived from the interbedded coals, can be used as a guide to the permeability of untested coals. However, the Steeple Aston coals probably have high permeability despite there being some sandstone beds with very low permeability in this borehole – probably as a result of intrusion of an igneous sill between 610-775 m depth.

5. Post-Carboniferous burial, faulting, and folding

Maturation of Westphalian UK coals generally took place at the end of Carboniferous times. This is because the maximum depth of burial occurred at this time prior to uplift associated with the Variscan orogeny. In areas including the Cleveland, Cheshire and East Irish Sea basins a further phase of deep burial occurred during Permo-Triassic and later Mesozoic times. This burial has resulted in 1.3% vitrinite reflectance being attained in Westphalian C-D Warwickshire Group sediments in the Knutsford borehole (Cheshire Basin). In excess of 6 km burial of the top of the Carboniferous may have occurred In the Cheshire Basin depocentre (Plant *et al* 1999).

Carboniferous faults may have disrupted the gas migration from coal seams, and large Permo-Triassic faults, typical of the Cheshire Basin, may also have prevented a consistent coal-degasification (Creedy 1988). Cleat orientations are modified near to large faults (Boardman & Rippon 1997).

Proximity to anticlines (*e.g.* Grand Valley CBM field in Piceance Basin, Colorado, USA) can lead to enhanced permeability and additional fracturing (Stevens 1993). In the UK, thinning of coal seams is reported over the Western Anticline of the North Staffordshire Coalfield (MacCarthy *et al*. 1993), and the Limestone Coal Group thins over the Plean, Balmule and Burntisland anticlines in the Midland Valley of Scotland (Cameron & Stephenson 1985, fig. 22) and NE-trending syn-sedimentary faults, south of Glasgow.

6. Fractures

Fractures in coal are known as cleat, and these include face, butt and cross-cleat systems (Fox 1964). Slips occur in high maturity coals and in the vicinity of fold belts. Cleats are probably formed at early stages of coal drying and compaction, but they appear to be deflected by some faults (Fox 1964, Ellison 1997, Rippon *et al*. 2006).

Cleat systems in coals

Cleats form initially by moisture loss during the peat to lignite phase of coalification or contemporaneous gas loss. Later cleat might be formed in response to crustal stress. All ranks of coal contain cleat, and organic shales also show similar jointing (Laubach *et al.* 1998).

In massive bands of durain the cleat is more widely spaced than in bright coal. Cleat frequency is also inversely proportional to bed thickness (Spears & Caswell 1986). Maximum cleat formation falls in a rank range of 88-92% carbon. Cleat frequency has also been related by Law (1993) to maturity (vitrinite reflectance, VR), with a large frequency range (12-2 cm) in the immature, pre-oil window stage and 2-0.5 cm ranges coinciding with VR values up to 4%.

A few local differences of cleat azimuth occur within different coals at the same colliery in Scotland (Dron 1925).

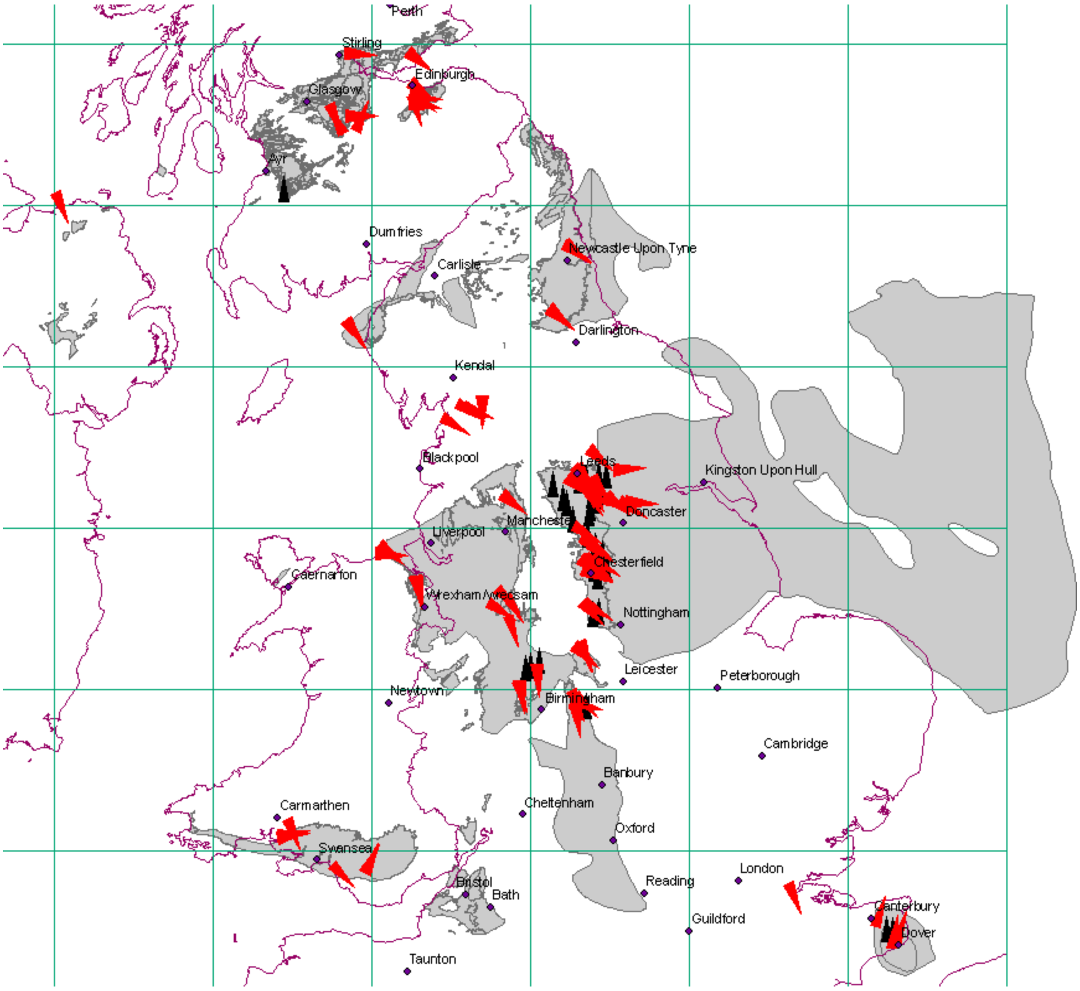

Fig. 17 Map of selected cleat directions (red) and cleats without recorded orientation (black). The symbols outside the Westphalian Coal Measures relate to Tertiary lignites and older coals.

The dominant trend of the face cleat is NW-SE in northern England (Fig. 17), matching the trend of the more widely-spaced joints in surrounding rocks (Moseley & Ahmed 1967). More detailed local maps are shown in Fox (1964), Ellison (1997) and Rippon *et al*. (2006). Some of the important and many small Carboniferous faults also have this trend, but the Carboniferous folds in the Craven Basin are perpendicular to this trend. The NW-SE face cleat trend of the Yorkshire and North Derbyshire coalfields becomes aligned N-S towards St George's Land (southern Nottinghamshire, South Staffordshire, Warwickshire and south Derbyshire-Leicestershire). A slightly more westerly trend is apparent in the Lothians, Northumberland and Durham coalfields. In Lancashire the trend is not so regular, trending WNW. The North Staffordshire Coalfield face cleats are mainly orientated NW. South of St George's Land, in south Wales face cleat trends are variable, with E-W trends in the anthracite field to the west and N-S trends east of the Neath Disturbance, and also in Kent.

Cross-cleat development is intermittent in many fields, and is locally complex. It may appear locally dominant over the main cleat (Fox 1964). The angle between the cleats varies considerably, but the mean is 85˚ (Strauss 1967).

The face cleat trend in the USA Black Warrior Basin in Alabama is NE, parallel to the adjacent Appalachian fold belt (Pitman *et al.* 2003), but perpendicular (SE trend) to the folds in Pennsylvania (Ayers *et al*. 1993).

Horizontal boreholes drilled perpendicular to the face (main) cleats yield much higher gas yields (up to ten times) compared with boreholes perpendicular to butt cleats, thus suggesting that face cleats are the primary conduit for CBM (Kulander *et al*. 1980). Ayers *et al*. (1993) also reported Russian mines having several times greater gas emission from mine faces lying perpendicular to the face (main) cleat.

Cleat mineralization

Mineralization of the cleats in the USA Black Warrior Basin is pyrite and calcite (Pitman *et al* 2003) and in Illinois pyrite, kaolinite, calcite, with lesser amounts of sphalerite, galena and quartz. Compared to the UK, ankerite is absent (Hatch *et al*. 1976). Cleat mineralization in most Midland coalfields was described as patchily developed (Baily *et al*. 1995).

In four coal seam profiles from the Cannock Coalfield, West Midlands, the cleat (joint) frequency is a function of lithotype (greatest in vitrain) and it is inversely related to bed thickness (Spears & Caswell 1986).The cleat minerals present are pyrite, marcasite, sphalerite, galena (sulphides), quartz, kaolinite (silicates), ankerite, calcite (carbonates) and apatite. The sulphide-silicate-carbonate sequence has features in common with diagenetic sequences recorded in other rock types, and it was concluded that the cleat minerals in coal form in response to pore fluid evolution and movement during burial diagenesis (Spears & Caswell 1986). Unfortunately no cleat orientations accompany these findings.

Midlands coalfields show fairly open fractures, containing thick ankerite fillings, whereas in South Wales the cleat planes are never so wide, permitting only thin films of ankerite or pyrite to form (Fox 1964).

Slip, feather and slickenside fractures

Slip fractures generally dip at 45-60˚ to the bedding, and occur in higher rank coals of the South Wales and Kent coalfields, often showing dip slip, slicken-lineated polished surfaces (Harris *et al*. 1996). Their strike is often parallel to the minor normal cross faults (Boardman & Rippon 1997). The slips, which are usually unmineralized, often contain dust, indicating that friction was present along these planes. They are mainly related to tectonic deformation, as these areas lie close to the Variscides (Fox 1964), but they are known in other coalfields near large faults. Feather fractures have variable orientations, and represent late stage deformation related to compression. Slickenside fractures have highly polished surfaces reactivating pre-existing discontinuities. Where all these fractures are intensely developed, friable coal is formed from the anthracite and is likely to desorb methane more rapidly (Harris *et al*. 1996).

