

Paleozoic gas potential in the Weald Basin of southern England



CHRISTOPHER P. PULLAN^{1*} & MALCOLM BUTLER²

¹*CP Exploration, Potterne, Devizes, Wiltshire, SN10 5LR, UK*

²*UK Onshore Geophysical Library, 46–50 Coombe Road, New Malden, Surrey, KT3 4QF*

M.B., 0000-0002-0462-9135

*Correspondence: chris.pullan1@btinternet.com

Abstract: Gas has been found in Mesozoic reservoirs in the Weald Basin, particularly along the northern margin. Most of the gas is dry, with a high methane content and often associated nitrogen. Isotopic evidence indicates that the gas is from a thermogenically mature marine source. Although there is evidence of some shallow, biogenic gas, only the lowermost Lias is projected to have reached the thermogenic gas window before Tertiary uplift. Estimated maturities from isotopic data from the main gas accumulations indicate significantly greater levels than those projected for Liassic shales: thus, the gas is thought to have originated from Paleozoic rocks.

Data on the distribution of Paleozoic rocks subcropping the Variscan unconformity is limited. However, available data suggest that their distribution owes more to Acadian erosion than to Variscan. It is thought that the Upper Devonian and Lower Carboniferous transgressed over a thick, folded Tremadocian shale sequence in the west, and over folded Silurian and Lower–Middle Devonian rocks in the central Weald. There is some evidence for the presence of isolated late Carboniferous or early Permian clastics but no significant coals have been encountered to date. Regional source studies suggest that the only Paleozoic rocks with potential are post-Acadian-aged Devonian shales.

The Weald Basin is the easternmost sub-basin of the southern England Mesozoic Basin and is located south of London (Fig. 1). Exploration began in the area in the late nineteenth century and the first significant discovery of gas was made at Heathfield in 1895 (Dawson 1898). Sporadic exploration subsequently was largely unsuccessful, although a gas field was discovered at Bletchingley in 1965 by Esso. The basin experienced a major phase of exploration during the late 1970s through to the oil-price collapse of the late 1980s. Oil fields were discovered on the southern and western edges of the basin, whilst both oil and gas discoveries were made along the northern edge of the area.

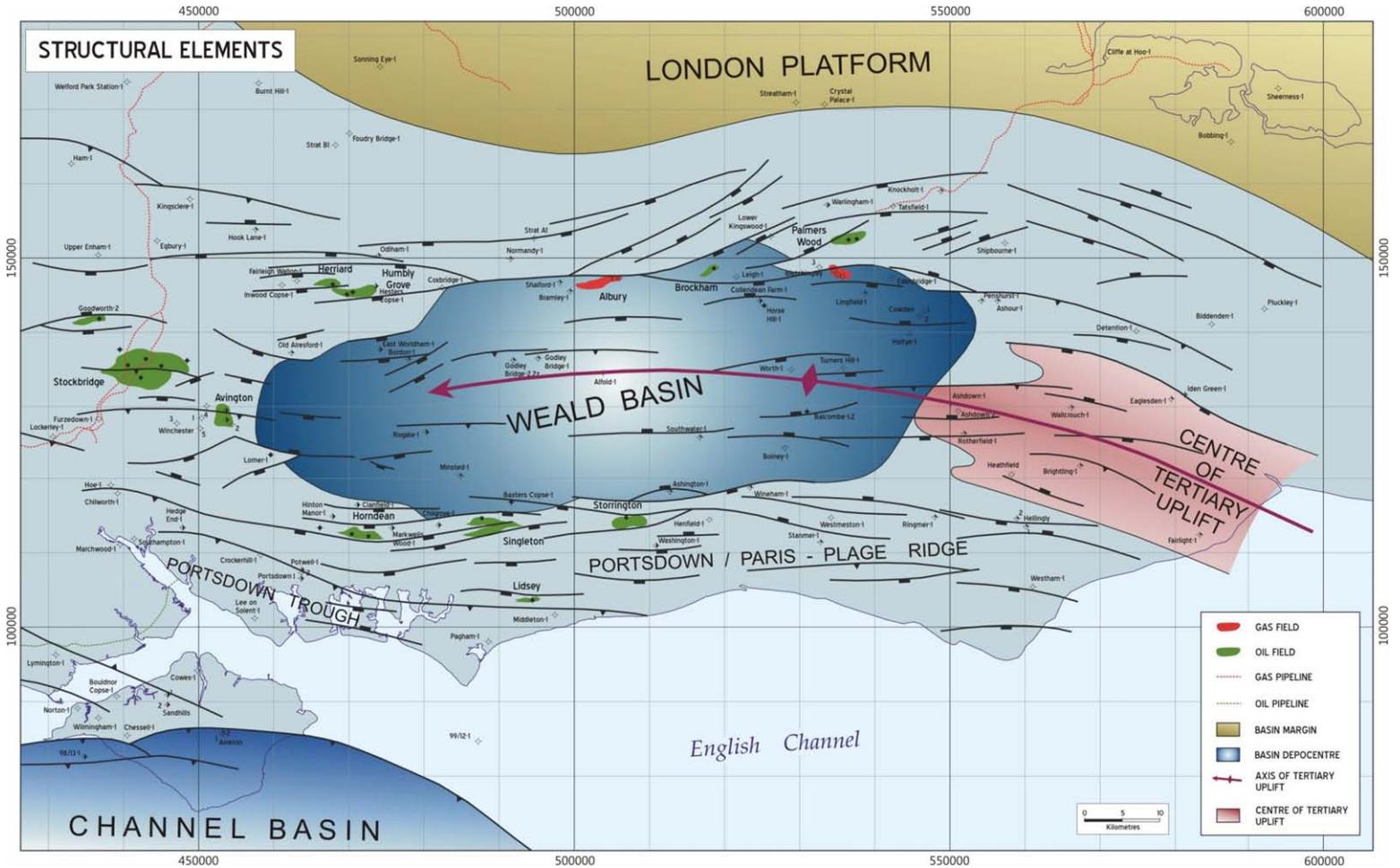
Numerous studies have shown that the oil in these discoveries is sourced from Jurassic shales, and, in particular, the Oxford Clay and Kimmeridge Clay intervals (Ebukanson & Kinghorn 1986; Burwood *et al.* 1991; Harriman 2010). Gas has been found in a number of places in the Weald, particularly along the northern margin of the basin. Several theories have been proposed for the source of the gas in the area but none have been definitively demonstrated (Andrews 2014); in this study, evidence is presented for a Paleozoic source. Although Jurassic reservoir development is generally poor, shows and accumulations have been encountered within porous zones in Middle–Upper Jurassic reservoir intervals

(Trueman 2003). Both Tertiary anticlinal and pre-Albian structural traps have been found to be hydrocarbon bearing (Fig. 2) (Hancock & Mithen 1987; Butler & Pullan 1990; Trueman 2003).

Basin development in southern England began during the Lower Permian, following the Variscan Orogeny, and development of the Weald Basin appears to have begun in the Triassic (Hawkes *et al.* 1998). Two phases of rifting are recognized: the first commenced in the Triassic and ended in the Middle Lias; the second, related to the opening of the Bay of Biscay and the North Atlantic, began in the Upper Jurassic (Kimmeridgian), continued into the Lower Cretaceous and ended with the Aptian unconformity, which marked drift onset in the Bay of Biscay (Fig. 3) (Butler & Pullan 1990; Hawkes *et al.* 1998). Tertiary compressional movements are recognized, and are considered to have had two phases of movement: the first, in the Paleogene, resulted in regional uplift and is thought to be associated with the North Atlantic opening; whilst the second, in the Miocene, appears to be related to Alpine tectonism (Jones 1999). These movements resulted in fault reactivation, as well as in regional uplift of the entire basin centred to the SE. Various studies have attempted to calculate the amount of uplift, with estimates ranging from 3700 to 6800 ft (1128–2073 m) (Butler & Pullan 1990; Jones 1999; Andrews 2014).

From: MONAGHAN, A. A., UNDERHILL, J. R., HEWETT, A. J. & MARSHALL, J. E. A. (eds) *Paleozoic Plays of NW Europe*. Geological Society, London, Special Publications, **471**, <https://doi.org/10.1144/SP471.1>

© 2018 The Author(s). This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0/>). Published by The Geological Society of London. Publishing disclaimer: www.geolsoc.org.uk/pub_ethics



C. PULLAN & M. BUTLER

Fig. 1. Weald Basin location, with structural elements. Adapted from Magellan Petroleum (UK) Ltd (2012).

PALEOZOIC GAS POTENTIAL IN THE WEALD BASIN

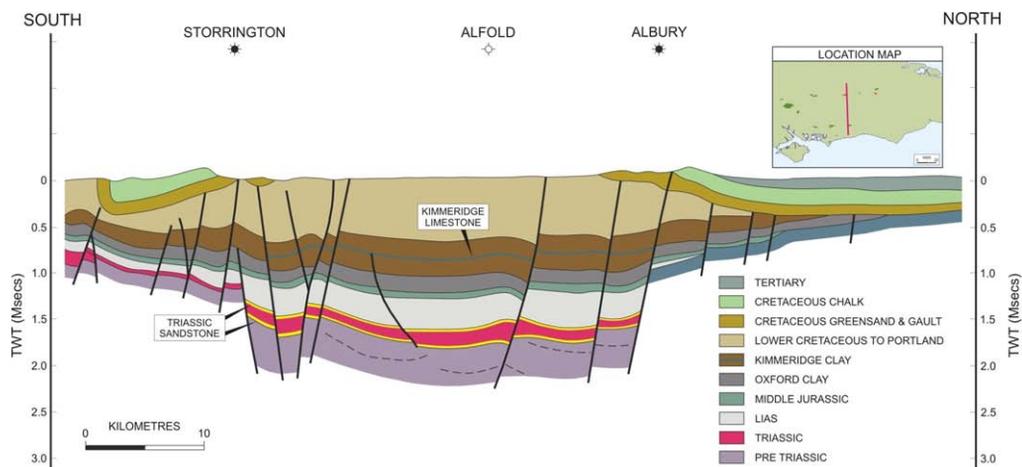


Fig. 2. Geological cross-section of the Weald Basin. After Butler & Jamieson (2013, plate 1).

Subsequently, the area has undergone major erosion, so that Lower Cretaceous rocks crop out in the basin centre, with Upper Cretaceous and Lower Tertiary strata cropping out around the flanks.

All the relevant available released well and regional reports, together with the comprehensive seismic database held in the UK Onshore Geophysical Library (UKOGL) database, over the area of interest have been used in this study for mapping and analysis.

Gas type

Results of the analysis of gas recovered during testing of Weald Basin wells are shown in Table 1 (see also Fig. 4). These data have been compiled from operators' final well reports and Annex B submissions. Only the final results are available, so there may be some questions over reliability in places.

The gas analysis shows that the majority of gas encountered is dry, with a high methane content, particularly when the gas is non-associated. In addition, much of the gas has a high nitrogen content (2.5–12.5%). Nitrogen is considered to be the product of source rocks at an advanced stage of thermal maturity (Tissot & Welte 1984). This amount of nitrogen is consistent with generation from a source in the dry-gas window ($R_o > 1.4\%$). No major compositional variations appear to exist between the shallow and deeper gas pools in the same field, as seen in the Godley Bridge or Humbly Grove fields.

The oils typically found in the area are light (39–41° API), low sulphur, waxy crudes. The gas/oil ratios (GORs) of the oils vary, being generally low to the south and west, but higher along the north flank. Most fields do not have a gas cap.

Only one analysed oil demonstrates evidence of post-emplacment modification and, therefore, biodegradation is not thought to be a widespread phenomenon. This is in keeping with the theory that the entire basin was widely 'pasteurized' prior to the Tertiary inversion (Wilhelms *et al.* 2001).

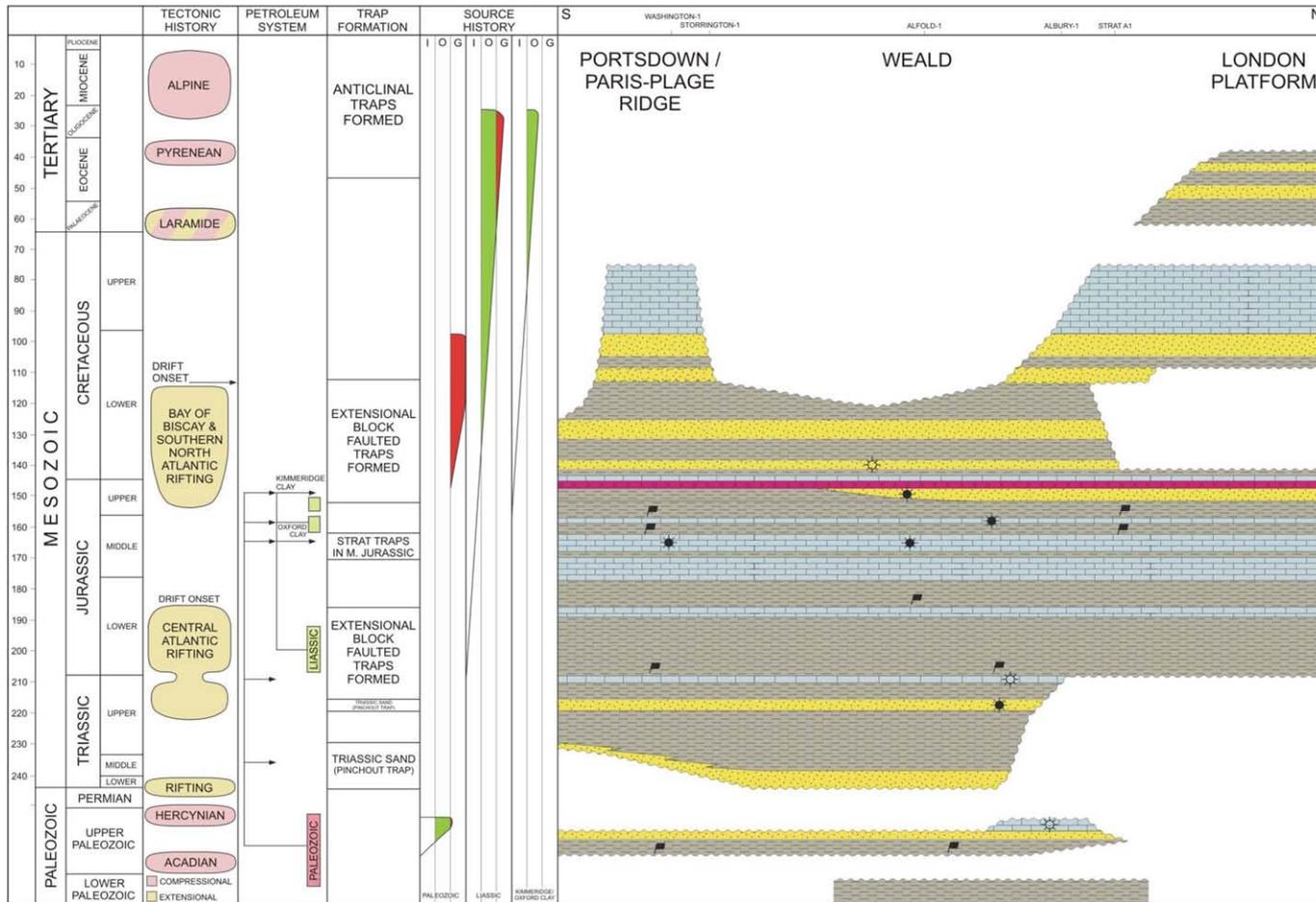
Isotope work on the gases by Conoco showed that the gas associated with the oil found at Godley Bridge, Baxters Copse and Palmers Wood has a mainly thermogenic origin (Figs 5 & 6) (Conoco (UK) Ltd 1986). Some of the methane at Godley Bridge may be derived from biodegradation of the associated oil. The data also suggest that all the gases were derived from a marine source (Type II/III), which is in the wet-gas window (vitrinite reflectance (VR) of 1.1–1.2%) (Stahl 1977).

