The Jurassic shales of the Wessex area: geology and shale oil and shale gas resource estimation

Lias, Black Ven, Dorset. Photograph from the Geologists' Association Carrack Archive. © NERC

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Foreword

This report has been produced under contract by the British Geological Survey (BGS), as an addendum to the Weald Basin study (Andrews, 2014). It is based on a recent analysis of all available information, together with published data and interpretations.

Additional information is available at the Oil and Gas Authority (OGA) website. https://www.ogauthority.co.uk/exploration-production/onshore/. This includes licensing regulations, maps, monthly production figures, basic well data and where to view and purchase data. Shale oil/gas related issues including hydraulic fracturing, induced-seismicity risk mitigation and the information regarding the onshore regulatory framework can also be found on this webpage.

Interactive maps, with licence data, seismic, relinquishment reports and stratigraphic tops for many wells are available at www.ukogl.org.uk.

A glossary of terms used and equivalences is tabled at the end of the report (see page 62).

All of the detailed figures in this report are attached in A4 or larger format (Appendix C); thumbnails are also included in the text for reference.

Acknowledgements

The author would like to thank the other contributors to this report, most notably Ian Andrews[1], Mike Sankey[1], Mark Kassyk[1], Toni Harvey[2] and Mark Quint[2].

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Contents

List of figures

List of tables

1 Summary

This report on the Jurassic shale oil and gas potential of the Wessex area follows previous assessments of the potential distribution and in-place resource for shale oil and gas onshore UK (Figure 1), including the Carboniferous shales of the Midland Valley of Scotland (Monaghan, 2014), the Carboniferous shales of the Bowland-Hodder (Andrews, 2013), and the Jurassic shales of the Weald (Andrews, 2014); it is intended as an addendum to the Weald Basin report. Following the methodology used in the assessment of the Weald Basin (Andrews, 2014), a preliminary in-place oil resource calculation has been performed for the main Jurassic shale intervals in the Wessex area. As in the Weald Basin, no significant shale gas resource is recognised in the Jurassic of the Wessex area. The resource assessment is of the hydrocarbons present in shale strata and does not include volumes which have migrated into potential tight conventional or hybrid plays.

The study area has a long history of conventional hydrocarbon exploration and production, with exploration activity since the 1930s (Lees & Cox, 1937), and first production in 1961 from the Kimmeridge Oilfield. The Wytch Farm Oilfield in Dorset lies within the Wessex area and is the largest onshore oil accumulation in North-West Europe. Two other oil fields – Waddock Cross and Wareham – are also situated within the study area.

The Wessex study area lies immediately to the west of the Weald Basin, and is composed of several fault-controlled sub-basins and highs (Chadwick, 1986). The Jurassic sedimentary section is composed of six shallowing-upward sequences of marine shales and siltstones capped by sandstones or limestones (Hawkes et al., 1998). The area has a complex tectonic history and has experienced two significant phases of uplift and erosion – one in the Aptian-Albian, and a Tertiary phase associated with Alpine compression (Lake & Karner, 1987; Butler, 1998; Underhill & Stoneley, 1998). These events have led to a considerable amount of missing Late Jurassic – Early Cretaceous and Tertiary section across much of the area.

Five marine shale units within the Jurassic of the Wessex area are the focus of this study: the Lower, Middle and Upper Lias (Lower Jurassic), the Oxford Clay (Middle-Upper Jurassic) and the Kimmeridge Clay (Upper Jurassic). The amount of organic matter in these units varies across the area, both laterally and temporally. Organic-rich shales (with total organic carbon (TOC) > 2%) occur regionally in the Kimmeridge Clay, in the lower section of the Oxford Clay and in the Lower Lias. The most significant shales in terms of TOC and S2 are the Kimmeridge Clay and all five shale intervals that comprise the Lower Lias. A distinct difference to the Weald Basin is the organic richness of the Lower Lias; the previous study identified only limited potential in this interval, yet in the Wessex area there are rich source intervals throughout the strata. The contrast in organic richness and lithology between the Wessex and Weald areas may be due to differences in palaeogeography and organic input or preservation. Although both the Upper and Middle Lias have well-developed clay intervals, potential in these sections is more limited.

The maturity of the shales is a function of burial depth and heat flow through time. In the Weald study (Andrews, 2014), the Jurassic shales are considered mature for oil generation at vitrinite reflectance, R_o, values between 0.6% and 1.1% at maximum burial depths between approximately 7000-8000 ft (2130-2440 m) and 12000-13000 ft (3660-3960 m) below surface; analysis of available vitrinite reflectance and T_{max} data for the study suggest that these depths are also applicable to the

Wessex area. Shales in the Wessex area may have experienced up to 6900 ft (2100 m) of uplift (England, 2010) during the two significant uplift and erosion events in the Cretaceous and Tertiary.

Burial depths indicate that only the Lower Lias in the Channel Basin, south of the Purbeck-Isle of Wight Disturbance, may be in the oil window present-day; however, palaeo-temperature data suggest the rocks reached higher maturity during the time of maximum burial attained prior to the uplift/erosion events. In the model presented here, accounting for maximum burial depth, only the deepest interval – the Lower Lias – is considered to have potential for oil in terms of source rock richness and (palaeo-) maturity, and only in a localised area, largely south of the Purbeck-Isle of Wight Disturbance. The existence of a mature source rock which has generated and expelled hydrocarbons, at least locally within the area, is supported by the presence of oil in conventional reservoirs that has been correlated to Lower Lias source rocks (Colter & Havard, 1981; England, 2010). Although minor amounts of gas have been produced at Wytch Farm and gas shows have been encountered in several onshore wells, the Lower Lias is not considered to ever have been sufficiently deeply buried to have generated significant amounts of gas onshore. Well 98/11-2 in Bournemouth Bay encountered dry gas in the Sherwood Sandstone (P1022 Relinquishment Document, 2009) and a thermogenic gas seep offshore at Anvil Point on the Dorset coast (Selley, 1992; Selley, 2012; APT UK Ltd., 2013) indicates that the Lower Lias maturity may increase into the Channel Basin depocentre.

Shales with an oil saturation index (Jarvie, 2012) of greater than 100 are identified in all of the intervals of the Lower Lias, and therefore can be considered to have excellent source potential. Interpreting the presence of producible oil in the organic-rich shales allows for an in-place resource volume to be calculated with a broad range of probabilities. The determination of oil-in-place was undertaken using the same methodology applied in the Weald study (Andrews, 2014) and is described in detail in Andrews et al. (2014). The total volume of potentially productive shale in the Wessex area was estimated using a 3D geological model built using seismic mapping integrated with well data. This gross volume was then reduced to a net mature organic-rich shale volume using a maximum, pre-uplift burial depth corresponding to a vitrinite reflectance of 0.6% (modelled at 7000 ft/2130 m and 8000 ft/2440 m). A further upwards truncation was then applied at two alternative levels – firstly at a depth of c. 3950 ft (1200 m) and secondly at a depth of c. 5000 ft (1500 m) (as proposed by Charpentier & Cook, 2011) below surface. A first truncation value of c. 3950 ft (1200 m) was used for this study (as opposed to c. 3000 ft (1000 m) used in the Weald study) due to recent legislation in the Infrastructure Act 2015 stating that hydraulic fracturing (fracking) is permitted only at depths greater than 1200 m below National Parks, groundwater source protection zones 1, World Heritage Sites and Areas of Outstanding Natural Beauty, which together cover most of the prospective area. These cut-offs are applied regionally; the depth at which shale oil (or shale gas) productivity becomes an issue in terms of pressure and hydrogeology will need to be addressed locally.

The volumes of potentially productive shale and average oil yields were used as the input parameters for a statistical calculation (using a Monte Carlo simulation, in which all the parameters were varied within their set distributions over 50,000 iterations) of the in-place oil resource (see Andrews, 2014). The results of the two scenarios modelled for each unit are presented in Table 1. This study offers a range of total in-place oil resource estimates for the various Jurassic shales of the Wessex area of 0.2-1.1-2.8 billion bbl (32-149-378 million tonnes) (P90-P50-P10). It should be

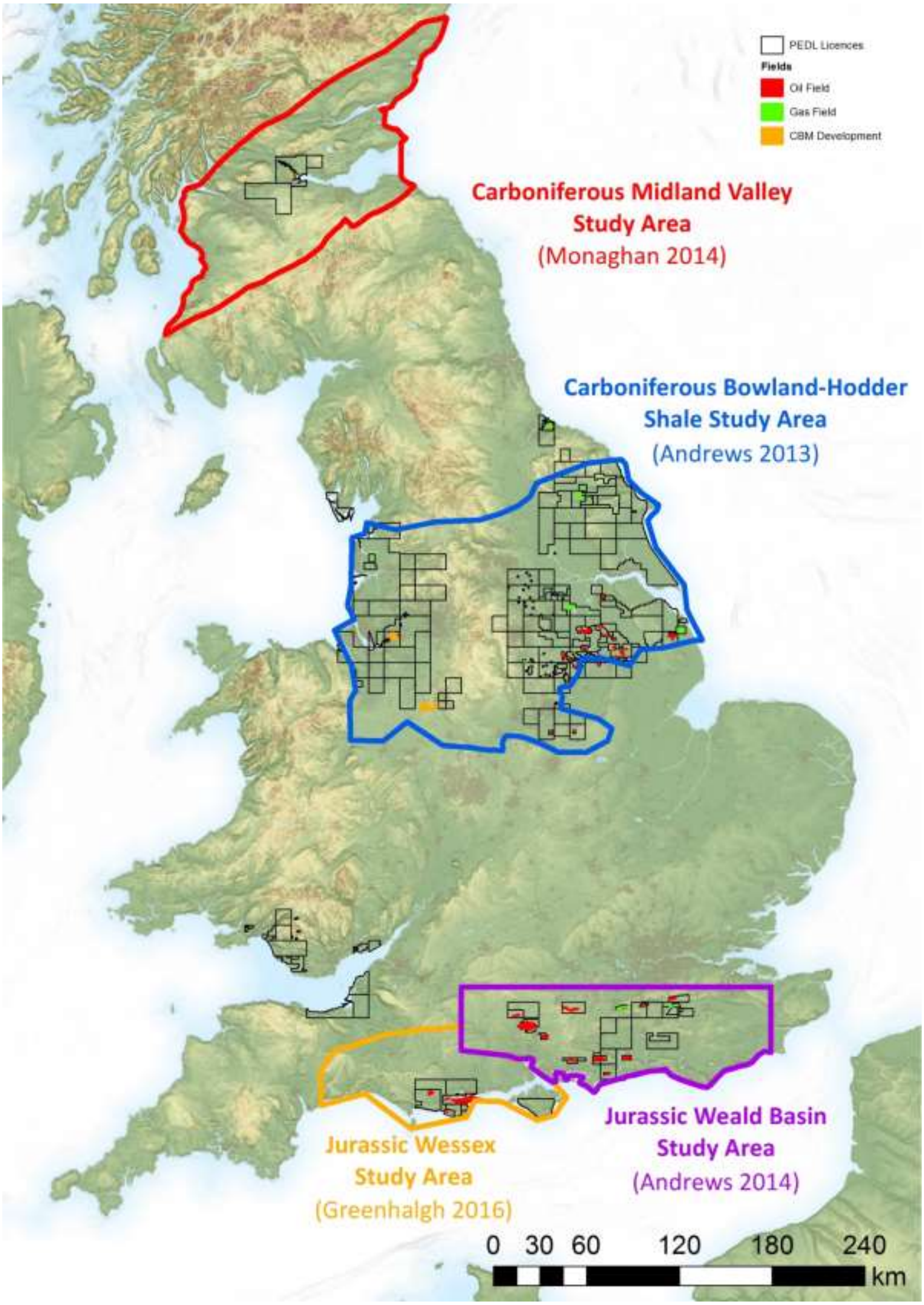


Figure 1. Location of the BGS/OGA Wessex study area in southern Britain, with previous BGS/DECC shale study areas, currently licensed blocks and hydrocarbon fields. Other shale oil and shale gas plays may exist.

emphasised that these 'oil-in-place' figures refer to an estimate for the entire volume of oil contained in the rock formation, not how much can be recovered. A more refined methodology, like the USGS's Technically Recoverable Resource "top-down" estimates, requires production data from wells, as yet unavailable for the study area.

Given the paucity of data, there is a high degree of uncertainty in these figures. There is likely to be little or no 'free oil' for the Oxford Clay, Upper Lias and Middle Lias based on the oil saturation index and although the Kimmeridge Clay does show excellent source potential, it is likely to be immature regionally. The Lower Lias appears to be the only interval with shale oil potential onshore, albeit with relatively small volumes in a localised area largely south of the Purbeck-Isle of Wight Disturbance.

	Total oil in-place estimates (billion bbl)		**Total oil in-place estimates (million tonnes)**	
	With top of oil window at 7000 ft (2130 m) maximum burial depth	**With top of oil window at 8000 ft (2440 m) maximum burial depth**	**With top of oil window at 7000 ft (2130 m) maximum burial depth**	**With top of oil window at 8000 ft (2440 m) maximum burial depth**
Kimmeridge Clay	0.00 – 0.01 – 0.04	0.00 – 0.00 – 0.00	0.24 – 1.50 – 4.77	0.00 – 0.00 – 0.00
Oxford Clay	0.00 – 0.01 – 0.03	0.00 – 0.00 – 0.00	0.20 – 1.17 – 3.52	0.01 – 0.06 – 0.19
Upper Lias Clay	0.00 – 0.00 – 0.01	0.00 – 0.00 – 0.00	0.12 – 0.39 – 1.00	0.03 – 0.09 – 0.20
Middle Lias Clay	0.01 – 0.03 – 0.08	0.00 – 0.01 – 0.02	1.31 – 4.38 – 11.53	0.38 – 1.21 – 2.93
Lower Lias	0.52 – 1.34 – 2.70	0.22 – 0.55 – 1.08	71.5 – 182.8 – 368.4	30.0 – 75.2 – 147.3
All Jurassic clay units - Wessex	**0.2 – 1.1 – 2.8**		**32 – 149 – 378**	
Kimmeridge Clay	0.41 – 2.03 – 4.77	0.11 – 0.61 – 1.44	55 – 270 – 636	15 – 81 – 192
Corallian Clay	0.20 – 0.52 – 1.04	0.11 – 0.30 – 0.61	27 – 69 – 139	15 – 40 – 81
Oxford Clay	0.59 – 1.39 – 2.46	0.41 – 0.96 – 1.70	79 – 185 – 328	55 – 128 – 227
Upper Lias Clay	0.28 – 0.63 – 1.05	0.22 – 0.52 – 0.85	37 – 84 – 140	29 – 69 – 113
Middle Lias Clay	0.33 – 0.79 – 1.43	0.27 – 0.64 – 1.15	44 – 105 – 191	36 – 85 – 153
All Jurassic clay units - Weald	**2.2 – 4.4 – 8.6**		**293 – 591 – 1143**	

Table 1. Estimates of the total potential in-place shale oil resource for the Jurassic in the Wessex study area (top) and in the Weald Basin (bottom, from Andrews (2014)), onshore southern England. P90, P50 and P10 values are given for each unit, where P10 is the most optimistic scenario. This estimate only covers unconventional oil, and excludes volumes in potential tight conventional or hybrid plays.

2 Introduction to the Wessex Study Area

2.1 Area of Interest

This study is an extension to the assessment of the in-place reserves of the Jurassic shales in the Weald Basin (Andrews, 2014). This assessment covers an area of 2455 miles^2 (6359 km^2) immediately west of the Weald Basin study (Figure 2) from the New Forest (Hampshire) to Honiton (East Devon). The area contains several sites which are considered protected areas for hydraulic fracturing under the Infrastructure Act 2015, including the Dorset Coast which is designated a World Heritage Site, groundwater source protection zones, the New Forest National Park, and the Isle of Wight, Dorset and Cranborne Chase, and West Wiltshire Downs Areas of Outstanding Natural Beauty (Figure 3). In these regions fracking can only take place at a minimum depth of c. 3950 ft (1200 m) below the surface.

This study is concerned only with a subsection of the onshore portion of the Wessex Basin, which is termed in this report the 'Wessex study area'. The Wessex study area encompasses three half-graben sub-basins – the Dorset (or Winterbourne Kingston Trough), Mere (or Vale of Wardour), and the onshore part of the Channel (or Portland-Wight) sub-basins – which together, along with the Pewsey Sub-basin, comprise the Wessex Basin (as defined by Underhill & Stoneley, 1998; see Section 3.5.1 of Andrews (2014) for a discussion of the terminology). The Pewsey Sub-basin was included in the Weald evaluation, as it can be considered a westward continuation of the Weald Basin (Andrews, 2014).

2.2 Interval of Interest

Shales of Jurassic age are the focus of this study. Source richness of Cretaceous-aged sediments has been identified in limestones of the Purbeck Group (Riboulleau et al., 2007; Schnyder et al., 2009), but are not prospective due to their immaturity basin-wide (England, 2010). There are no pre-Jurassic rocks with significant hydrocarbon potential identified within the study area (Stoneley, 1992), although organic-rich shales within the Triassic Mercia Mudstone Group were encountered in the Kimmeridge 5 well (Brand, 1980). To the west of the study area, around the Bristol Channel, dark shales of the Triassic Westbury Formation may contain some organic-rich intervals (Macquaker et al., 1986; Tuweni & Tyson, 1994). Knowledge of the Jurassic section within the study area comes from a number of wells which have penetrated the interval. The full Jurassic succession crops out within the study area (Figure 4), providing additional insight into lithology and facies variability. Three main source rock intervals have been identified – the Lower Lias, Oxford Clay and Kimmeridge Clay – whilst additional potential may exist in other shale units, including the Middle Lias Eype Clay and Upper Lias Downcliff Clay (Figure 5).

2.3 Exploration History

Oil and gas exploration in the Wessex area began in the 1930s when geologists from D'Arcy Exploration discovered oil seeps in Corallian, Purbeck and Wealden beds along the Dorset coast (Lees & Cox, 1937). After the 1934 Petroleum Production Act came into force, the first exploration licenses were issued in 1935 to D'Arcy Exploration (Evans et al., 1998), with early exploration

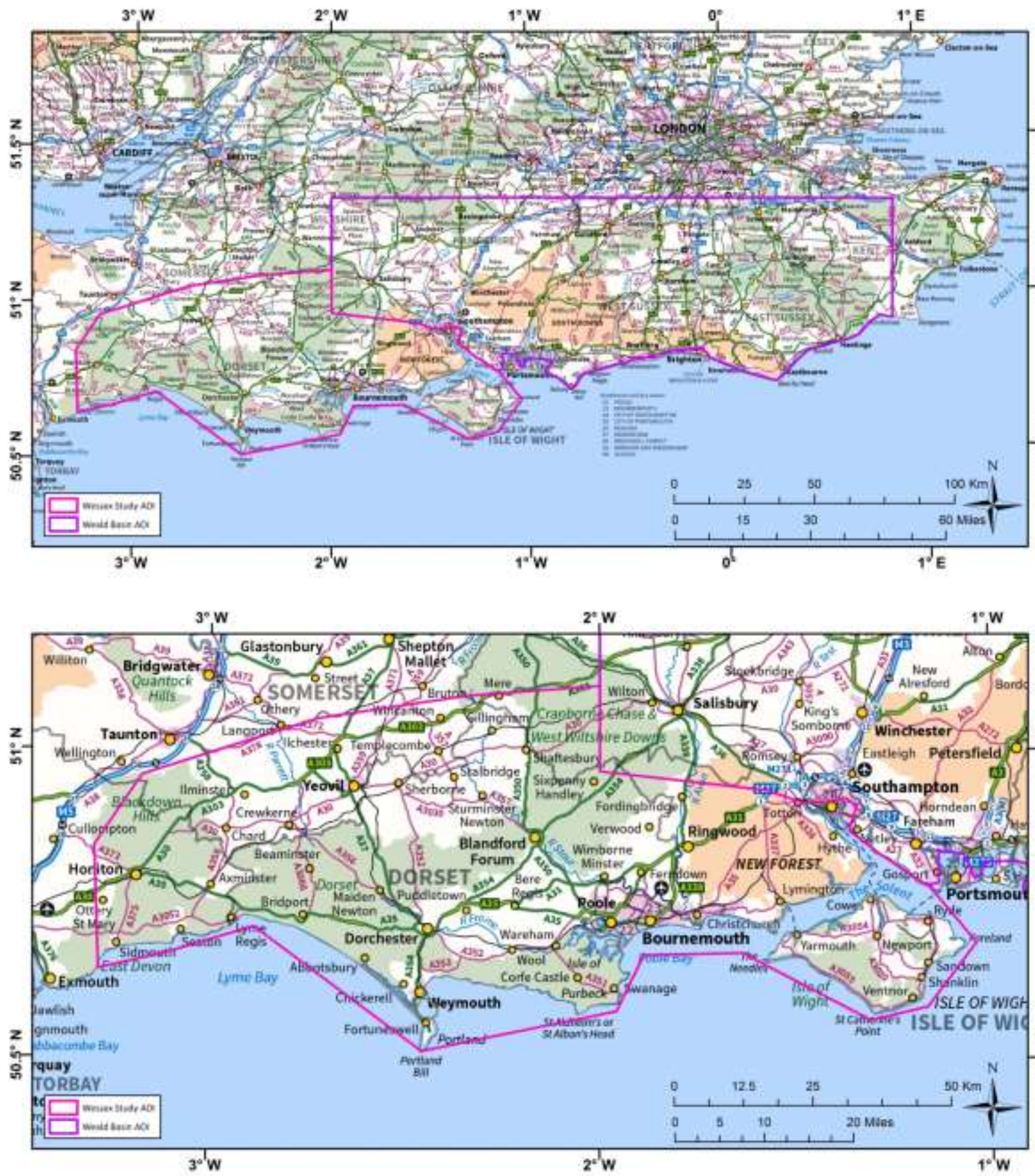


Figure 2. (Top) Location of the BGS/DECC shale oil Weald Basin study and the BGS/OGA Wessex study area, southern Britain. (Bottom) Zoom-in of location of the Wessex study area. Contains Ordnance Survey data © Crown copyright and database right 2016.

targeting anticlinal structures which had been mapped at surface (Buchanan, 1998). Since then (as of March 2016), there have been a total of 301 hydrocarbon wells drilled in the Wessex area, consisting of 77 exploration, 10 appraisal and 214 development wells. No unconventional or hybrid-play wells have so far been drilled within the study area.

2.3.1 Oil Fields

There are four oil fields within the study area, including the largest onshore oil field in North-West Europe, Wytch Farm. The other fields are Kimmeridge, Wareham and Waddock Cross (Figure 6); all

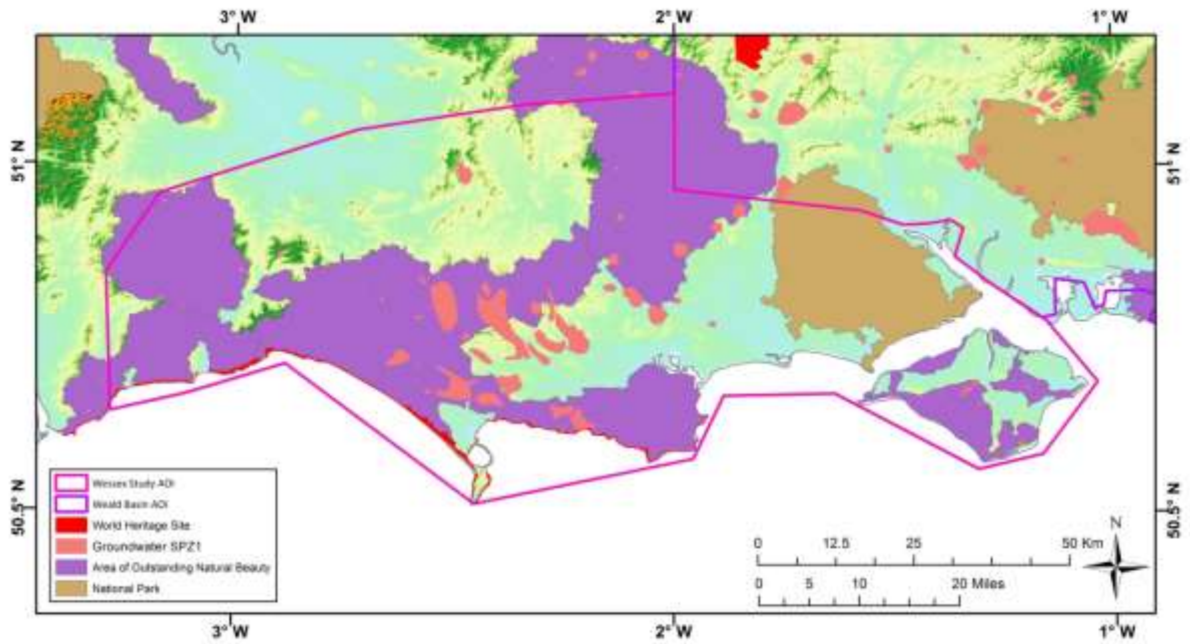


Figure 3. Areas considered to be protected under the 2015 Infrastructure Act, where hydraulic fracturing (fracking) may only be permitted at burial depths of 1200 m (c. 3950 ft) or greater. Background is shaded-relief topography. Contains Ordnance Survey data © Crown copyright and database right (2016). Data sources: Areas of Outstanding Natural Beauty & National Parks © Natural England copyright, 2016. Contains Ordnance Survey data © Crown copyright and database right (2016); World Heritage Sites © Historic England (2016). Contains Ordnance Survey data © Crown copyright and database right (2016) The Historic England GIS Data contained in this material was obtained on 21/04/2016. The most publicly available up to date Historic England GIS Data can be obtained from http://www.HistoricEngland.org.uk; Groundwater Source Protection Zones (SPZ) © Environment Agency copy right and/or database right 2016.

fields are located in the northern part of the Channel Basin, close to the Portland-Isle of Wight fault system, on Jurassic – Early Cretaceous palaeo-highs. Wytch Farm and Wareham are interpreted to have been charged by upwards and cross-fault migration of oil from mature Lower Liassic source rocks situated on the downthrown (south) side of the Purbeck-Isle of Wight fault system, prior to Cretaceous and Tertiary uplift (Underhill & Stoneley, 1998; Buchanan, 1998; Scotchman, 2001). The Kimmeridge field is unique in being the only commercial discovery in a trap created by Tertiary structural inversion and the only producing field in the hanging wall of the Purbeck-Isle of Wight Disturbance (Evans et al., 1998; Hawkes et al., 1998; Gluyas et al., 2003). So far, of the four sub-basins in the Wessex Basin (sensu Underhill & Stoneley, 1998), only the Channel Basin has proved a viable petroleum system (DECC, 2013).