Present day stress

Borehole breakouts reveal that the current maximum horizontal compressive stress is orientated NW-SE (Evans & Brereton 1990). Ayers *et* al. (1993) suggested that NW-SE trending cleats are the most likely to have remained open, but there is no evidence for this. Methane outbursts at Ireland Colliery (East Midlands) were aligned NE-SW, although faulting, jointing, main cleats, folding (Arscott & Hackett 1969) and (possibly) the maximum compressive stress are aligned NW-SE there. However, because the Variscan anticlines at Ireland Colliery trend NW-SE Variscan local maximum stress was probably NE-SW.

7. Thickness of coals and coal type

Carboniferous coals were deposited in paralic basins, subject to thin marine incursions. These basins do not generally have many seams greater than 2 m in thickness. There are also Carboniferous limnic coal basins on continental Europe (*e.g.* Saar-Lorraine), where thicker coals are known. Gondwana coals (*e.g.* India) and Mesozoic and Tertiary coals in America are often much thicker (*e.g*. Fruitland coals 7-15 m).

However, thicker paralic coals occur in some places (Figs. 18, 19) near the northern margin of St. George's Land (Wales-Brabant Massif), where subsidence was slower and there was less dilution by sand and mud than in the basin depocentres. The percentage of coal to drilled Westphalian Coal Measures thickness (Fig. 19) shows the location of these thick coals, which in effect represent the amalgamation of several seams (e.g. Thick Coal of Warwickshire Coalfield).

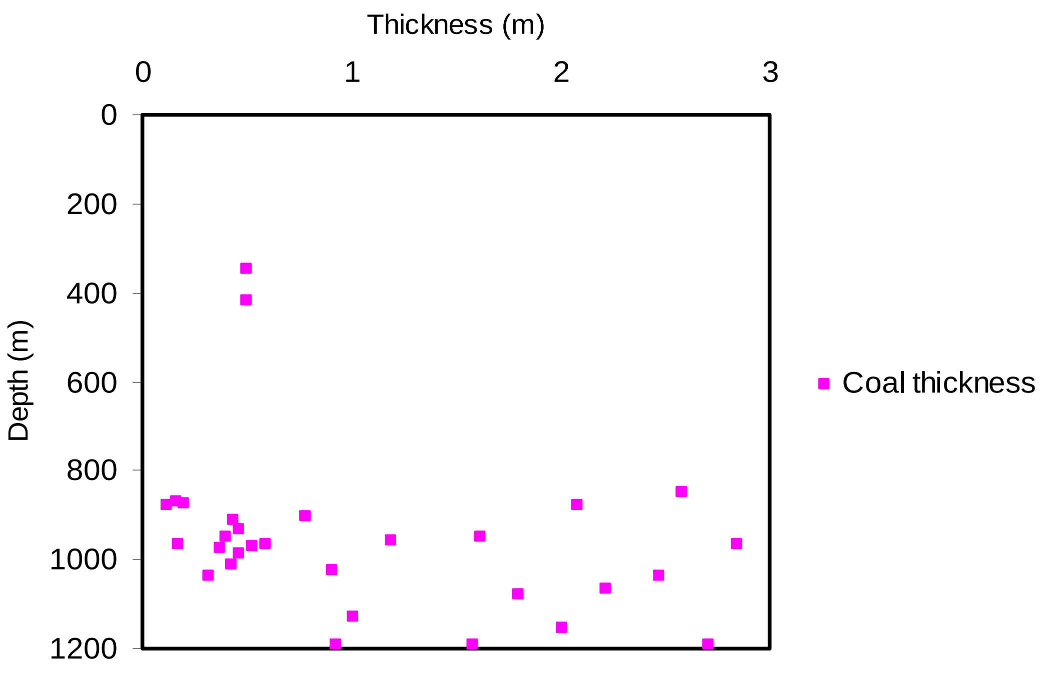

Fig. 18 Thickness of coals at Overton Bridge borehole, NE Wales (Fig. 3). The cumulative thickness of coal in the drilled interval is 32.39 m, and the ratio of coal to non-coal is 0.038. The coals at c 400 m are within the Halesowen Formation (Westphalian D). The underlying Etruria Formation (Westphalian C) about 200 m thick) is normally, as here, barren, and the deeper coals are from the Westphalian A-B Coal Measures.

Coals containing more mineral matter (high ash content), result in duller, more poorly-cleated, gas-poor types. Ash contents have been published for a large number of coals and coalfields (NCB Folios), and they tend to be higher near basin margins (Baily *et al*. 1995). These coals are randomly distributed within the Coal Measures (Fig. 13). Exinite adsorbs 1.5 times more gas than vitrinite, whereas fusinite adsorbs 0.6 times as much as vitrinite.

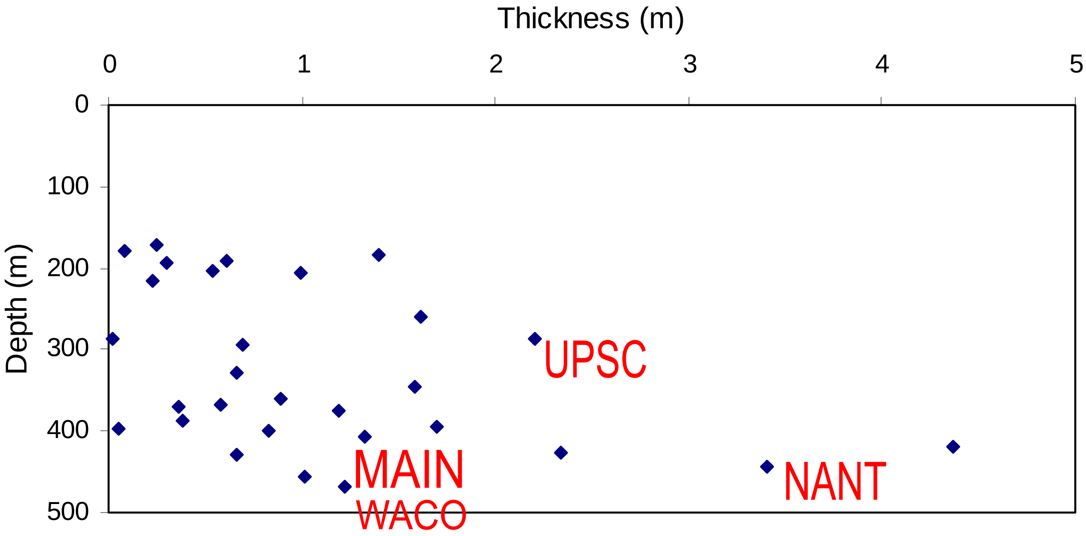

Fig. 19 Thickness of coals at Vauxhall Colliery Shaft, NE Wales (SJ34NW21) – most are thinner than 2 m thickness. The cumulative thickness of coal in the drilled interval is 31.49 m, and the ratio of coal to non-coal is 0.106. Thicker coals tend to be lower Westphalian B or Westphalian A in age. UPSC Upper Stinking coal, QUAC Main coal, NANT Nant coal, WACO Wall and Bench coal.

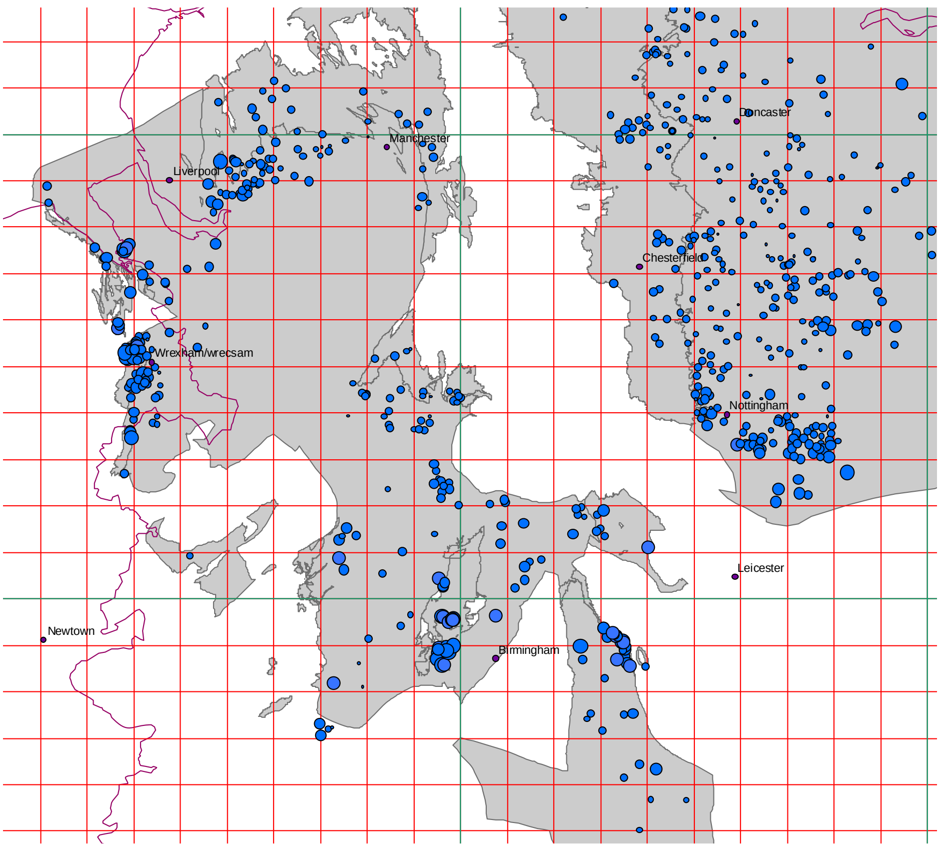

Fig. 20 Percentage of coal within Westphalian Coal Measures at a selection of coalfield borehole sites. The largest percentage of coals (thicker coals) occurs near to St George's Land, which had a fluctuating northern boundary in the English Midlands and NE Wales, with individual seams merging in a thin sequence in the Warwickshire, South Staffordshire, Belvoir and Denbighshire-Flintshire coalfields. Northwards, the Pennine Basin depocentre near Manchester has thinner coals.

8. Pressure and maximum methane adsorption capacity

The gas storage mechanism for CBM is unlike what is found in a conventional gas reservoir, where gas is compressed by the pressure in the formation and expansion of the gas provides the means for the gas to be produced. In a coal reservoir, the gas is stored within the coal matrix by a phenomenon known as adsorption. In adsorption, the gas molecules adhere to the surface of the coal. As the reservoir pressure is reduced, gas is released from the coal surface, diffuses through the coal matrix, and flows through the fracture system of the coal. The release of gas is commonly described by a pressure relationship called the Langmuir Isotherm.