Timing of gas charge

The available seismic data across known gas accumulations were studied and available diagenetic studies reviewed in an attempt to estimate the timing of the gas charge.

Gas was found at Godley Bridge at three stratigraphic levels: Inferior Oolite, Great Oolite and Portland Sandstone. The structure is a simple down-thrown closure against an earlier extensional fault (Fig. 7). Although there is no post-Lower Cretaceous cover, the Godley Bridge structure lies on trend to the Hindhead surface anticline (Thurrell *et al.* 1968; Butler & Pullan 1990), which is thought to be of Tertiary age by analogy with structures of similar style where a Tertiary age can be assigned with confidence: for example, the Winchester Anticline (Sterling Resources (UK) Ltd 2001). This suggests some of the gas migration occurred during the

CHRONOSTRATIGRAPHY - SOUTHERN ENGLAND



C. PULLAN & M. BUTLER

Fig. 3. Chronostratigraphy of the Weald Basin, making use of numerous sources including Butler & Pullan (1990) and Hawkes *et al.* (1998).

PALEOZOIC GAS POTENTIAL IN THE WEALD BASIN

Table 1. Gas composition (the details are shown in bold type when associated with oil)

	C1 (%)	C2 (%)	C3 (%)	C4 (%)	C5 (%)	N ₂ (%)	CO ₂ (%)
Albury	97.6	0.6	0.4	0.4	0.2	0.9	
Ashdown	92.2	0.2				7.6	
Bletchingley	79.5	3.5	2.3	1.6		12.8	
Bolney	86.5					10.7	
Godley Bridge – Port	85.6	5.1	2.8	1.2	0.4	4.2	0.2
Godley Bridge – Great Oolite	84.3	6.7	2.7	1.2	0.5	3.5	0.4
Godley Bridge – Inferior Oolite	82.9	6.9	3.2	1.5	0.7	4.1	0.3
Heathfield	93.4	2.3	1.6			2.7	
Henfield	73.8	6.9				19.3	
Humbly Grove – Great Oolite	81.5	5.6	1.9	0.7	0.3	9.6	0.1
Humbly Grove – Rh	82.0	6.5	3.8	1.2	0.3	5.4	0.4
Palmers Wood	83.7	4.4	5.2	1.2		2.2	0.1
Storrington	69.4	14.5	9.0	1.0		2.7	4.0

Tertiary, possibly as a result of remigration from existing traps during the uplift.

The gas found at Humbly Grove is in a structure that predates the Aptian unconformity (see Fig. 8) and has not undergone any Tertiary reactivation (Hancock & Mithen 1987; Trueman 2003). Unlike most of the Weald Basin Middle Jurassic Great Oolite fields, at Humbly Grove a gas cap exists at the Great Oolite level, but gas is also trapped in an underlying Triassic Penarth (Rhaetic) reservoir. Since the trap seems to have been formed by fault movement during the Wealden and early Lower Greensand (Fig. 8), the gas could have migrated into the structure from mid Cretaceous times on. This does not rule out a Tertiary charge; however, it would imply a very limited charge volume at that time since the trap is not gas filled to spill. In order to better constrain this timing, the diagenetic history of the gas reservoirs was reviewed.

In the Humbly Grove Oil Field, the Great Oolite carbonate reservoir is characterized by an upper, high-permeability oil- and gas-bearing zone, which overlies a poor-permeability oil-bearing reservoir (Fig. 9). This interface is sharp and occurs at a depth of 3395 ft (1035 m) subsea. Extensive cementation occurs below, with porosity reduced, on average, by 2.6%, but average permeability is reduced from 64 mD in the upper good zone to 0.6 mD in the lower poor zone (see Fig. 10). In addition, the contact is marked by a zone of sphalerite enrichment (Sellwood & Evans 1986; Heasley *et al.* 2000).

As can be seen from the structure map (Fig. 9), which is constrained by seismic and well control, the permeability contrast surface is coincident with the current structure and is almost flat. It has therefore undergone little later structural modification. The permeability contrast surface is thought to represent a palaeo-gas–water contact (Carless Exploration Ltd 1983).

In an attempt to gain an understanding of the controls on these reservoir qualities, the then operator (Carless Exploration) undertook a series of detailed diagenetic studies (Sellwood & Evans 1986, 1987; Sellwood *et al.* 1989a, b). These studies showed several diagenetic phases.

The first phase was an early, near-surface diagenesis, which lithified the sediments, and this was followed by a second phase characterized by the deposition of cements from hot, saline fluids (95–110°C, 18–19.5% NaCl), whose origin is unclear. These cements include non-ferroan calcite and saddle dolomite, with sphalerite and barytes being deposited in fractures and fissures and at the palaeo-hydrocarbon contact (Heasley *et al.* 2000). Studies on other wells in the basin (Sellwood & Evans 1986; McLeod 2002) show that this hot water flush was a regional phenomenon. The high temperatures (based on the present-day geothermal gradient of 2.2°F/100 ft (4.0°C/100 m) suggest an origin from depths in excess of 7500 ft (2286 m). Well and seismic data over the field show that the Variscan surface lies currently at around 4770 ft (1454 m). Subsea depth reconstructions suggest that during the Albian, the Variscan surface would lie at depths of 3750 ft (1143 m); this would indicate that the fluids originated from sediments below the Variscan unconformity in the Humbly Grove area or that the geothermal gradients were significantly greater in the past, for which the source-rock maturity data show no evidence. An origin from below the Mesozoic requires fault migration pathways due to the presence of Jurassic shale aquacludes, and this suggests fluid movement from early Cretaceous times onwards.

Subsequently, there was a change from waters with high salinities and temperatures to waters characterized by lower temperatures and salinities (40–80°C, 6.5–15% NaCl) and a third diagenetic phase,

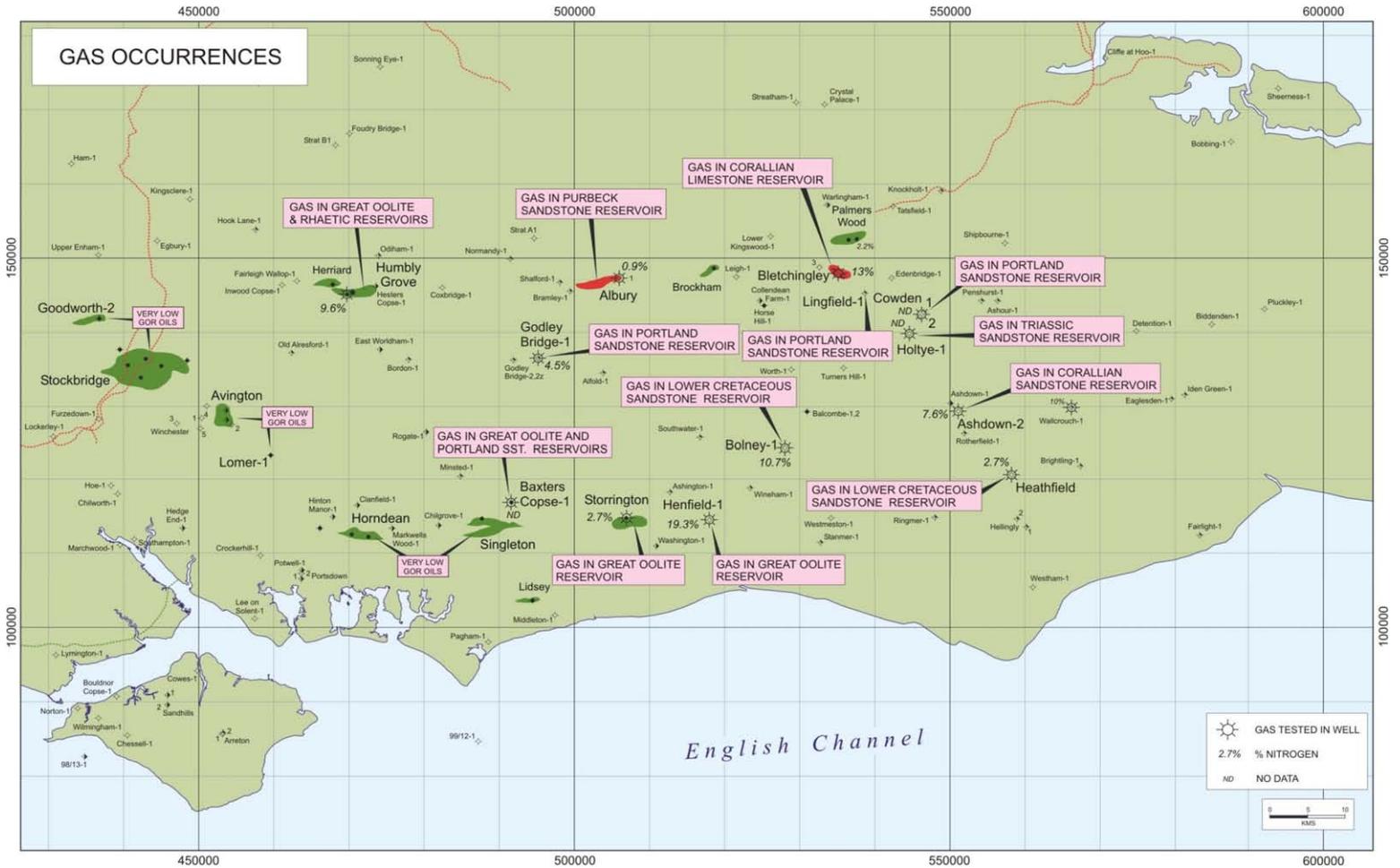


Fig. 4. Gas occurrences. Compiled from released well data.

PALEOZOIC GAS POTENTIAL IN THE WEALD BASIN

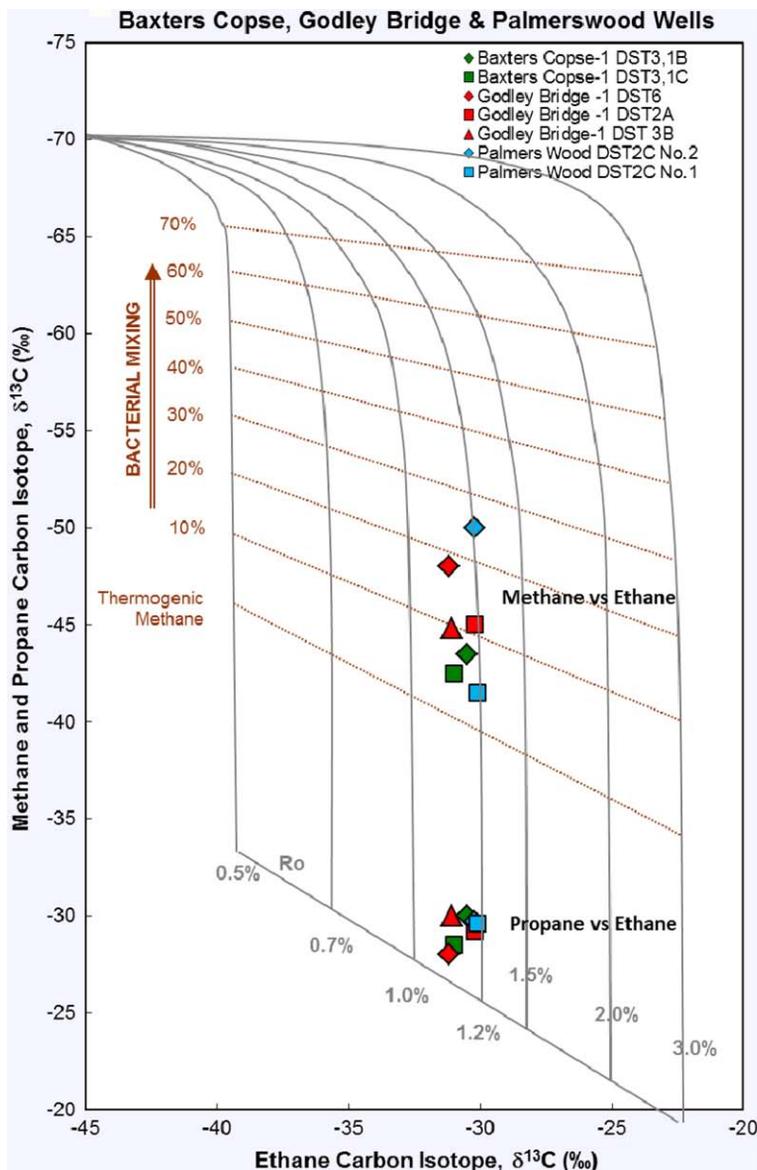


Fig. 5. Schoell plot for Weald Basin gases. Based on Conoco (UK) Ltd (1986).

which led to the deposition of mildly ferroan, coarse spar calcite cements. This diagenetic phase was the main Great Oolite porosity destruction event. Fluid-inclusion studies reveal that these cements are rich in oil inclusions, so it is suggested that the Jurassic-sourced oil was emplaced at the same time (Sellwood *et al.* 1989a; Heasley *et al.* 2000). Regional porosity mapping of the Middle Jurassic Great Oolite in the Weald (Butler & Pullan 1990) indicates that porosity loss is related to the depth of burial, and the area

of maximum loss is coincident with the zone of maximum burial during the late Cretaceous. Since the oil emplacement is associated with the second cementation phase and this appears to be coincident with burial in the Upper Cretaceous, it would imply that the oil charge was coincident with Upper Cretaceous burial and predated the Tertiary basin inversion.