The Wytch Farm structure is an east-west trending fault block bounded to the south by a normal fault down-thrown to the south, with minor faults to the north, east and west (Colter & Havard, 1981). The initial discovery well, Wytch Farm 1, was drilled by Gas Council (Exploration) in 1973 and encountered light oil in the Bridport Sands and oil shows in the Cornbrash. Wytch Farm D5, drilled in 1977, was the first test of the deeper Triassic Sherwood (Bunter) Sandstone and discovered light oil

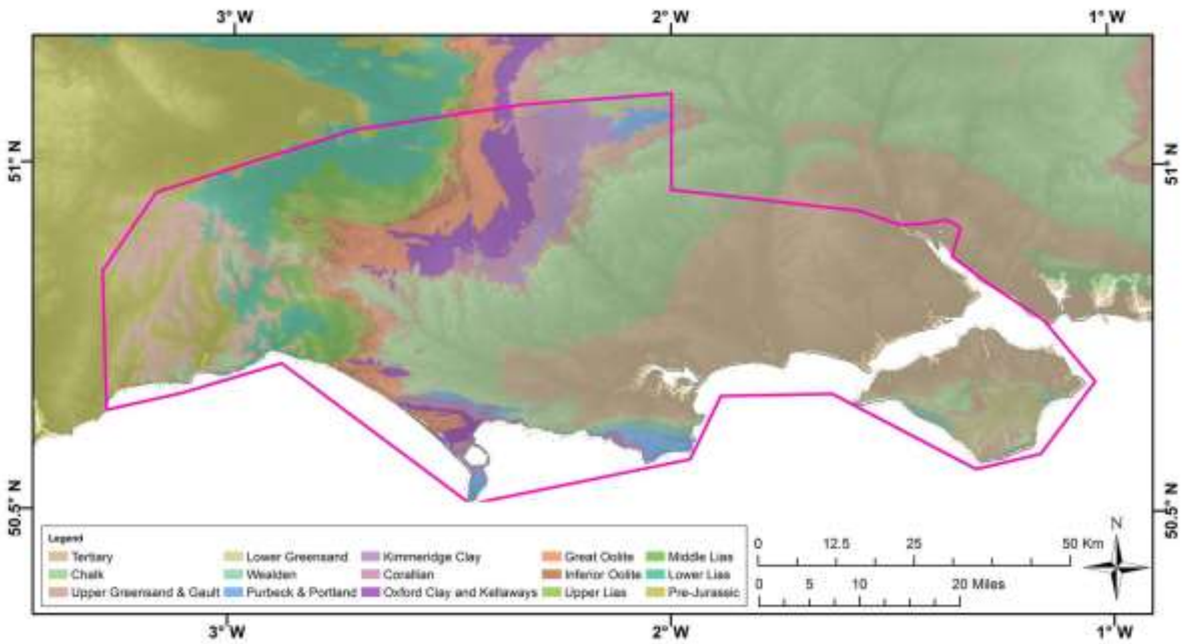


Figure 4. Surface geology of the study area with hill-shaded relief, with the Wessex study area (shown in pink). Surface geology from BGS 1:50,000 scale DiGMapGB © NERC.

in that interval (Colter & Havard, 1981). In addition to the Bridport Sands and Sherwood Sandstone reservoir intervals, oil shows are present in the Cornbrash and Forest Marble associated with vugs and fractures (Colter & Havard, 1981). Since production began in 1979, 200 wells have been drilled in the Wytch Farm Oilfield, which has produced approximately $76x10^6$ m^3 oil and $4x10^6$ m^3 gas (figures from OGA, Feb 2016; more recent production figures are available at https://www.ogauthority.co.uk/data-centre/data-downloads-and-publications/production-data/). Coupled with the offshore extensions, the Wytch Farm Oilfield is estimated to contain 500 mmbbls recoverable reserves (DECC, 2013).

The oldest commercial hydrocarbon discovery in the Wessex area is the Kimmeridge Oilfield (Evans et al., 1998; Gluyas et al., 2003). It was discovered by the BP-operated Kimmeridge 1 well in 1959, testing a large surface anticline (Colter & Havard, 1981). The trap is a faulted inversion anticline, formed in the Tertiary, immediately to the south (on the downthrown side) of the Purbeck-Isle of Wight Disturbance (Evans et al., 1998; Gluyas et al., 2003). Production is from underpressured, fractured tight limestones in the Cornbrash (Colter & Havard, 1981; Selley & Stoneley, 1987; Gluyas et al., 2003). Following the Wytch Farm discovery, Kimmeridge 5 was drilled in 1980 as a test of the deeper potential at the Kimmeridge Oilfield (Evans et al., 1998; Gluyas et al., 2003), recording oil shows in the Bridport Sands and Sherwood Sandstone. Produced volumes at the Kimmeridge Oilfield have exceeded the estimated trap volume, with several theories developed to explain this (Selley & Stoneley, 1987; Evans et al., 1998). It has been proposed that the field is receiving charge from a deeper reservoir present-day (Selley & Stoneley, 1987) although Evans et al. (1998) argue that the production decline curve does not support this. Alternatively, additional reserves may be trapped either offshore in an unmapped extension (Evans et al., 1998; Gluyas et al., 2003), the fracture system may extend the reservoir into the Oxford Clay (Evans et al., 1998) or the Cornbrash reservoir may be actively recharging from a mature lower Oxford Clay source (Fraser & Aryanto, in prep).

Wareham 1, drilled by BP in 1964, encountered oil in a thin fractured Inferior Oolite interval and at the top of the Bridport Sands (Colter & Havard, 1981). The well was initially interpreted to have failed to locate pay, but was subsequently re-evaluated, re-entered and tested in 1970 (Hurst & Colter, 1998). Wareham 2, drilled downdip from Wareham 1, produced oil from the Cornbrash after acid wash treatment (Colter & Havard, 1981). Good oil shows were encountered in Wareham W2 (D5), drilled by Gas Council (Exploration) in 1980, in the Inferior Oolite and Bridport Sands, with additional gas shows in the Oxford Clay, Kellaways, Cornbrash, Forest Marble, and Fuller's Earth

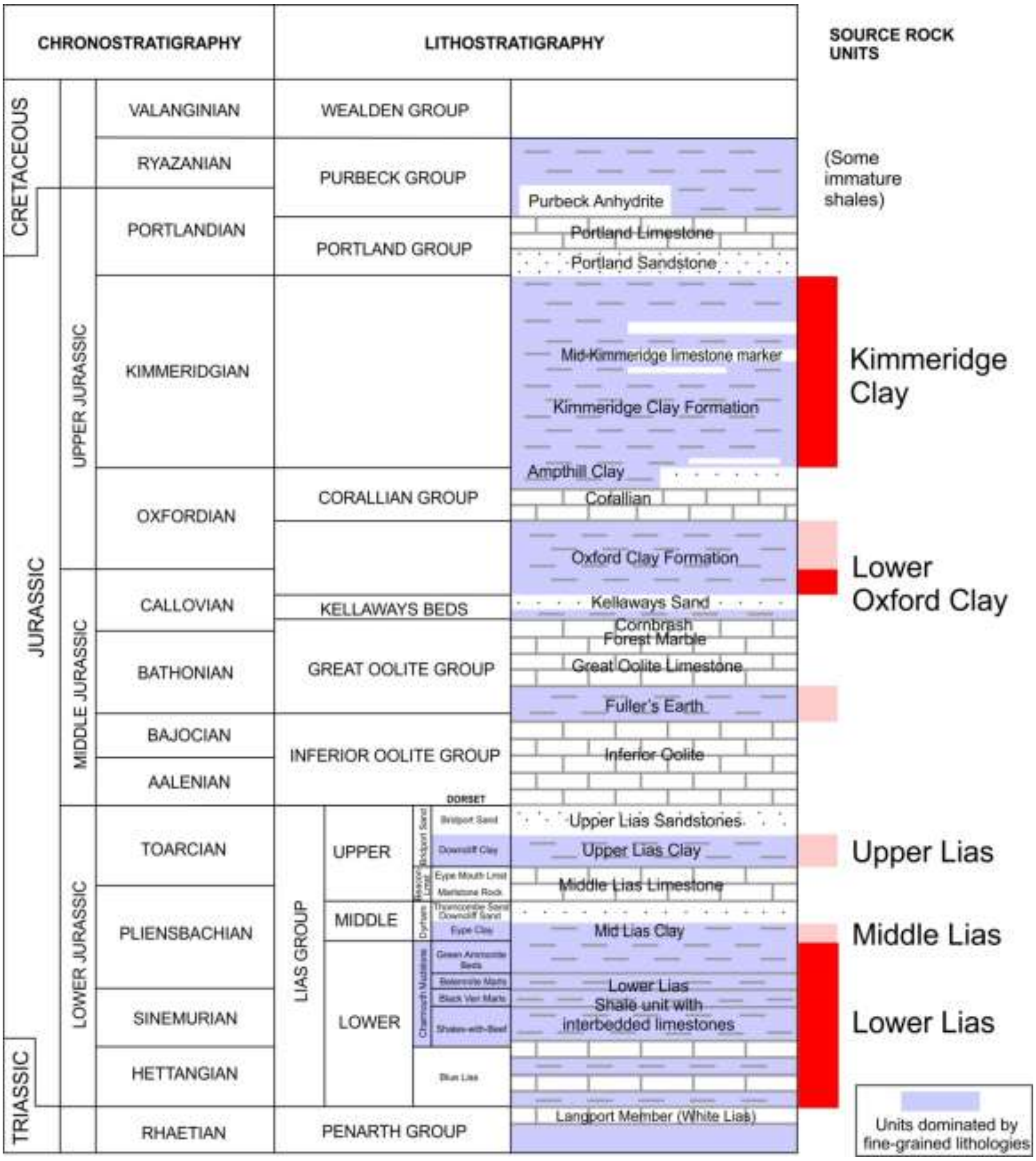


Figure 5. Generalised stratigraphic column for the Jurassic of the Wessex area showing the main source rock intervals (in red) and other potential source rock intervals (in pink). Adapted from Andrews (2014).

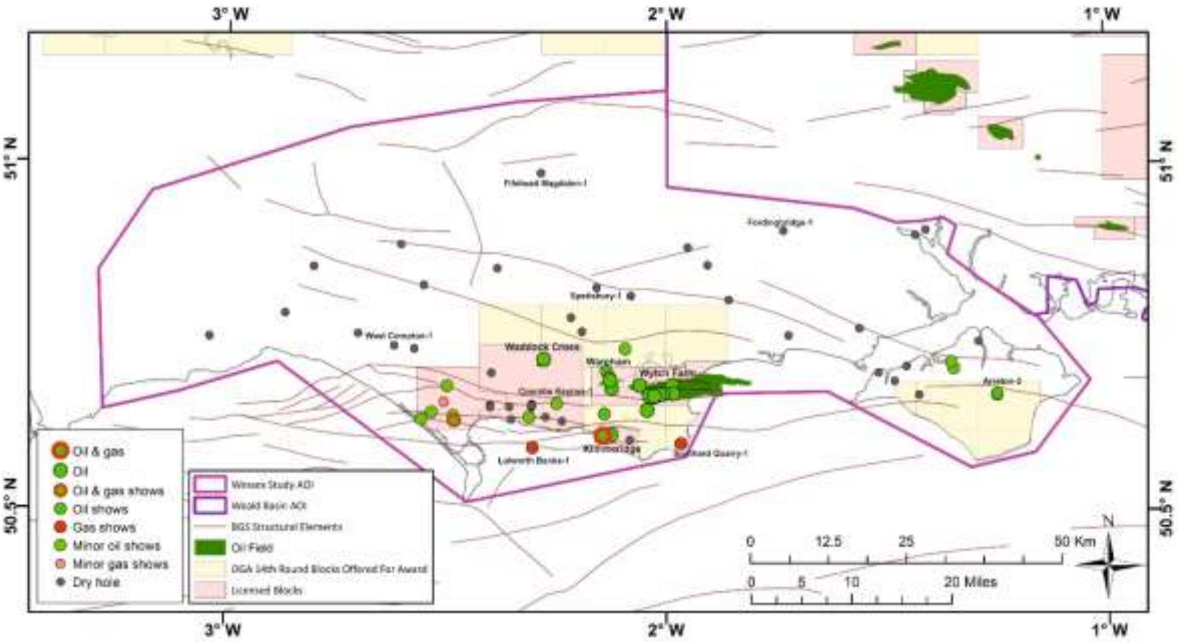


Figure 6. Distribution of producing oil fields, discovery wells and well with hydrocarbon shows within the study area, based on well reports and published literature. Also shown are areas currently licensed or offered for award for exploration, and main BGS structural elements (British Geological Survey, 1996). Contains British Geological Survey materials © NERC (2016).

formations. To date, less than 0.7 x 10^6 m^3 oil has been produced from the Wareham field (data from OGA, Feb 2016).

Waddock Cross 1 was drilled by Gas Council (Exploration) in 1982, and produced oil at sub-commercial flow rates from the Bridport Sandstone. The structure, a low-relief closure with four-way dip, was re-evaluated in 2003 by Egdon Resources with the drilling of Waddock Cross 2, which discovered a gross oil column of c. 78 ft (24 m) in the Bridport Sandstone (Waddock Cross 2 Wellsite Geological Report, 2004) and began producing in 2013.

2.3.2 Other Hydrocarbon Indications

Alongside the producing fields, numerous other wells in the Wessex area have encountered hydrocarbon shows (Figure 6), giving further indication of an active petroleum system. On the Isle of Wight the Arreton 2 well, drilled in 1974 by Gas Council (Exploration), was completed as a dry hole but encountered dead oil staining in several intervals. This suggests that the structures in the Jurassic have been flushed, possibly as a result of late faulting/folding (Gas Council Exploration, 1974). UK Oil & Gas Investments (UKOG) have re-evaluated the Arreton 2 data and interpreted it to be an undeveloped oil discovery, with 78 ft (23.8 m) oil pay in the Portland and 127 ft (38.7 m) oil pay in the Inferior Oolite, and a P50 oil-in-place volume of 219 mmbbl in the whole Arreton structure (UKOG press release, 2016).

Also on the Isle of Wight, but to the north of the Purbeck-Isle of Wight Disturbance, minor oil shows were encountered largely within limestones of the Great Oolite Group in Sandhills 1 (drilled in 1982), and Sandhills 2/2z (drilled in 2005). Geochemical analysis of samples from Sandhills 2/2Z indicates that the oil is residual and highly biodegraded (GHGeochem, 2005).

The Bushey Farm A1 well (and sidetrack A1Z) drilled by British Gas in 1981, was classified as a dry hole although light, low sulphur oil was encountered in the top of the Bridport Sandstone reservoir (Johnson & Lister, 1981). Oil was also found in the Bridport Sandstone reservoir within the Coombe Keynes 1 well, which additionally encountered small amounts of biodegraded oil within the Oxford Clay and Lower Lias; the biodegraded oils were of a similar type and maturity to the non-biodegraded oil within the reservoir (McQullken & Cocksedge, 1989). Geochemical analysis indicates the oil found in minor shows at Chickerell 1 (Forbes, 1987), Coombe Keynes 1 (McQullken & Cocksedge, 1989) and Bushey Farm A1 (Johnson & Lister, 1981) is derived from the same or similar source as the oil at the Wytch Farm, Wareham and Kimmeridge oil fields. Forbes (1987) found a good correlation between the oils and Lower Lias source rocks in the Chickerell 1 well, although the Lower Lias is immature at the well location.

High levels of gas (C1-C5) were encountered in the Lower Lias mudstones of the Hewish 1 well, although the target reservoir interval, the Sherwood Sandstone, was water wet. Elevated gas readings were common throughout the Jurassic and in the Triassic Sherwood Sandstone at Southard Quarry 1. However, despite log interpretations indicating the presence of hydrocarbons in the target reservoir intervals, poor hole conditions prevented open hole testing for a full assessment of the potential (Bromfield, 1990). Lulworth Banks 1, drilled offshore in Quadrant 97 but on an onshore license, discovered uncommercial gas in sandstones of the Bridport and Kellaways formations (DECC, 2014). Also offshore, in Bournemouth Bay, Well 98/11-2 was a sub-commercial gas discovery, with the Sherwood Sandstone as the main reservoir interval (BP, 2011).

2.4 Seeps

As previously mentioned, surface oil seepages along the Dorset coast gave exploration geologists an initial indication of an active petroleum system in the Wessex area (Lees & Cox, 1937) and have subsequently been reported at several locations on the coast, including at Osmington Mills, Worbarrow Bay, Mupe Bay, Lulworth Cove and Durdle Door (Ebukanson & Kinghorn, 1986b; Selley, 1992; Bigge & Farrimond, 1998; Underhill & Stoneley, 1998; Hawkes et al., 1998; Watson et al., 2000). The seeps are limited to where Jurassic – Early Cretaceous beds dip north into major faults (Selley & Stoneley, 1987). The cliff section of the Bencliff Grits (Middle Oxfordian age) at Osmington Mills is dominated by oil-stained sandstones (Watson et al., 2000), and an oil-water contact has been identified within the section (Cornford et al., 1988); Watson et al (2000) proposed that this is the remnant of a breached trap. In addition, thermogenic gas seeps have been reported from the sea-floor off Anvil Point, Swanage (Miles et al., 1993; Selley, 2012; APT UK Ltd, 2013). The gases are thought to be oil-associated, as they were generated at a maturity equivalent to approximately 1.0% R_o, and have a similar source to other hydrocarbons in the area (APT UK Ltd., 2013).

The Mupe Bay seep is of particular significance as it has been cited as evidence for an Early Cretaceous onset of petroleum generation and migration within the Wessex area (Cornford et al., 1988; Kinghorn et al., 1994; Wimbledon et al., 1996; Emmerton et al., 2013), although this view has been challenged (Miles et al., 1993; Miles et al. 1994; Bigge & Farrimond, 1998; Parfitt & Farrimond, 1998). The seep occurs in a Wealden fluvial channel conglomeratic bed which contains darker oil-cemented, poorly consolidated sandstone clasts in a matrix of sand permeated by light oil, with oil continuing to seep into the sandstone at the present time (Lees & Cox, 1937; Selley, 1992; Emmerton et al., 2013). Hesselbo & Allen (1991) inferred a local source for the clasts, either through collapse of a river bank or another surface degradation process. The seep oils have all been heavily biodegraded (Bigge & Farrimond, 1998; Parfitt & Farrimond, 1998).

Cornford et al. (1988) proposed a two-phase staining model for the seep based on maturity differences between the oils in the clasts and matrix. In this model, oil generated in the Early Cretaceous seeped to the surface and stained and cemented alluvial channel sands. These were then eroded and re-deposited as oil-cemented clasts in a conglomeratic sandstone, with the matrix then stained by a subsequent migration of oil. This model is supported by sedimentological (Wimbledon et al., 1996) and palaeomagnetic studies (Emmerton et al., 2013). Others have suggested that the apparent difference in maturity can be explained by differential biodegradation between the clasts and matrix (Miles et al., 1993; Bigge & Farrimond, 1998), or that in fact there is no difference in maturity (Parfitt & Farrimond, 1998), although this does not preclude two phases of oil staining or Early Cretaceous generation and migration.

3 Database

The assessment of the Jurassic shales of the Wessex area was carried out with the development of a 3D model created from detailed seismic mapping integrated with all available hydrocarbon well data, relevant deep stratigraphic borehole information and outcrop geology. A total of 301 hydrocarbon wells have been drilled in the study area, and numerous boreholes have been drilled for resources, commercial development or scientific studies (Figure 7). Boreholes are generally relatively shallow and lack downhole geophysical data that are commonly acquired with hydrocarbon wells.

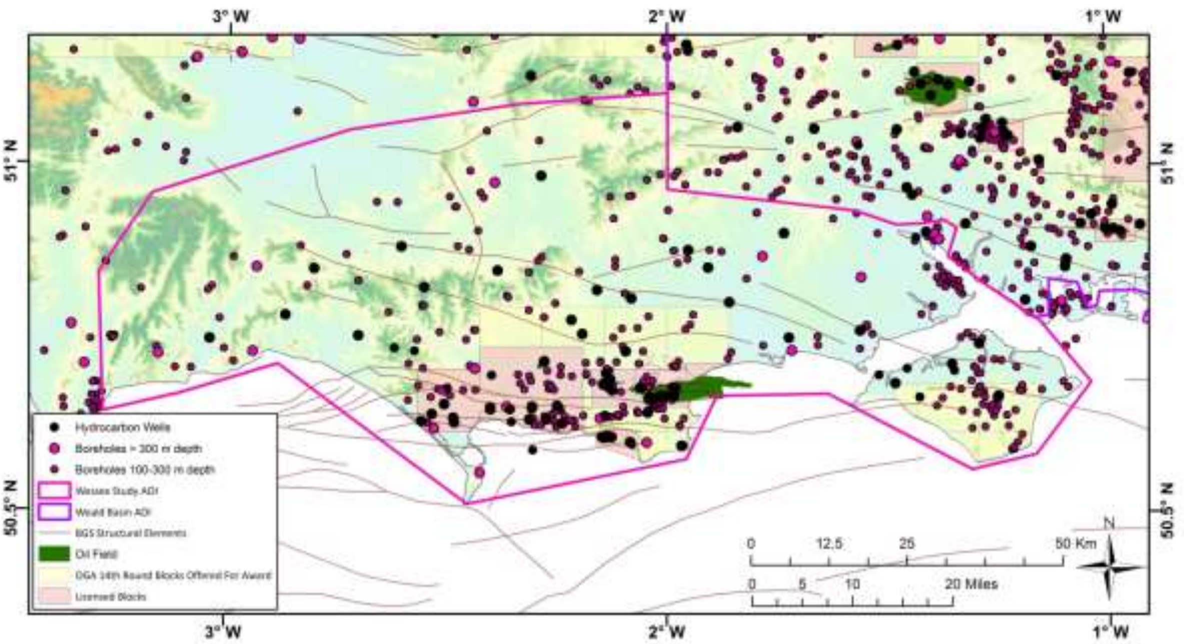


Figure 7. Exploration, appraisal and development wells, and deep boreholes (> 100 m total depth) of the Wessex area. Background is hill-shaded topography. Contains Ordnance Survey data © Crown copyright and database right (2016). Contains British Geological Survey materials © NERC (2016).