During CBM production water is usually removed to depressurize the coal seam and allow the methane gas to "desorb" from the coal surface and then be produced. The act of desorption is a process were the gas that is bound to the coal surface is released with the reduction of pressure in the coal seam. As depicted in Figure 21, there is typically a phase in early CBM production in American analogues, dominated by the production of water during which the coal seam is depressurized. Usually this depressurization is required to facilitate the production of methane gas from a coal bed reservoir. Once the reservoir pressure has been reduced, the methane gas is released/desorbed from the surface of the coal and can be produced at the well head. Ideally, water production begins to decrease early and gas production rises eventually reaching a peak before a slow decline as the gas resource is depleted from the coal seam. Water production typically continues to decrease or may even stop as the amount of water within the reservoir is reduced. Gas production can continue after water production has ceased, but CBM wells often produce at lower gas rates than conventional reservoirs. However, Creedy (1983) stated that in the UK coalfields only Point of Ayr Colliery is possibly at or above hydrostatic pressure, with most of the rest of the coalfields substantially lower than hydrostatic pressure, so the time to peak flow through dewatering in the UK may not follow the American production profiles.

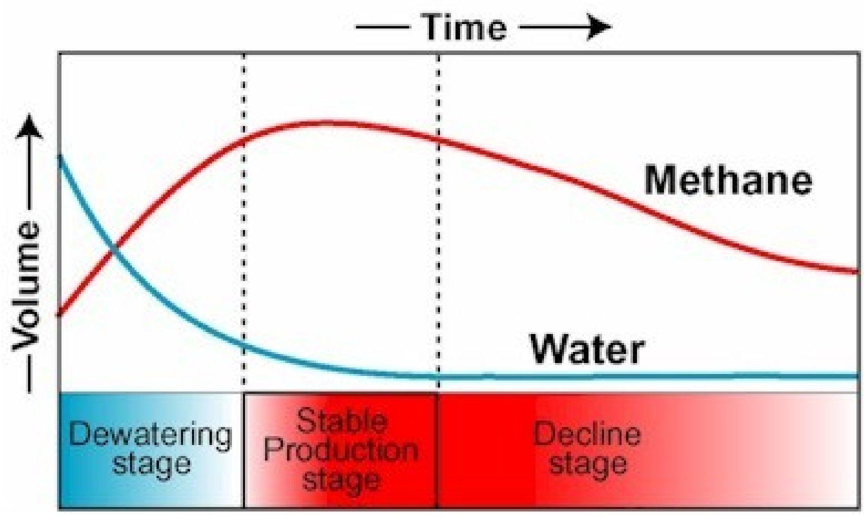

Fig. 21 Typical CBM production profile – derived from http://www.empr.gov.bc.ca /MINING/ GEOSCIENCE/COAL/COALBC/CBM/Pages/CBMBrochure.aspx

The methane desorption process follows a curve (of gas content vs. reservoir pressure) called a Langmuir isotherm. The isotherm can be analytically described by a maximum gas content (at infinite pressure), and the pressure at which half that gas exists within the coal. These parameters (called the Langmuir volume and Langmuir pressure, respectively) are properties of the coal, and vary widely. Two different coals may have radically different Langmuir parameters, despite otherwise similar coal properties.

Gas storage capacity = (1-fa-fm) Langmuir volume constant (scf/t) x Pressure (psia)/Langmuir pressure constant (psia) + Pressure (psia) – where fa =Ash content (fraction) and fm = Moisture content (fraction).

So the factors controlling the maximum methane capacity a coal can adsorb are pressure, temperature, moisture content and rank. Gas which is not trapped in the coal will migrate along faults or other permeable horizons into conventional reservoirs. Creedy (1988) measured a maximum adsorption capacity of Deep Softs Group coals in Roe Hill borehole as 11.2 m^3/t, whereas their actual gas content is less than half that amount.

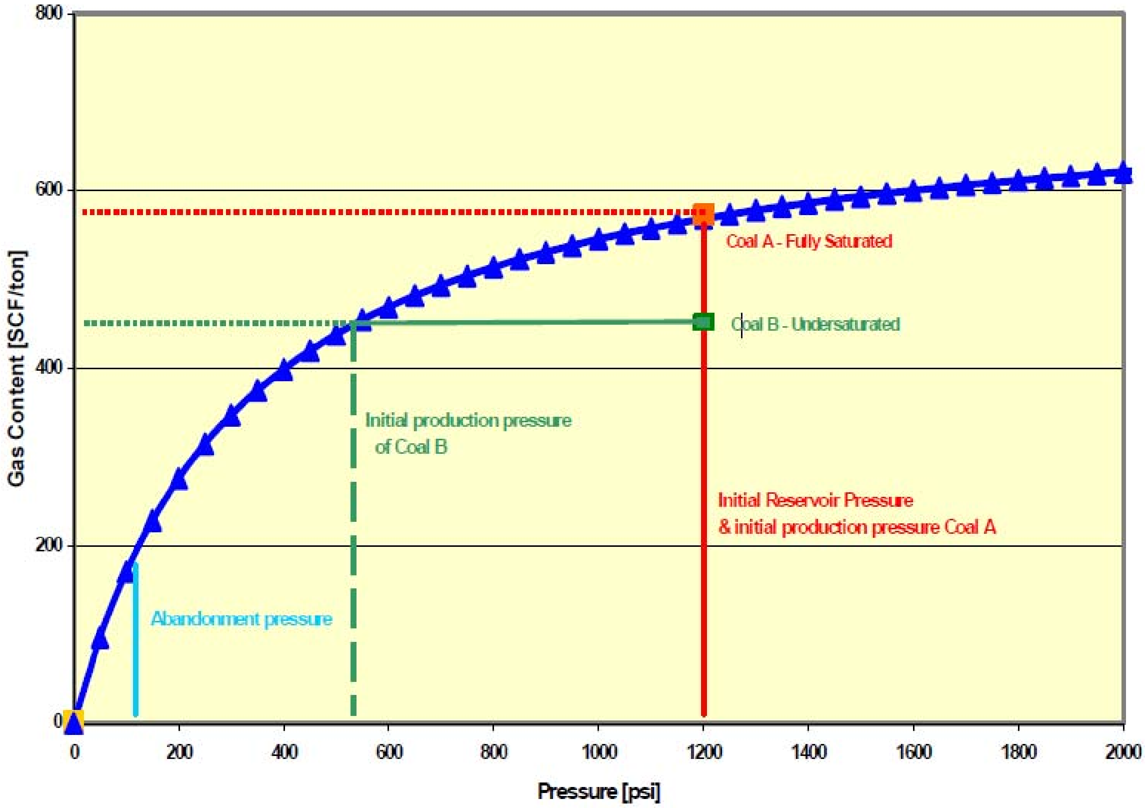

Fig. 22 The relationship of gas content and the adsorption isotherm determines the gas recovery factor, derived from http://www.cbmwellinfo.com/resources/adsorption_isotherms_procedures.pdf

In this example of reservoir pressure has been determined at 1200 psi for two coal samples (A and B) at very similar depth. Coal A is fully saturated and coal B is undersaturated (78%) relative to the maximum gas capacity at this pressure. The gas content and gas capacity of coal A coincide and so the critical desorption pressure for coal A is 1200 psi and gas should begin to be released from the reservoir almost immediately it is penetrated. For coal B the critical desorption pressure is much lower and can be determined at the intersection of the isotherm curve and a horizontal line at 450 scf/t gas content; i.e. approximately 550 psi. Reservoir pressure must be reduced from 1200 psi to 550 psi before gas will begin to be released from the reservoir at this location. If expected abandonment pressure is 125 psi then the available recoverable gas is much less for coal B than coal A. For A the unit gas volume potentially recoverable is the difference between 575 sc/t (at 1200 psi) and 175 scf/t (at 125 psi), or 400 scf/t of coal in-place. But coal B, the maximum potential recoverable unit gas content is the difference between 450 scf/t (at 550 psi) and 175 scf/t at abandonment pressure; *i.e.* only 275 scf/t.

Isotherm samples analysis are not currently available in the public domain for recent CBM drilling in the UK. DECC will work with industry to make CBM well adsorption isotherm data available in the future.

Jolly *et al*. (1968) measured methane adsorption capacity for 31 coals from the Nottinghamshire Coalfield and Brora, Scotland, with pressures varying from 515-1170 psi. Their methane capacity varies between 270 f^3/t and 1050 f^3/t (Cynheidre Pumpquart anthracite). Even the Jurassic Brora coal has a capacity of 790 f^3/t (22 m^3/t). The other coals, where known, are from depths of 460-630 m. A moisture content of 1.3% reduces the methane adsorption capacity by 21% and a temperature increase of 10˚C reduces the capacity by a similar amount.

9. Completion, pumping and testing

Perforation of about 10 coal seams and fracture stimulation for each seam were used in the earliest UK CBM production from vertical wells in Airth field (Bacon 1995). The operating company, Hillfarm Coal Co., pumped multiple sand and water injections, stipulating no use of gel. Fracture stimulation of the coal reservoir needs to consider the rock stresses, gas stored in adjacent reservoirs, and permeability. Reviewing the results of the fracture stimulation will be necessary to eradicate coal fines or fracture sand if these are produced, and to prevent fracture-induced diagenesis between proppant and fractured rock. Horizontal completions can have discrete ports for precise fracturing and monitoring, using non-damaging fluids and low temperature diverters (Department of Trade and Industry 2005).

Pumping and testing

Pumping continued for a long time at Airth field, beginning in early 1994. The water rate declined from 260 bpd to 30 bpd by early 1995 (Bacon 1995). The gas rate started high (60 mcfd), fluctuated as low as 6 mcfd and was producing at 35 mcfd in early 1995. This gas production was thought to be possibly from interbedded sandstones or gas in solution, since this is found elsewhere in Scotland in the Limestone Coal Group (Robins 1990).

Dewatering

The success of dewatering is obviously critical to a CBM well. The time taken for the well or a wider area to be dewatered has been modelled by different operators. Bacon (1998) envisaged a theoretical increase in gas production after 17 months (perhaps based on results from Airth production). Some wells never do dewater sufficiently, however, and this was acknowledged by Bacon's statement that 'only bounded CBM wells will work, unbounded wells will not'.

The salinity of Carboniferous formation water is shown to broadly increase with depth, particularly for the densest data in the East Midlands (Fig. 23).