The Rhaetic gas reservoir is a hydrothermally altered limestone conglomerate and calcarenite that has been chertified. A study by the field operator

GAS ISOTOPE DATA

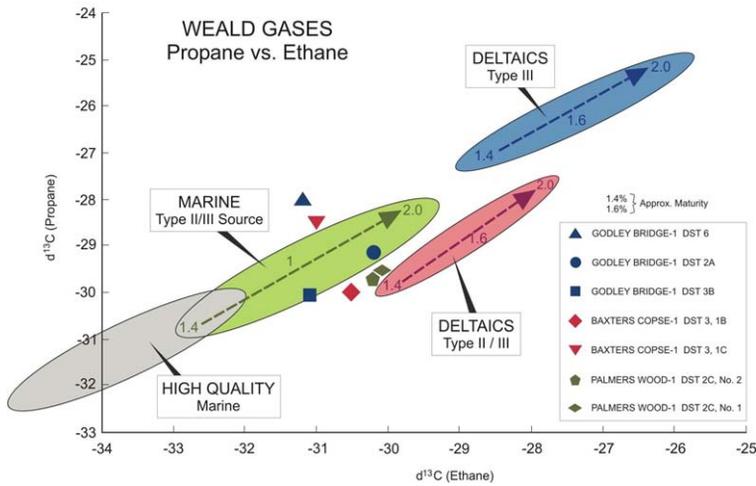


Fig. 6. Isotope plot of ethane v. propane. Based on Conoco (UK) Ltd (1986).

(Carless Exploration 1983) showed that, where gas bearing, the reservoir appears to have undergone a similar high-temperature diagenetic episode with sphalerite deposition, as seen in the Great Oolite. On the basis of these studies, it is postulated that the mineralization in the Rhaetic and Great Oolite reservoirs was coeval. A similar diagenetic alteration is found in rocks at outcrop in the Lower Lias- and Inferior Oolite-aged Harptree Beds, on the flanks

of the Mendip Hills, where it occurs in association with the Biddle Fault, and is possibly post-Albian in age (Green & Welch 1965).

The gas charge is thought to have occurred before the deposition of the mildly ferroan, coarse spar calcite cements (third diagenetic phase). It is considered that this early gas charge reached the Humbly Grove trap, filling the Great Oolite reservoir with gas, preserving the permeability and also charging

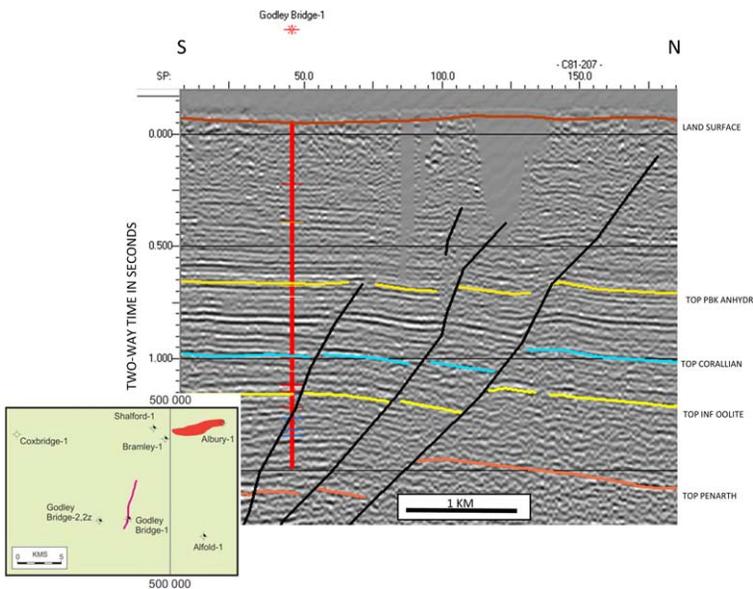


Fig. 7. North-south seismic line across the Godley Bridge Field.

PALEOZOIC GAS POTENTIAL IN THE WEALD BASIN

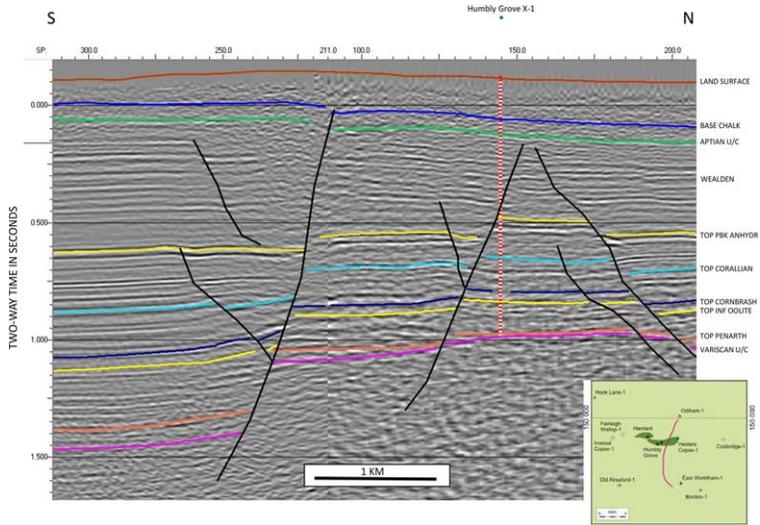


Fig. 8. North-south seismic line across the Humbly Grove Field. (U/C, unconformity.)

the Rhaetic reservoir. Later burial and compression is thought to have confined the gas to the crestal areas of the reservoir, allowing space for an oil charge into the preserved high-permeability reservoir. A later Upper Cretaceous hydrocarbon charge from Jurassic source rocks then created the main oil accumulation.

Interpretation suggests that this gas charge occurred after the Aptian, associated with the main regional faulting event which occurred before the Aptian unconformity (Chadwick & Evans 2005). Most Weald Basin Great Oolite fields do not have

a gas cap but also do not have a high-permeability reservoir present. The Herriard Field, just to the NW of Humbly Grove, does not have a gas cap or high-permeability reservoir despite an apparently identical structural history.

Interpretation suggests that the basin had an early Cretaceous gas charge, followed by an oil charge later in the Cretaceous, with remigration of both oil and gas in the Tertiary. This remigration is demonstrated not only at Godley Bridge but also at the Stockbridge, Singleton and Storrington fields (Trueman 2003).

HUMBLY GROVE OIL FIELD - MIDDLE JURASSIC RESERVOIR

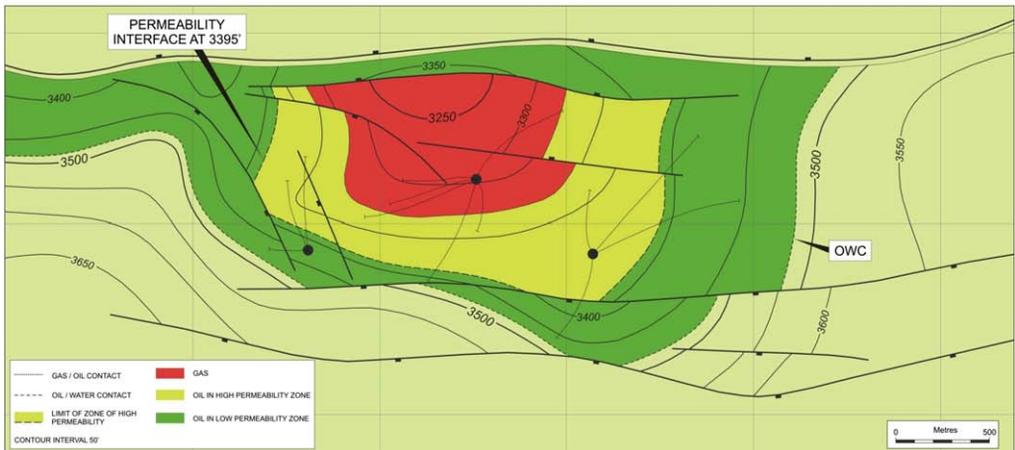


Fig. 9. Humbly Grove: depth structure map at the Top Great Oolite Reservoir. Adapted from Hancock & Mithen (1987).

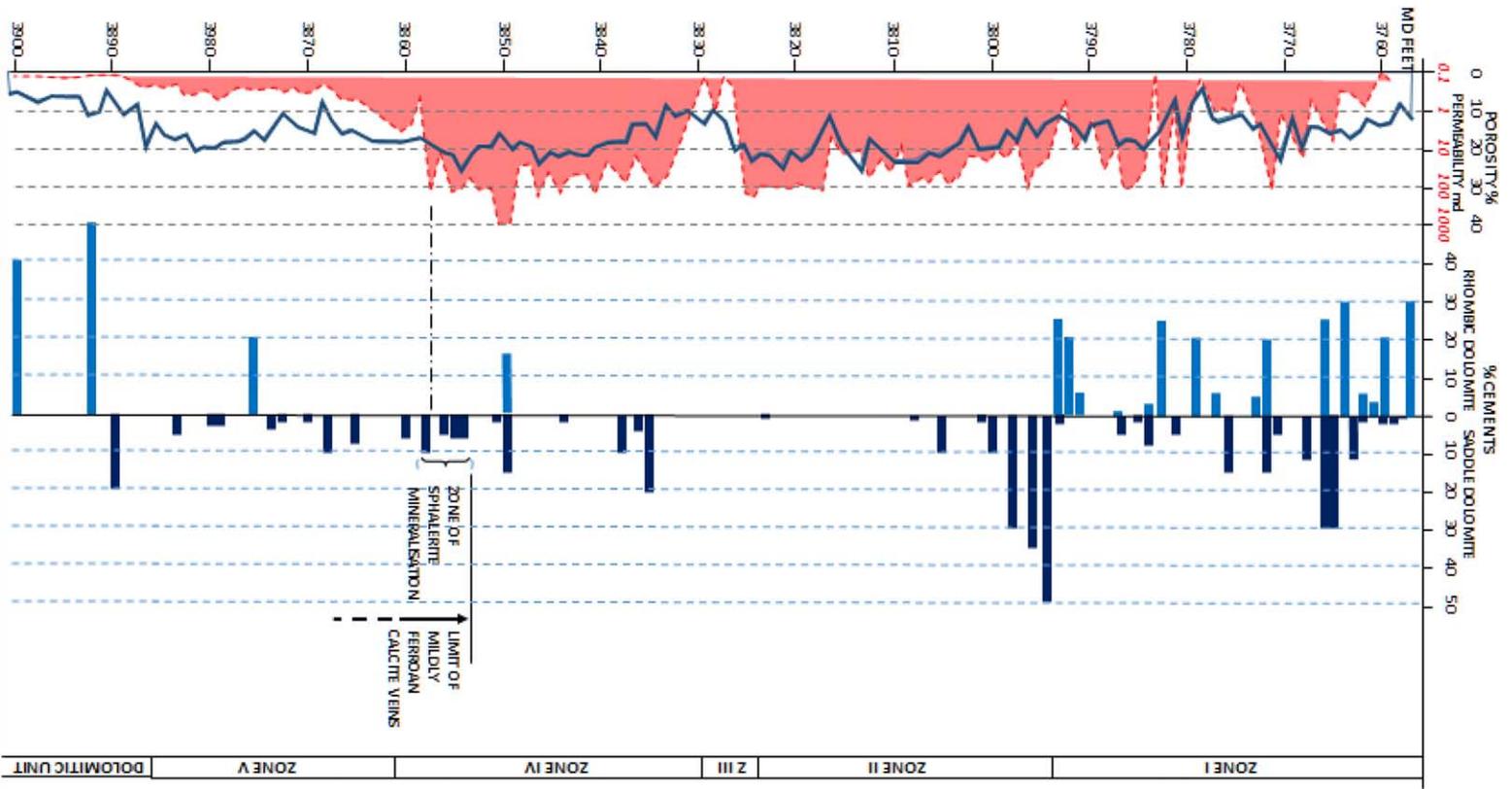


Fig. 10. Humby Grove – Great Oolite: core porosity–permeability plot. Redrawn from Sellwood & Evans (1986).

Origin of gas

Several theories have been put forward for the origin of this gas (Ebukanson & Kinghorn 1986; Conoco (UK) Ltd 1986; Andrews 2014):

- the gas comes from mature Lower Jurassic shales, deeply buried in the basin centre;
- the gas encountered is biogenic rather than thermogenic;
- the gas has been released by ex-solution caused by uplift in the Tertiary;
- gas reserves in the Weald Basin were not sourced from the Jurassic but, rather, from a deeper Paleozoic source rock interval.

These theories are not mutually exclusive: the gases may have had contributions from different source rocks and may be mixed.

Jurassic source

Thermogenic gas being derived from a Jurassic source is compatible with the isotope data. However, Figure 11 shows that the gas occurrences are not coincident with areas where the Lower Jurassic shales are most mature.

The maturity modelling of the Liassic in Figure 11 is based on regional seismic mapping of the top Penarth event. In the Celtique Energie study, an unpublished interpretation was used in which synsedimentary thickening of the Liassic across the bounding faults in the basin centre had the effect of deepening the Liassic in this area. In order to compensate for the Tertiary inversion effect, the Top Cretaceous was flattened using the Top Chalk structure map of Butler & Pullan (1990). Individual wells were modelled using Platt River[®] BasinMod software and verified using existing well maturity studies in order to check the assumed temperature gradients. A series of dummy wells based on seismically controlled sections were used to calibrate the untested basin centre (Fig. 12). This work shows that only in the very centre of the basin have the Lower Liassic shales reached the gas window. An alternative interpretation by the British Geological Survey (BGS) (Andrews 2014) does not have the Liassic sediments thickening across the bounding faults, so the Penarth is shallower in this area and the Lower Lias does not reach the gas window. Maturity modelling by the Central Weald Group (Magellan Petroleum (UK) Ltd 2012) shows that the Lower Jurassic interval only reached the gas window in the latest Cretaceous or Tertiary, which does not agree with the timing derived from the Humbly Grove data. This modelling work also suggests that the source has not been buried sufficiently to have started the generation of nitrogen, although it could be argued that this was caused by the

mixing and contamination of the hydrocarbon gas pool by a nitrogen-rich flush from a deeper source.

The model for the gas to have been derived from mature Jurassic shales faces two additional problems. The distribution of the gas away from the potential gas kitchen area implies widespread lateral migration of over 15 km for the gas discoveries on the north flank. This is problematic since the Liassic interval lacks any regional carrier beds and has extremely poor reservoir development. An additional problem is that where seen in the wells in the area, the Liassic shales are generally of fair hydrocarbon-generation quality at best. It can be argued that better source quality will exist in the basin centre, which is undrilled. Work by the BGS has concluded that the Lower Lias has a minimal source potential (Andrews 2014).