Out of the total 87 exploration and appraisal wells drilled in the study area, time-depth data was available on 47 of these wells (Figure 8) which were used to tie the seismic interpretation and build the velocity model for the depth conversion. A selection of these key wells are illustrated in six correlation panels (Appendix B), which extend into the Weald Basin study area (Figure 9). Geochemical data were available on a total of 14 wells, three boreholes and from eight outcrop localities (Figure 10). The boreholes at Swanworth Quarry and Metherhills, southern Dorset, were drilled as part of the Natural Environment Research Council's Rapid Global Geological Events (RGGE) special topic 'Anatomy of a Source Rock', and cored the complete Kimmeridge Clay Formation (Morgans-Bell et al., 2001). There are numerous wells and boreholes in the 'core mature area' of the Lower Lias in southern Dorset and on the Isle of Wight, however many are too shallow or lack time-depth data for use in this project. Geochemical data is limited to one well on the Isle of Wight

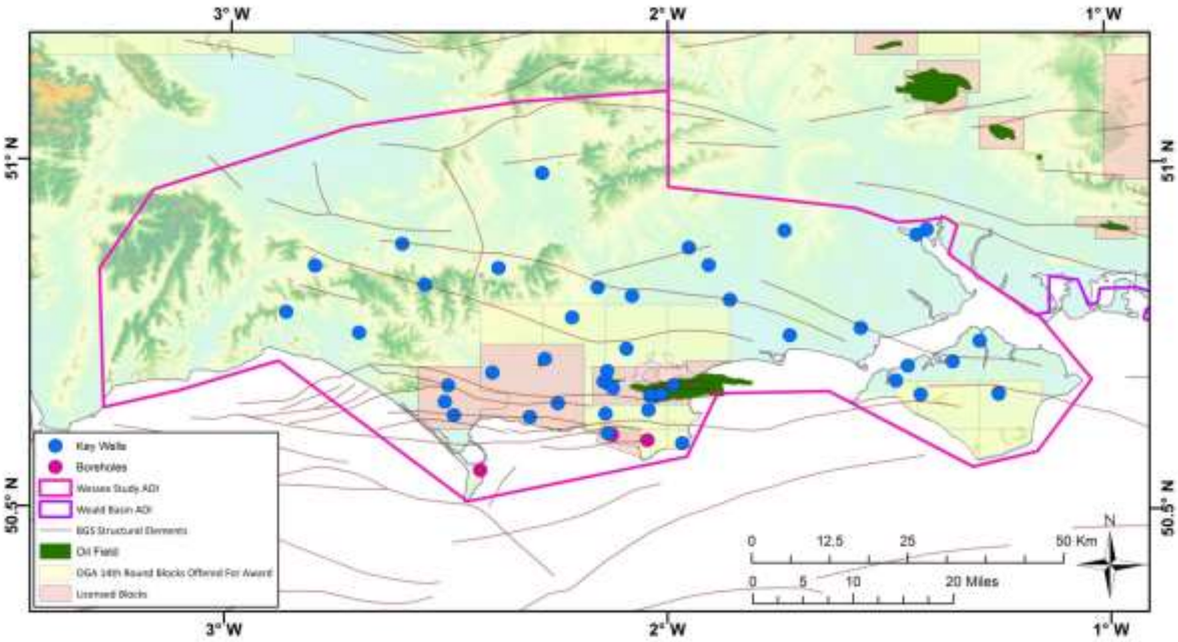


Figure 8. Distribution of wells with time-depth data available for this study (blue). Also shown are the boreholes for which stratigraphical and geochemical data were available (pink). Background is hill-shaded topography. Contains Ordnance Survey data © Crown copyright and database right (2016). Contains British Geological Survey materials © NERC (2016).

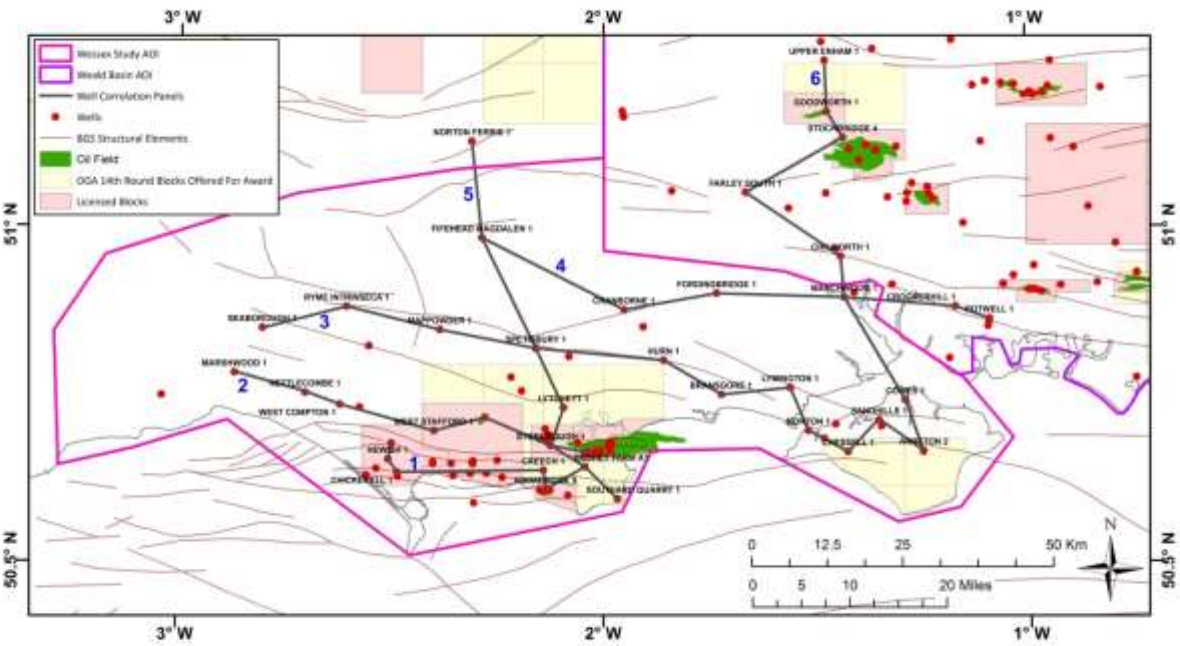


Figure 9. Location of the six well correlation panels shown in Appendix B, with the main BGS structural elements (British Geological Survey, 1996). Contains British Geological Survey materials © NERC (2016).

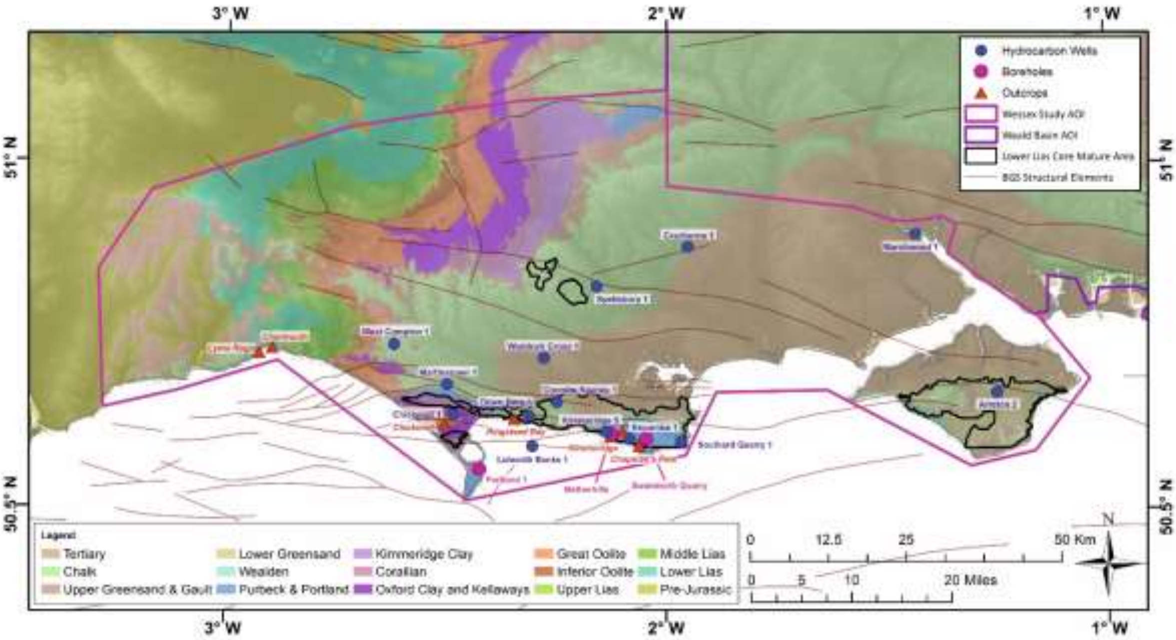


Figure 10. Location of wells, boreholes and outcrops for which geochemical data were available for this study. Also shown is the area within which the Lower Lias is believed to have reached sufficient maturity for oil generation (black polygon). Background is the outcrop geology from BGS 1:50,000 scale DiGMapGB © NERC. Contains British Geological Survey materials © NERC (2016).

(Arreton 2) and towards the edge or outside of the Lower Lias core mature area in southern Dorset (Figure 10).

Seismic interpretation of six key horizons – the Base Greensand Unconformity, Kimmeridge Clay, Corallian, Great Oolite, Lower Lias and Penarth – was completed on approximately 2734 miles (4400 km) of 2D seismic data of various vintages and quality, and a coarse grid from the 1998-vintage Wytch Farm 3D covering an area of c. 35 miles^2 (90 km^2) (Figure 11), all obtained from the UK Onshore Geophysical Library (UKOGL). Examples of the 2D seismic data are shown in Figure 12. Generally data is of fair to good quality in areas with little structural deformation, but quickly deteriorates across major fault zones.

The interpretation was tied to wells where surface picks, time-depth curves (and deviation surveys if necessary) were available and to the existing interpretation covering the Weald Basin, as well as being constrained by the outcrop geology (Figure 4). After gridding, the time interpretation was depth converted using a 3D velocity model which incorporated well time-depth data and faults to account for the major lateral changes in velocity in areas of complex structure. The resulting depth structure grids to the top of each prospective interval were then merged with the Weald Basin study grids, and are presented in Section 3.

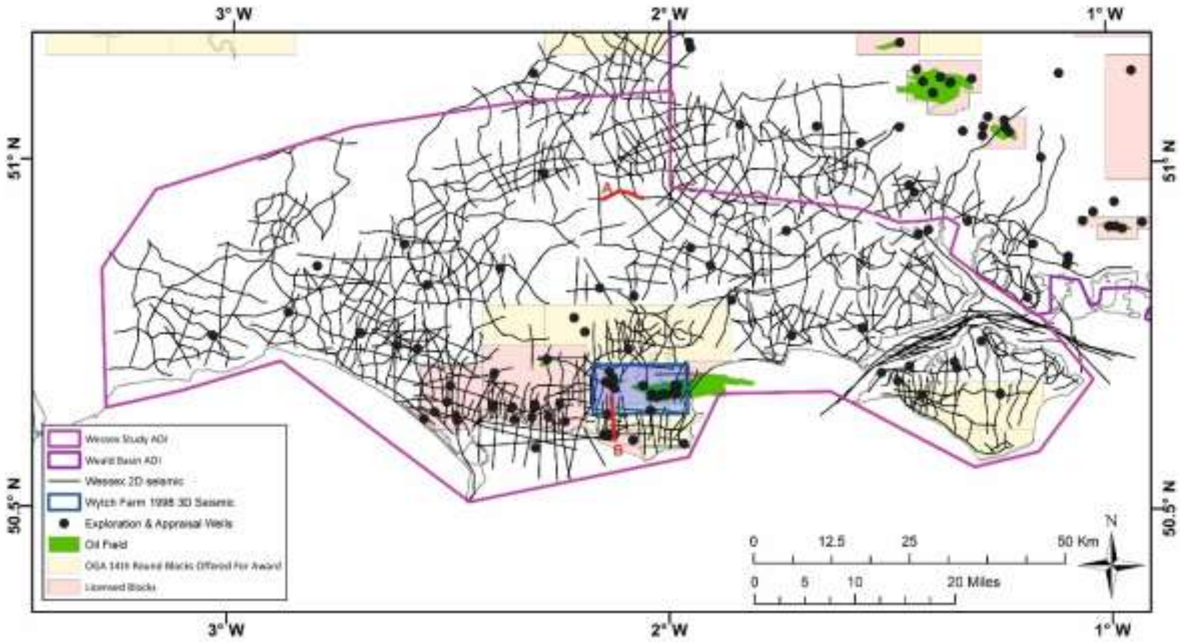


Figure 11. Location of 2D and Wytch Farm 3D seismic data used to map the subsurface in the study area. Lines A & B show the location of the data shown in Figure 12. All seismic data were obtained from the UK Onshore Geophysical Library (UKOGL http://ukogl.org.uk/).

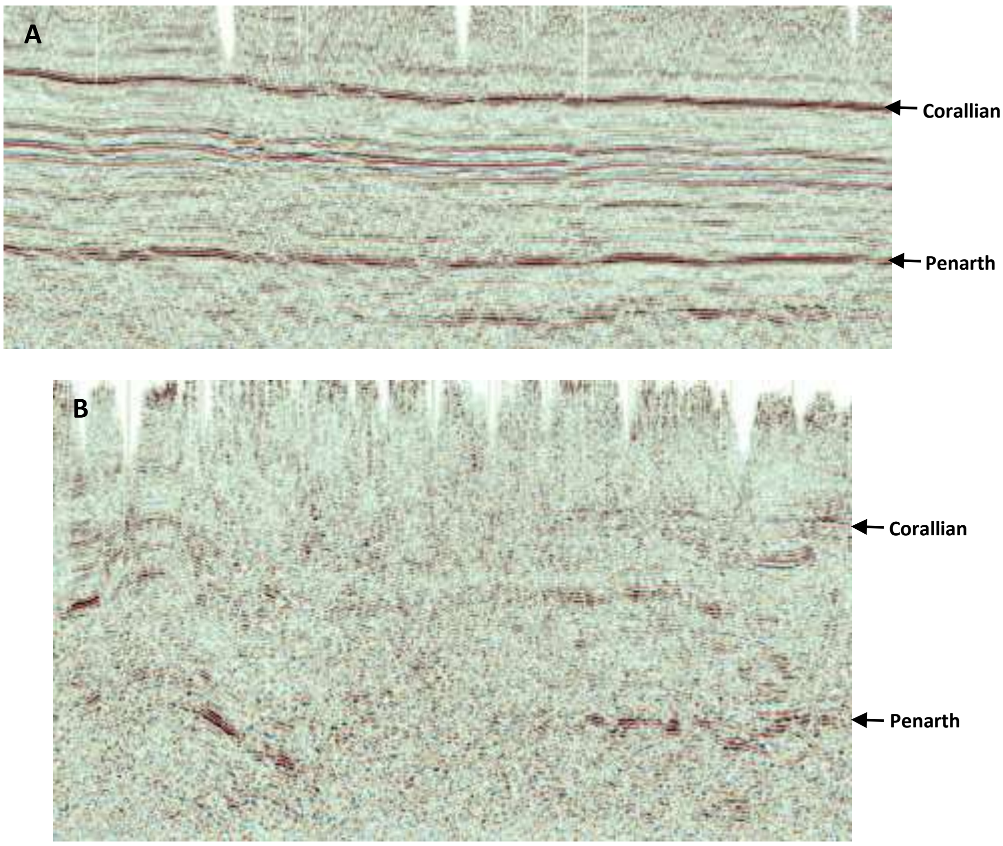


Figure 12. Comparison of seismic data quality from a tectonically quiet area (A – Line HB-84-014) with a structurally complex area (B – Line BP78-02-233), demonstrating the reduction in data quality in highly faulted areas. Seismic lines provided by UKOGL.

4 Structure and Tectonic History

4.1 Structural Elements

The Wessex study area is located entirely within the Wessex Basin (sensu Underhill & Stoneley, 1998; Figure 13) and adjoins the Weald Basin study by Andrews (2014). The Wessex Basin is a system of extensional basins and intra-basinal highs, bounded by major east-west trending normal faults, developed during episodic pulses of Permian-Cretaceous extension (Penn et al., 1987; Selley & Stoneley, 1987; Chadwick, 1993; Underhill & Stoneley, 1998; Chadwick & Evans, 2005). The basin (as delineated by Underhill & Stoneley, 1998), consisting of four sub-basins, covers much of southern England (Figure 13) and extends offshore to the Central Channel High. The Wessex and Weald basins have a similar tectono-stratigraphic history and at times formed a single depositional basin (Scott & Colter, 1987), but today the boundary is constrained by a fundamental change in subsurface geology extending north-west from Southampton, under the Hampshire-Dieppe High (Underhill & Stoneley, 1998; Newell, 2000). Locally the preserved Permian-Tertiary sediment thickness can be greater than c. 9840 ft (3000 m), although this thins to the west (Chadwick, 1986).

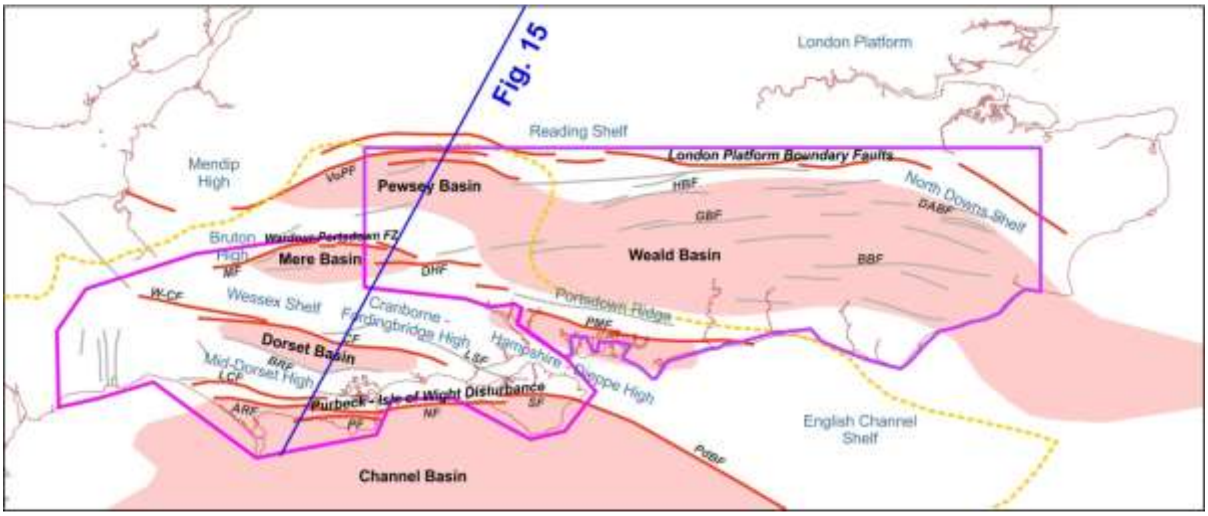


Figure 13. The major Mesozoic structural features of southern England. Adapted from Andrews (2014), and based on Stoneley (1982); Chadwick (1983); Lake (1985); Sellwood et al. (1985); Hancock & Mithen (1987); Butler & Pullan (1990); Butler (1998); Hawkes et al. (1998); Underhill & Stoneley (1998); Chadwick & Evans (2005). The Wessex Basin sensu Underhill & Stoneley (1998) lies southwest of the orange dashed line. Study area outlines in pink (Wessex) and purple (Weald). Abbreviations: ARF = Abbotsbury-Ridgeway Fault; LCF = Litton-Cheney Fault; PF = Purbeck Fault; NF = Needles Faults; SF = Sandhills Fault; PdBF = Pays de Bray Fault; BRF = Bere Regis Fault; W-CF = Watchet-Cothelstone Fault; CF = Cranborne Fault; LSF = Lymington-Sandhills Fault; MF = Mere Fault; DHF = Dean Hill Fault; PMF = Portsdown-Middleton Fault; VoPF = Vale of Pewsey Faults; HBF = Hog's Back Fault; GBF = Godley Bridge Fault; BBF = Brightling-Bolney Fault; DABF = Detention-Ashour-Bletchingley Fault; FZ = Fault Zone.

Structurally, the study area is dominated by three major east-west trending lines of inversion developed along the basin bounding faults: the Vale of Pewsey Faults, the Wardour-Portsdown Fault Zone and the Purbeck-Isle of Wight Disturbance (Figure 13; Chadwick & Evans, 2005). The predominant east-west trends of the basins and highs are offset by northwest-southeast trending faults (Ruffell & Wignall, 1990; Butler, 1998; Lake & Karner, 1987) which are visible on gravity data (Figure 14). The basin-bounding faults consist of several en-echelon fault segments (Underhill & Stoneley, 1998).

The present-day structure is a result of the interplay between tectonic inheritance, the extensional graben system, and subsequent regional inversion (Chadwick & Evans, 2005). Extension and basin formation has been linked to the reactivation of Variscan faults (Figure 15; Chadwick, 1986; Penn et al., 1987; Selley & Stoneley, 1987; Taylor et al., 2001) which imparted the strong east-west (from thrusts) and northwest-southeast (from transfers) structural grains (Lake & Karner, 1987; Karner et al., 1987; Hawkes et al., 1998).

4.2 Tectonic History

Evidence suggests that the Wessex Basin (sensu Underhill & Stoneley, 1998) experienced several episodes of crustal extension, including in the Permian, the Early Triassic, the Early Jurassic and Late Jurassic-Early Cretaceous (Chadwick, 1986). Basin development initiated in the west, forming the Dorset Basin in the Permo-Triassic, and migrated to the east, forming the Weald Basin in the Early Jurassic (Lake & Karner, 1987). Differential subsidence led to the formation of a series of asymmetric grabens and half-grabens (Penn et al., 1987). Rifting in the Jurassic was accompanied by a widespread marine transgression (Taylor et al., 2001). Rapid subsidence during the Late Jurassic-Early Cretaceous rifting phase resulted in the deposition of thick clastic sequences which led to sufficient burial for maturation of the Jurassic source rocks in the Weald and Channel basins (Lake & Karner, 1987; Hawkes et al., 1998; McMahon & Turner, 1998).

Two main intervals of active faulting are determined from syn-depositional movement on the east-west trending faults during the Early and Late Jurassic, correlating with the Central and North Atlantic rifting phases respectively (Jenkyns & Senior, 1991; Butler, 1998). The faults are predominantly downthrown to the south, and there are considerable thickness changes in these age sediments across the fault (Selley & Stoneley, 1987; Jenkyns & Senior, 1991; Chadwick & Evans, 2005; Evans et al., 2011). The total pre-Tertiary displacement across the Purbeck-Isle of Wight fault system exceeded c. 6560 ft (2000 m) in places (Underhill & Stoneley, 1998).