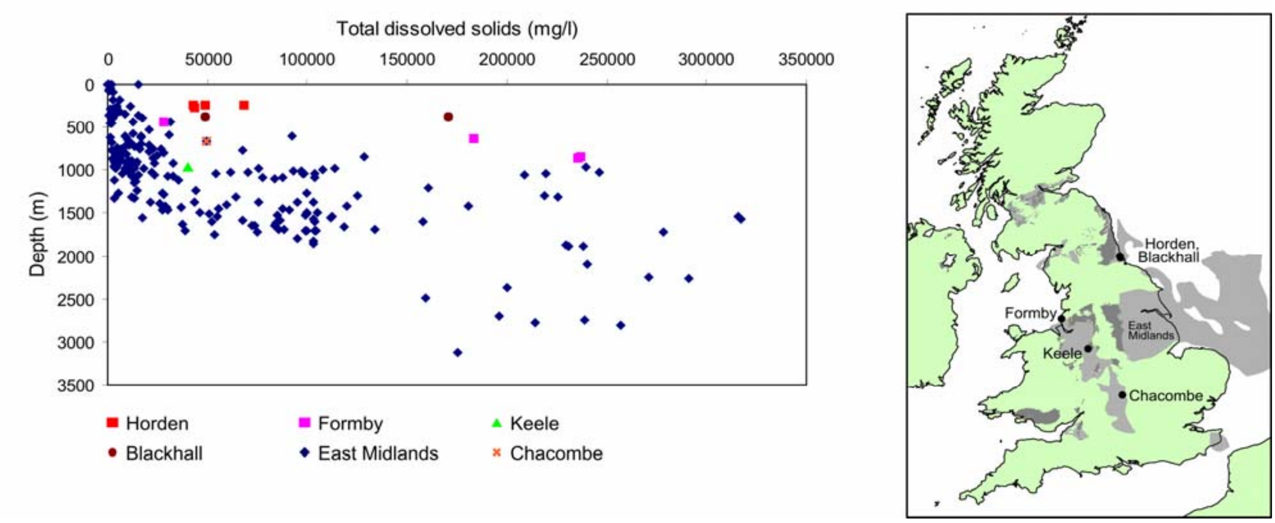

Fig. 23 A plot of total dissolved solids in water within Westphalian Coal Measures, showing an increase with depth but with a range of values so broad that equally saline water can vary in depth by up to 1750 m.

Disposal

At Airth field the produced formation water was put into road tankers and disposed of in the nearby Firth of Forth. Total dissolved solids, TDS is about 20000 mg/l at Airth, and iron has to be removed prior to disposal (Goold 2008). Drinking water should be less than 500 TDS.

10. Selected regions and licences

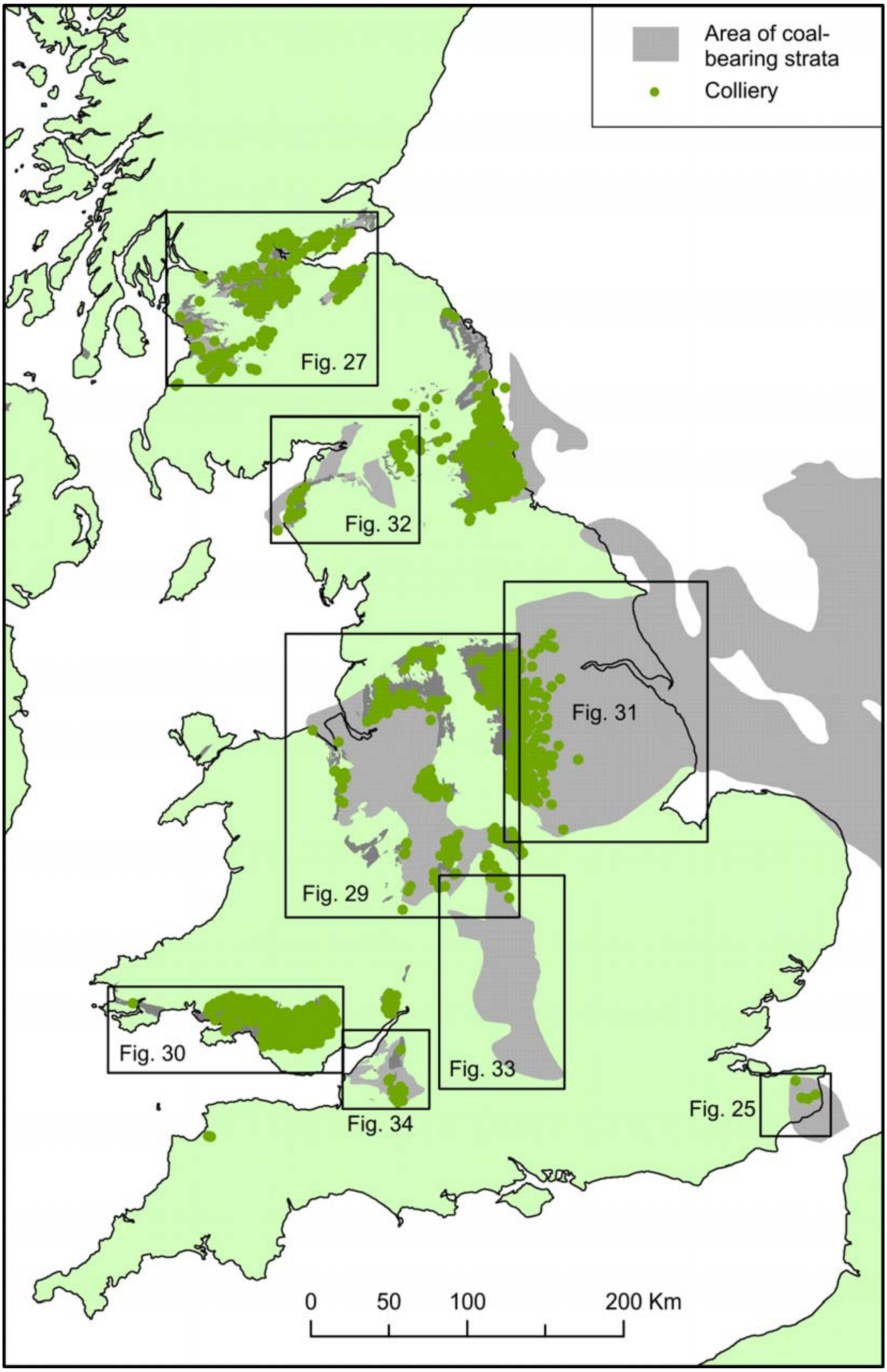

Fig. 24 Location of coal mines in the UK, and of Figures 25, 27 and 29-34

Unmined areas of the UK include Oxfordshire, Berkshire, Cheshire and between the Cumbrian and Canonbie coalfields (compare Figs 17 & 24).

Kent Coalfield

Measured gas contents in the Kent Coalfield are low (2.3 m^3/t on Kent 6 coal from a Tilmanstone face, Creedy 1986), and are very low in relation to their rank. Very few problems with methane were encountered in Kent coal mining except at Betteshanger (Fig. 25). The multiple unconformities on the NE margin of the Mesozoic Weald Basin and the permeable overlying limestones and sandstones (Fig. 26) may have allowed migration of gas out of the coalfield over an extended period of time. More gas content measurements are needed here before prospects can be written off again (see Fails 1996), especially as freshwater influx from Mesozoic aquifers (Fig. 26) may have formed biogenic methane.

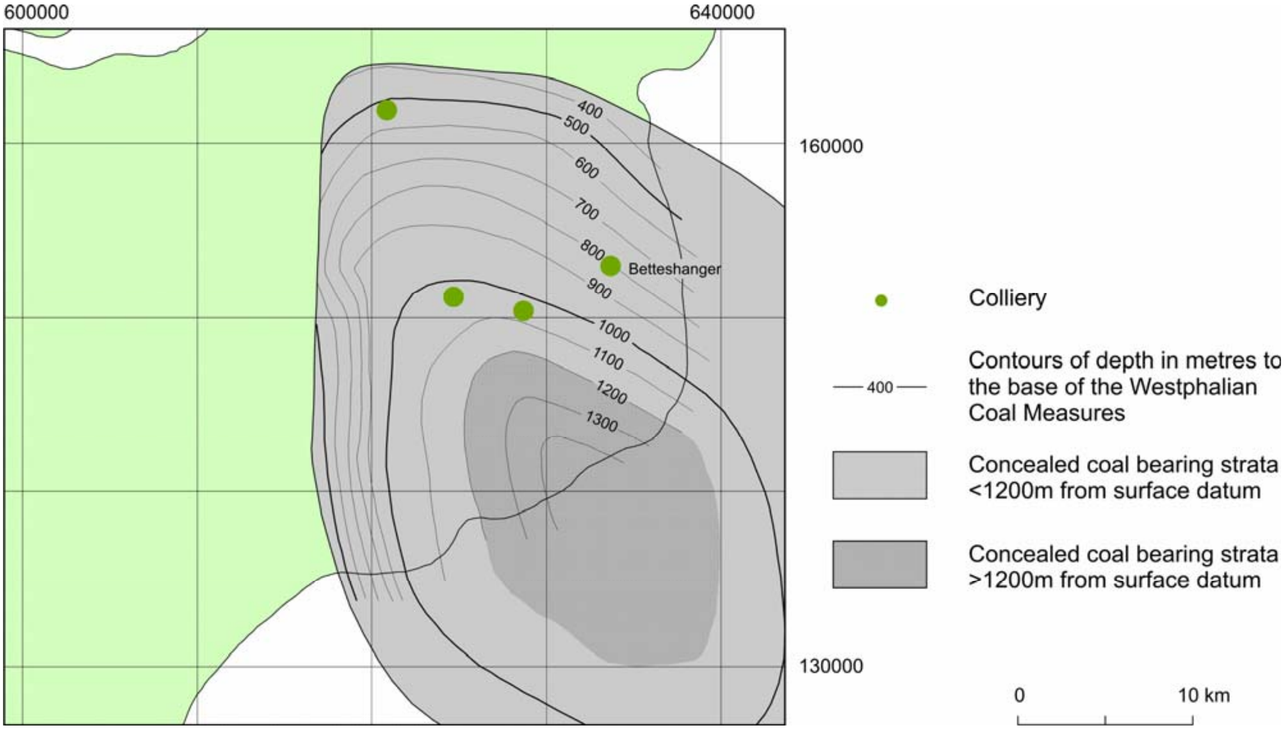

Fig. 25 Kent Coalfield mines and depth in metres to the base of the Westphalian Coal Measures. Note that no part of the Kent Coalfield is considered to have 'good' coalbed methane potential based on the low NCB gas contents (but see discussion in text and Fig. 7).