Biogenic origin

The available isotopic data (Conoco (UK) Ltd 1986) suggest that most of the gas is thermogenic and therefore does not have a biogenic origin. A biogenic origin would also not explain the high nitrogen content seen in the gas.

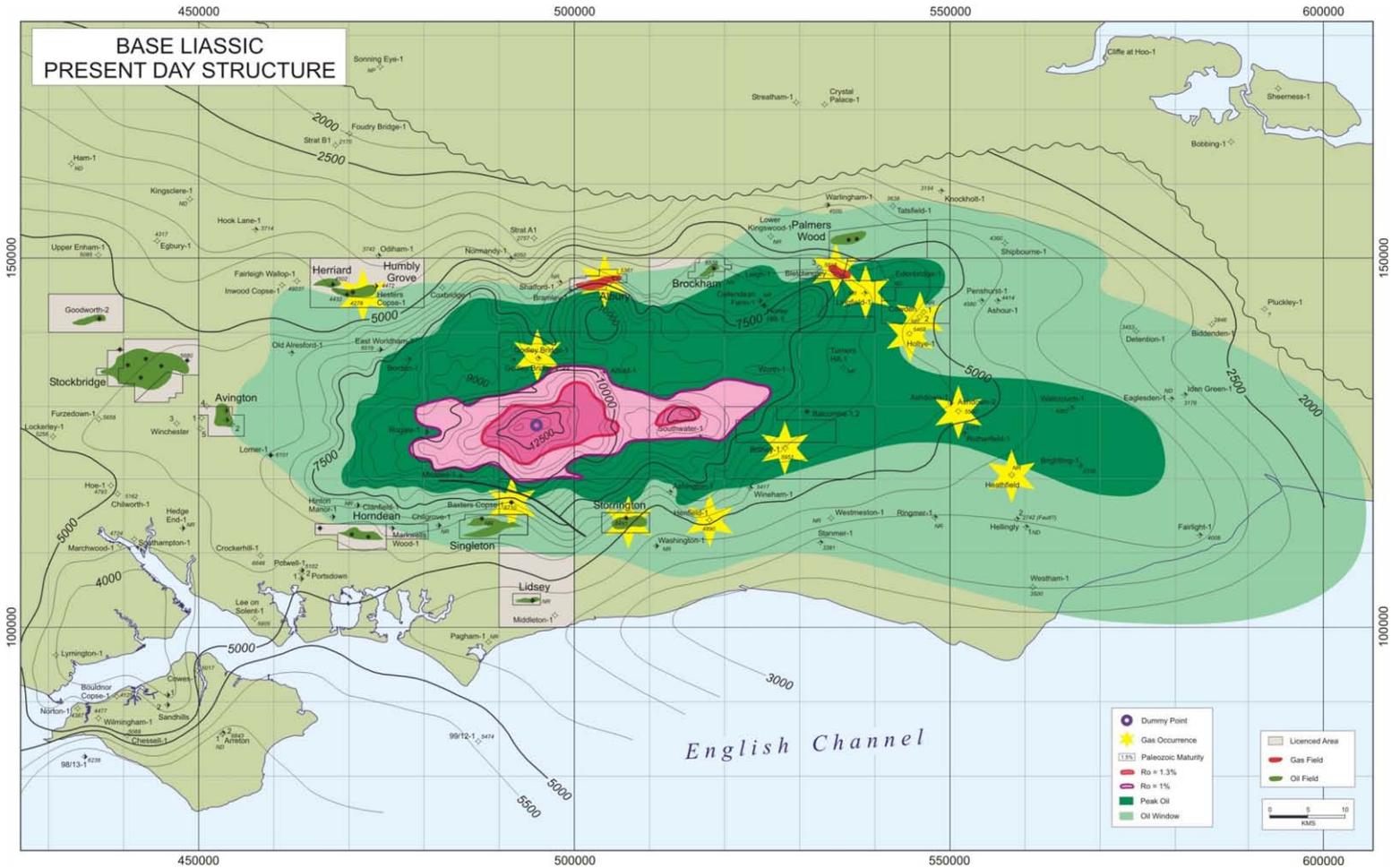
Shallow gas has been discovered in the basin centre at Heathfield and Bolney, in Lower Cretaceous reservoirs; but, unfortunately, no samples are available to ascertain whether these gases have a biogenic origin.

Peak biogenic methane production occurs at temperatures of 40°C (Clayton 2009), which equates to a burial depth of approximately 3000 ft (914 m). Analysis suggests that only the Lower Cretaceous in the centre of the basin was in the zone of peak biogenic gas productivity at end Cretaceous times, prior to Tertiary uplift.

Isotopic data indicate that the Godley Bridge-1 gas discovery, also located in the basin centre, has gas that has been contaminated with a biogenic component (see Fig. 5). Figure 13 shows the age of the strata which lie at the base of the zone of pasteurization (70°C) at the end of the Cretaceous, prior to uplift. Analysis of the Portlandian reservoir in Godley Bridge-1 indicates that it most likely did not reach pasteurization temperatures of 70°C. The temperature of the reservoir at the present day is approximately 39°C. In Brockham-2, the analysis indicates that the Portlandian reservoir only reached temperatures of approximately 50°C prior to uplift, which would explain the slight biodegradation of the oil at that locality.

Exsolution

An alternative explanation for the occurrence of gas in the Weald Basin is that, during and following the Tertiary uplift, gas was released from porewaters



C. P. PULLAN & M. BUTLER

Fig. 11. Gas occurrences placed on a map showing the maturity at the base of the Lower Jurassic. Based on unpublished maturity modelling by Celtique Energie.

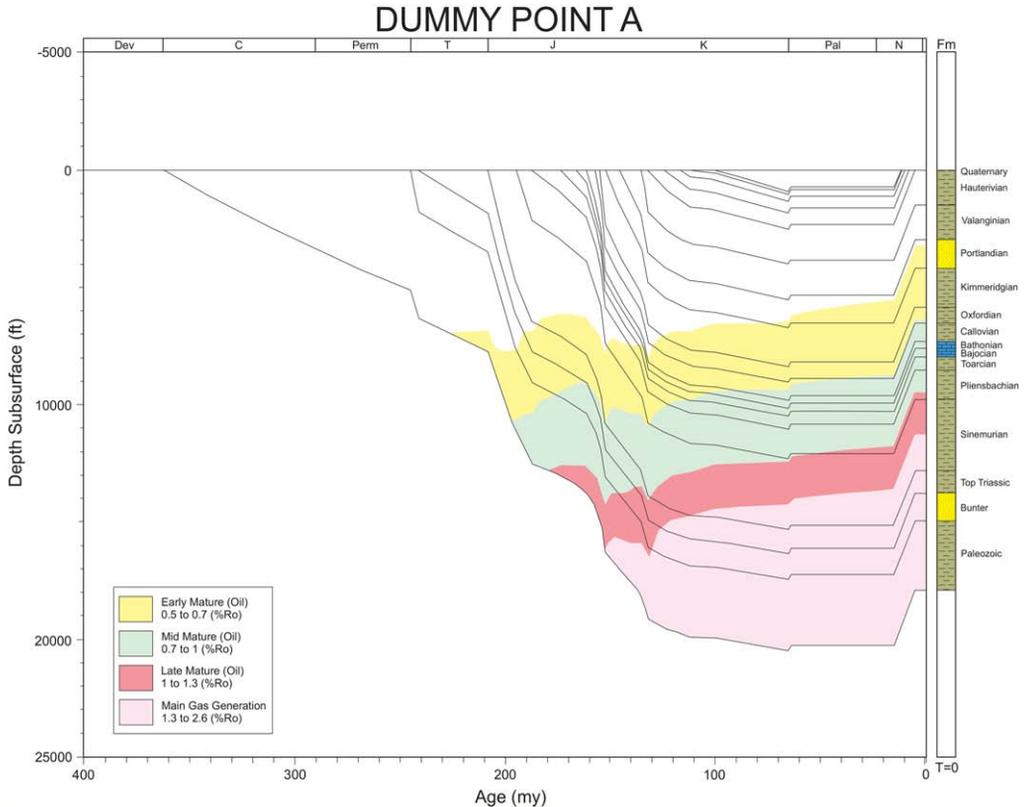


Fig. 12. Burial depth plot for the deepest part of the Weald Basin. Based on unpublished maturity modelling by Celtique Energie.

through ex-solution of dissolved gas. This was a model proposed by Conoco (UK) Ltd (1986), in which it was thought that, during burial, Jurassic strata would have been generating wet gas, some of which would have been dissolved in the porewaters. During inversion, the associated reduction in confining pressure and temperature would significantly decrease the solubility of methane and the dry gas in solution would ex-solve. According to the Conoco modelling, gas ex-solved from porewaters is estimated to be more than 8 Tcf (trillion cubic ft). This gas could have displaced previously trapped oil to the basin peripheries. This ex-solved gas would be much drier and preferentially rich in methane due to its higher solubility in water in comparison to ethane/propane. Furthermore, all the gases would have a carbon isotope signature indicative of thermogenic generation associated with the oil. It was believed by Conoco that the porewaters were saturated with methane at an early stage, which would explain the difference in maturity compared to the ethane and propane.

The ex-solution theory does not account for all the observations made. If this were the mechanism,

one would expect to see more gas occurrences in the area of greatest uplift. This is not the case, with the majority of gas occurring at the peripheries of the basin. A further problem is that the oils seen are generally low GOR, non-gassy oils. This may suggest that little gas was generated in the first place, although it is possible that these low GOR oils have already ex-solved volumes of gas originally in solution. However, although the gas is dry, consistent with the ex-solution model, the high nitrogen content cannot be explained since the source rocks did not reach sufficient maturity to generate nitrogen.

Paleozoic origin

Most oil and gas exploration companies have taken the view that the Paleozoic of southern England does not have any petroleum potential due to overmaturity caused by the Variscan Orogeny. Figure 14 demonstrates the oil and gas shows encountered in Paleozoic rocks of southern England. Paleozoic oil and gas shows also occur to the north of the Weald Basin, on the London Brabant Massif. Such shows are located over 30 km away from mature



Fig. 14. Southern England Paleozoic hydrocarbon occurrences. Based on reports from released wells.

Jurassic source rocks, whilst those to the west occur over 100 km from the nearest mature Jurassic source, and it is therefore difficult to explain all the occurrences as a result of a charge from the Jurassic. Furthermore, since the oil occurrences at Foudry Bridge-1 occur 470 ft (143 m) below the Variscan unconformity surface and in the White Thistle Laundry borehole, near Willesden in London, the shows occur 620 ft (189 m) below the Variscan unconformity surface, it is difficult to explain using a Jurassic source and downwards migration. The presence of a Paleozoic source system is implied. Unfortunately, most of these wells are old and no samples are available, so no attempt could be made to type the occurrences to a Paleozoic source interval.

The source potential of the Paleozoic section in the Weald is poorly known, since of the wells that penetrated the Paleozoic most only reached the Carboniferous and many only penetrated a thin (<100 ft) (30 m) interval of the Paleozoic. Many of the intervals were defined on lithological grounds (Fig. 15), since dating is limited and often difficult due to widespread caving.

Paleozoic source rocks

In order to gain an understanding of the source potential of the Paleozoic, a review of geochemical data from wells and outcrops in southern and central England was undertaken. This study reveals that a number of potential source rock horizons exist in the Cambrian, Devonian and Upper Carboniferous intervals (Fig. 16).

The Cambrian shales are known as the White Leaved Oak or Bentley Foot Shales at outcrop in the Midlands and the Welsh Borderlands, and have total organic carbon (TOC) values of 4–7% (Fig. 17). The interval is a proven source rock in the Baltic Sea area, North America and North Africa. Although a potential source to the NW, no shales of this age have been encountered in wells in the Weald Basin.

Two wells to the west, Shrewton-1 and Cooles Farm-1, penetrated a very thick section of early Ordovician (Tremadocian) age but, although these rocks had minor hydrocarbon shows, geochemical analysis reveals that the interval has little to no source potential with only lean shales encountered.

Silurian shales have been encountered in wells in the east and north of the Weald. Analysis by Celtique Energie (Harriman 2010) and other authors (Lamb 1983; Andrews 2014) have failed to find any significant source potential within the intervals, which are of post-Lower Llandovery age. However, work in North Africa and the rest of Europe has shown that the best source development occurs in the basal Silurian Lower Llandovery (Boote *et al.* 1998;

Lüning *et al.* 2003), an interval not encountered in the drilling to date. Therefore, the possibility exists of encountering these older shales with source potential in the Weald.

The Devonian section can be subdivided into pre- and post-Acadian intervals. Unfortunately, few wells penetrate a significant section of the Devonian, except those to the north on the London Brabant Massif. Other than outcrops to the west of the Weald Basin, the most complete sections have been penetrated in the eastern part of the basin. Shipborne-1 encountered a 600 ft (188 m) section of Old Red Sandstone facies, the upper parts of which Shell identified as being of Eifelian–Famnenian age, which is considered to be post-Acadian Middle–Upper Devonian, overlying Lower Devonian, Pridoli and Ludlovian rocks. Brightling-1, also in the eastern part of the Basin, penetrated a 602 ft (183 m) section of Old Red Sandstone facies dated as probably Lower Devonian (Falcon & Kent 1960). Devonian marine shales were deposited during the Givetian–Frasnian transgression, following the Acadian unconformity, and inner–outer shelf conditions existed to the north with deeper marine conditions in the south. Butler (1981) shows marine Frasnian to extend from the SE up to a line running from north Essex to southern Pembrokeshire, with deeper marine shales over much of the Weald. As part of the current study, these shales have been dated and analysed in a number of wells and were found to have source potential in Coxbridge-1 (Molyneux 2010a), where the section was reliably dated for the first time, and Detention-1 (Molyneux 2010b) (Figs 18 & 19). Uppermost Devonian sands and shales have been encountered in the Weald Basin either below the Variscan unconformity surface or conformably below the Lower Carboniferous limestones. These shales are often reddened and, where analysed, have no source potential.

In the Carboniferous, black shales are known from near the base of the Lower Carboniferous at outcrop: for example, in the Mendips (Black Rock Limestone). Numerous studies have shown that these shales do not have any source potential (Geochem Laboratories Ltd 1980; Lamb 1983; PetraChem Ltd 1986). To the SW, in the Wessex Basin, a change from shallow-water carbonates to deeper-water shales is seen within the Lower Carboniferous sequence. However, in this area, these rocks are overmature and their potential cannot be established (Cornford *et al.* 1987).