In the Early Cretaceous, the entire Wessex Basin experienced regional uplift, which was more pronounced in the west and south, imparting a strong easterly tilt (Lake & Karner, 1987; Butler, 1998; Underhill & Stoneley, 1998). A widespread unconformity at the Aptian-Albian coincides with the onset of sea-floor spreading in the Bay of Biscay and the North Atlantic (Lake & Karner, 1987; Hawkes et al., 1998; McMahon & Turner, 1998). It is believed this Base Greensand Unconformity (also commonly referred to as the Late Cimmerian Unconformity) is a result of regional thermal uplift associated with the rifting and continental breakup (Hawkes et al., 1998) and is marked by a progressively westward truncation of older strata (Figures 16 & 17), with considerable thicknesses of sediments having been removed by erosion (Underhill & Stoneley, 1998). The mid-Cretaceous is

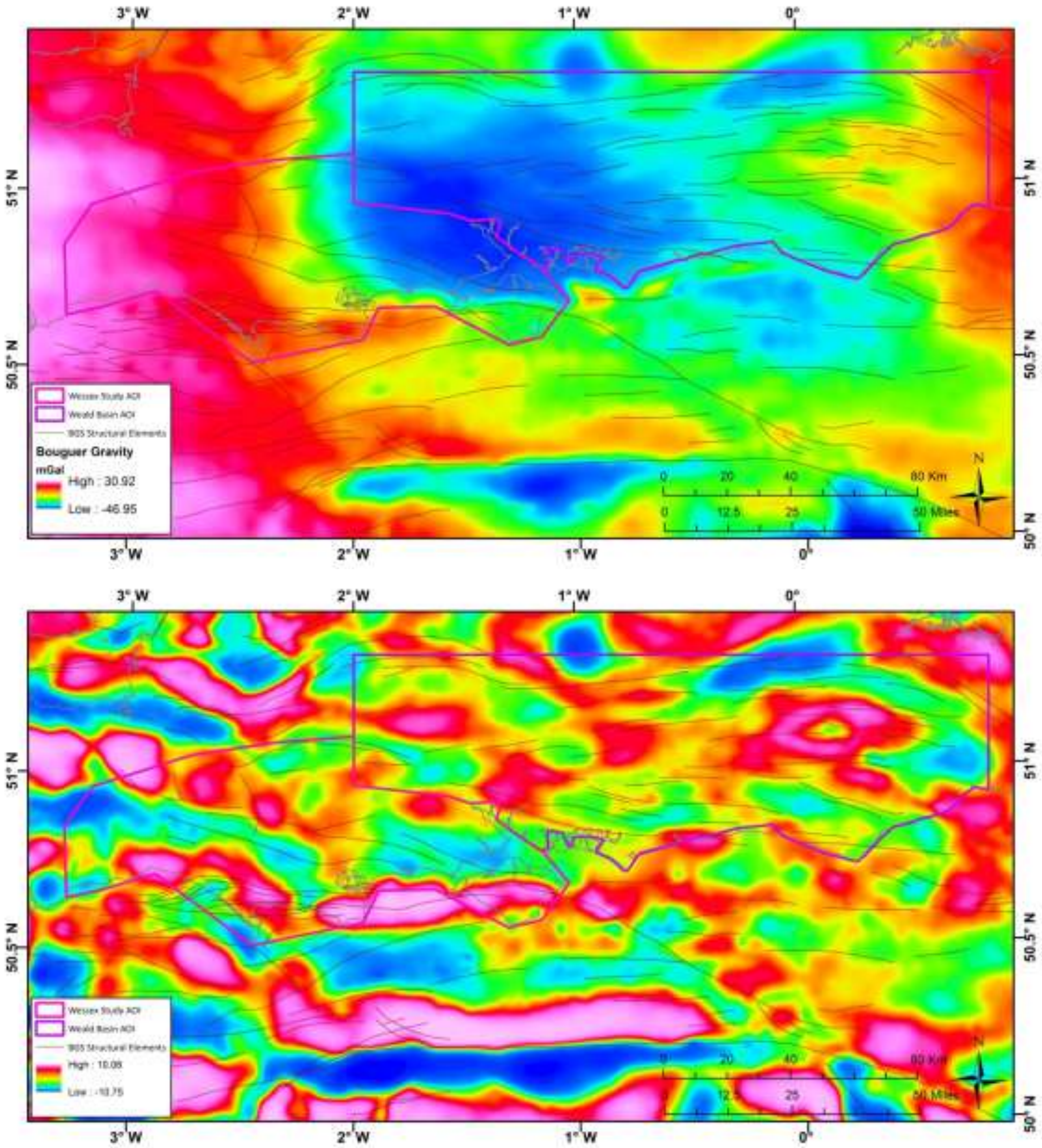
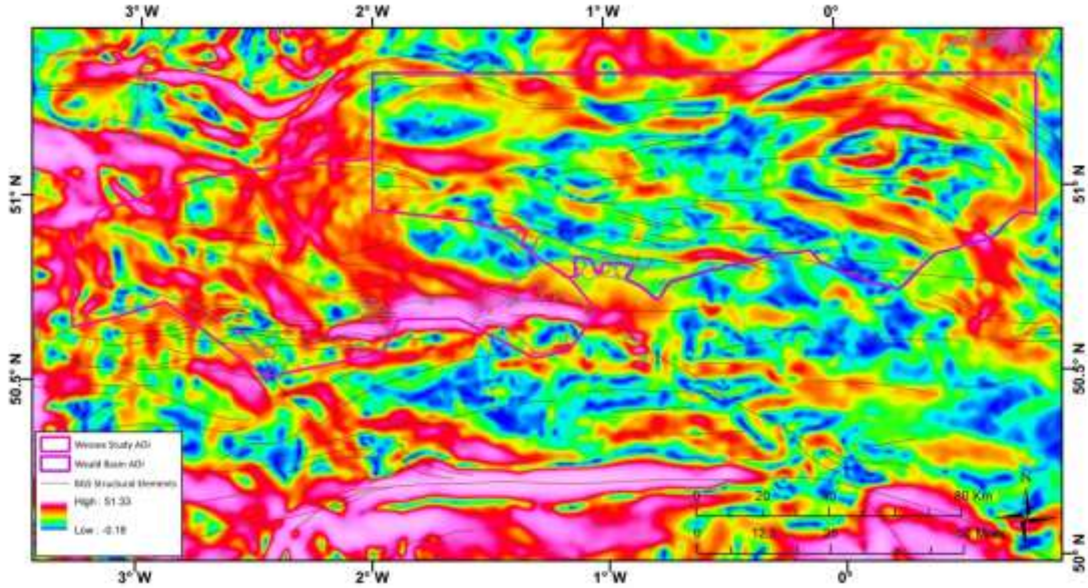


Figure 14. Bouguer gravity (mGal) (top), 50 km high-pass filtered Bouguer gravity (bottom), horizontal gradient of Bouguer gravity (next page, top) and tilt derivative (next page, bottom) of southern England. All images show the main BGS structural elements (British Geological Survey, 1996) and Wessex (pink polygon) and Weald (purple polygon) study areas. Regional east-west and northwest-southeast trends are clearly visible. Gravity data from the BGS UKCS compilation, which is based on a compilation of BGS and open-file data. Contains British Geological Survey materials © NERC (2016).

characterised by a change in tectonic style, from fault-related subsidence to regional flexural subsidence, which continued until the end of the Cretaceous (Chadwick, 1986; Penn et al., 1987), with the strata above the Base Greensand Unconformity generally unfaulted (Hamblin et al., 1992).

Late Cretaceous subsidence was succeeded, towards the end of the Cretaceous or in the Early Tertiary, by a north-south compressive tectonic regime, fault reversal and basin inversion (Penn et



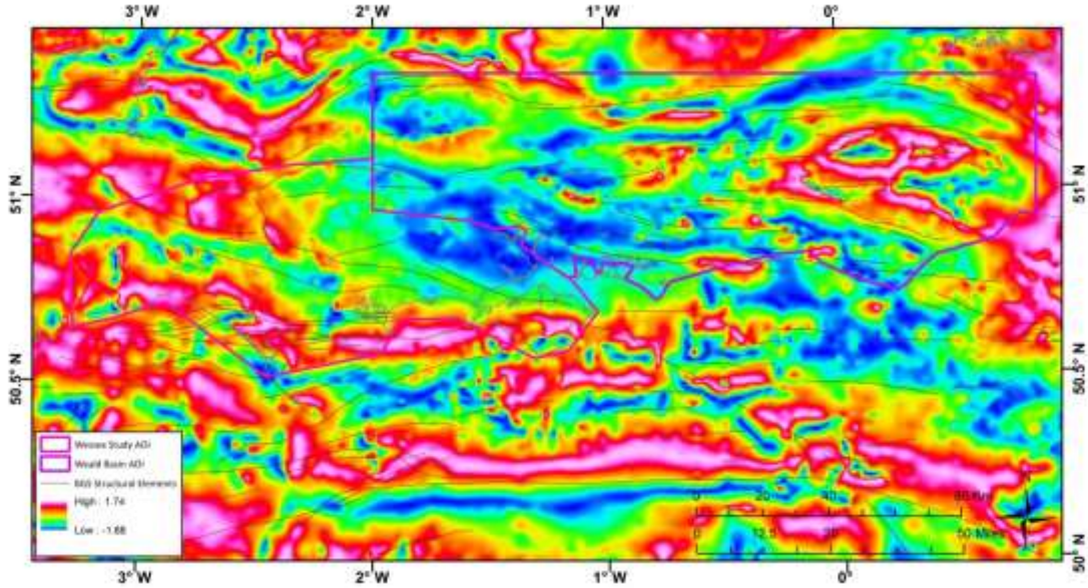


Figure 14 continued.

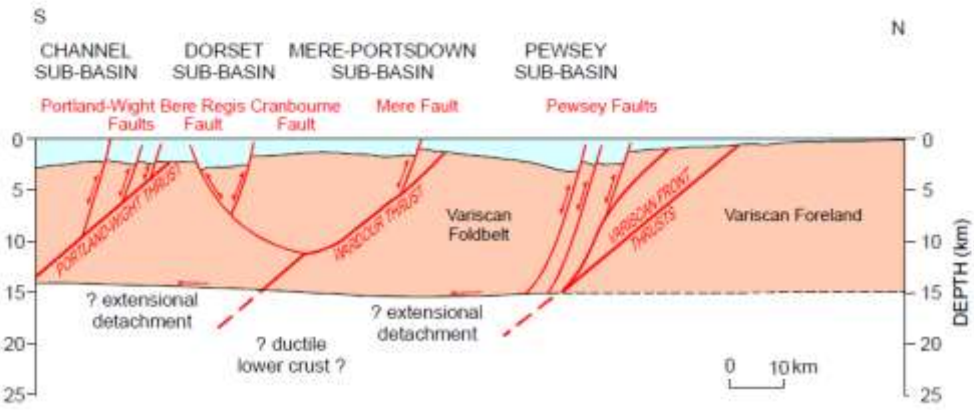


Figure 15. Crustal section across the Wessex and Weald areas, illustrating the influence of extensional reactivation of Variscan thrusts, after Chadwick (1986). See Figure 13 for location.

al., 1987; Lake & Karner, 1987; Selley & Stoneley, 1987; Underhill & Stoneley, 1998; Smith & Hatton, 1998). Reverse movements along reactivated faults created major northwards-verging monoclinal folds. The zones of most intense Tertiary inversion are generally coincident with regions of greatest Jurassic-Lower Cretaceous sedimentary thickness, although gentle inversions are also documented in the Dorset Basin (Butler, 1998). In addition, structural highs also became inverted to become Tertiary depocentres (Lake & Karner, 1987; Karner et al., 1987) and the Wessex Basin depocentre switched to the newly-formed Hampshire Basin at the location of the former Hampshire-Dieppe High (Underhill & Stoneley, 1998). The exact timing of Tertiary inversion is debated; according to Stoneley (1982), Chadwick (1986) and Evans et al. (2011), the inversion occurred in the Miocene, whereas Selley & Stoneley (1987), Bray et al. (1998), and Gale et al. (1999) have dated the inversion to the Eocene, whilst Lake & Karner (1987) believed Tertiary inversion to be intermittent throughout the Eocene to the Oligocene-Miocene. Uplift in the Early Miocene was associated with regional tilting (Lagarde et al., 2003).

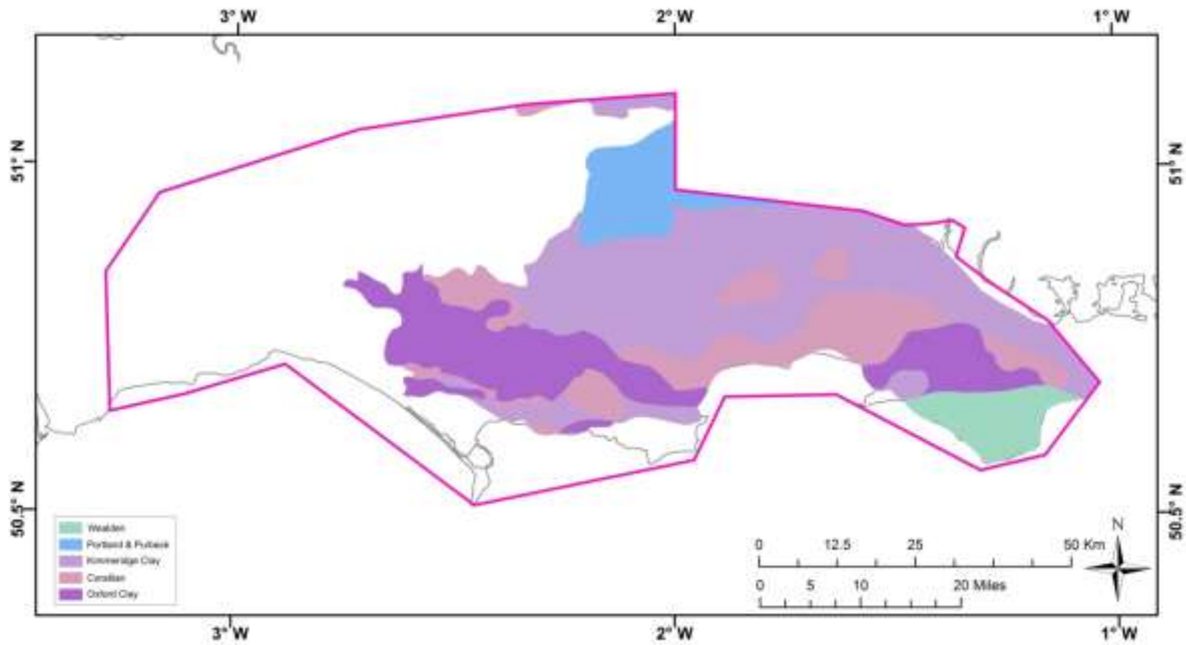


Figure 16. Generalised subcrop map beneath the Base Greensand Unconformity, determined from seismic and well data, and Whittaker (1985). Pink polygon outlines the Wessex study area.

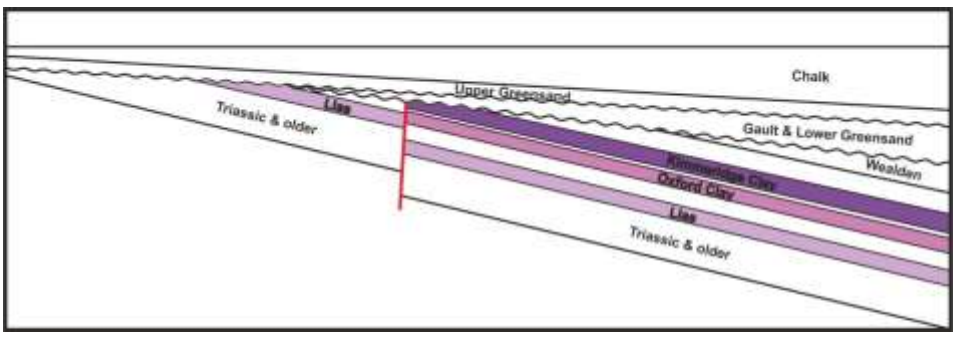


Figure 17. Schematic cross-section showing the progressively westward truncation of Jurassic (and older) strata beneath the Base Greensand Unconformity in the Wessex area, after Underhill & Stoneley (1998).

4.3 Background Seismicity of the Wessex Area

Since 1970, BGS has recorded eleven earthquakes within the Wessex study area (Figure 18) with magnitudes ranging from 1.1 to 2.9 ML and focal depths of 2.6 to 12.7 km. Just over half of these earthquakes show conformance to major fault zones. Historical data (from 1700 to 1970, when BGS began instrumental monitoring of UK seismic events) suggest the study area lies in a relatively seismically quiet setting, with a maximum earthquake magnitude < 4 ML (Musson, 1996). The maximum horizontal compressive stress for southern England has a northwest-southeast orientation (Baptie, 2010).

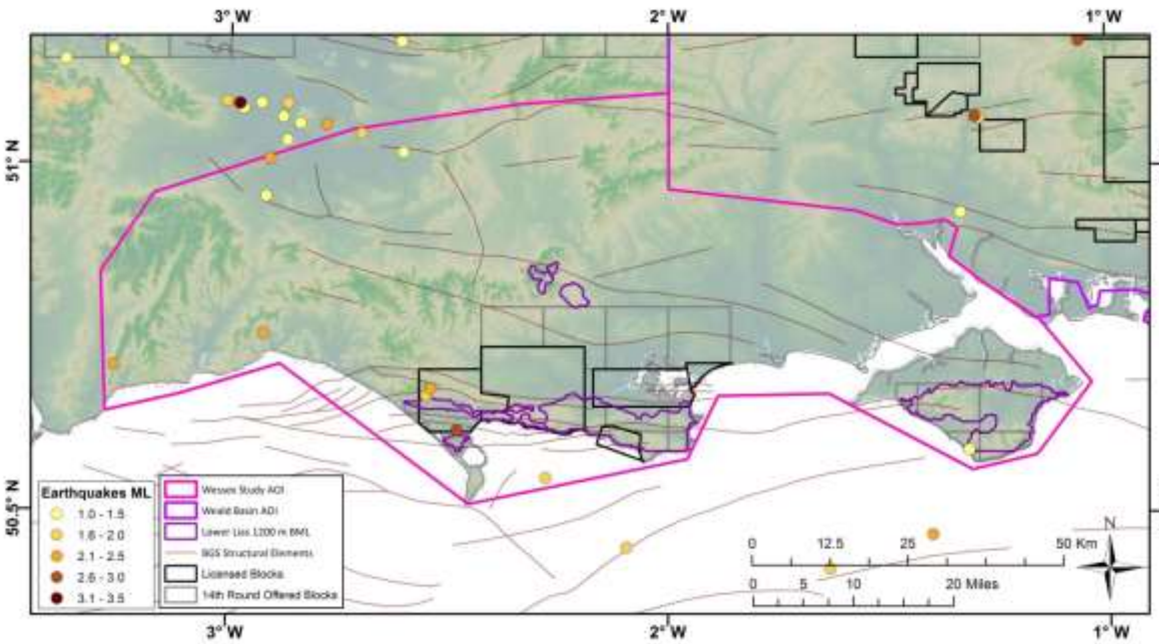


Figure 18. Earthquakes recorded by BGS from 1970 to 2016 for the Wessex area, coloured by magnitude. Also shown are the BGS structural elements (British Geological Survey, 1996) and the area in which the Lower Lias is predicted to be mature with a 1200 m below ground-level cut-off. Background is hill-shaded topography. Contains Ordnance Survey data © Crown copyright and database right (2016). Contains British Geological Survey materials © NERC (2016). Earthquake database available from BGS at *http://earthquakes.bgs.ac.uk/earthquakes/dataSearch.html*

4.4 Depth Grids

The depth grids to the top of each interval of interest (the Kimmeridge Clay, Oxford Clay, and Upper, Middle and Lower Lias), as interpreted in this study and for the Weald (Andrews, 2014) are presented in Figures 19-23. The Wessex area has an overall trend of deepening to the south-east; the Lias reaches its greatest depth (present-day) south of the Purbeck-Isle of Wight Disturbance on the Isle of Wight. None of the intervals are now as deep in the Wessex area as in the Weald depocentre; at its deepest point in the Wessex area, the top of the Lower Lias is over 200 ft shallower than the deepest point in the Weald (Figure 21). The westward extent of each horizon decreases with younging age as the outcrop geology gets older to the west, due to overall tilting. Further to the outcrop geology limiting the extent of the Oxford Clay and Kimmeridge Clay, they also suffered heavy erosion at the Base Greensand Unconformity (Figures 16-17; 19-20); these formations may locally exist in small fault blocks but their regional extent is limited.

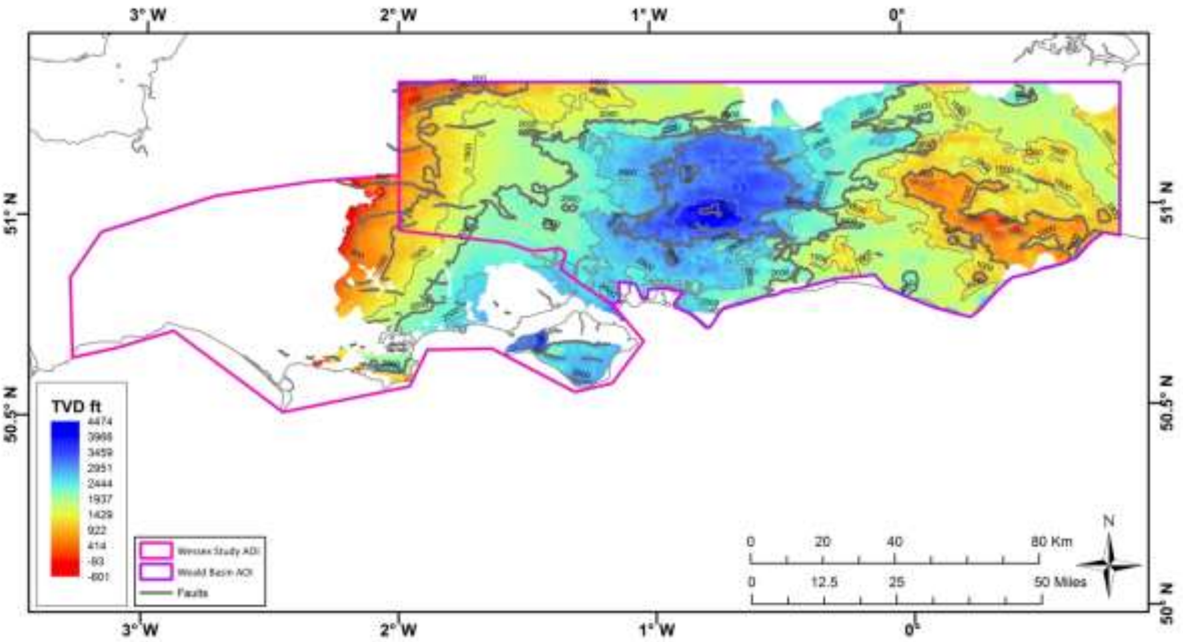


Figure 19. Depth to Top Kimmeridge Clay Fm, as mapped by this study for the Wessex area and by Andrews (2014) for the Weald Basin. Contour interval = 500 ft.

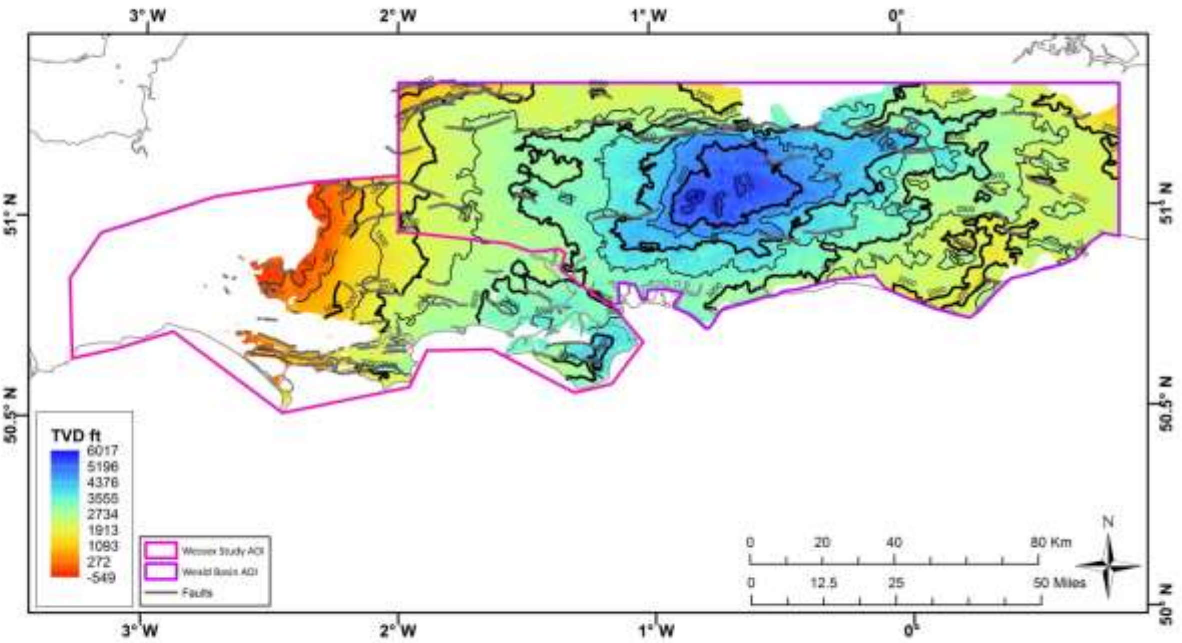


Figure 20. Depth to Top Oxford Clay Fm, as mapped by this study for the Wessex area and by Andrews (2014) for the Weald Basin. Contour interval = 500 ft.

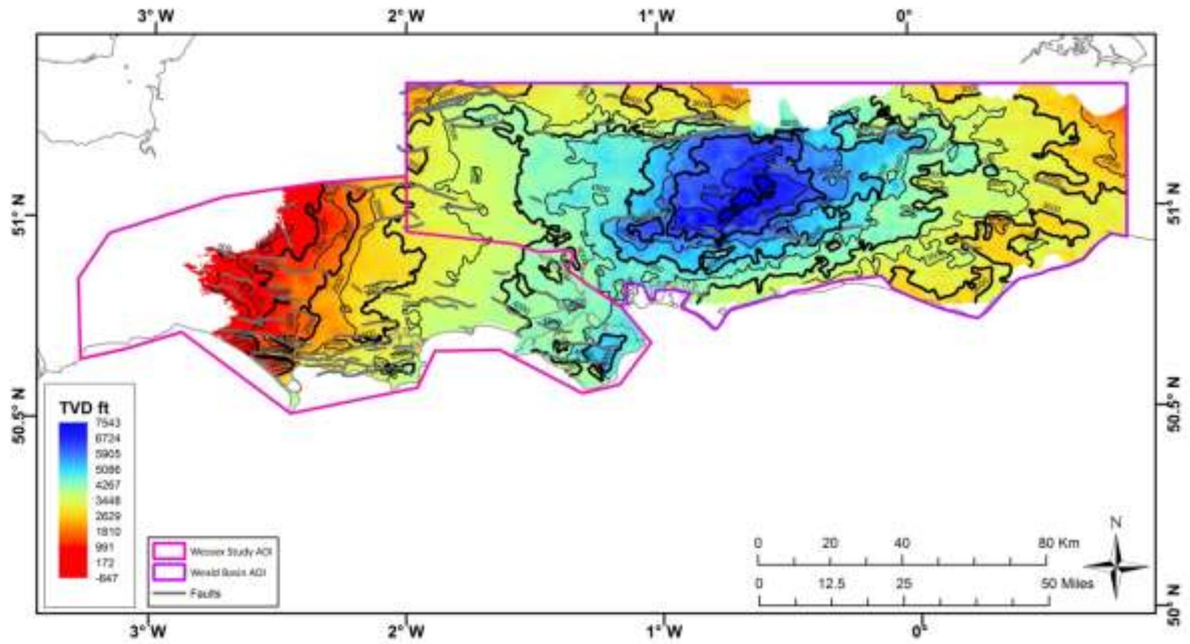


Figure 21. Depth to Top Upper Lias, as mapped by this study for the Wessex area and by Andrews (2014) for the Weald Basin. Contour interval = 500 ft.