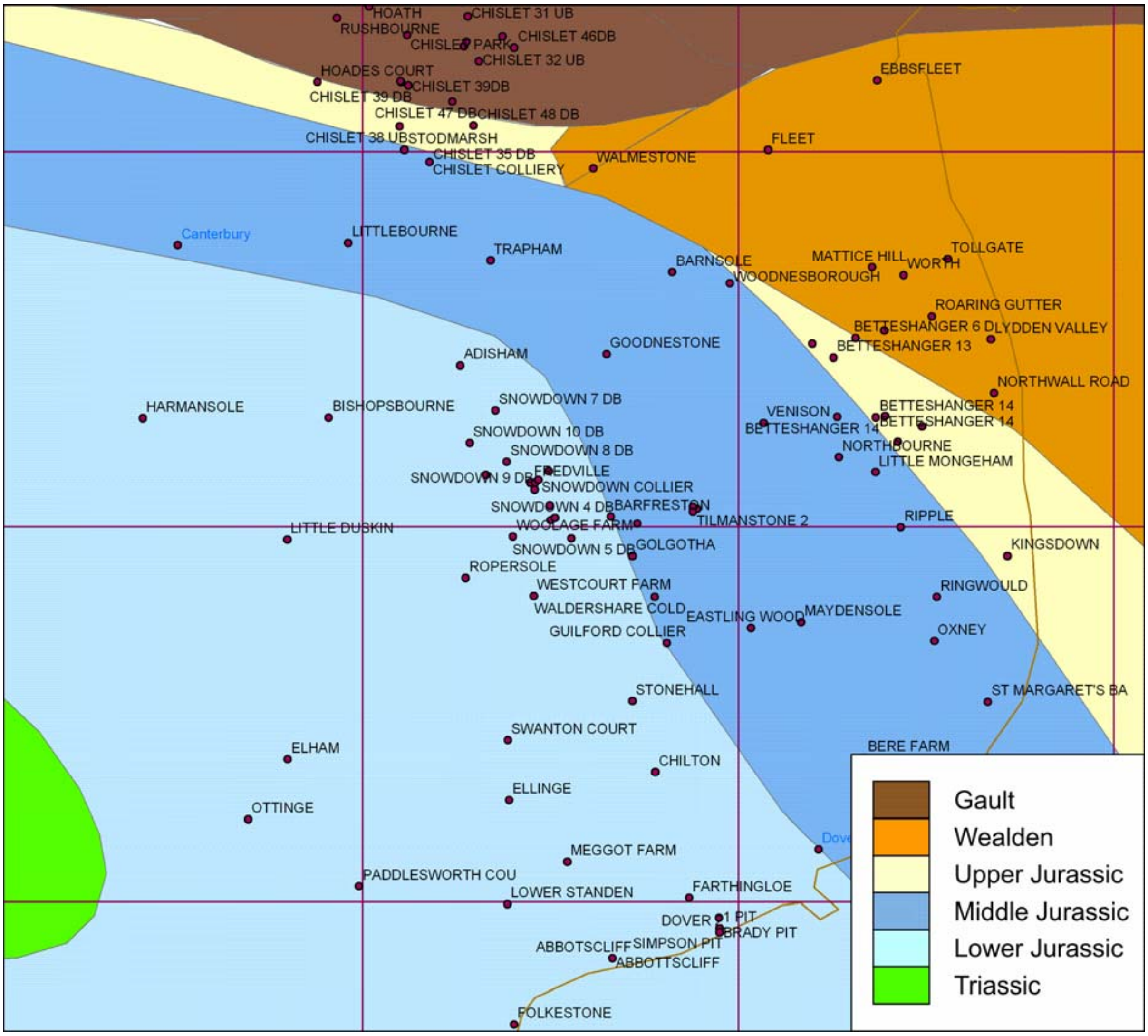

Fig. 26 Kent Coalfield exploration boreholes and supercrop

Scottish coalfields

The prospectivity of various unconventional hydrocarbon technologies in Scotland was assessed by Jones *et al*. (2004). Two of the prospective areas (Fig. 27) are discussed here.

Airth CBM pilot field, EXL 237, NS88NE

This field was initiated by Hillfarm Coal Co. in 1993 after their careful comparison of the gassiness of mined coals in old records in the Limestone Coal Group (Bacon 1998). Gas content in the Cloven and Kilsyth seams at Carodwan Colliery varies between 3.6-4.9 m^3/t. Other National Coal Board data had indicated low gas contents in the overlying Upper Limestone Group and Coal Measures (Creedy 1986). At Airth 1 well the Bannockburn seams have high methane contents (8-10 m^3/t) and after hydrofracturing their permeability was 25 mD. Water production declined from 260 bpd to 30 bpd in 1995 (Bacon 1995) but possibly rose again to 50 bpd in 2001. Gas production began at 60 mcfd (January 1994), fell as low as 6 mcfd and reached 35 mcfd in 1995 (Bacon 1995). Coalbed Methane Ltd took over the licence by 1996 and drilled Airth 2, 3 and 4 wells – their production rates are unknown. Composite Energy took over Coalbed Methane's interests by 2004, drilling Airth 5-11 inclusive by 2007 as horizontal completions. No public domain information is available on the gas content, permeability or water and gas production of these wells at this time.

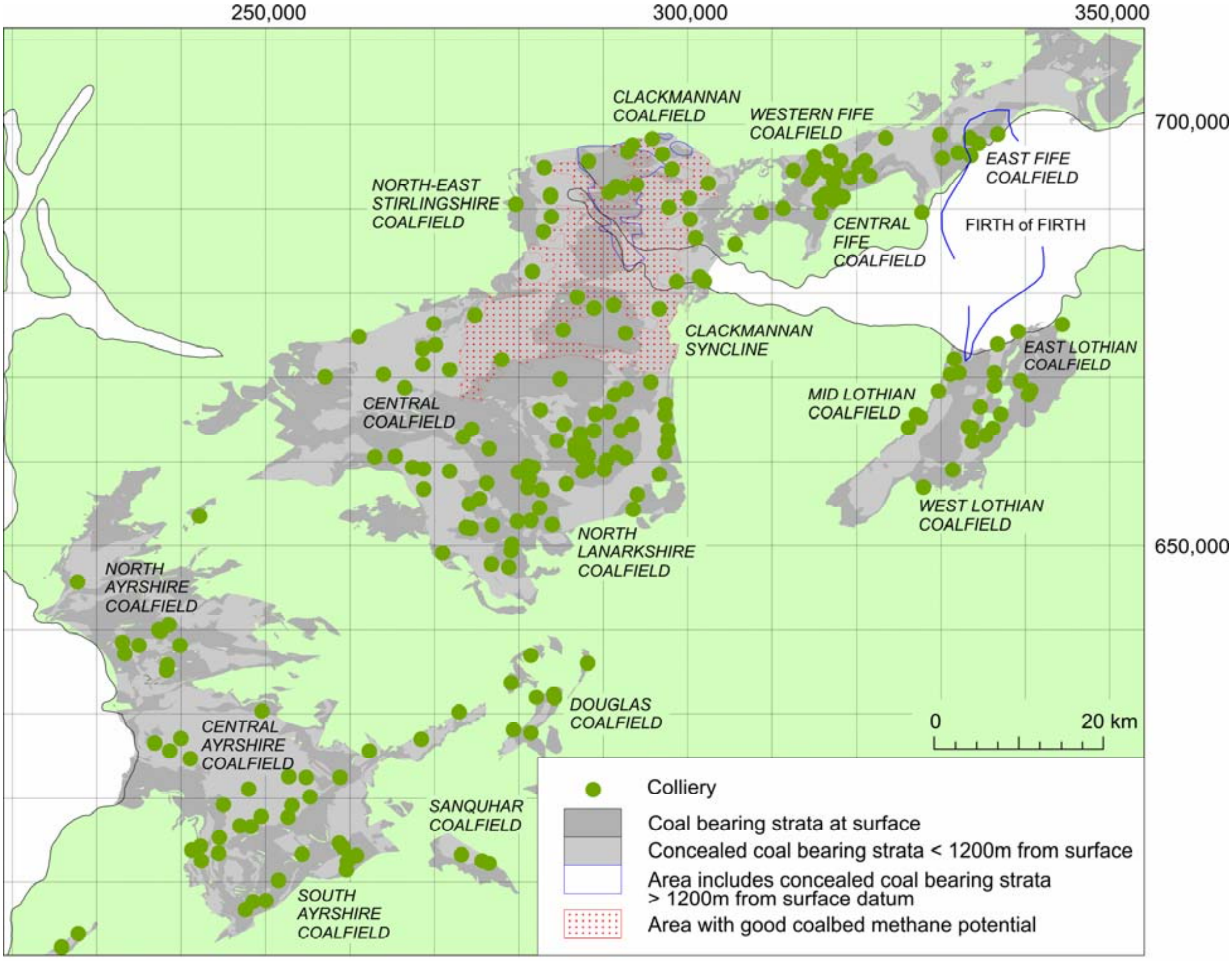

Fig. 27 Scottish coalfields – summary map of unconventional hydrocarbon potential

The Airth field, lying within the Clackmannan syncline of the Midland Valley of Scotland, spudded into Westphalian A Lower Coal Measures. Coals down to the Index Limestone have low gas content values according to Composite Energy's website, and to National Coal Board data (Creedy 1986, Fig. 28, Table 1). Higher gas values are found in the Bannockburn seams in the Limestone Coal Group (Namurian) about 500 m deeper than the Hirst coals. These coals were known to be gassy from explosions in nearby mines (Quarter and Herbertshire collieries, Goold 2008).

South Letham borehole (National Coal Board) nearby recorded ankerite mineralization in the joints of a coal seam and oil shows in the Limestone Coal Group.

Fife (EXL 240)

Data from Airth 1 well were used in an unpublished appraisal of Fife CBM potential by Pentex Energy (1995), based on their Milton of Balgonie wells. The Limestone Coal Group has over 60 seams in Milton of Balgonie (net coal 7%). Pentex estimated gas in place in their licence to be 647 bcf, based on the Airth values (Pentex 1995). Their resource estimate also includes gas in place in the Oil Shale Group, Lower Limestone Group and Upper Limestone Group, but exclude coals below 662 m in the Milton of Balgonie 1 well.