Coals are developed in the Upper Carboniferous Coal Measures, and are well known to the east in the Kent Coalfield and to the north in the Berkshire–Oxfordshire Coalfield (Foster *et al.* 1989). These coals would represent an excellent gas source (Kettel 1989). No Upper Carboniferous coals have been seen in the Weald Basin south of

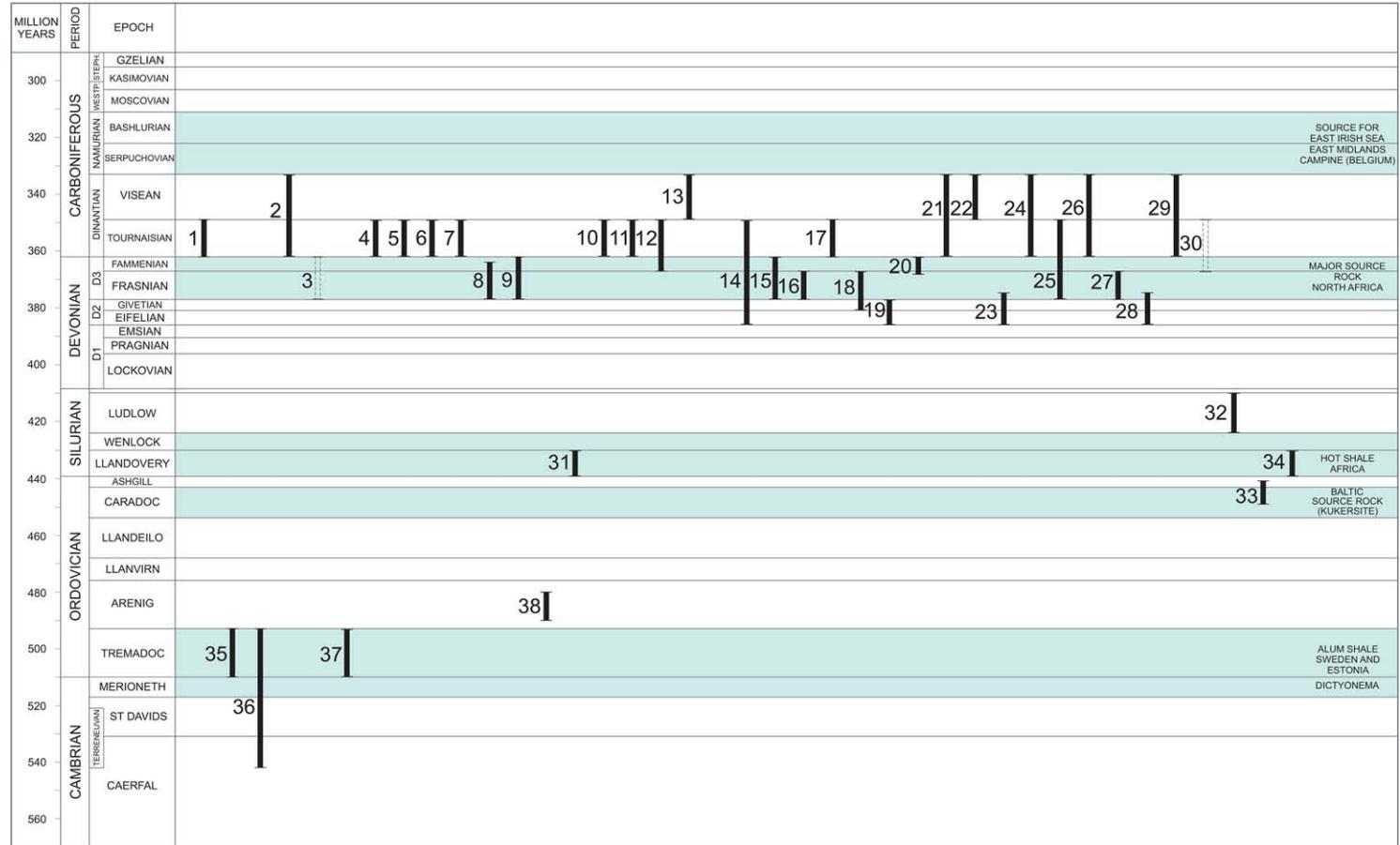


Fig. 15. Paleozoic well penetrations: 1, Devizes 1; 2, Farleigh Wallop 1; 3, Lomer 1; 4, Herriard 1; 5, Humbly Grove 1; 6, Humbly Grove 2; 7, Hesters Copse 1; 8, Coxbridge 1; 9, Baxters Copse 1; 10, Albury 1; 11, Brockham 1; 12, Horse Hill 1; 13, Wineham 1; 14, Bolney 1; 15, Stanmer 1; 16, Bletchingley 1; 17, Warlingham 1; 18, Palmers Wood 1; 19, Tatsfield 1; 20, Holtye 1; 21, Penshurst 1; 22, Ashour 1; 23, Shipbourne 1; 24, Hellingly 2; 25, Westham 1; 26, Wallcrouch 1; 27, Brightling 1; 28, Detention 1; 29, Iden Green 1; 30, Fairlight 1; 31, Shalford 1; 32, Biddenden 1; 33, Bobbing 1; 34, Chilham 1; 35, Shrewton 1; 36, Cooles Farm 1; 37, East Worldham 1; 38, Strat A1.

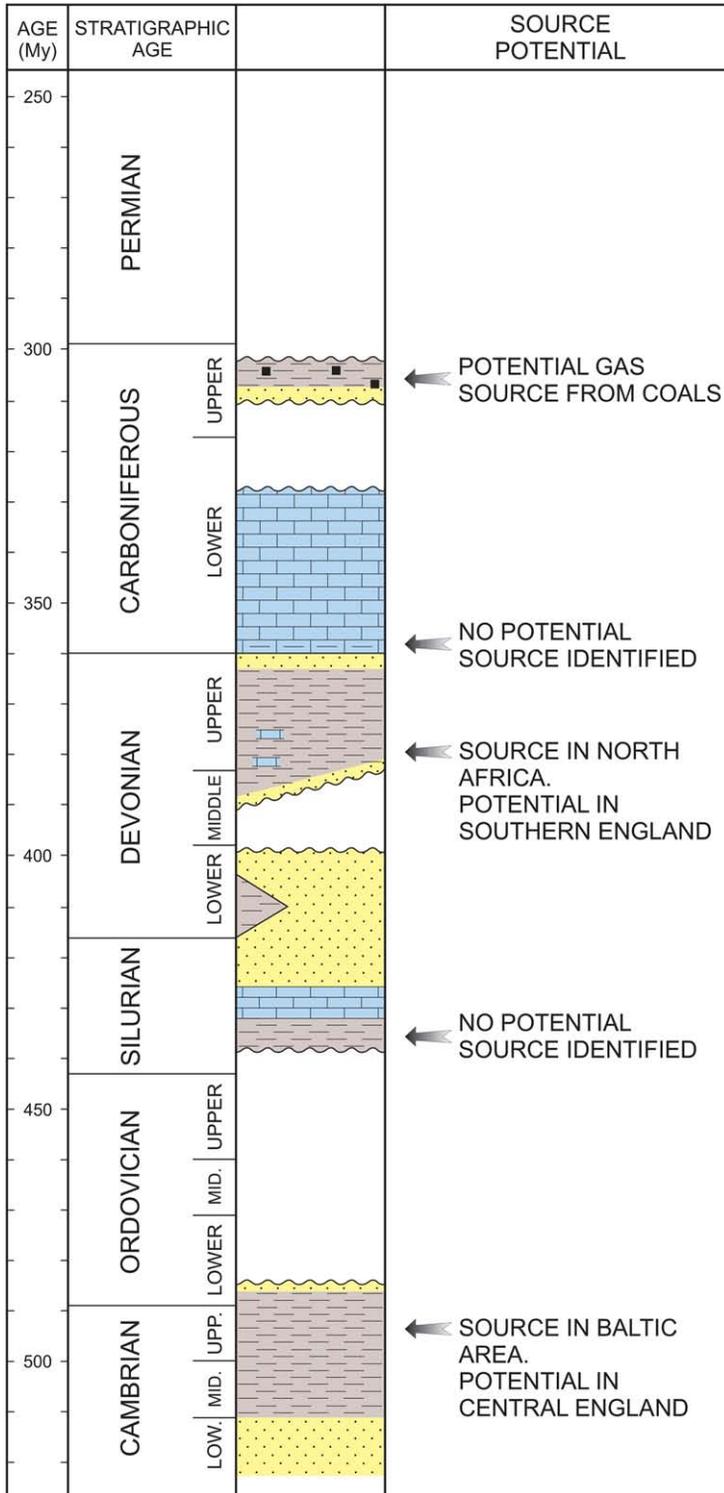


Fig. 16. Potential Paleozoic source rock intervals.

PALEOZOIC GAS POTENTIAL IN THE WEALD BASIN

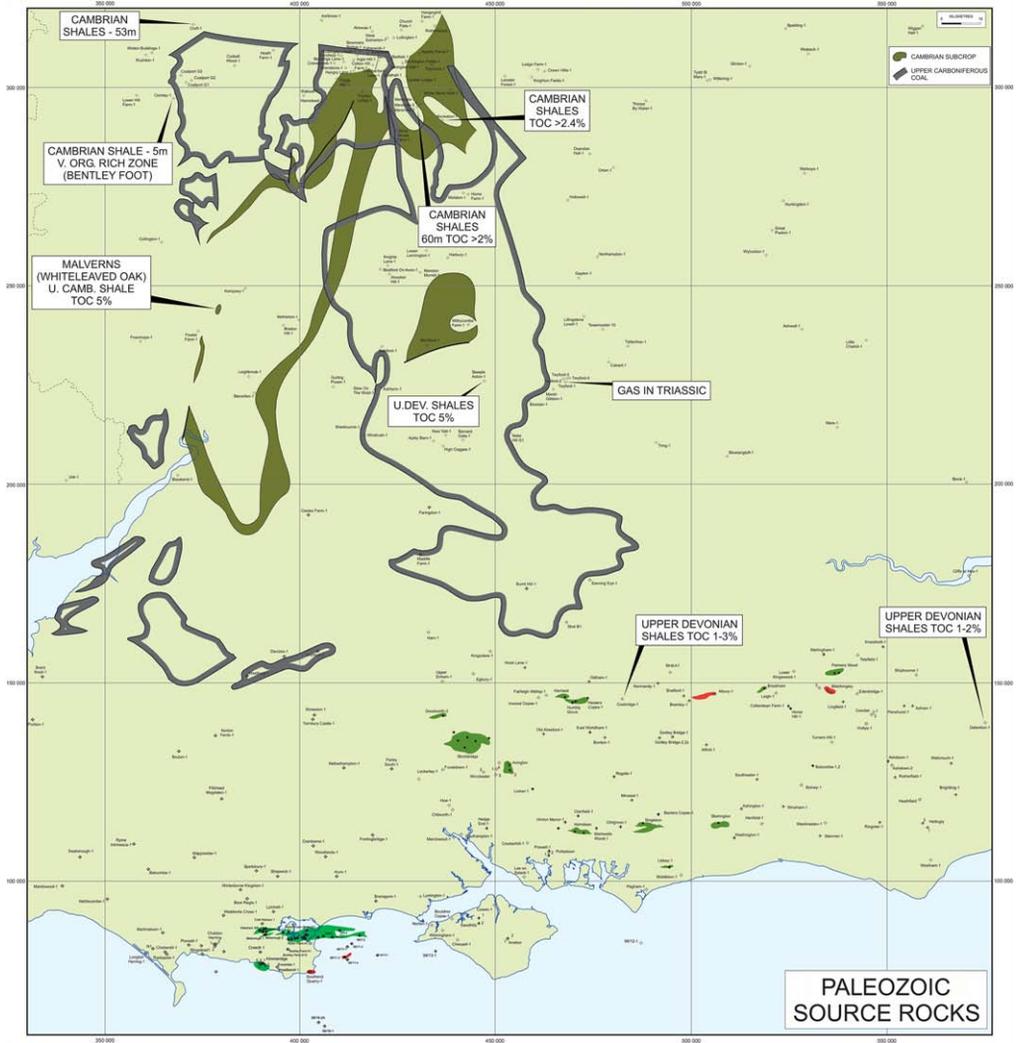


Fig. 17. Paleozoic source rock occurrences.

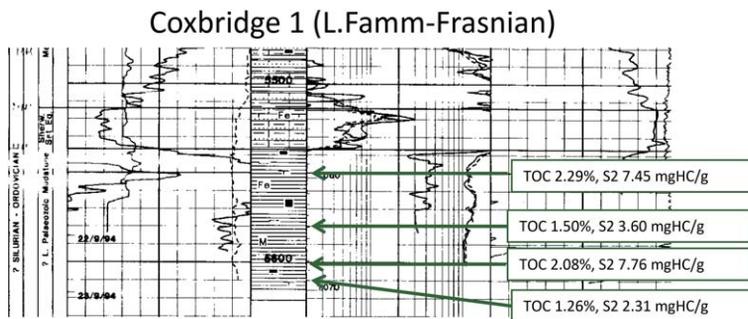


Fig. 18. Devonian section: Coxbridge 1. Released well data.

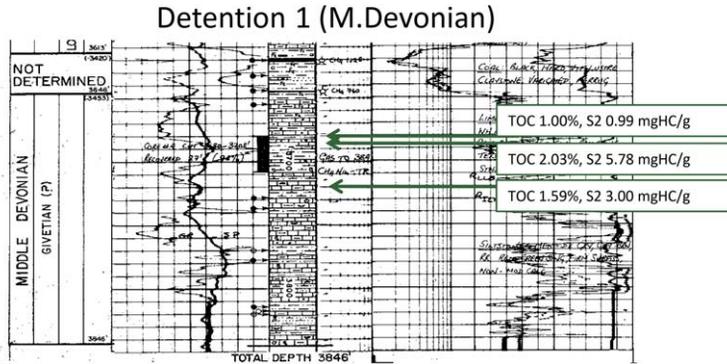


Fig. 19. Devonian section: Detention 1. Released well data.

the northern bounding fault. This may be a sampling problem, since most wells are located on palaeo-highs; but with over 37 well penetrations, the absence of coals suggests that these rocks are not present and were either not deposited or were eroded prior to Triassic deposition. In a number of wells to the east, thin coals of possibly early Jurassic or Upper Triassic age have been encountered. In the Southern England Basin only one well, the Westbury borehole located south of the Bristol–Radstock Coal Basin, encountered Coal Measures south of the northern basin-bounding fault, often referred to as the Variscan Front. There is some evidence for the development of isolated basins of possible late Carboniferous or early Permian red-bed clastics in the southern Weald (e.g. Middleton-1).