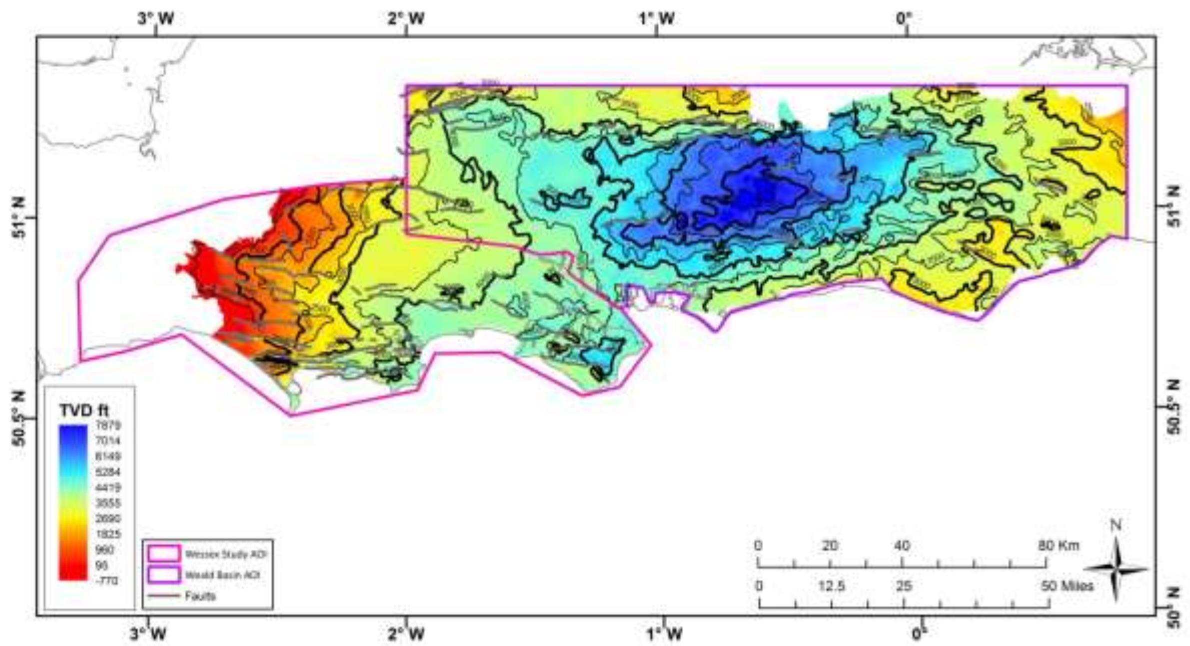


Figure 22. Depth to Top Middle Lias, as mapped by this study for the Wessex area and by Andrews (2014) for the Weald Basin. Contour interval = 500 ft.

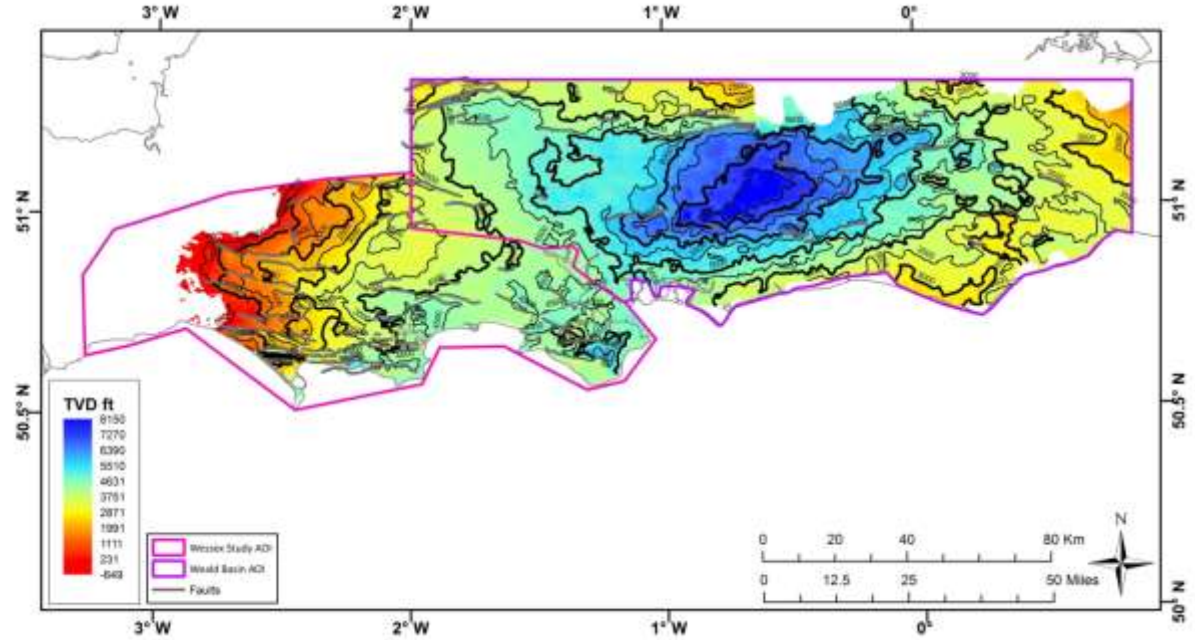


Figure 23. Depth to Top Lower Lias, as mapped by this study for the Wessex area and by Andrews (2014) for the Weald Basin. Contour interval = 500 ft.

5 Stratigraphy of the Jurassic in the Wessex Area

The Permian-Tertiary sedimentary fill of the Wessex area lies unconformably on Variscan metamorphic basement (Colter & Havard, 1981). The Jurassic sedimentary succession (Figure 24), the focus of this study, consists of six shallowing-upwards depositional sequences (Hawkes et al., 1998); the base of each sequence are shale and mudstones, which grade upwards into sandstones or shallow water carbonates in sediment-starved areas. Whilst erosion has removed much of the Upper Jurassic strata across the study area, all Jurassic formations are present in the Arreton 2 and Southard Quarry 1 wells. A brief summary of the stratigraphy of the Jurassic in the Wessex area follows; for a more detailed description the reader is referred to several BGS publications which cover parts of the study area, including for Dorset and SE Devon (Barton et al., 2011), the Wincanton district (Bristow et al., 1999), Shaftesbury (Bristow et al., 1995) and the Isle of Wight (Hopson & Farrant, 2015).

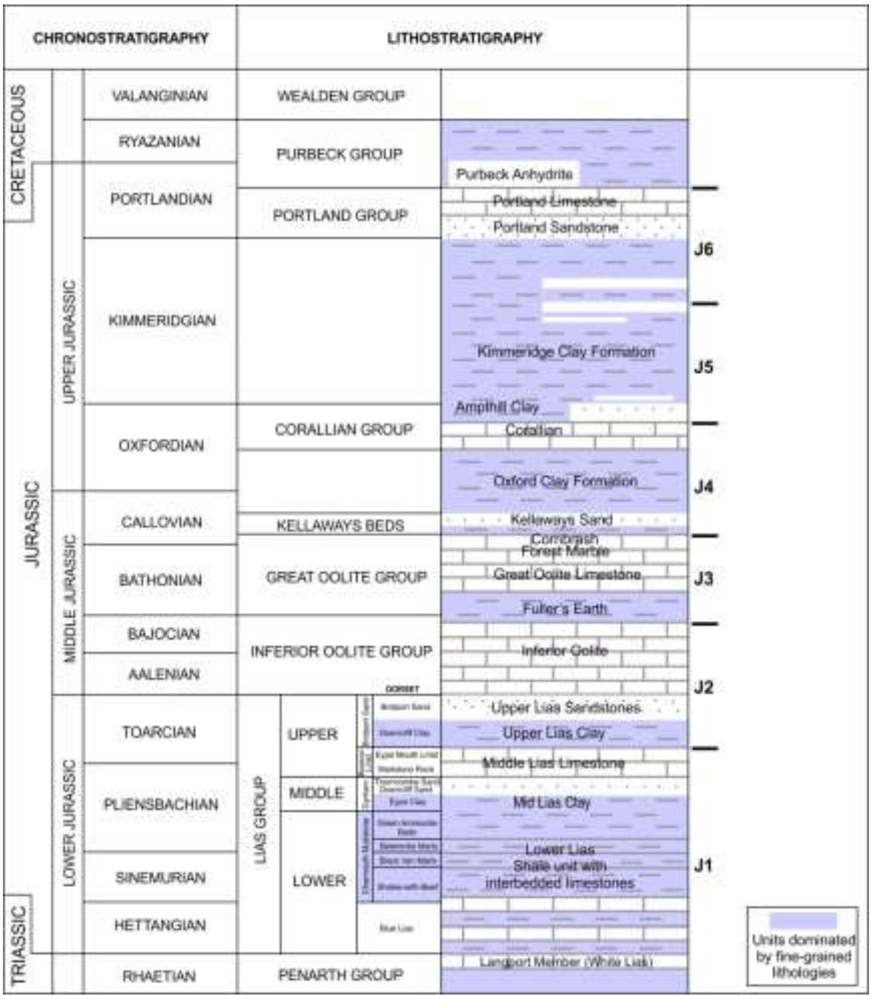


Figure 24. Generalised stratigraphic column for the Jurassic of the Wessex area. J1-J6 are the Jurassic megasequences as defined by Hawkes et al. (1998).

5.1 Lower Lias

The Lower Lias in the Wessex area is comprised of the Blue Lias Formation (a commonly limestone-rich unit) and the Charmouth Mudstone Formation (a more clay-rich unit), consisting (in depositional order) of the Shales-with-Beef, Black Ven Marl, Belemnite Marl and Green Ammonite Beds members, deposited as a marine transgression established a mud-dominated shelf across the region (Hawkes et al., 1998; Barton et al., 2011). The Blue Lias Formation is characterised by cyclical interbeds of bioturbated, oxic limestone and anoxic, laminated shale (Ainsworth et al., 1998). The Shales-with-Beef consists of alternating shales and calcareous mudstones, thin beds of fibrous calcite, and minor concretion bands (Gallois, 2008). The Black Ven Marls are more shale dominated, containing only occasional limestone interbeds. Alternating beds of light grey, calcareous, carbonate-rich, silty mudstones and darker carbon-rich, less calcareous mudstones characterise the Belemnite Marls (Weedon & Jenkyns, 1990) whilst the Green Ammonite Beds comprise of a medium to dark grey mudstone which coarsens upwards (Barton et al., 2011).

Structural control on sedimentation during the whole Lias interval is reflected in the laterally varying thicknesses of all formations. A major change in thickness occurs across the Purbeck-Isle of Wight Disturbance, with the interval becoming thicker to the south. The interval also thins considerably over the Cranborne-Fordingbridge High.

A major difference between the Wessex area and Weald Basin is the organic content of the Lower Lias. The Lower Lias becomes more limestone-dominant towards the east into the Weald Basin, as evident in the well correlations (Appendix B), with significant differences between the log responses in wells of the two areas (Figure 24; Whittaker et al*.,* 1985; Bessa & Hesselbo, 1997).

5.2 Middle Lias

The Middle Lias (Dyrham Formation) consists of the Eype Clay and the Down Cliff and Thorncombe Sand (or equivalents) members, deposited during a marine regression. The interval is capped by a highly condensed, ammonite-rich limestone, often called the Marlstone Rock Bed, Junction Bed or, as proposed by Cox et al. (1999), the Beacon Limestone Fm.

The Eype Clay largely comprises micaceous mudstone with minor amounts of calcareous sandstone. Overlying this member are the Down Cliff Sand, followed by the Thorncombe Sand, which form a single unit inland from the Dorset coast (Barton et al., 2011). Towards the north of the study area, and to the south of the Purbeck-Isle of Wight Disturbance, the interval is variably shale or siltstone-dominated, with only minor sands encountered.

5.3 Upper Lias

Renewed transgression was marked by the deposition of the Downcliff Clay, a sandy mudstone, with the shallow water depositional environment restricting the development of source potential. The formation grades up into silt and fine-grained sand of the Bridport Sands Member, one of the main reservoir intervals in the area. This highly bioturbated interval was deposited in a high energy lower-middle shoreface environment (Holloway, 1986; Fleet et al., 1987) and shows marked thickness variation in the area, due to the persistent fault activity (Hampson et al., 2015).

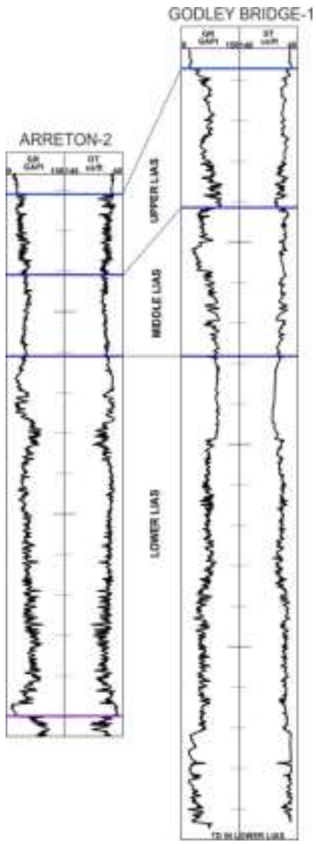


Figure 25. Comparison of gamma ray and sonic logs for the Lias of the Wessex (Arreton 2) and Weald (Godley Bridge 1) study areas.

In the study area, the Upper Lias is dominantly sand or silt-prone. On the Isle of Wight, the Upper Lias is expressed as a calcareous sandy siltstone to sandy argillaceous limestone (Hopson & Farrant, 2015), whereas at Marchwood, it contains a thick sand section.

5.4 Inferior Oolite

During the Middle Jurassic, a carbonate platform developed in the eastern side of the Wessex area and across the Weald Basin – a consequence of a change in drainage pattern which removed the clastic source to the area (Hawkes et al., 1998). The Inferior Oolite within the study area is generally a condensed, shelly micritic limestone (Holloway, 1986), although with sharp lateral variations in thickness (Bristow et al., 1995). At the eastern edge of the Wessex Basin, the Inferior Oolite of the Weald Basin thins dramatically south-westwards from hundreds of metres to a few metres (Scott & Colter, 1987). The Inferior Oolite has a distinctive gamma-ray log response and was used as the datum for the correlation panels in Appendix B.

5.5 Great Oolite Group

The Great Oolite Group consists, in decreasing age, of the Fuller’s Earth, Frome Clay, Forest Marble and Cornbrash formations. This succession is dominated by mudstones with thin limestones

(Holloway, 1986). The Fuller's Earth and Frome Clay are predominantly deeper water mudstone facies (Barton et al., 2011). The gamma ray signatures for these are lower than for other Jurassic mudstones, reflecting a generally more uniform calcareous nature (Whittaker et al., 1985). These pass upwards into the Forest Marble Formation, comprised of shallow water sandstones, sandy mudstones & limestones, and thin limestones of the Cornbrash. The Great Oolite develops south-west into the Wessex study area into a thicker, more argillaceous section compared to the Weald Basin (Scott & Colter, 1987). In the Wincanton district the Great Oolite Group is dominated by mudstones deposited in a low-energy environment.

5.6 Oxford Clay and Kellaways

The Kellaways Beds form a generally thin unit at the base of this section, and comprise mainly of siltstones, with lesser amount of mudstone and limestones, or interbedded calcareous fine-grained sandstone and mudstone on the Isle of Wight (Hopson & Farrant, 2015). It is overlain by the Oxford Clay, which consists of three members – the Peterborough, Stewartby and Weymouth Members. The Peterborough Member is a dark, fissile and fossiliferous shale (Kenig et al., 1994) deposited in a dysoxic environment during a period of renewed marine transgression and deepening of the water column (Hawkes et al., 1998). The Stewartby and Weymouth members are predominantly lean calcareous grey clays with minor siltstone (Penn et al., 1987; Kenig et al., 1994).

5.7 Corallian

The Corallian Beds are comprised of a cyclical pattern of shallow water sandstones, mudstones and limestones, laid down during a period of widespread uplift (Barton et al., 2011; Hopson & Farrant, 2015). The sediments were deposited on a ramp-type margin on an intra-basinal high that dipped towards the southwest, but with thickness variations due to complex uplift and subsidence associated with active normal faulting (Newell, 2000). Log correlation within the Wessex area is complicated due to significant lateral and vertical lithology variations (Ahmadi, 1997). Differences in lithology between the Wessex and Weald areas is reflected in the log signatures, with the Corallian of the Weald generally more argillaceous (Whittaker et al., 1985).

5.8 Kimmeridge Clay

Extensive knowledge of the Kimmeridge Clay has been gained from many outcrop and borehole studies, in particular the boreholes at Swanworth Quarry and Metherhills in Dorset, which cored the complete formation. From these two boreholes, Morgans-Bell et al. (2001) identified four main mudrock lithologies of the Kimmeridge Clay: medium-dark grey marl, medium-dark to dark grey-greenish black shale, dark grey to olive-black laminated shale, and greyish-black to brownish-black mudstone; the formation also contains minor amounts of siltstone, limestone and dolostone. Rhythmic alternations in clay mineralogy and organic content occur throughout the succession (Herbin et al., 1995; Morgans-Bell et al., 2001; Taylor et al., 2001).

The Kimmeridge Clay was largely deposited in an extensive, and periodically anoxic, epicontinental shelf sea, during a major marine transgression (Farrimond et al., 1984; Morgans-Bell et al., 2001; Taylor et al., 2001), with the sequence reflecting an overall shallowing upwards depositional sequence (Hawkes et al., 1998). The principal depocentres were the Weald and Channel basins, with marked thinning on structural highs and towards the margins of the Wessex area, where the formation is commonly sandier, more calcareous and therefore leaner (Taylor et al., 2001).

The mid-Kimmeridge Micrites (coccolith micrite beds) form the main reservoir for two recent hybrid-play oil discoveries in the Weald Basin – Balcombe 2 (2013) and Horse Hill 1 (2014). Although they have low primary porosity and permeability, oil has been produced from natural fractures. The micrites are thickest in the centre of the Weald Basin, but pinch out towards the basin margins and do not extend into the Wessex area, which is readily apparent in the log signature (Figure 25). Conversely, the Kimmeridge oil shale present in the Wessex area is absent in the Weald Basin.

5.9 Portland and Purbeck Beds

The presence of the Portland and Purbeck Beds, absent over much of the study area due to the regional uplift events, is limited to the south of the Purbeck-Isle of Wight Disturbance and in the north of the study area. The Portland Beds coarsen upwards from siltstones into fine-grained sands and then into shallow marine limestones, representing a progressive shallowing of the depositional environment. Of the Purbeck Group, only the basal strata, consisting of finely laminated limestones, are of Jurassic age (Barton et al., 2011).

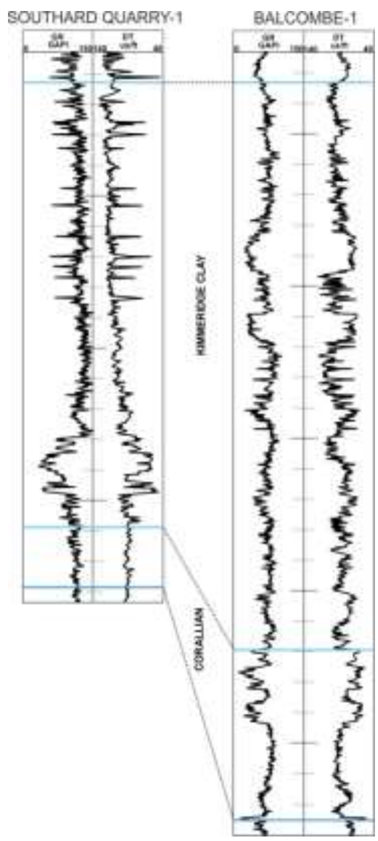


Figure 26. Comparison of gamma ray and sonic logs for the Kimmeridge Clay of the Wessex (Southard Quarry 1) and Weald (Balcombe 1) study areas.

6 Estimate of the Magnitude of Missing Section

6.1 This Study

Estimating the amount of missing section is fundamental for determining the maximum burial depth of the Jurassic shale intervals and assessing in which location(s) they may have reached maturity for oil generation. Both the magnitude and timing of uplift/erosion events in the Wessex area are debated (e.g. Law, 1998; England, 2010). The magnitude of uplift/erosion can be determined using different methodologies, most commonly by using palaeo-temperature profiles derived from Apatite Fission Track Analysis (AFTA) and Vitrinite Reflectance (R_o) (e.g. Bray et al., 1998), interval velocity analysis (Hillis, 1995; Law, 1998) and stratigraphic restoration. For this study, interval velocity comparisons and stratigraphic restoration have been carried out to estimate the amount of erosion across the Wessex area.

Variations in sonic velocity between wells relative to a time-depth function based on an assumed normal compaction relationship for a given interval can be used to give regional estimates of uplift (Hillis, 1995; Law, 1998). Sedimentary rock porosity decreases, and therefore sonic velocity increases, with burial depth; this effect is largely irreversible with exhumation (Hillis, 1995; Hillis et al., 2008). Anomalously high interval velocities relative to the normal compaction relationship can then be interpreted to represent uplift of a formation. This methodology is extremely sensitive to errors in the normal compaction relationship and variations in sedimentary facies or diagenesis (Law, 1998), therefore the Oxford Clay was used as the 'type' section which as a regionally consistent, thick shale section is less likely to have such errors.

All available time-depth data for the Top Oxford Clay and Top Great Oolite Group were collated and used to calculate interval velocities for the Oxford Clay, which were then plotted against the corresponding mid-point of the section in true vertical depth sub-sea level (Figure 27). The normal compaction relationship is derived by finding the best-fit linear function passing through the data points with the lower interval velocity for a given burial depth (Law, 1998). A comparison of the interval velocity versus depth data points from the Wessex and Weald studies and the normal compaction trend used for the Weald study (Figure 27) shows the compaction trend to hold for the Wessex area. This trend was then used to give an estimate of the amount of erosion at each well location using the following equation (Hillis, 1995; Law, 1998):

$$Ea = \frac{1}{m}(V_i - V_0) - z_i$$

Where m = the gradient of the normal compaction line, V_0 is the surface intercept of the normal compaction relationship, V_i = interval velocity of the interval under consideration and z_i is the mid-point depth of the interval.

As discussed in a previous section, the Wessex area has experienced (at least) two major phases of uplift and erosion, during the Aptian-Albian and the Mid-Tertiary, with overall regional tilting to the east. To gain an estimate of the magnitude of missing section, well data, structural history and palaeogeographies were considered in order to independently determine the amount of erosion. The uplift events have removed evidence for the original depositional thickness of the Upper Jurassic

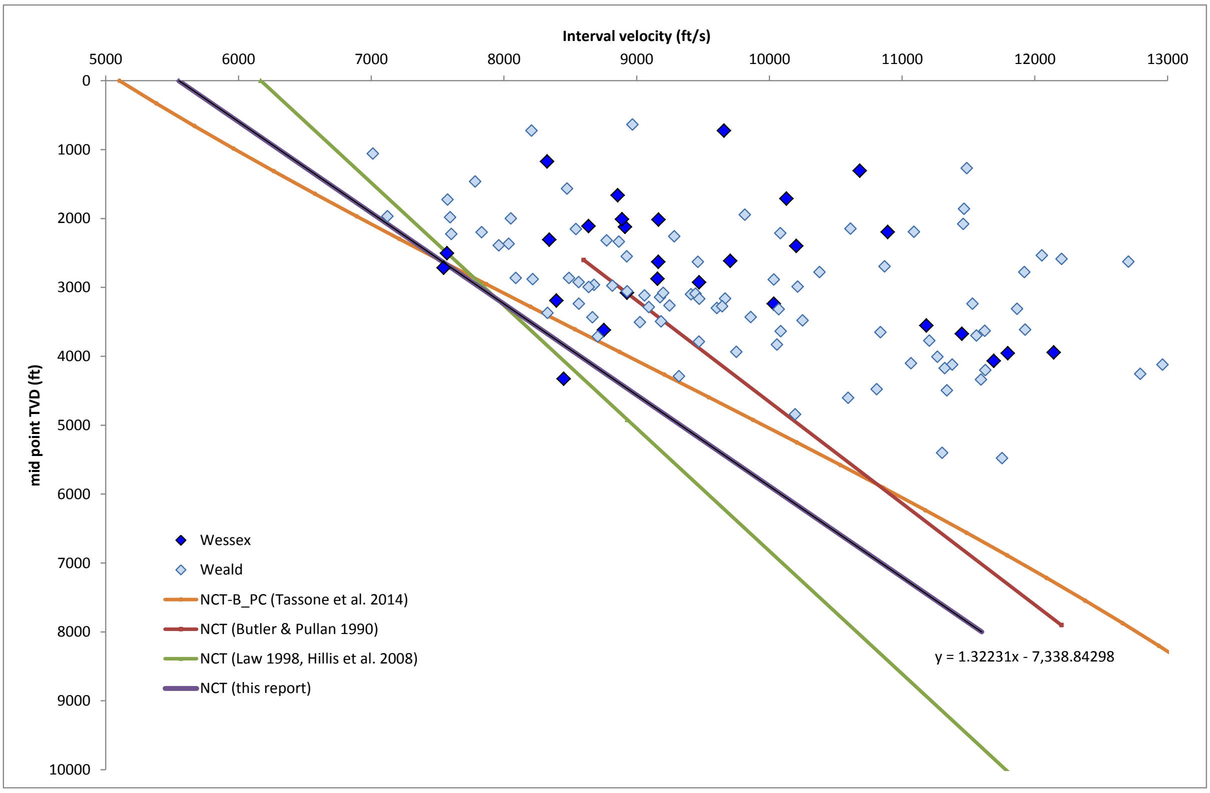


Figure 27. Interval velocities vs TVD for determination of the normal compaction trend (NCT) for the Oxford Clay of the Wessex and Weald areas, used to estimate the amount of erosion.

to Tertiary successions in some areas, however knowledge of the palaeogeography and the interplay of eustatic changes and tectonics can help to determine their original depositional extent.