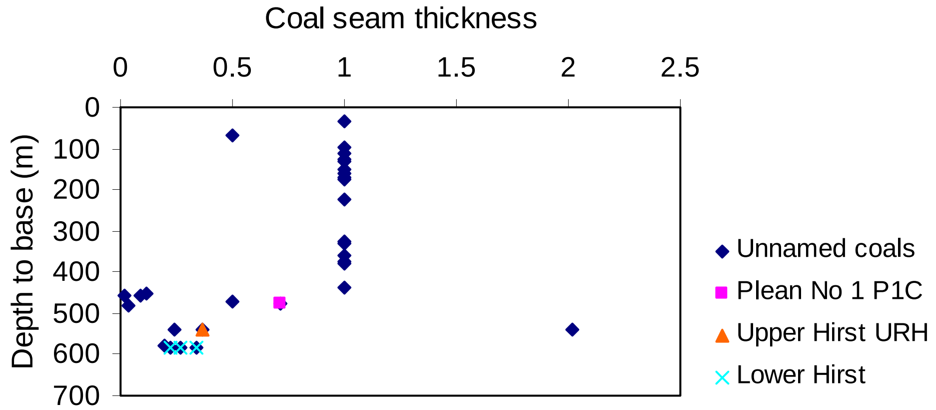

Fig. 28 A plot of coal seam thickness in the Westphalian Coal Measures and Namurian to early Westphalian Passage Group vs. depth in the Inglewood borehole, near Airth. Some unnamed coals have been allocated an arbitrary 1 m thickness. Plean No. 1 and Upper Hirst seams both have 0.35 m^3/t gas content

Formation /age	Borehole	Easting	Northing	SEAM NAME	Ash-free CH_4	DEPTH OD (m)
CA	Seafield	327800	689400	Dysart Main	1.2	
LSC	Polkemmet	243089	663821	(Woodmuir) Jewel	1.5	
LSC	Monktonhall	332200	670200	Stairhead	0.8	
CA	Frances	331980	692490	Bowhouse	0.6	
ULGS	Castlehill	284016	652075	Upper Hirst	0.4	
ULGS	Bogside	320630	698510	Upper Hirst	2.7	
LSC	Cardowan	297800	690000	Kilsyth	4.9	
LSC	Cardowan	297800	690000	Cloven (?Dumbreck)	3.6	
CB	Killoch Colliery	248000	620300	Ayr Hard	2.8	500
LSC	Killoch Colliery	248000	620300	Main, CE	2	600
LSC	Killoch Colliery	248000	620300	Main, CE		783
ULGS	Airth 1	288521	485487	Plean No 1	low	
ULGS	Airth 1	288521	485487	Upper Hirst	low	470
LSC	Airth 1	288521	485487	?	8	
LSC	Airth 1	288521	485487	Bannockburn	10	850

Table 1 Methane content data for Scottish coals. Westphalian and younger Namurian coals have very low methane values in Scotland (Creedy 1986). CA Westphalian A, CB Westphalian B, ULGS Upper Limestone Group, LSC Limestone Coal Formation. Ash free CH^4 is in m^3/t.

Midlands and NW England

These coalfields generally have increasing gas contents northwards. Exploration is being conducted by Composite Energy, Nexen-Island Gas and others.

North Staffordshire (SJ84)

Island Gas and Nexen are currently drilling the Keele Campus or Business Park CBM well (http://www.islandgas.com/uploads/100614igasspuddingatkeele.pdf). The target is the 3.4 m thick Great Row seam at 535 m depth. Island Gas refer to the nearby Willoughbridge well as a source of permeability data – this well encountered 17.4 m of net coal, including one 2.4 m thick seam and another of 2 m thickness. Three former National Coal Board boreholes nearby and Cliffords Wood borehole record the presence of similar thickness of the Great Row seam.

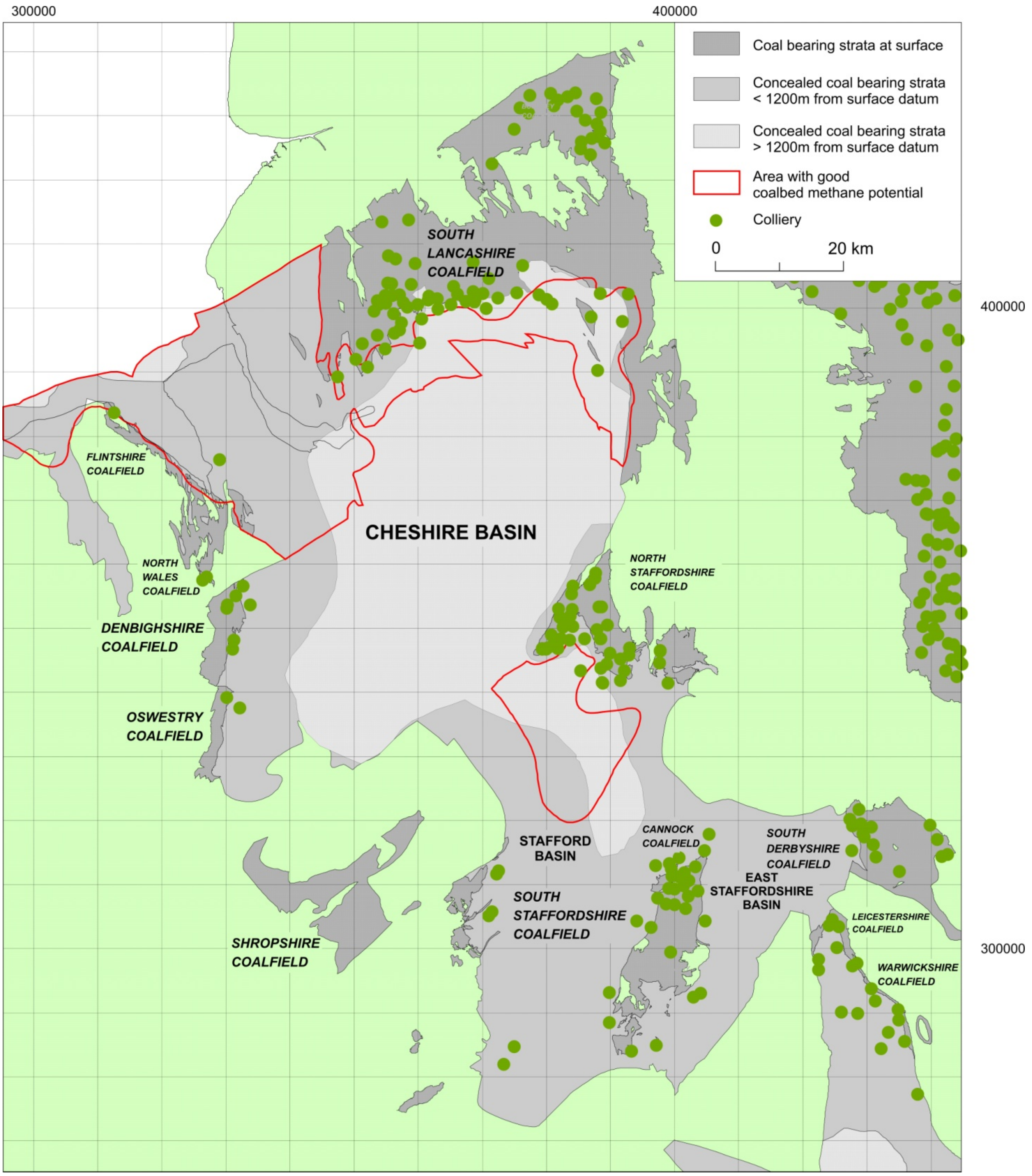

Fig. 29 Midlands and NW England – summary map of unconventional hydrocarbon potential

Doe Green CBM pilot field

Island Gas and Nexen's Doe Green 2 well has been producing gas at 45 mcfd. The first UK pilot production of electricity was established from CBM here (PESGB Newsletter, May 2009) from Westphalian coals of the Lancashire Coalfield subsurface.

Cheshire-Stafford Basin EXL282

MacCarthy *et* al. (1996) reported a net thickness of coal of around 40 m in a succession that thins markedly over the Western Anticline to the north-west. The Keele well data depicted in Figures 10 and 13 is relevant for this licence. Data show that the synclines contain more mature coals. The average ash content is 5.9% in Keele well, although the Cannel Row and Rowhurst seams average 17.8% ash in other boreholes and the Winghay seam reaches 22% ash at Silverdale Colliery Indeed ash content can be variable within the same seam (Fig. 13, MacCarthy *et al*. 1996). Gas content was reported to be up to 9 m^3/t, but is about 6 m^3/t in the eastern part of the coalfield. At Darlaston borehole nitrogen comprises 3-14% of gases at all depths, and carbon dioxide decreases with depth (Creedy & Pritchard 1983). MacCarthy *et al.* (1996) record main cleat orientations at 125˚ and subordinate sets at 105˚ and 155˚ at opencast sites. The main cleat orientation is at 163˚ at Barlaston workings. Gas outbursts in the North Staffordshire coal mines during the early 1960s were recorded by Rhydderch & Yates (1964), confirming that permeabilities are lower than 5 mD.

South Wales Coalfield

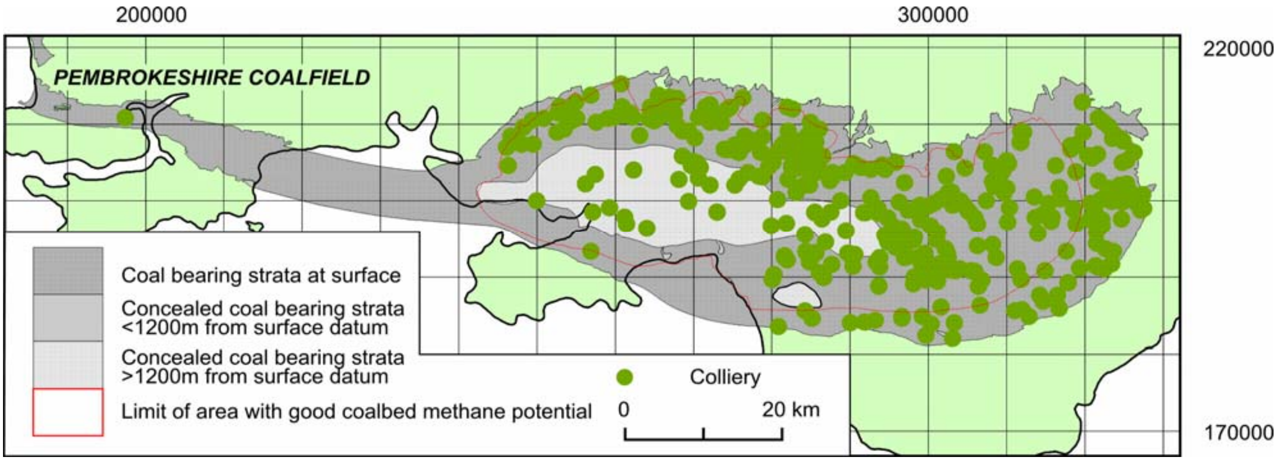

Fig. 30 South Wales Coalfield – summary map of unconventional hydrocarbon potential