Regional distribution

In order to get an understanding of the distribution of potential Paleozoic rocks, it is necessary to define the Paleozoic subcrop to the Variscan unconformity surface.

In southern England, the effects of several tectonic episodes during the Paleozoic control the resultant subcrop. The Caledonian Orogeny was characterized by deformation phases caused by two plate-docking episodes (Fig. 20). The first of these was the closure of the Tornquist Ocean (between Avalonia and Baltica) in the east in late Ordovician–early Silurian times, which was marked by the Shelvian unconformity when erosion down to the Precambrian took place in parts of the Midlands Microcraton. The second was the closure of the Iapetus Ocean (between Avalonia and Laurentia) to the NW in the late Silurian–early Devonian. The latter, Acadian, orogenic phase is marked by a pronounced unconformity below the Upper Devonian across southern England.

The first phase of the Variscan Orogeny seen in southern England began in the Middle Carboniferous and ended in the late Carboniferous–early Permian. It marked the progressive closure of the Rheic Ocean as the Avalonian and Armorican plates moved together. The deformation in southern England is thought to represent a north-verging east–west-trending thrust belt, with Paleozoic rocks being thrust northwards towards the foreland of the Midlands Microcraton–London Brabant Massif. The activity was periodic and reflected in the development of a series of unconformities but, overall, the deformation decreases in age northwards.

The new subcrop map of southern England (Fig. 21) is based on well data, seismic interpretation and coalfield mapping, and makes use of previous work carried out by Busby & Smith (2001). Seismic lines have been used where events can be mapped at Paleozoic levels outside the Mesozoic depocentres. Unfortunately, over much of the Weald Basin, the subcrop map is reliant on limited well control because of poor seismic penetration and, therefore, poor quality, and there are few deep well penetrations in the basin centre.

The problems in determining the Paleozoic structure beneath the Weald Basin are well illustrated at Horse Hill. The seismic data show beds dipping to the south, which depth conversion would tend to accentuate slightly; however, the dip-meter in the well demonstrates that the interval has reasonably consistent dips of 20°–35° to the north (shown in white in Fig. 22; see also Fig. 23).

In the NW of the Wessex Basin (the Western Sub-basin of the Southern England Basin: Hawkes *et al.* 1998), the Paleozoic section can sometimes be resolved on the seismic data and can be tied to deep well control. Figure 24 links the Yambury-1 and Shrewton-1 boreholes to the south, which encountered Lower Ordovician Tremadocian sequences below the Mesozoic (Whittaker 1980),

PALEOZOIC GAS POTENTIAL IN THE WEALD BASIN

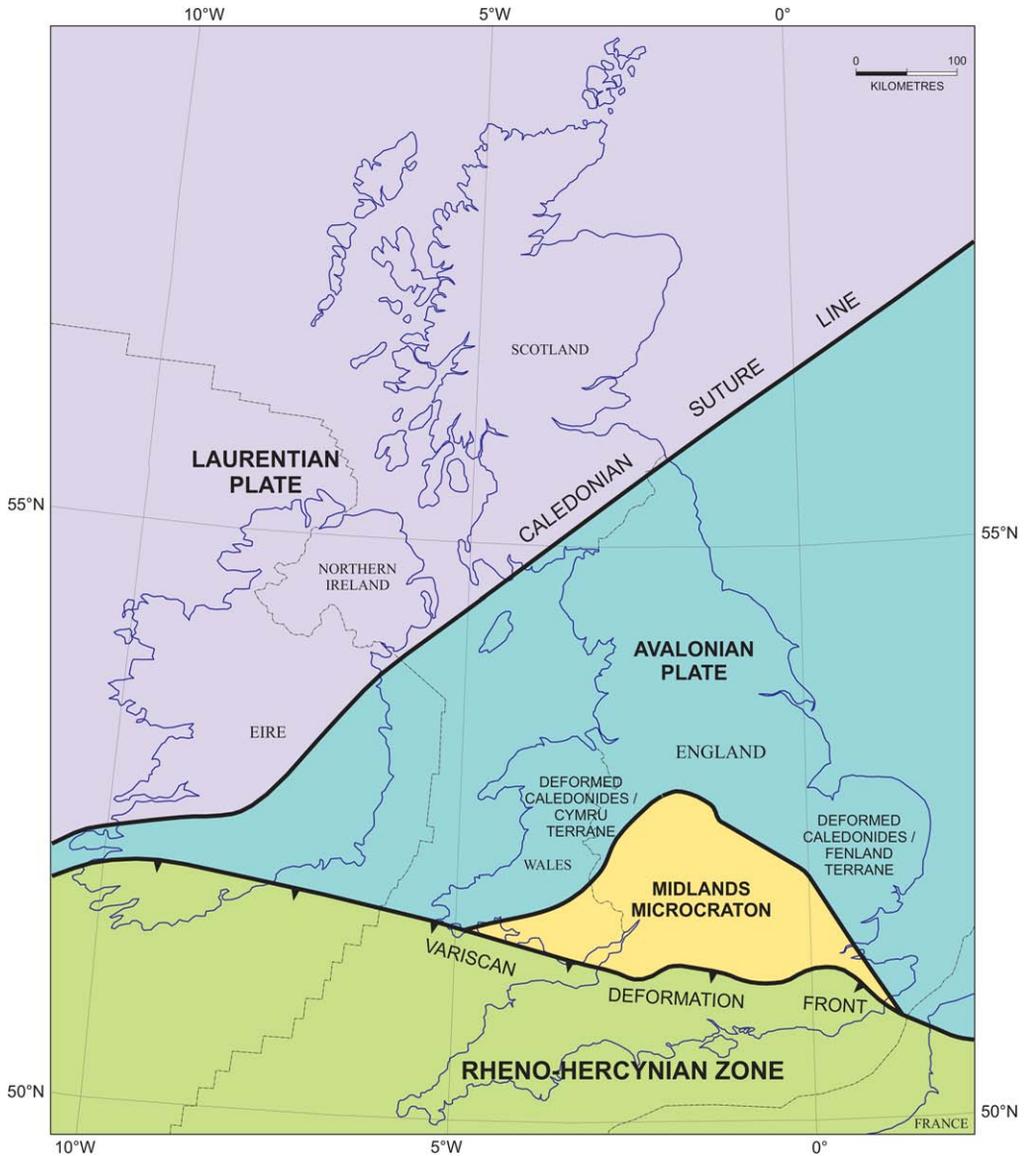


Fig. 20. Regional structural setting. Simplified from Chadwick & Evans (2005).

with the Devizes-1 borehole (c. 20 km to the north), which encountered Lower Carboniferous limestones below the Mesozoic, with an apparently conformable transition from the presumed Upper Devonian beneath. The line gives no indication of a major dislocation between the two subcrop areas and suggests that the Upper Devonian lies unconformably on the Tremadocian in this area. This would be consistent with outcrop information in the eastern Mendips and Tortworth inlier, where the Acadian unconformity has cut down at least to the Llandoverly

(Green & Welch 1965; Cave 1977), and with the gravity interpretation of the Vale of Wardour (Chadwick *et al.* 1981). The Tremadocian subcrops below the Variscan unconformity in East Worldham 1 and the Ordovician subcrops in Strat A 1, in the central part of the Weald Basin. Whereas the presence of the Tremadocian subcrop beneath the centre of the Weald might be considered to be due to deep erosion of younger beds during Variscan movements and the consequent loss of potential late Devonian source rocks, it seems more likely that Acadian erosion of

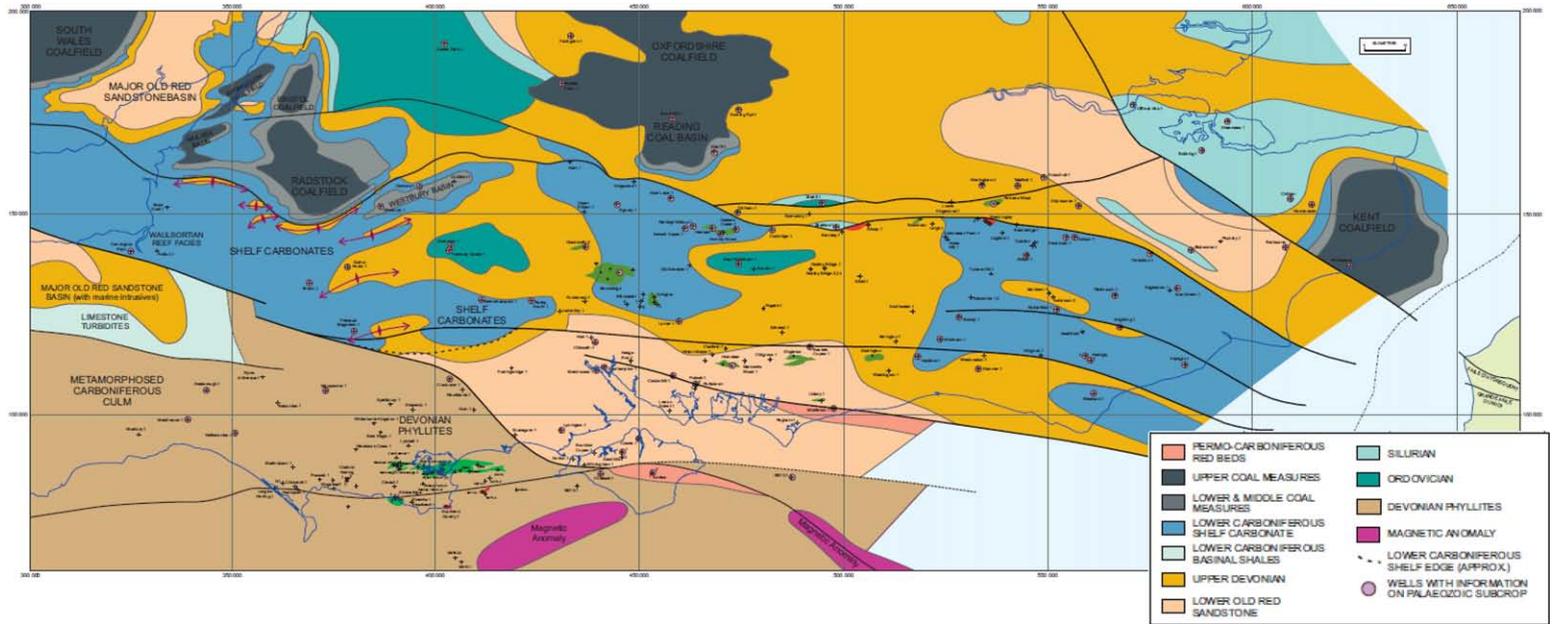


Fig. 21. Variscan subcrop map based on seismic mapping, well and coalfield data, and making use of Busby & Smith (2001).

PALEOZOIC GAS POTENTIAL IN THE WEALD BASIN

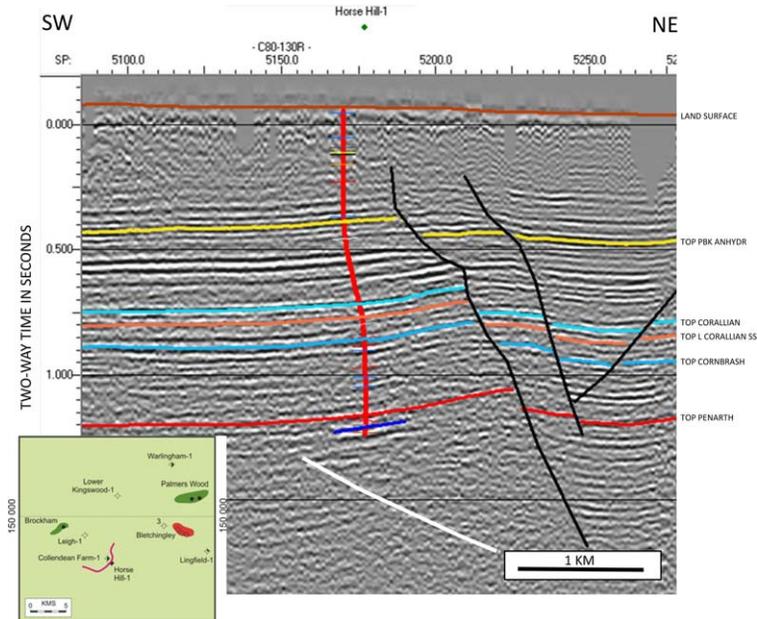


Fig. 22. Seismic line through the Horse Hill structure.

early Devonian and Silurian beds led the post-Acadian Frasnian unconformity to lie directly on Tremadocian rocks that were later exposed to the surface by minor Variscan erosion. This leads to the conclusion that there may be a wide distribution of potential source rocks in the late Devonian across east and central parts of the Weald Basin (Fig. 21).

The subcrop data in the Weald Basin suggest that the Upper Devonian and Lower Carboniferous transgressed over thick, folded but unmetamorphosed Lower Devonian, and that older Lower Paleozoic rocks deformed during Acadian movements. The entire section, including Upper Paleozoic post-Acadian sediments, then deformed during the Variscan movements. To the east, the metamorphosed Lower Paleozoic rocks of the Acadian-age Anglo-Brabant Deformation Belt underlie the Upper Devonian and Lower Carboniferous in the Kent Coalfield.

Paleozoic maturity

The available maturity data for the Paleozoic of the Weald Basin are shown in Figure 25 and demonstrate that the Paleozoic petroleum system is a valid source objective since it is not overmature in the Weald Basin. Also shown on this map is the extent of the Mesozoic depocentre, where burial is calculated to have allowed the restarting of hydrocarbon generation from the deeper buried Paleozoic source rocks during the Cretaceous.

The data in Figure 25 have been compiled from well samples near or at the top of the Paleozoic sequences, just below the Hercynian unconformity surface. Although of variable quality, the data demonstrate that the sediments in the north of the area are still in the oil window (VR of 0.5–1.1%), while those from more basinal wells indicate an increase in maturity and a move into the gas window (VR of 1.3–1.6%). There is no significant break in the maturity profile with respect to the overlying Mesozoic in the north and centre of the basin. However, to the south and SW, the effects of Variscan metamorphism are seen (Cornford *et al.* 1987). Since these values are measured at the top of the interval, they do not represent the maturity of the deeper Paleozoic, which would be higher and can be projected to reach the gas window. The majority of the data come from the post-Acadian Devonian and Carboniferous sequences. The maturity levels are commensurate with the results of the isotope analyses, as well as the nitrogen content of the gases.

Due to the absence of vitrinite, maturity of the Lower Paleozoic has been measured (Molyneux 2010a) using the acritarch alteration index (AAI), as well as spore coloration. These measurements were then converted to vitrinite equivalents (Legall *et al.* 1981).