The Kimmeridge Clay was deposited during a period of high global sea-level and active crustal extension, so it is probable that deposition was thick and widespread, with most of southern England being submerged (Chadwick, 1985a; Hamblin et al., 1992). Deposition during the latest Jurassic to early Cretaceous times was more localised due to a major fall in global sea-level coupled with post-rift isostatic restoration (Chadwick, 1985b), with sedimentation within the study area restricted to the Channel Basin, south of the Purbeck-Isle of Wight Disturbance (Hamblin et al., 1992). Two major transgressive phases occurred in the Mid-Cretaceous, establishing sedimentation over a widespread area once again, with the deposition of marine sediments of the Lower Greensand, Gault and Upper Greensand formations (Chadwick, 1985c); these formations thin towards the western and northern margins of the Wessex area. The Chalk, laid down in the Late Cretaceous, was deposited over most of southern Britain (Chadwick, 1985d). In the Wessex area, although rates of tectonically-driven subsidence are thought to have been very slow, a thick Chalk section was deposited due to accommodation created by compaction under loading of the thick, pre-Chalk Mesozoic sequence (Chadwick, 1985d). Thick Lower and Middle Tertiary sediments were deposited in the south and east of England prior to major structural inversion (Chadwick, 1985e).

The interval velocity analysis method gives an estimate of the total erosion at a given location, but to account for the structural complexity of the region, two restored isopachs were created – one from the Top Oxford Clay to the Base Greensand Unconformity, and one from the Base Greensand

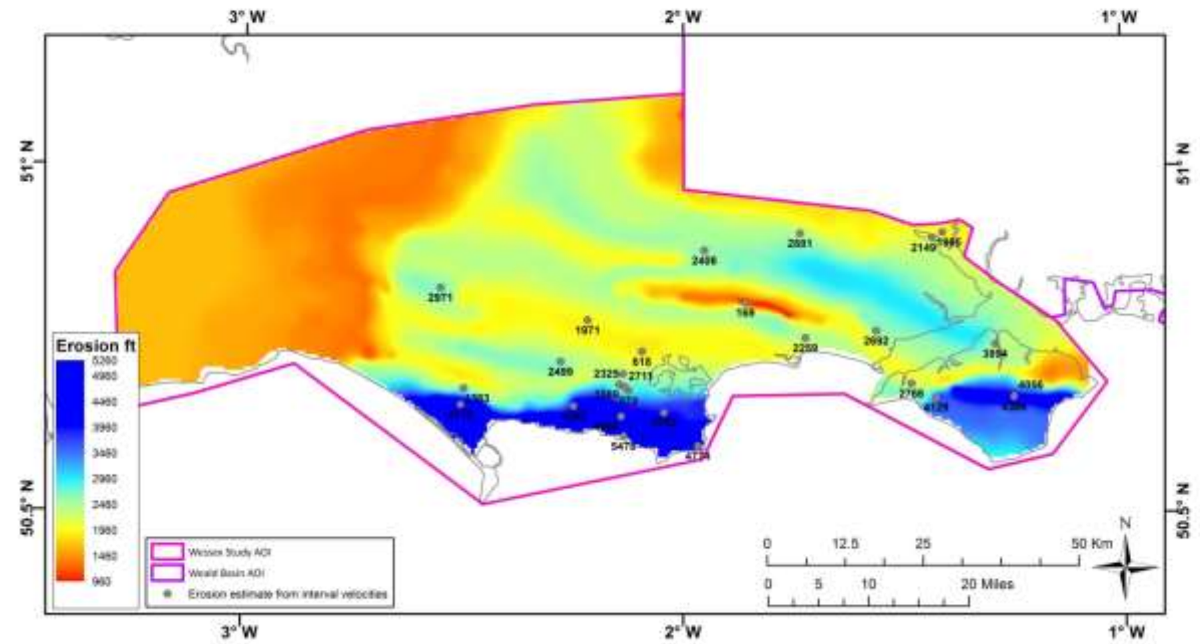


Figure 28. Total erosion for the Wessex area estimated in this study from interval velocity analysis and stratigraphic restoration. Plotted values are those estimated using the NCT (determined in Figure 27) for individual wells.

Unconformity to the Mid-Tertiary. These restored isopachs were then summed to the topography to give a pseudo Top Oxford Clay depth grid, which was then subtracted from the present-day Top Oxford Clay depth grid to give an estimate of the overall missing section (Figure 28). Estimated erosion from the interval velocity analysis is also plotted for comparison. This study predicts a maximum missing section thickness of approximately 5250 ft (1600 m), with the greatest estimates south of the Purbeck-Isle of Wight Disturbance where the Tertiary uplift event dominates.

6.2 Published Studies

Both palaeo-temperature and interval velocity studies of the Wessex area have predicted maximum erosion on the km-scale (Law, 1998; Bray et al., 1998). The interval velocity analysis method used by Law (1998) gives comparable estimates of erosion to those determined from AFTA/R_o data in inverted areas, but significantly lower results in more tectonically stable areas. Law (1998) estimated a maximum missing section thickness of 1640 ft (500 m) for the Wytch Farm area, whereas AFTA/R_o data suggest c. 3280-6560 ft (1000-2000 m) uplift has occurred in this region (Bray et al., 1998). Similar values were determined by Stoneley (1982) and Ebukanson & Kinghorn (1986a) who estimated c. 1640-3940 ft (500-1200 m) of Early Cretaceous uplift in the Wytch Farm and Bushey Farm areas. On the Isle of Wight, Gale et al. (1999) determined a minimum uplift of 1640 ft (500 m) on the northern limb of the Sandown Pericline from the stratigraphical distribution of reworked material. A total of 4844 ft (1476 m) of missing section, from the Aptian to the base of the Miocene, at Arreton 2 was estimated to have been removed during Miocene tectonic inversion (Ebukanson & Kinghorn, 1986a). Across the Wessex Basin (sensu Underhill & Stoneley, 1998) as a whole, Bray et al. (1998) estimated up to a maximum c. 7545 ft (2300 m) of Early Cretaceous uplift, and Jones et al. (2002) determined a maximum denudation of between c. 4920-6560 ft (1500-2000 m). Offshore in the very southern extension of the Wessex Basin on the Central Channel High, Beeley & Norton (1998) estimated post-Cretaceous uplift of up to c. 4920 ft (1500 m).

There is a degree of uncertainty in the amount of missing section across the Wessex study area (as evident in the varied amounts predicted by published studies), complicated by the presence of the significant unconformities. Whilst there is a general agreement that erosion is greatest over major structures (Chadwick, 1986a; Lake & Karner, 1987; Hillis et al., 2008), estimates of the magnitude are varied, depending on the methodology and assumptions used for the calculation. This may be further compounded by the differing (and often interchangeable) terminology, as is common in studies of uplift/exhumation (Doré et al., 2002), meaning values are not necessarily directly comparable. Nevertheless, the consensus in published studies is for km-scale erosion, certainly south of the Purbeck-Isle of Wight Disturbance, with which this study is in agreement.

AFTA is used to determine the timing and magnitude of peak palaeo-temperatures. The predicted uplift is controlled by the value used for the geothermal gradient at the time of uplift (Blundell, 2002). The higher palaeo-temperatures inferred from the AFTA/R_o data may instead be due to a phase of crustal heating rather than a result of deeper burial (Bray et al., 1998). Alternatively, as the AFTA/R_o data show that none of the studied wells are at their maximum burial depth present-day, the reference wells used in the interval velocity study to determine the normal compaction curve may themselves have been uplifted (Bray et al., 1998). The R_o data should be used with caution as the data often form a wide scatter at a given depth or are anomalously low due to vitrinite suppression in organic-rich material (see Section 7.2).

7 Geochemistry

Hydrocarbon discoveries, shows and seeps within the Wessex area demonstrate the presence of a mature oil-prone source rock in (or in the vicinity of) the study area, with the Mupe Bay palaeo-seep cited as evidence that petroleum generation had begun by the Early Cretaceous (Selley, 1992; Emmerton et al., 2013). The source potential of the Jurassic in the Wessex area has long been recognised; oil shales of the Kimmeridge Clay were commercially exploited at Kimmeridge (Dorset) for fuel and raw materials in the 18th and 19th centuries (Gallois, 1978). However, despite this, and the long history of exploration, the available geochemical data in the public domain for the Wessex area is sparse. Figure 10 shows the location of wells, boreholes and outcrops with geochemical data used in this study, collated from well reports, published papers and academic work.

There are three main intervals with good source rock potential in the Wessex area: the Lower Lias, the Oxford Clay and the Kimmeridge Clay formations (e.g. Ebukanson & Kinghorn, 1985; Ebukanson & Kinghorn, 1990; England, 2010). These intervals all have variations in lithology, sedimentation rate, organic content and kerogen type (Ebukanson & Kinghorn, 1985). The richest source rock intervals are characterised by laminated dark shales, consistent with increased preservation of organic matter in an anoxic environment (Ebukanson & Kinghorn, 1990; Morgans-Bell et al., 2001). In addition, the Upper Lias and Middle Lias also have well-developed clay sections, and are included in the evaluation for consistency with the Weald study; the limited geochemical data available for these intervals suggest they have fair source potential at best. Additionally, good source intervals are occasionally present in the Frome Clay and Fuller's Earth (Great Oolite Group), and within limestones of the Corallian and Inferior Oolite. Geochemical studies suggest the oils in the producing fields of the Wessex area are all sourced from the Lower Lias, from the source rock kitchen to the south of the Purbeck-Isle of Wight Disturbance (Underhill & Stoneley, 1998; Scotchman, 2001; England, 2010).

Source rock quality has been determined from Rock Eval analysis, including measurements of total organic carbon (TOC), hydrogen index (HI), S1 (free hydrocarbons) and S2 (bound hydrocarbons). Unfortunately, no oxygen index (OI) data was available for this study. It is commonly accepted that a rock requires a minimum TOC of 1.5-2% when immature to expel oil during maturation (Lewan, 1987). However, a high TOC alone does not imply a good source rock (Peters & Cassa, 1994), so other Rock Eval parameters need to be considered to determine the source potential of a rock. S2 values > 5-10 mgHC/gRock indicate good source rocks, whilst those > 50 mgHC/gRock represent world class potential (Smith et al., 2014). HI is the ratio of S2/TOC and gives an indication of kerogen type, whether oil or gas-prone. S1 is a measurement of the amount of hydrocarbons already generated and present in the source rock, and of the free oil component that can potentially be extracted after fracture stimulation.

7.1 Source Rock Potential

7.1.1 Kimmeridge Clay Formation

The Kimmeridge Clay Formation contains extremely organic-rich intervals although the section is largely immature across the Wessex area (Colter & Havard, 1981; Ebukanson & Kinghorn, 1985; Penn et al., 1987; Cornford et al., 1988; Figures 29; 30). The highest TOC of 35.09% was recorded in the

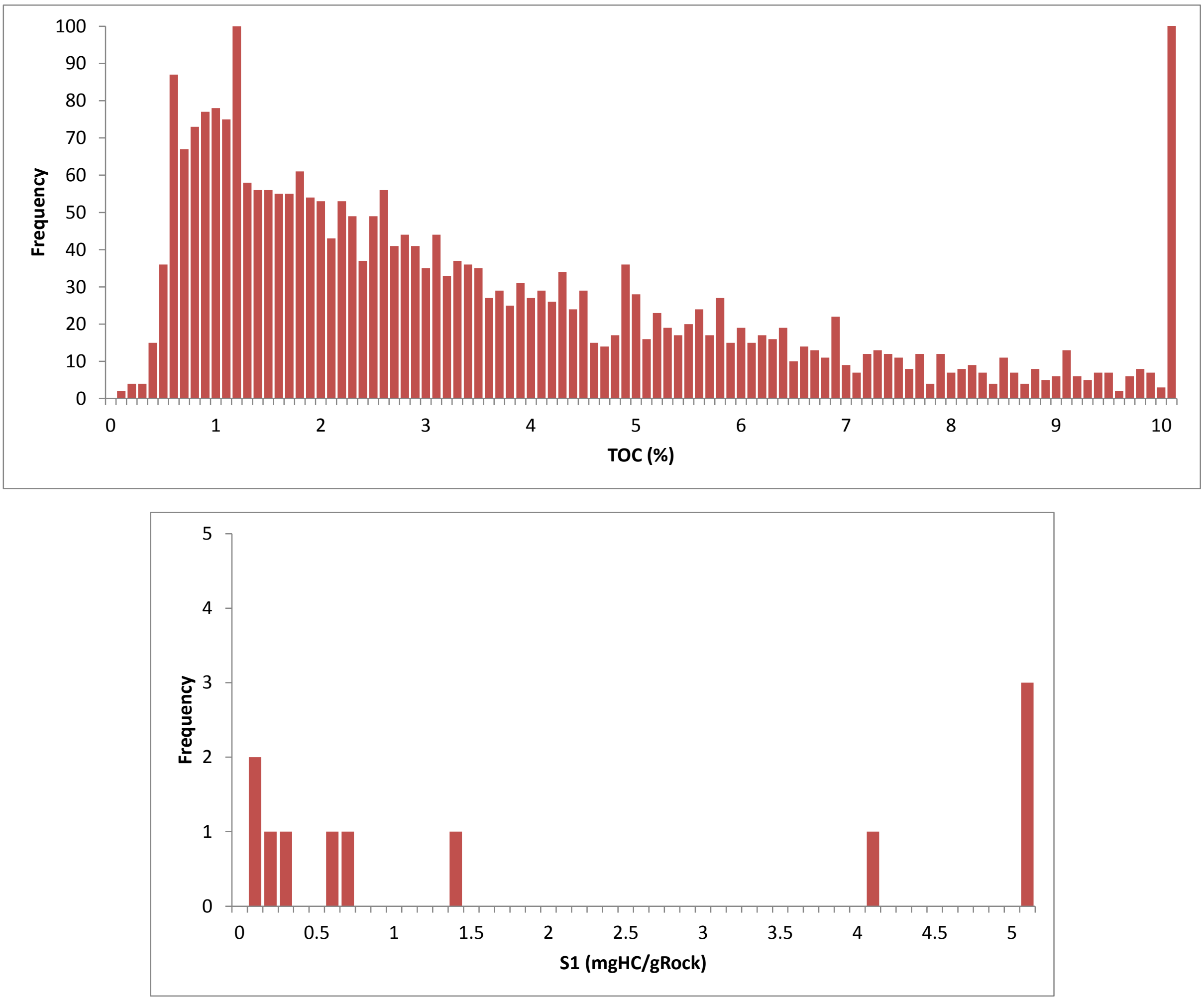


Figure 29. TOC and S1 vs frequency plots for the Kimmeridge Clay in the Wessex area. Out of a total of 2813 data points, 150 have TOC values > 10%. The high S1 (>= 5 mgHC/gRock) are from samples taken from oil shales at outcrop. Data from Farrimond et al. (1984); Ebukanson & Kinghorn (1985); Morgans-Bell et al. (2001); and well reports.

Swanworth Quarry 1 borehole, but high TOCs (>10%) are recorded throughout the section, in approximately 6% of the samples, in both the Swanworth Quarry 1 and Metherhills 1 boreholes (Tyson, 2004). These boreholes were drilled specifically to target the organic content variability within the Kimmeridge Clay, and identified five main organic-rich intervals, thought to be linked to maximum flooding surfaces (Morgans-Bell et al., 2001). Tyson (2004) found the mean TOC within the Swanworth Quarry and Metherhills boreholes to be negatively correlated with sedimentation rate, indicating that dilution is a significant controlling variable. High TOCs of 16.34% and 16.37% have also been measured from outcrops at the Ringstead Bay area and the Chapman's Poole area respectively (Ebukanson & Kinghorn, 1985; Ebukanson & Kinghorn, 1990) and Farrimond et al. (1984) reported TOC of up to 57.2% in an oil shale from an outcrop sample east of Kimmeridge Bay (Dorset). Good quality intervals (TOC > 2%) are also present in the Arreton 2, Marchwood 1 and Cranborne 1 wells.

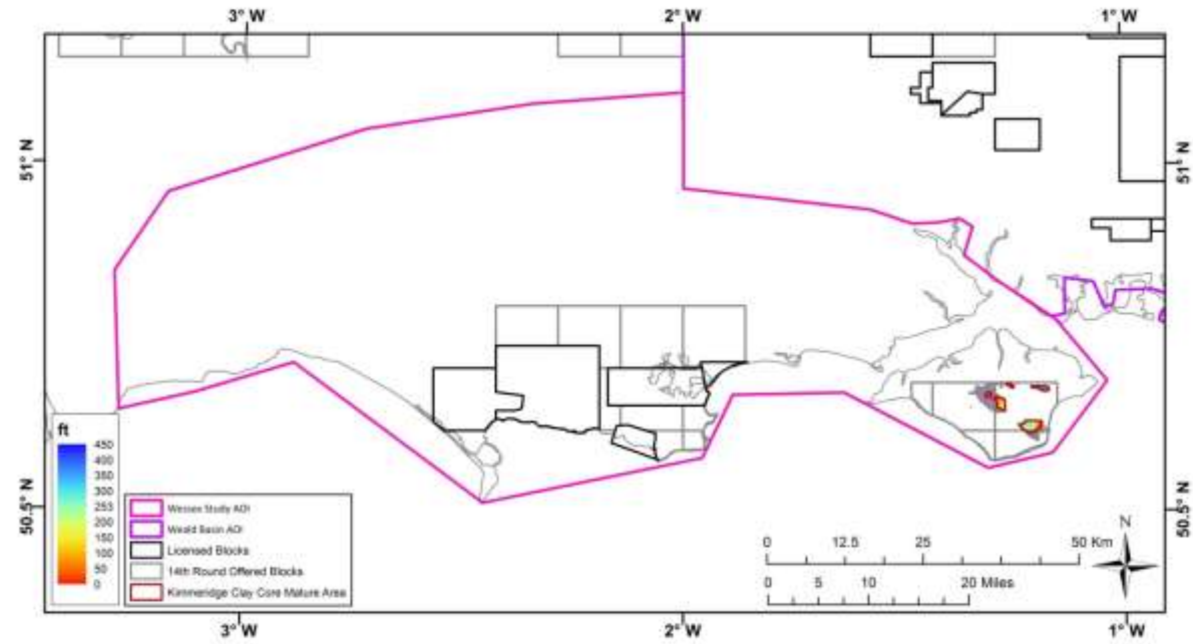


Figure 30. Gross thickness of the Kimmeridge Clay Formation within the area it has been predicted to have reached oil maturity, and below a present-day burial depth of c. 3950 ft (1200 m). No part of the predicted mature section is presently at depths of c. 5000 ft (1500 m) or greater below the surface. The P50 estimate for the proportion of organic-rich shale is 0.35. Shaded region is the area of mature Kimmeridge Clay with no top-down truncation applied.

S1 data are only available from outcrop samples (Farrimond et al., 1984) and are generally ≤ 1.5 mgHC/gRock (Figure 29), as expected for an immature source rock; the highest value, of 28.0 mgHC/gRock was measured in an oil shale. HI data are only available from outcrop samples (Farrimond et al., 1984) and at a limited number of depths in the Marchwood 1 well, but the values are generally ≥ 500 mgHC/gTOC indicating a dominantly oil-prone source. The Kimmeridge Clay kerogen type ranges from type I to type III (Williams, 1986; Tyson, 2004).

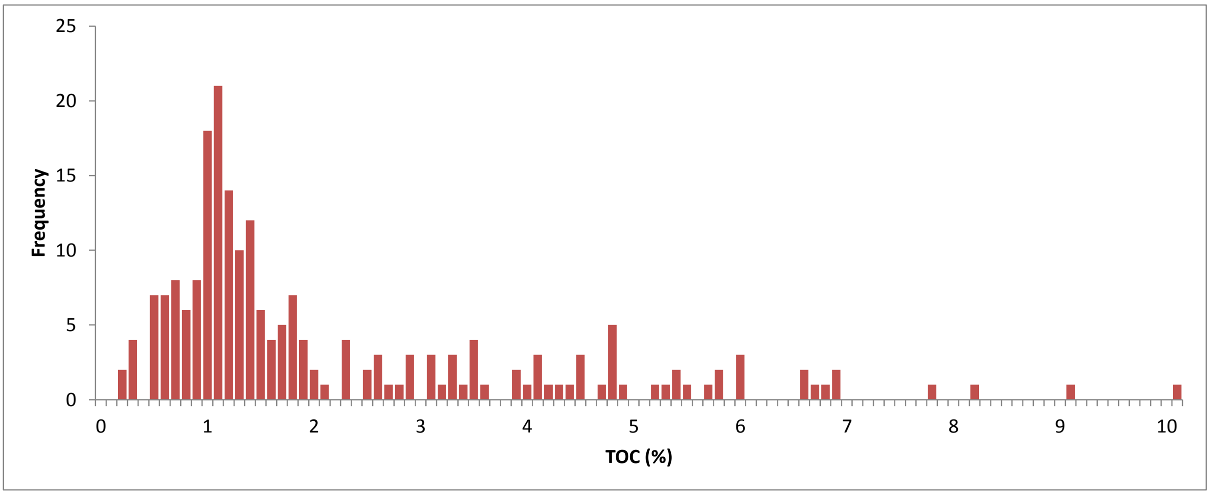
This study predicts the Kimmeridge Clay to have reached maturity (R_o > 0.6%) at its maximum burial only in isolated segments on the Isle of Wight, even without the top-down truncation of c. 3950 ft (1200 m) applied (Figure 30). It has a maximum gross thickness of potentially mature source of c. 450 ft (140 m) and an average gross thickness of 170 ft (52 m). A detailed petrophysical study of available log and core data was not undertaken for this study, so the distribution of the net thickness of organic-rich shale could not be confidently mapped (for any interval). However, on average across the core mature area, the Kimmeridge Clay has an estimated net to gross of 0.9, with the proportion of organic-rich shale estimated at 0.35 (P50 value).

The limited maturity data from vitrinite reflectance, spore colouration and thermal alteration index indicates the Kimmeridge Clay is immature across the Wessex area (Ebukanson & Kinghorn, 1985; Cornford et al., 1988). However, Ebukanson & Kinghorn (1986a) suggested that the Kimmeridge Clay in the Arreton 2 well is just entering the early oil maturity window, based on spore colour and basin modelling which predicted a vitrinite reflectance of approximately 0.6% at the base of the Kimmeridge Clay at maximum burial. This view was supported by Williams (1986), who modelled the base of the Kimmeridge Clay on the Isle of Wight as entering the oil window in the Late Cretaceous. An alternative model using Lopatin Time Temperature Index calculations by Penn et al.

(1987) suggests that the Kimmeridge Clay has only reached maturity in the northernmost part of the Channel Basin. Higher maturity of the Kimmeridge Clay is observed in outcrop samples from the southern side of the Purbeck-Isle of Wight Disturbance compared to those from the northern side of that structure (Ebukanson & Kinghorn, 1986a).

7.1.2 Oxford Clay Formation

The lower Oxford Clay (Peterborough Member) is demonstrated to have good source potential across the Wessex area (England, 2010), although it is largely immature across the study area (Figures 31, 32). The highest TOC of 12.36% is measured from an outcrop at Chickerell, but TOCs > 5% are also measured in intervals within the Encombe 1, Lulworth Bank 1, Southard Quarry 1, Arreton 2, Marchwood 1, Cranborne 1, Coombe Keynes 1 and Spetisbury 1 wells. S1 data are only available for the Spetisbury 1 and Coombe Keynes 1 wells, with all values < 1 mgHC/gRock (Figure 31). S2 data support the presence of intervals with excellent source potential within the Oxford



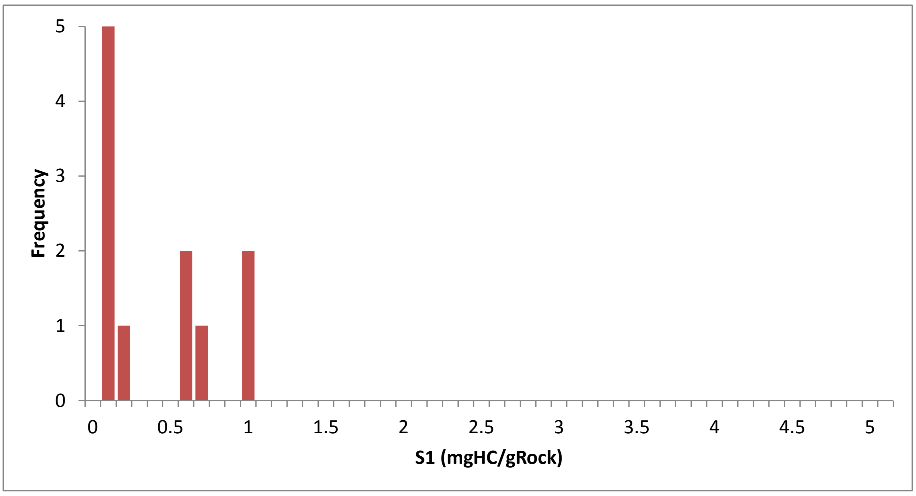


Figure 31. TOC and S1 vs frequency plots for the Oxford Clay Formation in the Wessex area. Data are from Ebukanson & Kinghorn (1985); England (2010); and well reports.