The fixed carbon ratio map indicates that the highest coal maturities, the highest illite crystallinity values in Dinantian to early Westphalian strata, and the highest volatile matter percentage (dry mineral matter free), spore carbonisation and vitrinite reflectance all occur in the north-west of the South Wales coalfield (Mohafez 1966, Gill *et al*. 1979, fig. 6). The Carboniferous strata also thicken towards the north-west, away from the Usk Uplift. Removed late Westphalian strata may also have been very thick in this area, but they would have needed to have been about 7 km thickness to have produced the anthracitic coals here by burial alone. Fails (1996) was quite optimistic about South Wales CBM potential compared to other foredeep basins where the low gas contents suggest degassing. He suggested that subaerial exposure of the Carboniferous in South Wales was delayed as late as the Tertiary, enabling retention of higher gas contents in common with other foredeep basins where the cover is relatively young. Fails' hypothesis about degassing of the South Wales coals may be flawed, because the Westphalian Warwickshire Group coals (part of his degassed zone) have low maturity and gas contents away from the Variscan Front. By analogy with the Ruhr coalfield, Permo-Triassic oxidation, deep weathering and lowering water tables may instead have caused the degassing – this oxidised zone is either absent or has been subsequently removed by erosion where Cretaceous or younger strata form unconformably overlying supercrop. The Kent Coalfield is the only UK coalfield where rocks younger than Triassic unconformably overlie Westphalian strata.

Centrica licences, South Wales

At the Society of Petroleum Exploration's March 2010 meeting, A. Gunning (CBM Operations Manager, Centrica Energy) reported that Centrica have 20-30 target coal seams, with seam thickness reaching 3-4 m, and with an average methane content of 13 m^3/t. Phase 1 of Centrica's exploration programme involves drilling vertical wells at 12 sites between 2010-2013.

South Wales PEDL 100

Recoverable gas in this licence has been estimated by Eden Energy to be 380-670 bcf. This Australian company drilled 3 wells in 2007-8 before selling their interests after discharging their farm-in obligations.

According to reports on Eden's website, Aberavon 1 well drilled 15.81 m net coal in 12 seams, ranging in thickness from 0.25-2.35 m. The gas content in these seams increases from 1 m^3/t in an upper seam (permeability 44 mD) to 9 m^3/t near total depth (permeability 18 mD). These permeabilities are the highest known in the UK (Fig. 16 - Aberavon). Llangeinor 1 well intersected 19 m of net coal in 18 seams ranging from 0.1-3.3 m thickness. In seams from 534-670 m depth gas content reaches 11 m^3/t, with an average of 8.4 m^3/t. No permeability data were reported. No gas content or permeability data is available from Eden's third and last Pencoed 1 well.

Eastern England coalfields

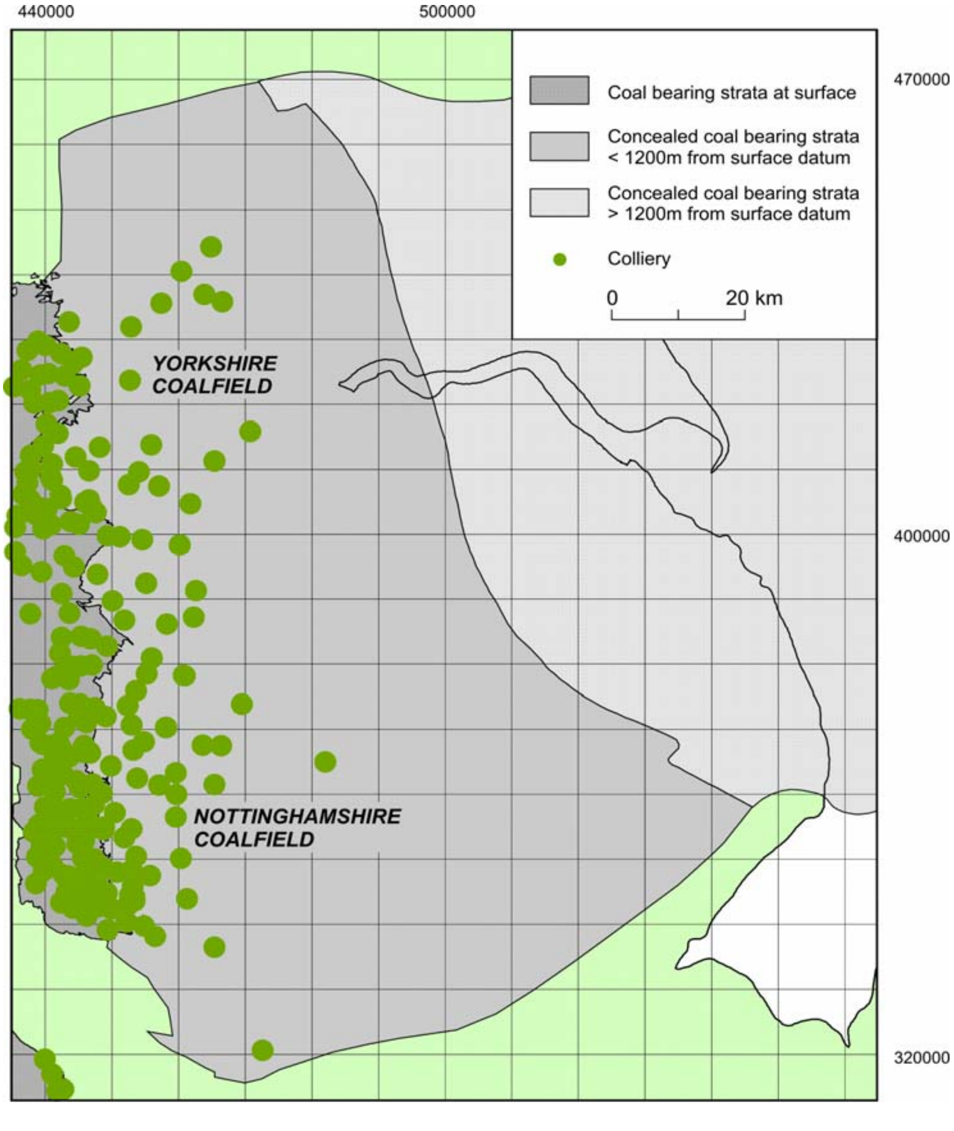

Fig. 31 Eastern England – summary map of unconventional hydrocarbon potential

Although part of the same basin as the coalfields west of the Pennines, these coalfields have lower gas contents. The East Midlands area has small conventional oil and gas fields, indicating that the porosity and permeability of reservoirs adjacent to the CBM-targeted coals is adequate for production. This may indicate that the coals also have better permeability.

Selby Coalfield

Creedy *et al*. (2001) assumed that 40% of the gas content at Selby could be produced, providing a potential resource of $13.3x10^6$ m^3/km^2. Their calculation assumed a gas content of 5.3 m^3/t (Barnsley seam at

Stillingfleet) and an approximate net thickness of coal of 6.28 m (from 150 m above to 40 m below the Barnsley seam).

Yorkshire and Nottinghamshire coalfields

There is a clear increase in gas content to the north-west in all East Midlands coals (Creedy 1983), and of total thickness of the Westphalian Coal Measures. This gas content trend does not correspond with the eastward increase in post Carboniferous cover (Smith 1985). Nexen, Greenpark and Composite Energy are exploring in the Yorkshire and Nottinghamshire coalfields.

Cumbria-Canonbie coalfields

The gas contents are high in these coalfields and a large subsurface area, between the two coalfields has never been mined. Greenpark-Marathon are conducting exploration here. It is not known whether Coal Measures are present beneath the Vale of Eden Basin (area in SE. Fig. 32), as there are few boreholes and no seismic data.

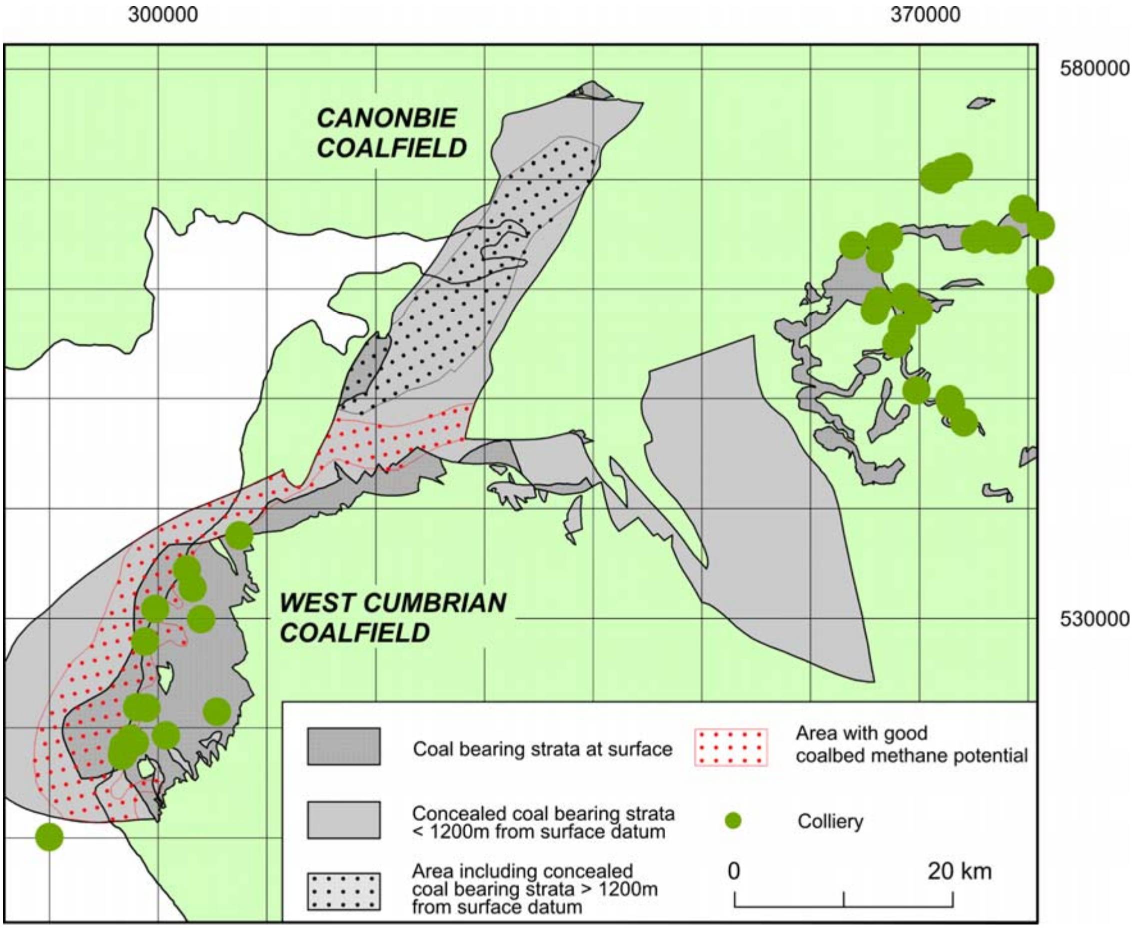

Fig. 32 Cumbria-Canonbie – summary map of unconventional hydrocarbon potential

Warwickshire Coalfield-Oxfordshire-Berkshire

There has been no coal mining in these two southern counties. The basin is dominated by thick Warwickshire Group at crop in the Warwickshire Coalfield and in the subsurface to the south. In the coalfield thick coals (Fig. 20) also occur beneath the Warwickshire Group but these are absent to the south. The maturity and gas content is low where measured as the basin straddles the Wales-Brabant Massif, connecting the Pennine Basin with the Variscan foreland basin. Maturities may increase near the southern boundary (Variscan Front, Smith 1993), but no gas content data were acquired here. Mustang drilled a shallow well at Kingsbury for CBM exploration in the west of the Warwickshire Coalfield.