In order to put these data into a regional perspective, the available data from the rest of southern England have been compiled in Figure 26.

HORSE HILL-1

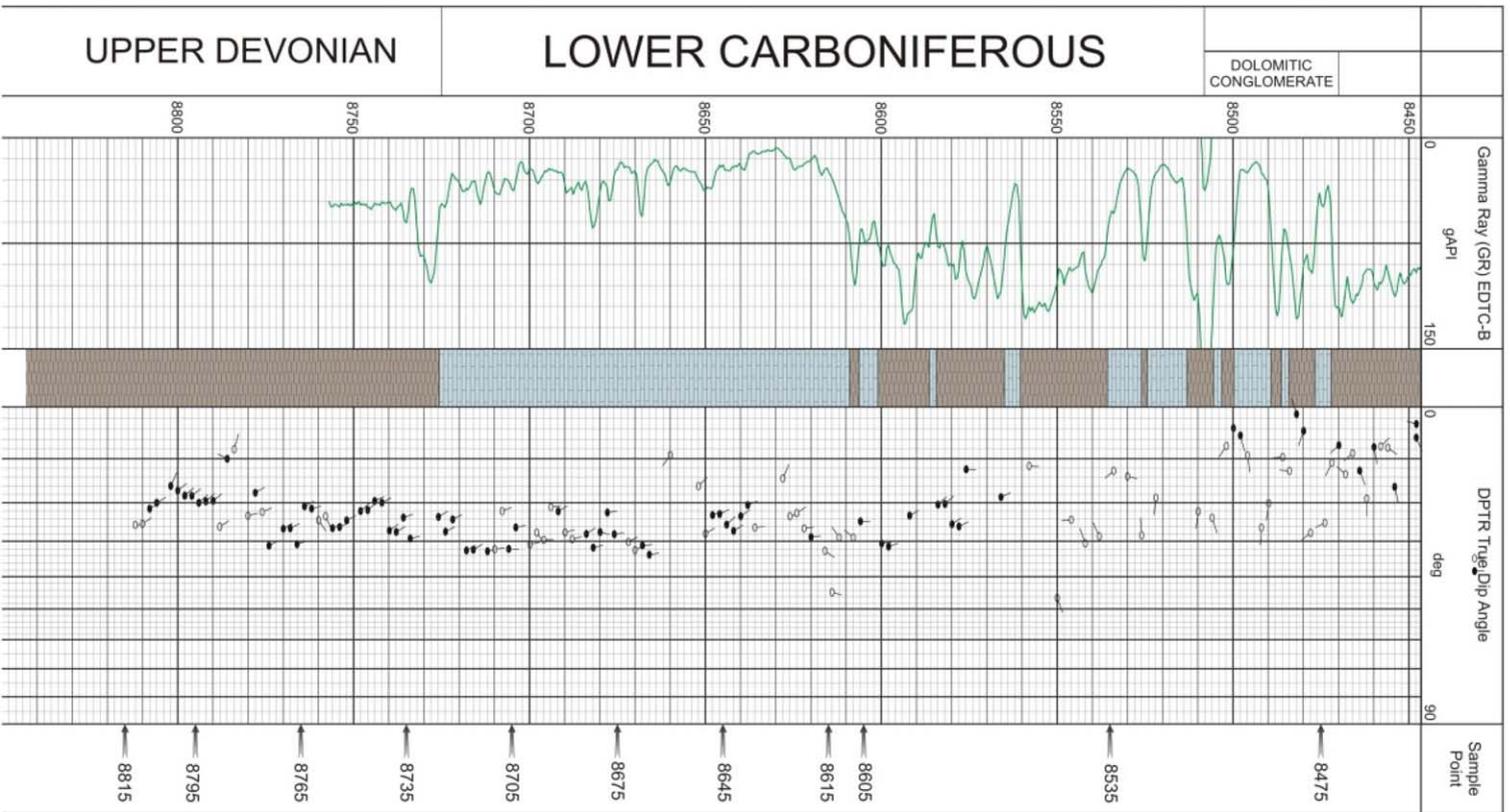


Fig. 23. Well Horse Hill 1 dipmeter. Published with the permission of UKOG plc.

PALEOZOIC GAS POTENTIAL IN THE WEALD BASIN

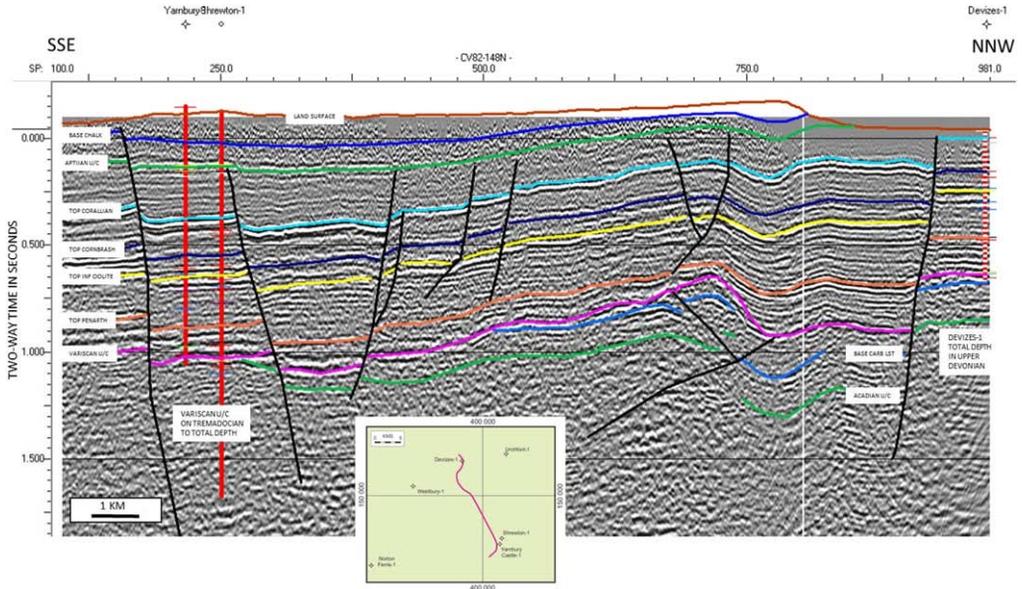


Fig. 24. SSE–NNW seismic line: NW Wessex Basin.

These data show that the Paleozoic in the southern Wessex Basin is at a post-gas generation stage. The rocks reach metamorphic grades, suggesting a position in the internal part of the Hercynian Deformation Belt. This higher grade of maturity appears to extend to the east of the southern flank of the Weald Basin, often called the Portsdown–Paris–Plage Ridge (see Fig. 1) in the literature (Butler & Pullan 1990; Andrews 2014). Although there is no maturity data from the wells in this area, the log and lithological data indicate that the rocks are more indurated, deformed and are likely to be mildly metamorphosed. In this area, the seismic shows no response in the Paleozoic, suggesting strong deformation, whilst the overlying Mesozoic thins markedly and is cut by numerous extensional faults. This change in structural character, compared to the relatively undeformed and unfaulted Mesozoic of the Central Weald, suggests a different basement fabric.

The maturity data from the Tremadocian and Cambrian of the Shrewton 1 and Cooles Farm 1 wells (Whittaker 1980; Harriman 2010) show that these rocks are in the wet-gas window. Since the post-Acadian and Mesozoic burial in the vicinity of these wells has not been high, it is believed that this maturity was reached as a result of pre-Acadian burial.

Discussion

A vexed question in the literature has been the position of the northern limit of intense Variscan

deformation, the ‘Variscan Front’, in southern England since it does not crop out but lies beneath the Mesozoic cover. With the realization that much of the deformation of the Paleozoic sequences may result from Acadian movements, the limit of Variscan deformation has become more difficult to define.

To the SW, in Devon and Cornwall at outcrop, the Upper Paleozoic rocks are folded and metamorphosed, and the deformation front has been taken to lie in southernmost Wales where outcrop information allows the limit of intense deformation to be more clearly defined, although Variscan folding and thrusting continues well north of this line (Chadwick & Evans 2005). Previous workers, including Chadwick (1986) and Busby & Smith (2001), have extrapolated this front as a line running eastwards from the Mendip Hills across southern England and Tertiary reactivated faults, such as the Pewsey Fault and the Hog’s Back Fault, as the surface trace. It is clear that Upper Paleozoic rocks in the Weald were deformed and folded prior to Variscan erosion (as demonstrated in the Horse Hill well). Although to the north of this ‘Variscan Front’ line the Paleozoic section appears less deformed, there are still indications of east–west-orientated Variscan structures on seismic lines across from Wiltshire into north Kent, the most important of which are shown on Figure 21. Chadwick & Evans (2005, fig. 32) projected that the main Variscan thrust subcrops the Permian–Triassic some way north of the Pewsey Fault, and Butler & Jamieson (2013, plates 1 & 4) show



C. PULLAN & M. BUTLER

Fig. 25. Top Paleozoic maturity. From released well and industry reports.

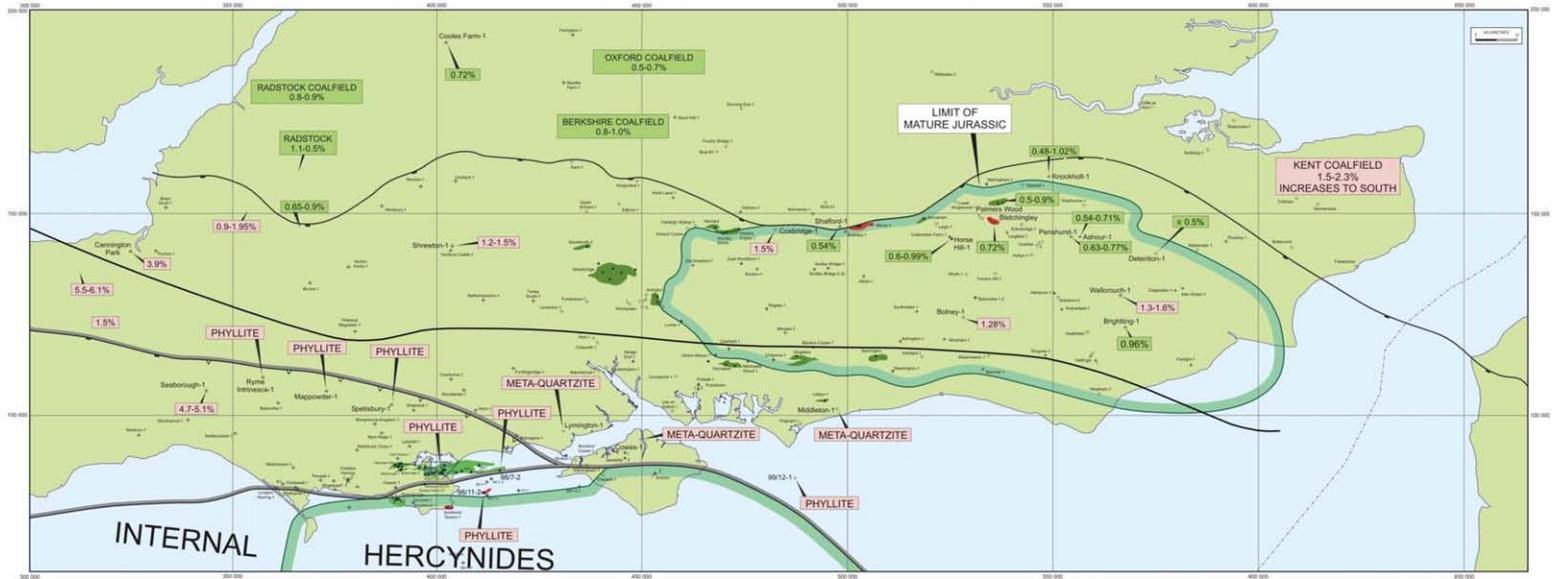


Fig. 26. Southern England: Top Paleozoic maturity. Compiled from various sources, including Taylor (1986) and Smith (1993).

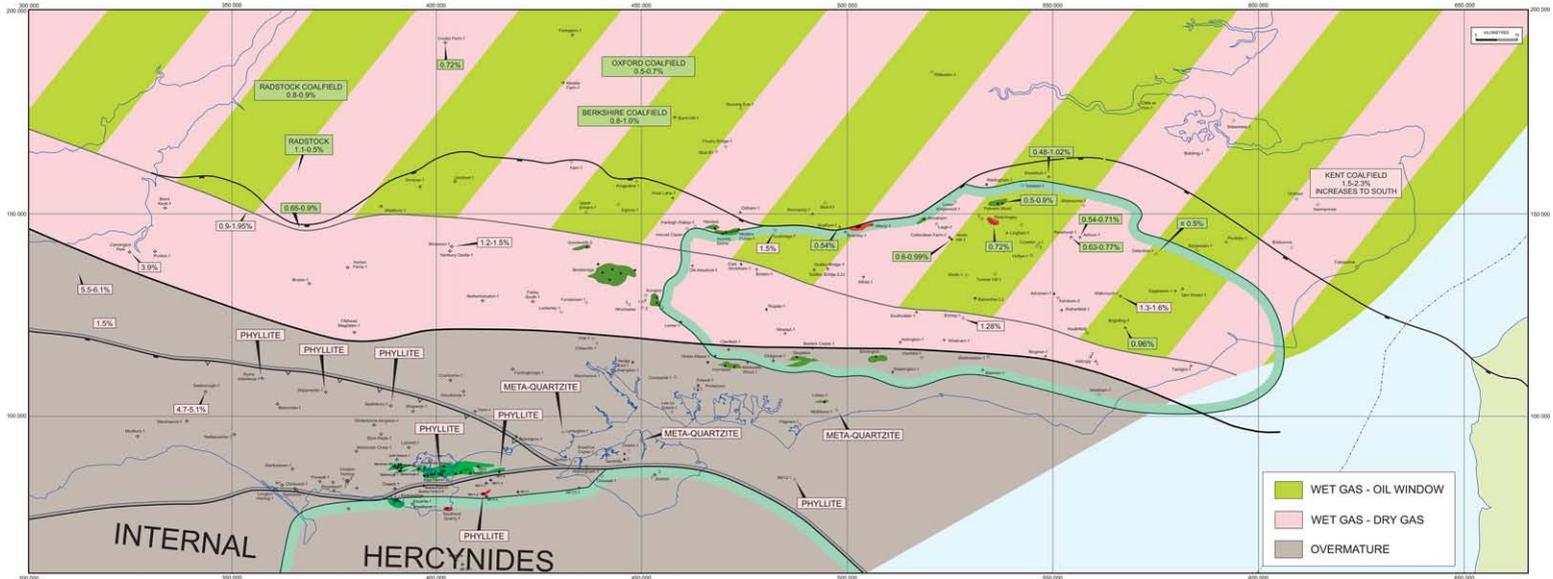


Fig. 27. Southern England: Top Paleozoic hydrocarbon-generation zones.

apparent Variscan thrusting and folding of the Paleozoic well north of the Pewsey and Hog's Back faults. On the basis of the scattered evidence from seismic data and well penetrations, it seems likely that the structure of the Paleozoic rocks beneath the Weald itself is similar to that postulated by Williams & Brooks (1984) for the area SE of the Mendips. However, the rocks are not metamorphosed. In the absence of good seismic definition of pre-Mesozoic structures, it seems sensible to define the limit of intense Variscan deformation by the onset of low-grade metamorphism in the Paleozoic subcrop, which lies on the southern edge of the Weald Basin (Fig. 27).