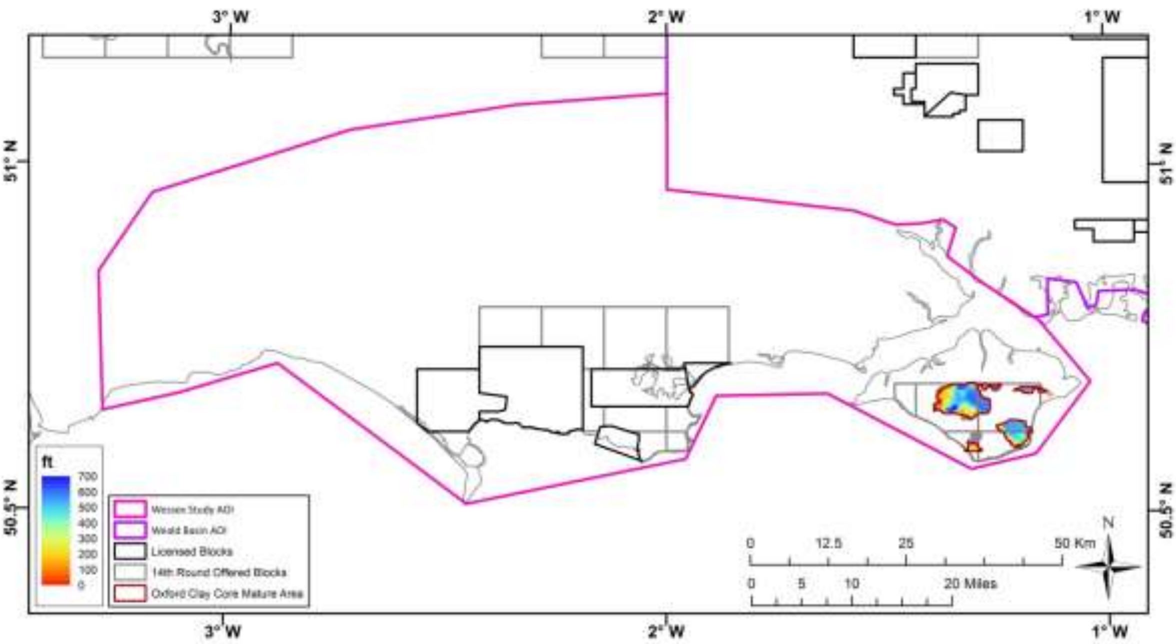


Figure 32. Gross thickness of the Oxford Clay Formation within the area it has been predicted to have reached oil maturity, and below a present-day burial depth of c. 3950 ft (1200 m). Only a very minor volume of the predicted mature section is below a present-day burial depth of c. 5000 ft (1500 m) (contour not shown). The P50 estimate for the proportion of organic-rich shale is 0.28. Shaded region is the area of mature Oxford Clay with no top-down truncation applied.

Clay, with a maximum value of 57.85 mgHC/gRock measured in the Spetisbury 1 well; Encombe 1, Arreton 2, Southard Quarry 1 and Lulworth Bank 1 also have several intervals of good source potential.

A maximum HI of 800 mgHC/gTOC is measured in the Southard Quarry 1 well, but values ≥ 200 are common, indicating an oil-prone marine type II kerogen source in the organic-rich Peterborough Member (Ebukanson & Kinghorn, 1985). The higher HI values in the Southard Quarry 1 well probably reflect greater levels of preservation and/or increased marine input in this part of the basin (England, 2010). Only the Peterborough Member, the lowest interval of the Oxford Clay, has organic-rich shales whereas the overlying Stewartby and Weymouth members are composed of relatively lean calcareous mudstones (England, 2010). There is a clearly defined trend of kerogen type from type II at the base through mixed type II/III, type III to type IV at the top of the formation (Ebukanson & Kinghorn, 1985). Variation in bottom-water oxygen availability is thought to be the main control on the level of preservation of organic matter (Ebukanson & Kinghorn, 1985; Kenig et al., 2004).

Vitrinite reflectance data generally show low values for the Oxford Clay and T_{max} values range from 415-440°C in the available data set. The Oxford Clay is not thought to have reached sufficient maturity onshore for the expulsion of hydrocarbons, although within the Portland-Wight Basin depocentre the formation may have reached early oil maturity at maximum burial (Ebukanson & Kinghorn, 1986b; Penn et al., 1987; England, 2010). Results from this study are in agreement with this conclusion, with a maximum gross thickness of c. 700 ft (213 m) and a mean gross thickness of c.

395 ft (120 m) of mature Oxford Clay section predicted on the Isle of Wight (Figure 32), with an estimated net organic rich shale of 28% (P50 value).

Additional potential may exist at Kimmeridge Bay and the surrounding areas. England (2010) suggested that the Oxford Clay in Encombe 1 and Southard Quarry 1 may be close to the onset of oil generation, on the basis of the C29 steranes and estimated vitrinite reflectance values; this is supported by 1D basin modelling at Kimmeridge 5 (Figure 33; England, 2010; Fraser & Aryanto, in prep) and Southard Quarry 1 (England, 2010), which places the Oxford Clay in the early maturity window for oil generation. Although the model presented in this study does not predict any mature Oxford Clay section at these locations, such a result is certainly possible within the bounds of uncertainty governing the determination of the maximum burial depth.

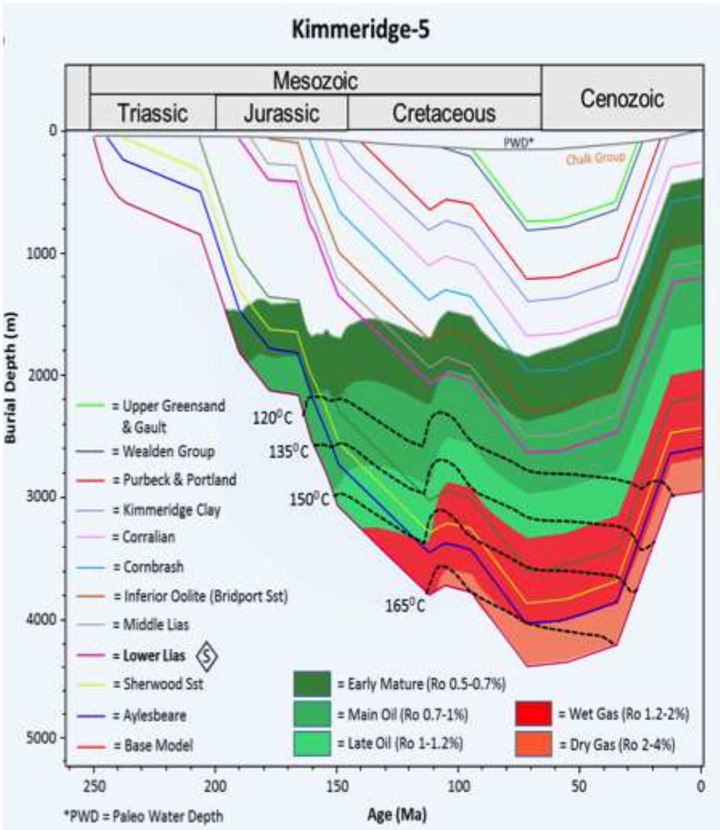
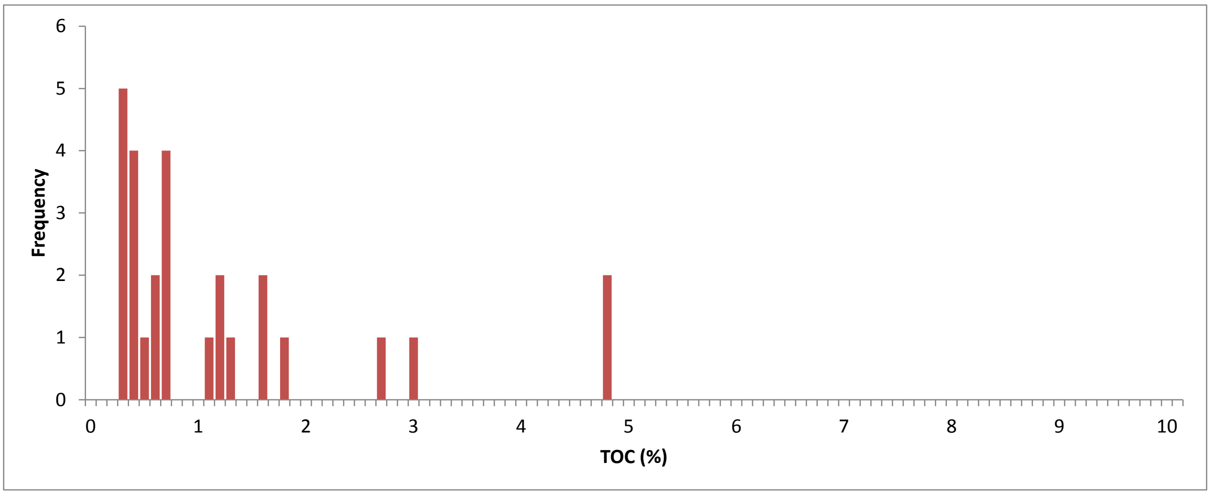


Figure 33. 1D basin model for Kimmeridge 5 indicating that the Oxford Clay has reached early maturity for oil generation at this location (from Fraser & Aryanto, in prep).

7.1.3 Upper Lias

The Upper Lias (Toarcian) is proven to be the main source rock interval in the contiguous Paris Basin (Burwood et al., 1991). However the Wessex area was characterised by a high energy, shallow water depositional environment during this time resulting in the formation of the Bridport Sands (Fleet et al., 1987), thus limiting the development of potential source rocks, as evident in the generally low TOC and S1 values (Figure 34). TOC values for the Upper Lias range from 0.23-4.79% with values



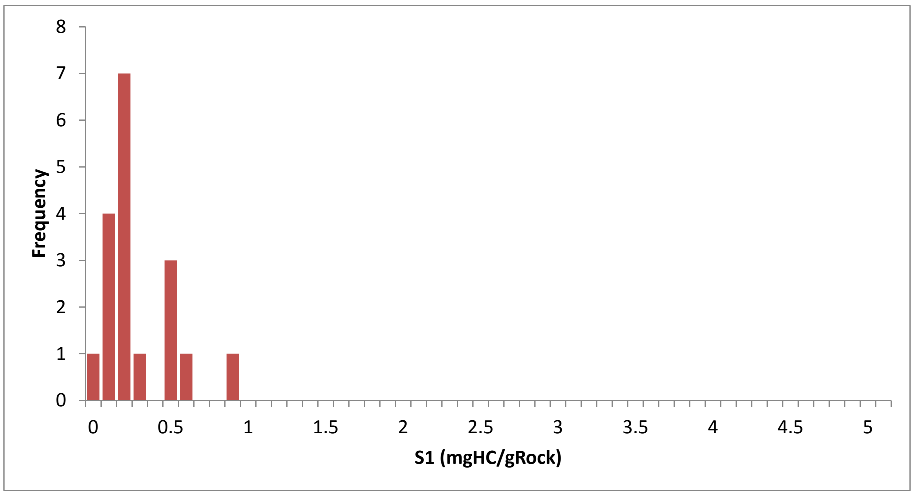


Figure 34. TOC and S1 vs frequency plots for the Upper Lias in the Wessex area. Data are from Ferguson (2002); England (2010); and well reports.

> 2% only present in the Spetisbury 1 well. S2 values range from 0.1-28.9 mgHC/gRock, with values > 5 mgHC/gRock (indicating good source potential) measured in Martinstown 1 and Spetisbury 1. HI data are limited, but the values corresponding to a fair TOC (> 1%) range from 247-456 mgHC/gTOC indicating a type II to II/III kerogen source.

The interval, in this study, is predicted to have reached maturity onshore only on the Isle of Wight and around Kimmeridge Bay (Figure 35), with the top-down truncation of c. 3950 ft (1200 m) not impacting the mature area. The mature section has a maximum gross thickness of 778 ft (237 m) and a mean gross thickness of 228 ft (69 m). The net percentage of prospective shale is estimated to be 3% (P50 value). Vitrinite reflectance data indicate a range of maturity from immature at Spetisbury 1 (R_o = 0.42%), to marginal maturity at Marchwood 1 (R_o = 0.47-0.54%, to late oil window/wet gas window at Arreton 2 (R_o = 0.7-1.23%). However, the values in Arreton 2 don't have a trend showing an overall increase with depth – instead the highest values are in the upper part of the Upper Lias. T_{max} values range from 428-439°C.

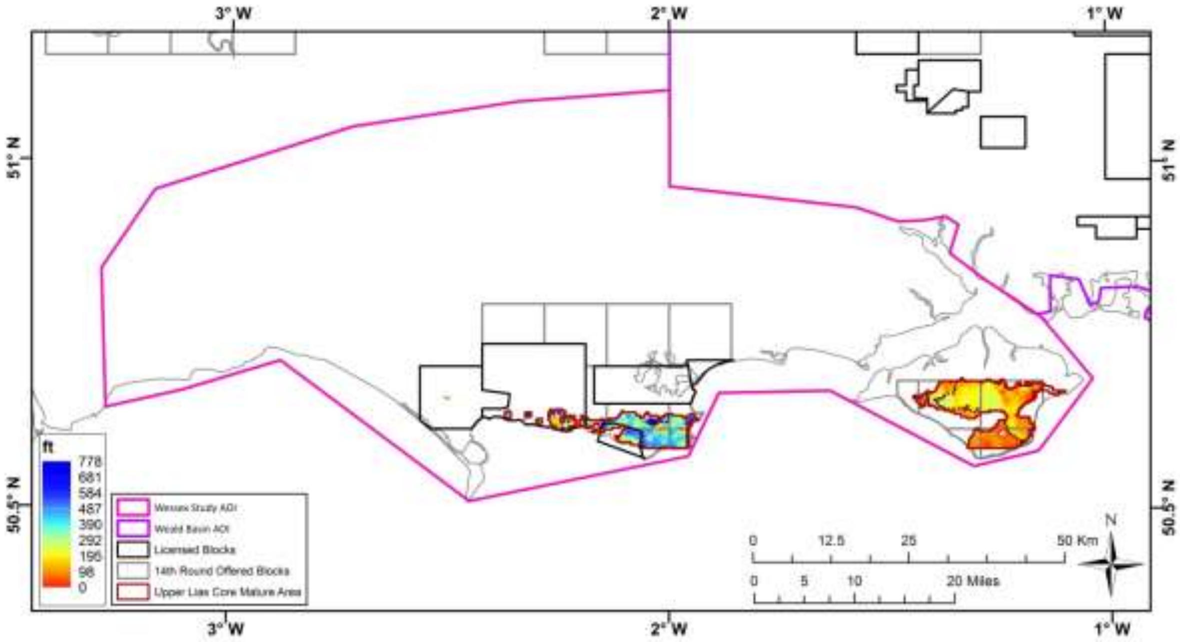


Figure 35. Gross thickness of the Upper Lias within the area it has been predicted to have reached oil maturity, and below a present-day burial depth of c. 3950 ft (1200 m). Dashed line is the extent of the predicted mature area below a present-day burial depth of c. 5000 ft (1500 m).

7.1.4 Middle Lias

In the study area, TOCs for the Middle Lias are all less than 2% with the exception of one (limestone) interval in the Martinstown 1 well which has a TOC of 3%, although several wells do have intervals with TOC > 1% (Figure 36). Spetisbury 1 and Martinstown 1 both have intervals with S2 > 5 mgHC/gRock, with Martinstown 1 having a maximum S2 of 11 mgHC/gRock. For samples with a fair TOC, HI ranges from 144-367 mgHC/gTOC indicating types II – II/III – III kerogen.

The interval is predicted to have reached maturity onshore in the southern part of the study area, on the Isle of Wight and in Dorset, south of the Purbeck-Isle of Wight Disturbance (Figure 37). The mature section has a maximum gross thickness of 1300 ft (396 m) and a mean gross thickness of 197 ft (60 m). The percentage of prospective shale (in the Eype Clay) across the whole interval is estimated at 5% (P50 value), as the gross interval is dominated by the Thorncombe Sands. T_{max} data range from 423-440°C and measured vitrinite reflectance values range from 0.35-0.92%, with values > 0.7% present in both the Spetisbury 1 and Arreton 2 wells.

7.1.5 Lower Lias

The Lower Lias is the primary source within the Wessex study area, with the quality generally deteriorating towards the east into the Weald Basin (Table 2; Burwood et al., 1991; Andrews, 2014), where the interval becomes dominated by limestones. Although it has excellent potential in the Wessex area (Figure 38), there are significant variations in the source rock richness both geographically and temporally (England, 2010). Deposition of the Lower Lias occurred in an anoxic environment with high productivity (Scotchman, 2001).

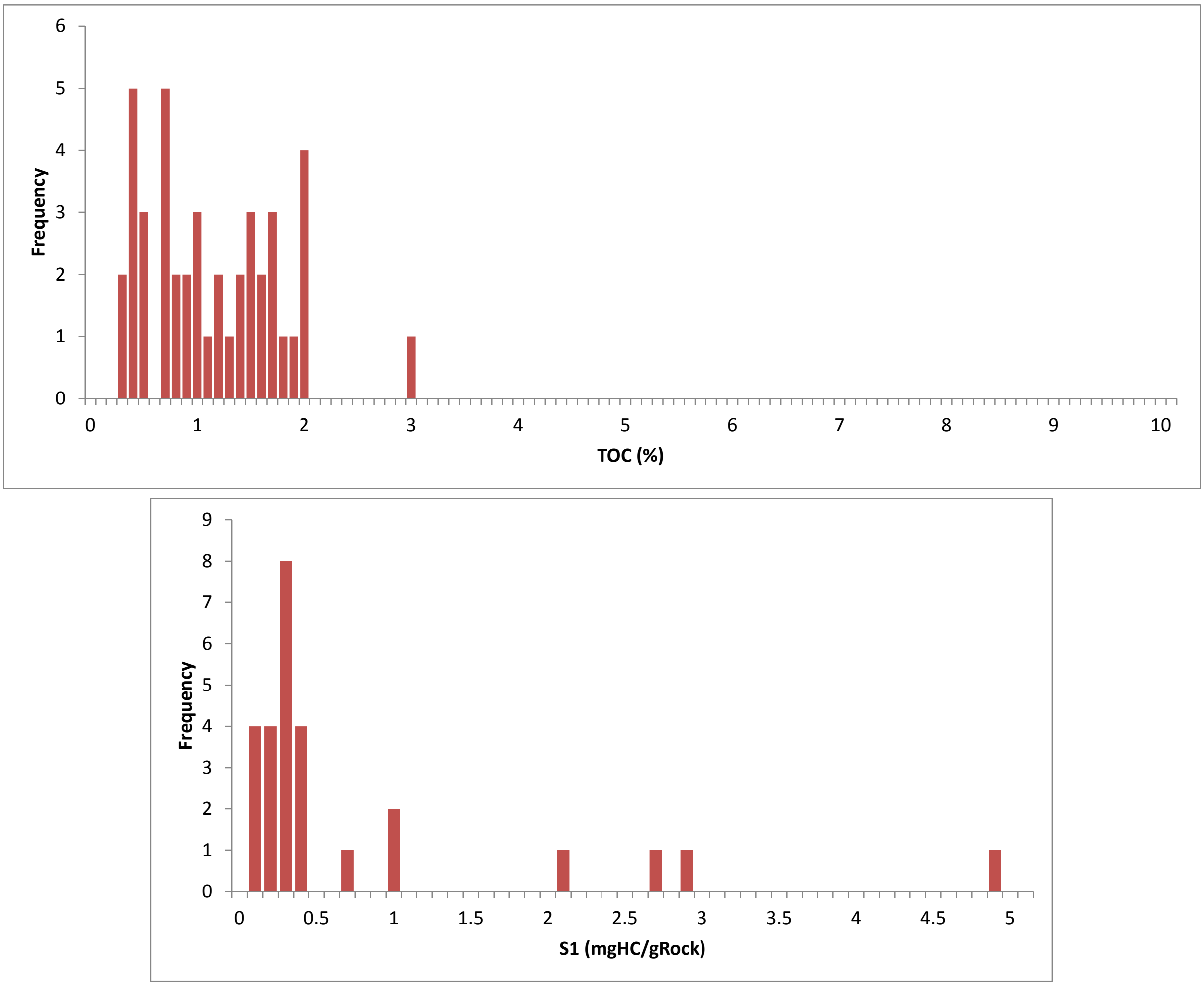


Figure 36. TOC and S1 vs frequency plots for the Middle Lias (including the Eype Clay) in the Wessex area. Data are from Ferguson (2002); El-Mahdi (2004); England (2010); and well reports.

In the available data set, TOCs for the Lower Lias range from 0.05-7.43%. The highest values are measured from outcrop samples at Lyme Regis and Charmouth, but intervals with TOC > 5% are also found in the Spetisbury 1, West Compton 1, Chickerell 1 and Down Barn Farm 1 wells. The highest TOCs are found in the Shales-with-Beef and Blue Lias intervals although good TOCs are seen in all the laminated shale intervals in the Lower Lias. Interbedded calcareous mudstones and limestone have, at best, moderate potential (Fleet et al., 1987). The average TOC for the whole of the Lower Lias within the Wessex area is 2.3%, considerably higher than the average for the Weald Basin of 1.1% (Figure 38), where the Lower Lias contains a higher proportion of limestone (Andrews, 2014). Weedon & Jenkyns (1990) reported TOC values over 5% in dark beds of the Belemnite Marls. Similarly, Kiriakoulakis et al. (2000) determined TOCs of 5.7-6.7% in the Shales-with-Beef. For the Blue Lias Formation, Deconinck et al. (2003) reported TOCs ranging from 0.25-12.2% with an average of 4%.

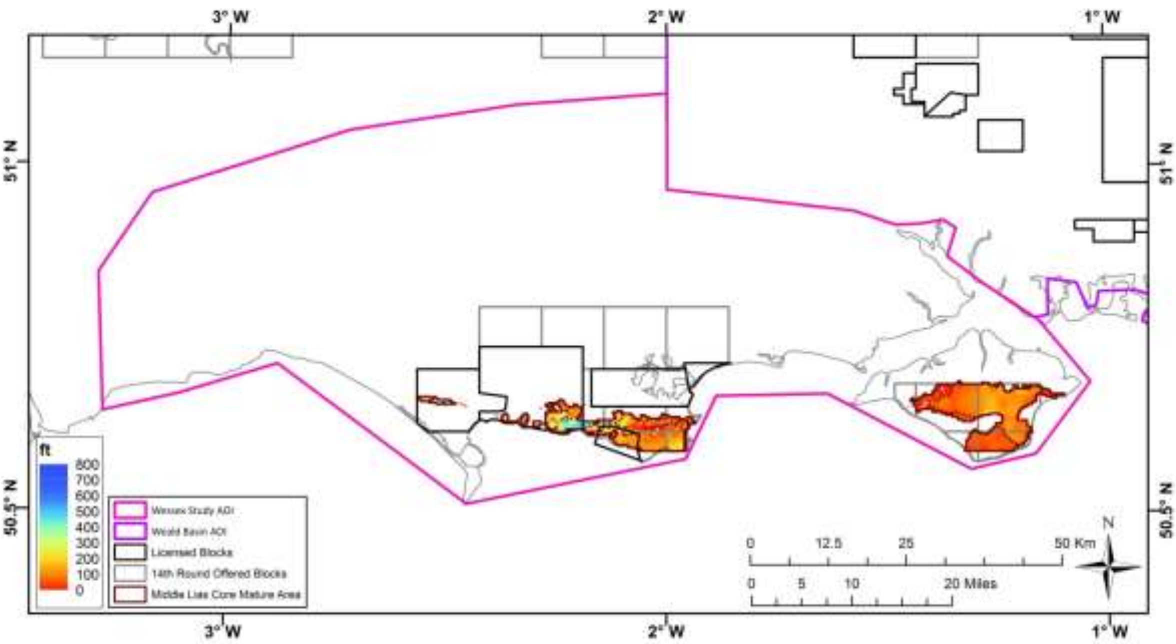


Figure 37. Gross thickness of the Middle Lias within the area it has been predicted to have reached oil maturity, and below a present-day burial depth of c. 3950 ft (1200 m). Dashed line is the extent of the predicted mature area below a present-day burial depth of c. 5000 ft (1500 m). Removing the top-down truncation does not alter the predicted mature area or gross rock volume significantly.