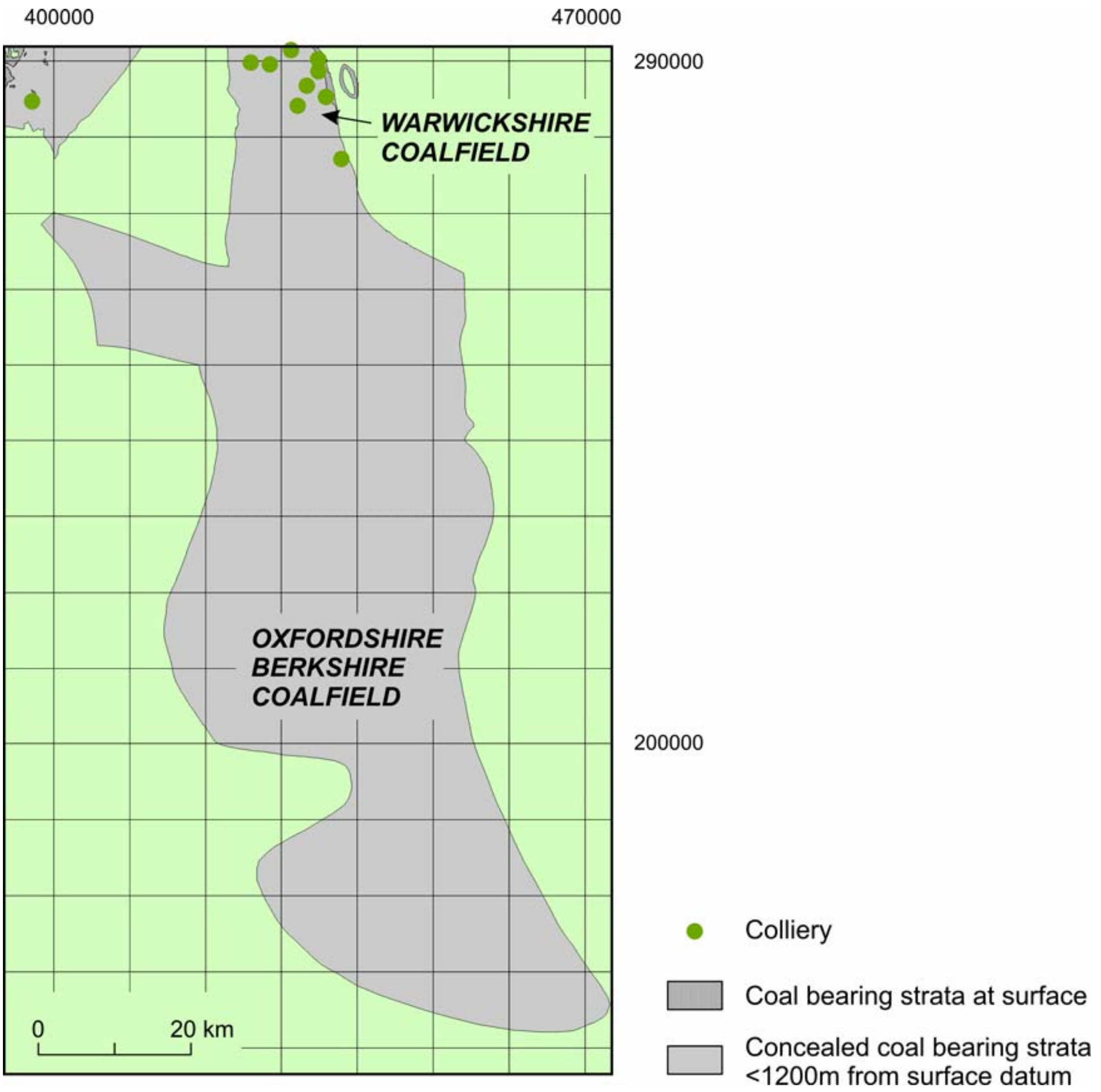

Fig. 33 Warwickshire-Oxfordshire-Berkshire – summary map of unconventional hydrocarbon potential

Somerset Coalfield - PEDL074

Formerly licensed to Geomet, a relinquishment report by Goodwin (1999) on this licence is available from the DECC website (https://www.og.decc.gov.uk/upstream/licensing/relinqlics/pedl074.htm). This report draws the distinction between Westphalian C-D Warwickshire Group coal mining in which naked light working was universal and mining of the Westphalian A-B Coal Measures, which had extensive problems with methane. No measured gas content data are available. Volatile matter data are also limited. The area is affected by thrusts, and there are a few areas concealed beneath post-Carboniferous strata. Two exploration boreholes were recommended in Goodwin's report, at 1 km east of Chew Magna and 1.5 km east of Hinton Blewitt (Fig. 34).

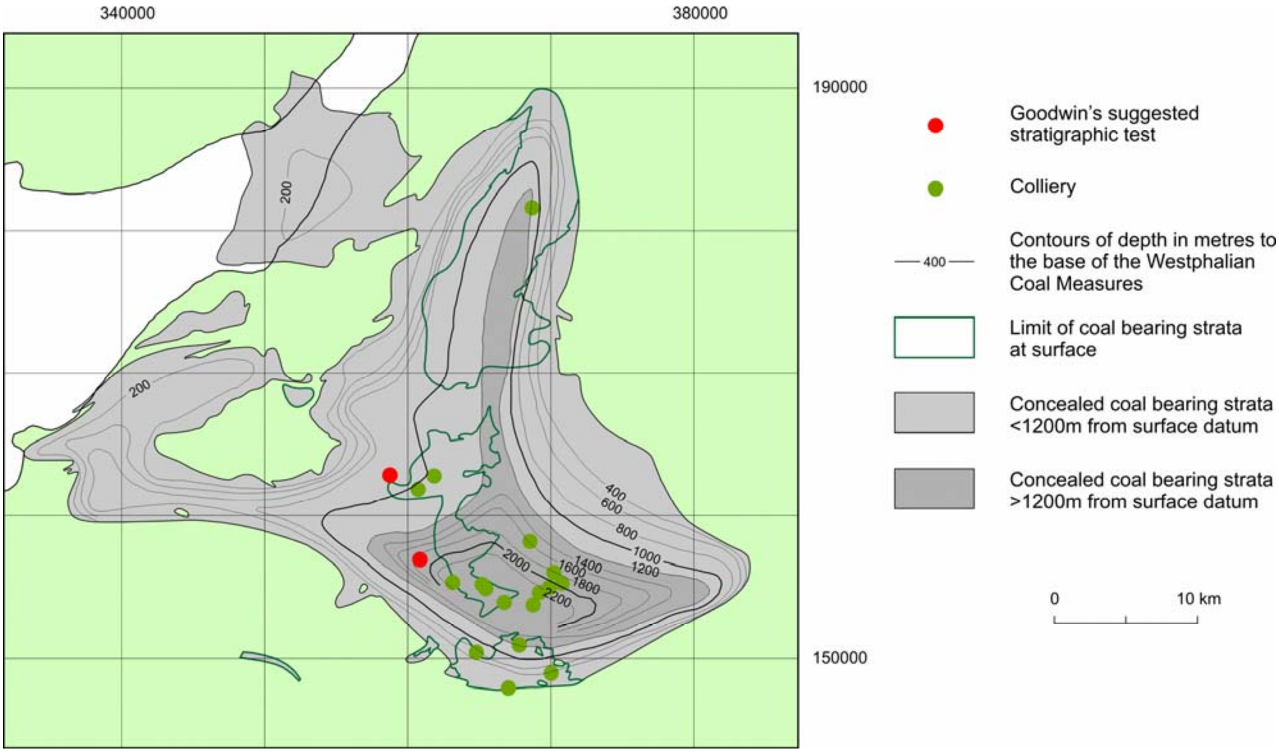

Fig. 35 Contours of depth to the base of the Westphalian Coal Measures in the Bristol-Somerset Coalfield.

More recent mapping near Bath shows the Coal Measures are absent here, but they are possibly present in small areas between Bath, Lucknam and Hamswell to the north-east. The main southern basin is unmined east of Hemington. The Ebbor thrust slice south of the Mendips is a rare example of Upper Carboniferous strata south of the Variscan Front, and the Westbury borehole is probably an equivalent subsurface proving.

11. Conclusions

The UK has a very great potential for CBM production with extensive Carboniferous coals, however, most of the exploration drilling to date has encountered lower permeability coals than their Appalachian Basin analogies in the USA, and despite pilot production, investments have not yet been made in full scale CBM development. There are a number of small but commercially viable mine vent gas operations in current production.

Although there is a wealth of National Coal Board borehole data, publicly released recent CBM well and core test data is limited and DECC will be working with Operators to make the maximum amount of information readily accessible once the confidentiality period specified in licences has passed.

UK CBM commercial success will build on new multi-lateral drilling and completion technology - finding a way of releasing the gas trapped in coal, within the constraints of local authority planning and environmental requirements. DECC is committed to ensuring that we maximise economic recovery of the UK's hydrocarbon resources, and support industry in pursuit of this.

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