In the Wyth Farm Oil Field in Dorset, England, the largest onshore oil field in NW Europe, a conventional play reliant on Triassic Sherwood sandstone reservoirs sealed by Triassic and Lower Jurassic shales and sourced by Lower Jurassic through fault juxtaposition has been proven. An extension of this play into the Weald Basin has suffered from being unable to demonstrate a hydrocarbon charge to the deeper reservoir targets. These indications of a deeper gas source open up the opportunity for plays beneath the established Jurassic reservoirs of the Weald Basin, with hydrocarbons trapped in Paleozoic and Triassic reservoirs sourced by the underlying Paleozoic shales. Since Triassic river systems are expected to have followed the depositional axis of the basin, flowing from east to west down-dip of structural highs, the thickest Triassic sands may be expected in the undrilled basin centre. This play remains untested.

Acknowledgements The authors would like to thank Celtique Energie and Magellan Petroleum for permission to publish this work and to UKOG plc for permission to publish information from Horse Hill-1. Thanks also go to the technical team at Celtique Energie who assisted with the geological, geophysical and petrophysical interpretation; in particular, Martin Berry, Ken Dups and Sarah Shirt. Thanks also go to Gareth Harriman (GH Geochem) for his geochemical analyses and advice. Very helpful discussions were had with Bernard Cooper of Horus Petroleum, who had thought deeply about the same issue. Thanks also go to Eric Stuckey of Windmill Graphics for drafting the figures and maps.

Funding The authors would like to thank the UK Onshore Geophysical Library (UKOGL) for providing financial support for this publication.

References

ANDREWS, I.J. 2014. *The Jurassic Shales of the Weald Basin: Geology and Shale oil and Shale Gas Resource Estimate*. British Geological Survey for Department of Energy and Climate Change, London.

- BOOTE, D.R.D., CLARK-LOWES, D.D. & TRAUT, M.W. 1998. Palaeozoic petroleum systems of North Africa. In: MACGREGOR, D.S., MOODY, R.T. & CLARKE-LOWES, D.D. (eds) *Petroleum Geology of North Africa*. Geological Society, London, Special Publications, **132**, 7–68, <https://doi.org/10.1144/GSL.SP.1998.132.01.02>
- BURWOOD, R., STAFFURTH, J., DE WALQUE, L. & DE WITTE, S.M. 1991. Petroleum geochemistry of the Weald–Wessex Basin of southern England: a problem in source-oil correlation. In: MANNING, D. (ed.) *Organic Geochemistry: Advances and Applications in Energy and the Natural Environment. Extended Abstracts. 15th Meeting of the European Association of Organic Geochemists*. Manchester University Press, Manchester, UK, 22–27.
- BUSBY, J.P. & SMITH, N.J. 2001. The nature of the Variscan basement in southeast England: evidence from integrated potential field modelling. *Geological Magazine*, **138**, 669–685.
- BUTLER, D.E. 1981. Marine faunas from concealed Devonian rocks of southern England and their reflection of the Frasnian transgression. *Geological Magazine*, **118**, 679–697.
- BUTLER, M. & JAMIESON, R. 2013. *Preliminary Interpretation of Six Regional Seismic Lines Across Onshore Basins of England*. UK Onshore Geophysical Library, London.
- BUTLER, M. & PULLAN, C.P. 1990. Tertiary structures and hydrocarbon entrapment in the Weald Basin of southern England. In: HARDMAN, R.F. & BROOKS, J. (eds) *Tectonic Events Responsible for Britain's Oil and Gas Reserves*. Geological Society, London, Special Publications, **55**, 371–391, <https://doi.org/10.1144/GSL.SP.1990.055.01.19>
- CARLESS EXPLORATION LTD 1983. *The Humbly Grove Oilfield – Field Development and Production Programme, Annex B*. Available online through UKOGL, <https://ukogl.org.uk/industry-reports>
- CAVE, R. 1977. *Geology of the Malmesbury District*. HMSO, London.
- CHADWICK, R. 1986. Extension tectonics in the Wessex Basin, southern England. *Journal of the Geological Society, London*, **143**, 465–488, <https://doi.org/10.1144/gsjgs.143.3.0465>
- CHADWICK, R.A. & EVANS, D.J. 2005. *A Seismic Atlas of Southern Britain – Images of Subsurface Structure*. British Geological Survey, Occasional Publications, **7**. British Geological Survey, Keyworth, Nottingham, UK.
- CHADWICK, R.A., KIRBY, G.A., KUBALA, M., SOBEY, R.A., WHITTAKER, A., KENOLTY, N. & PENN, I.E. 1981. *A Hydrocarbon Prospectivity Study of the Vale of Wardour Area*. Deep Geology Report DP 81/1. Institute of Geological Sciences, London.
- CLAYTON, C. 2009. *A New Understanding of Biogenic Gas: An Explorers Guide*. Petroleum Exploration Society of Great Britain (PESGB), Croydon, UK.
- CONOCO (UK) LTD 1986. *Weald Basin Gas Hydrocarbon Generation Montage*. Available online through UKOGL, <https://ukogl.org.uk/industry-reports>
- CORNFORD, C., YARNELL, L. & MURCHISON, D.G. 1987. Initial vitrinite reflectance results from the Carboniferous of north Devon and north Cornwall. *Proceedings of the Ussher Society*, **6**, 461–467.

- DAWSON, C. 1898. On the discovery of natural gas in East Sussex. *Quarterly Journal of the Geological Society, London*, **54**, 564–574, <https://doi.org/10.1144/GSL.JGS.1898.054.01-04.38>
- EBUKANSON, E.J. & KINGHORN, R.R. 1986. Oil and gas accumulations and their possible source rocks in southern England. *Journal of Petroleum Geology*, **9**, 413–428.
- FALCON, N.L. & KENT, P.E. 1960. *Geological Results of Petroleum Exploration in Britain 1945–1957*. Geological Society, London, Memoirs, **2**, <https://doi.org/10.1144/GSL.MEM.1960.002.01.01>
- FOSTER, D., HOLLIDAY, D.W., JONES, C.M., OWENS, B. & WELSH, A. 1989. The concealed Upper Palaeozoic rocks of Berkshire and South Oxfordshire. *Proceedings of the Geologists' Association*, **100**, 395–407.
- GEOCHEM LABORATORIES LTD 1980. *Geochemical Evaluation of Carboniferous Outcrop Samples from Maesbury and Windsor Hill, Mendips. Report for St. Joe Petroleum Ltd*. Available online through UKOGL, <https://ukogl.org.uk/industry-reports>
- GREEN, G.W. & WELCH, F.B.A. 1965. *Geology of the Country around Wells and Cheddar*. HMSO, London.
- HANCOCK, F.R. & MITHEN, D.P. 1987. The geology of the Humbly Grove Oilfield, Hampshire, U.K. In: BROOKS, J. & GLENNIE, K.W. (eds) *Petroleum Geology of Northwest Europe: Proceedings of the 3rd Conference*. Graham & Trotman, London, 119–128.
- HARRIMAN, G.H. 2010. *Geochemical Evaluation of Oils and Samples in the Weald Basin*. Unpublished report for Magellan Petroleum (UK) Ltd
- HAWKES, P.W., FRASER, A.J. & EINCHOMB, C.C. 1998. The tectono-stratigraphic development and exploration history of the Weald and Wessex basins, Southern England, UK. In: UNDERHILL, J.R. (ed.) *Development, Evolution and Petroleum Geology of the Wessex Basin*. Geological Society, London, Special Publications, **133**, 39–65, <https://doi.org/10.1144/GSL.SP.1998.133.01.03>
- 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. *Marine and Petroleum Geology*, **17**, 639–654.
- JONES, D.K. 1999. Uplift and denudation of the Weald. In: SMITH, B.J. & WORKE, P.A. (eds) *Uplift, Erosion, and Stability: Perspectives on Long-term Landscape Development*. Geological Society, London, Special Publications, **162**, 25–43, <https://doi.org/10.1144/GSL.SP.1999.162.01.03>
- KETTEL, D. 1989. Upper Carboniferous source rocks north and south of the Variscan Front (NW and Central Europe). *Marine and Petroleum Geology*, **6**, 170–181.
- LAMB, R.C. 1983. *Hydrocarbon Prospectivity of the Weald and Eastern English Channel. Volume 5: Source Rock Potential and Maturity*. IGS Deep Geology Unit Report to Department of Energy 83/3/5.
- LEGALL, F.D., BARNES, C.R. & MACQUEEN, R.W. 1981. Thermal maturation, burial history and hotspot development, Palaeozoic strata of southern Ontario–Quebec, from conodont and acritarch alteration studies. *Bulletin of Canadian Petroleum Geology*, **29**, 492–539.
- LÜNING, S., ADAMSON, K. & CRAIG, J. 2003. Frasnian organic-rich shales in North Africa: regional distribution and depositional model. In: ARTHUR, T.J., MACGREGOR, D.S. & CAMERON, N.R. (eds) *Petroleum Geology of Africa: New Themes and Developing Technologies*. Geological Society, London, Special Publications, **207**, 165–184, <https://doi.org/10.1144/GSL.SP.2003.207.9>
- MAGELLAN PETROLEUM (UK) LTD 2012. *Relinquishment Report PEDLs 135 and 242*. Available online through UKOGL, <https://ukogl.org.uk/industry-reports/>
- MCLEOD, R. 2002. *A reservoir study of the Great Oolite Limestone Formation in the Wiltshire–Hampshire high, Weald Basin*. MSc thesis, University of Reading, Reading, UK.
- MOLYNEUX, S.G. 2010a. *Palynology Report on Palaeozoic Samples from Bobbing, Cooles Farm 1, Coxbridge 1, East Worldham 1, Harmansole, Shalford 1, Shrewton 1 and Strat A1 Boreholes*. British Geological Survey Commissioned Report CR/10/123. UKOGL, London.
- MOLYNEUX, S.G. 2010b. *Palynology Report on Palaeozoic Samples from Baxters Cope 1, Brockham 1, Coxbridge 1, Detention 1, Goodworth 1, Knockholt 1, Lomer 1 and Palmers Wood 1 Boreholes*. British Geological Survey Commissioned Report CR/11/054. UKOGL, London.
- PETRA-CHEM LTD 1986. *Geochemical Source Rock Evaluation of Carboniferous and Lower Jurassic Sediments from Selected Wells/Locations Adjacent to XLI30, Somerset, UK*. Available online through UKOGL, <https://ukogl.org.uk/industry-reports>
- SELLWOOD, B.W. & EVANS, M.R. 1986. *Regional Sedimentology and Diagenesis of the Great Oolite in the Wessex and Weald Basins. First Report, Carless Exploration Ltd*. Available online through UKOGL, <https://ukogl.org.uk/industry-reports>
- SELLWOOD, B.W. & EVANS, M.R. 1987. *Regional Sedimentology and Diagenesis of the Great Oolite in the Wessex and Weald Basins. Second Report, Carless Exploration Ltd*. Available online through UKOGL, <https://ukogl.org.uk/industry-reports>
- SELLWOOD, B.W., SHEPHERD, T.J., EVANS, M.R. & JAMES, B. 1989a. Origin of late cements in oolitic reservoir facies: a fluid inclusion and isotopic study (Mid-Jurassic), southern England. *Sedimentology Geology*, **61**, 223–237.
- SELLWOOD, B.W., WILKES, M. & JAMES, B. 1989b. Hydrocarbon inclusions in late calcite cements: migration indicators in the Great Oolite Group, Weald Basin, southern England). *Sedimentology Geology*, **84**, 51–55.
- SMITH, N.J. 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, <https://doi.org/10.1144/0040667>
- STAHL, W.J. 1977. Carbon and nitrogen isotopes in hydrocarbon research and exploration. *Chemical Geology*, **20**, 121–149.
- STERLING RESOURCES (UK) LTD 2001. *UK Onshore 10th Round Application Weald*. Available online through UKOGL, <https://ukogl.org.uk/industry-reports>
- 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 NW Europe*. Geological Society, London, Special Publications, **23**, 37–53, <https://doi.org/10.1144/GSL.SP.1986.023.01.03>

PALEOZOIC GAS POTENTIAL IN THE WEALD BASIN

- THURRELL, R.G., WORSSAM, B.C. & EDMONDS, E.A. 1968. *Geology of the Country Around Haslemere*. HMSO, London.
- TISSOT, B.P. & WELTE, D.H. 1984. *Petroleum Formation and Occurrence*. 2nd edn. Springer, Berlin.
- TRUEMAN, S. 2003. The Humbly Grove, Herriard, Storrington, Singleton, Stockbridge, Goodworth, Horndean, Palmers Wood, Bletchingley and Albury Fields, Hampshire, Surrey and Sussex, UK. In: GLUYAS, J.G. & HICHENS, H.M. (eds) *United Kingdom Oil and Gas Fields Commemorative Millennium Volume*. Geological Society, London, Memoirs, **20**, 929–941, <https://doi.org/10.1144/GSL.MEM.2003.020.01.79>
- WHITTAKER, A. 1980. *Shrewton No. 1 Geological Well Completion Report*. Report of the Deep Geology Unit Institute of Geological Sciences 80/1. Institute of Geological Sciences, London.
- WILHELMS, A., LARTER, S.R., HEAD, I., FARRIMOND, P., DI-PRIMO, R. & ZWACH, C. 2001. Biodegradation of oil in uplifted basins prevented by deep-burial sterilization. *Nature*, **411**, 1034–1037.
- WILLIAMS, G.D. & BROOKS, M. 1984. A reinterpretation of the concealed Variscan structure beneath southern England by section balancing. *Journal of the Geological Society, London*, **142**, 689–695, <https://doi.org/10.1144/gsjgs.142.4.0689>