Study	S2 mg/g	TOC %	HI mg/g
Lower Lias (Burwood et al., 1991, average southern England)	6.0	1.8	325
Lower Lias (Burwood et al., 1991, maximum southern England)	38.0	6.0	630
Blue Lias (Akande 2012, Lyme Regis, Dorset)	46.3	8.1	569
Lower Lias (Ferguson 2002, maximum Chickerell 1, Dorset)	27.5	5.7	480
Lower Lias (Ferguson 2002 average Chickerell 1, Dorset)	9.0	2.7	334
Lower Lias (El-Mahdi 2004, maximum Down Barn Farm 1, Dorset)	21.5	5.2	413
Lower Lias (El-Mahdi 2004, average Down Barn Farm 1, Dorset)	10.2	2.81	347
Lower Lias (Eltera 2004, maximum Kimmeridge 5, Dorset)	3.0	4.05	215
Lower Lias (Eltera 2004, average Kimmeridge 5, Dorset)	1.8	1.73	114
Lower Lias (England 2010 maximum Wessex Basin)	38.7	7.43	571
Lower Lias (England 2010 average Wessex Basin)	5.56	2.20	249
Lower Lias (average for all Weald wells, 2014 study)	1.7	0.9	196
Lower Lias (maximum for all Weald wells, 2014 study)	15.5	2.0	773

Table 2. Comparison of geochemical data (S2, TOC and HI) for the Lower Lias of the Wessex area and Weald Basin (updated from Andrews, 2014).

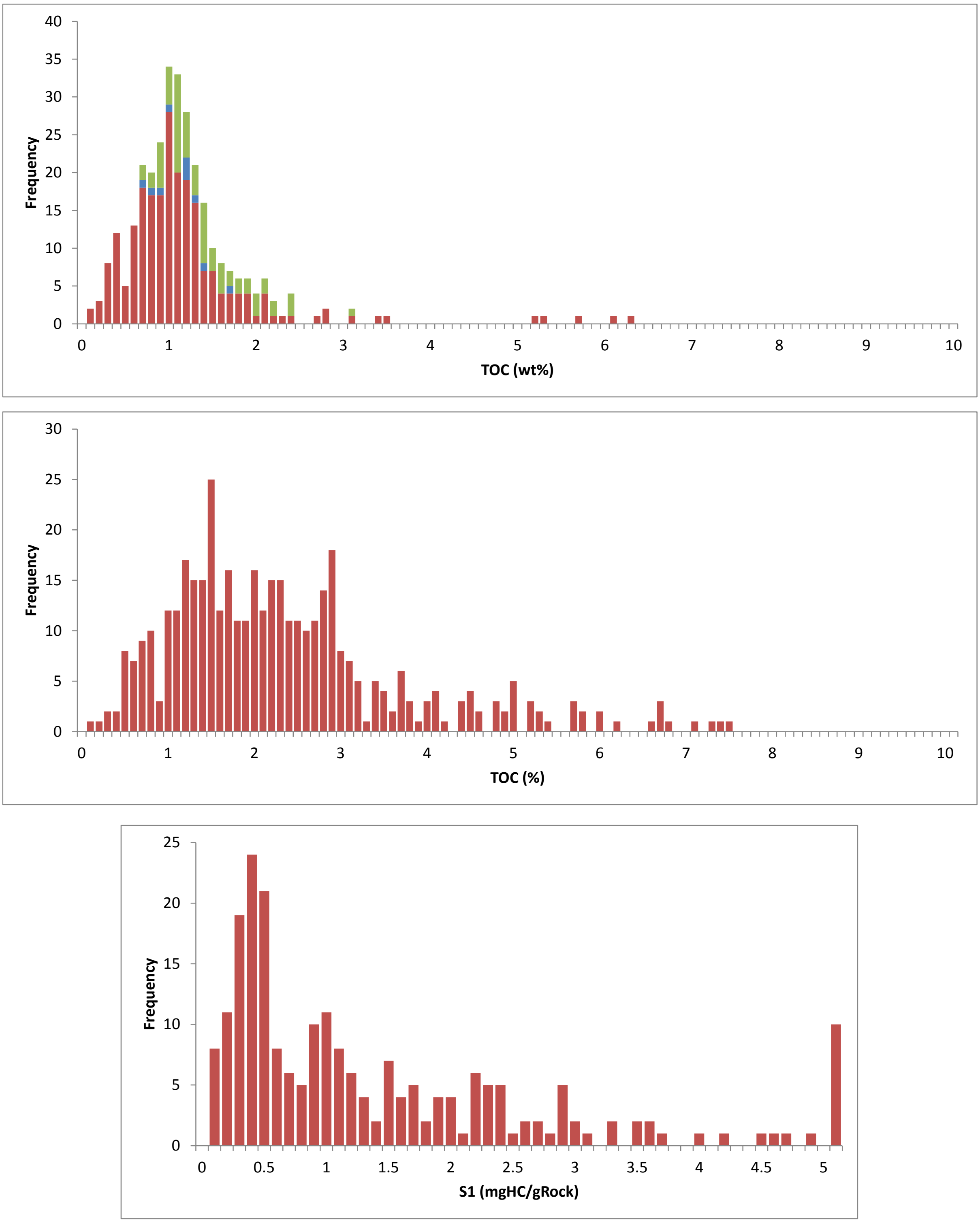


Figure 38. (Top) TOC vs frequency from the Lower Lias in the Weald Basin (from Andrews, 2014). Red = legacy data; blue = BGS data (see Appendix B of the Weald report); green = pyrolysis-derived TOCs, courtesy of Celtique Energie. TOC (middle) and S1 (bottom) vs frequency plots for the Lower Lias in the Wessex area. Data are from Ebukanson & Kinghorn (1990); Kiriakoulakis et al. (2000); Scotchman (2001); Ferguson (2002); Najm (2003) – data courtesy of P. Farrimond; El-Mahdi (2004); Eltera (2004); England (2010); Farrimond (unpublished); and well reports.

S2 ranges from 0.5-38.7 mgHC/gRock, with the highest value measured in a sample from an outcrop at Lyme Regis. Deconinck et al. (2003) published HI values ranging from 55-728 mgHC/gTOC. There are several wells with high S2, TOC and HI values, supporting the presence of good to excellent oil-prone source rocks in the Lower Lias. The Lower Lias contains a mixture of type II, II/III, and III kerogens that show no clear trend with stratigraphy (Deconinck et al., 2003; England, 2010), although the type II/III and III kerogens are generally present towards the margins of the area, whilst the basin depocentre is largely type II (Scotchman, 2001).

The Lower Lias 'core mature area' has the greatest areal extent of the five intervals considered in this study (Figure 39). The mature section has a maximum gross thickness of 2288 ft (697 m) and a mean gross thickness of 431 ft (131 m). The net prospective shale is estimated to be 35% (P50 value). The main mature area is south of the Purbeck-Isle of Wight Disturbance, although a small area close to the Spetisbury 1 well in the Winterborne Kingston Trough is also predicted in this study. The results of this study are, however, in general agreement with published models of Lower Lias maturity in the Wessex area. Penn et al. (1987) determined, from Lopatin Time Temperature calculations, that the deeper basin contained mature to over-mature Lias. This is supported by vitrinite reflectance data which reach values of $R_o > 1.0\%$ south of the Purbeck-Isle of Wight Disturbance (Ebukanson & Kinghorn, 1986b; England, 2010). Further, both Ebukanson & Kinghorn (1986a) and Holloway (1986) suggested that the base of the Lias section has reached early maturity in the Winterborne Kingston Trough.

Basin modelling suggests the onset of hydrocarbon expulsion from the Lower Lias occurred around 150 Ma (England, 2010), consistent with observations from the Mupe Bay palaeoseep (Selley, 1992),

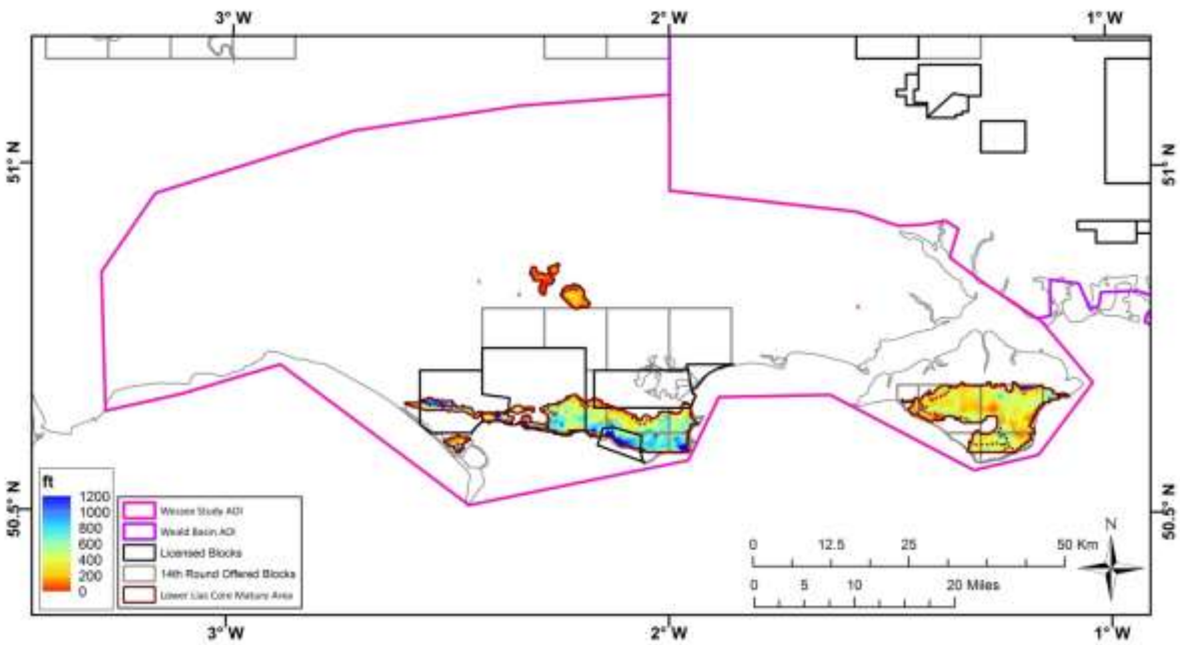


Figure 39. Gross thickness of the Lower Lias within the area it has been predicted to have reached oil maturity, and below a present-day burial depth of c. 3950 ft (1200 m). Dashed line is the extent of the predicted mature area below a present-day burial depth of c. 5000 ft (1500 m). Removing the top-down truncation does not alter the predicted mature area or gross rock volume significantly.

with peak generation in the Mid to Late Cretaceous (Ebukanson & Kinghorn, 1986a; Penn et al., 1987; Underhill & Stoneley, 1998). In the Jurassic depocentre south of the Purbeck-Isle of Wight Disturbance, the Lower Lias attained its maximum burial depth prior to the Miocene tectonic inversion (Ebukanson & Kinghorn, 1986b; Bray et al., 1998), whilst north of the fault system, maximum burial occurred in the Early Cretaceous, prior to Aptian-Albian uplift (Ebukanson & Kinghorn, 1986a; Bray et al., 1998). Source rock maturation ceased in these respective areas coincident with the major uplift (Underhill & Stoneley, 1998).

7.2 Data Quality

Due to the lack of cored shales, often the geochemical analyses has been completed on cuttings which limits sample quality due to caving and mixing of lithologies. In addition, the age of some of the wells means there may have been a small reduction of TOC through oxidation and of S1 by evaporative loss over time. There is also a risk of contamination in the samples from the West Compton 1, Portland 1 and Down Barn 1 wells as they were drilled with oil-based mud.

The measures of maturity – vitrinite reflectance and T_{max} data – used in this study both potentially have a high degree of uncertainty. For a single sample depth with multiple data points, a wide range of vitrinite reflectance values are often reported. For example, in the Cranborne 1 well at a depth of 1719 ft (524 m) MD in the Kimmeridge Clay Formation, the vitrinite reflectance values range from 0.38-1.1% with an average of 0.74%; this is an over-estimate of the maturity at this location. Figure 40 shows all of the vitrinite reflectance data points in the Wessex area available to this study, plotted against present-day burial depth. Vitrinite enhancement (or suppression) is indicated by a wide spread of data points at a given burial depth. Enhancement (as per the Cranborne 1 example) is likely due to a large amount of reworked vitrinite within the samples. Suppression, on the other hand, occurs in the presence of large amounts of amorphous organic matter, or in the presence of significant caved particles (Peters & Cassa, 1994). England (2010) suggests that the vitrinite reflectance values in the Peterborough Member of the Oxford Clay are suppressed.

T_{max} data are less reliable when TOC is low or when S2 < 0.5 mgHC/gRock, or in cases of severe recycling of organic material (Smith et al., 2014). England (2010) documented the suppression of T_{max} within the more organic-rich sediments of the Lower Lias. An estimated vitrinite reflectance can be derived from T_{max} data, using a relationship derived originally by Jarvie et al. (2001) for the Barnett Shale. A plot of measured versus calculated vitrinite reflectance (Figure 41) shows considerable scatter around the early maturity values, although there is a more defined trend at higher maturities. The calculated vitrinite reflectance is plotted alongside cleaned measured vitrinite reflectance data (Figure 40), with the T_{max} data largely predicting higher maturity for a given burial depth than the measured data. Butler & Pullan (1990) determined that vitrinite reflectance data in the Weald Basin gave low estimates of the maturity, and it is possible that this trend continues into the Wessex area.

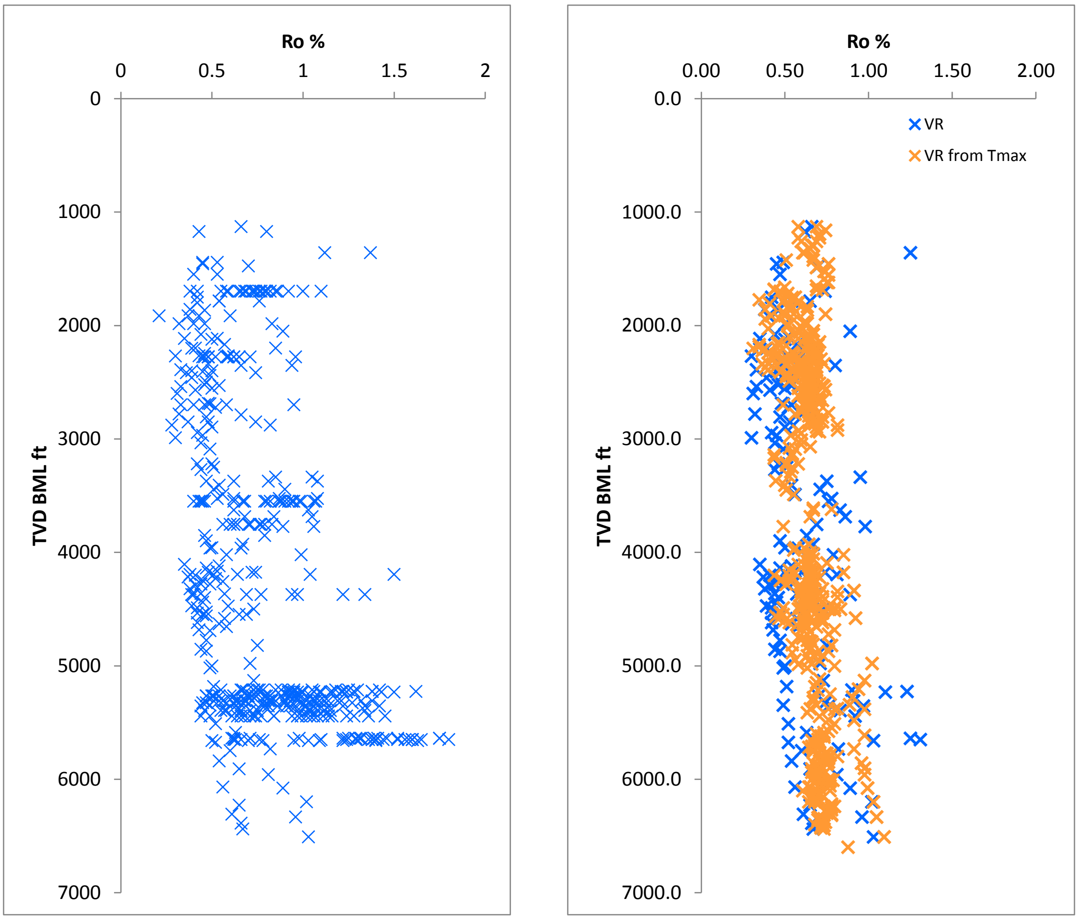


Figure 40. (Left) All vitrinite reflectance data points in the Wessex area available to this study, plotted against burial depth. (Right) Measured vitrinite reflectance (averaged where multiple values exist for a single depth within a well) in blue and vitrinite reflectance calculated from T_{max} in orange, plotted against burial depth.

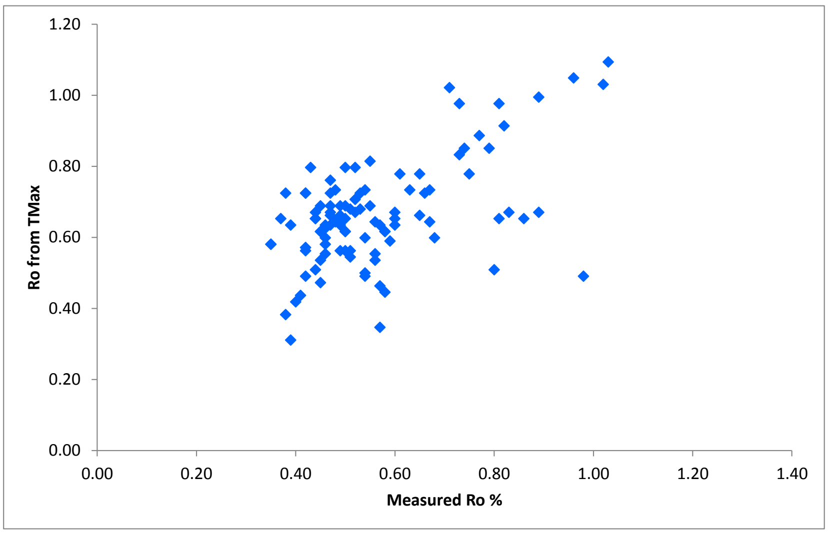


Figure 41. Vitrinite reflectance derived from T_{max} versus measured vitrinite reflectance data for the Wessex area.

7.3 Source of Conventional Discoveries

The oils discovered in the Wessex area are all thought to have the same source, as compositional variations can largely be attributed to maturity, migration and/or biodegradation effects (England, 2010). The carbon isotope ratios of the oils at Wytch Farm and Kimmeridge range from -28.5 to -29.8‰, so the source rock is interpreted to have been deposited in a restricted marine environment (Colter & Havard, 1981; Ebukanson & Kinghorn, 1986b). Oil APIs range from 35° at Wytch Farm to 45° at Kimmeridge (Ebukanson & Kinghorn, 1986b; Gluyas et al., 2003). The lighter gravity of the Kimmeridge oil is thought to be either because it was expelled from more mature source rocks or because some fractionation occurred during migration (Evans et al., 1998). A full range of n-alkanes in the C15-C30 oils are present in the oils at Wytch Farm and Kimmeridge, indicating the oils have not experienced significant thermal alteration or biodegradation (Ebukanson & Kinghorn, 1986b), although minor biodegradation is observed in samples from fields to the west of these (England, 2010).

There is a good correlation between the oils and Lower Lias source rock in the Chickerell 1 well, although the source rock is immature at the well location (Forbes, 1987). The oils in the Wessex area have been determined to be sourced from the Lower Lias on the southern side of the Purbeck-Isle of Wight Disturbance, based on maturity, the n-alkane distribution, alkane ratios, stable carbon isotopes and hydrogen isotope ratios (Ebukanson & Kinghorn, 1986b). The Lower Lias sediments around Wytch Farm did not reach sufficient maturity, even at maximum burial, for hydrocarbon generation (Bray et al., 1998), but the early history of movement on the Purbeck-Isle of Wight Disturbance preserved a full Jurassic section on the southern side of the fault system which, along with the Cretaceous Wealden and Lower Greensand formations, buried the Lias sediments in this region deep enough to reach maturity (Colter & Havard, 1981; Scott & Colter, 1987). Penn et al. (1987) estimated that in the Cretaceous, the Lias within the Channel Basin was approximately 3300 ft (1000 m) deeper than the Sherwood Sandstone Formation at Wytch Farm.

There has been some debate in the literature regarding the difference between the estimated trap volume and produced volume at the Kimmeridge Oilfield (see section 2.3.1). Fraser & Aryanto (in prep) have proposed that the Kimmeridge reservoir (the Cornbrash Fm, Great Oolite Group), which is underpressured, is being actively recharged from the Oxford Clay source rock directly above it through downward migration. 1D basin modelling at Kimmeridge 5 (England, 2010; Fraser & Aryanto, in prep) places the Oxford Clay in the early oil mature window. Although it may not have reached sufficient maturity onshore for hydrocarbon expulsion to occur (England, 2010), the maturity of the Oxford Clay is expected to increase offshore into the Channel Basin depocentre. An oil-source rock correlation for the Wessex area concluded, based on the biomarker data, that the Oxford Clay is not a source of the hydrocarbons in the area (England, 2010). However, England (2010) did observe compositional differences in DST oil samples from Kimmeridge 1 and Wytch Farm, but attributed the composition at Kimmeridge to be a consequence of the mixing of a low maturity biodegraded oil with a subsequent condensate charge. Biomarker analyses of more recent oil samples may help to assess the contribution of an Oxford Clay source to the Kimmeridge Oilfield.

8 Estimation of Oil-in-Place

The methodologies used to assess in-place and recoverable resources in shale gas basins are summarised in Andrews (2013) and for shale oil in Andrews (2014). In the absence of production data, a 'bottom-up' approach is used in this study, consistent with the Weald study. For the calculation on the in-place shale oil resource, an estimation of the in-situ free oil content of each shale unit is required.

S1, a measurement of the amount of free hydrocarbons already generated in the source rock (and the free oil component that can potentially be extracted after fracture stimulation), can be determined through Rock-Eval analysis. This measurement can then be up-scaled to calculate oil-in-place for a given formation (Downey et al., 2011). It is reasonable to model two end members: 1) assuming the measured S1 is bound within kerogen if the oil saturation index is less than 100 or 2) assuming the sorbed oil is restricted to S2 and that all the S1 is free oil.

As with the Weald Basin, the paucity of data available for the Wessex study area precludes a full understanding of free oil contents. Ideally S1 values should be obtained from whole core at a sampling density of one per foot (Downey et al., 2011). However, most data available for this study is from analysis performed on cuttings. Future analysis may be improved by a new pyrolysis program which separates the S1 peak into two sub-peaks based on the thermal properties and chemical composition (Romero-Sarmiento et al., 2015; Romero-Sarmiento et al., 2016), but will continue to be limited by the lack of cored shale intervals available for the Wessex area.

The oil saturation index (OSI) is a measure of the free oil from Rock-Eval measured S1 in relation to TOC:

$$OSI = (S1*100)/TOC$$

When the OSI exceeds the sorption potential of oil in kerogen, potentially producible oil is likely to be present in the pore space. Experimentation suggests that the sorption potential for oil in kerogen is approximately 100 mg oil/g kerogen so OSI values above 100 are taken to indicate the presence of potentially producible oil (Jarvie & Baker, 1984; Sandvik et al., 1992; Jarvie 2012). The minimum case for the Monte Carlo simulation of oil-in-place volumes is where the free oil component of S1 is zero (i.e. the oil is bound within the kerogen and not likely to be producible).

The correction of S1 for 'evaporative loss' is an important factor in converting the present-day S1 figures into data that are likely to pertain to the shales under reservoir conditions at depth. The loss of light oil (up to C^{10}) from samples between down-hole collection and its analysis (often decades later) is often estimated to be 35% (a correction factor of 1.33), but is highly dependent on organic richness, lithofacies, oil type, sample type, storage conditions and method of preservation (Jarvie, 2012; Jarvie, 2014; Jiang et al., 2016); correction factors over 5.0 may be necessary (Jarvie et al., 2012). Additionally, Michael et al. (2013) demonstrated that oil gravity has a major control on evaporative loss. Studies have indicated that evaporative loss of light hydrocarbons from cuttings could happen very quickly (matter of days) after sample preparation (Jarvie & Baker, 1984; Jiang et al., 2016). Jarvie (2014) states that old cuttings yield, at best, the minimum S1 oil values; this is an important consideration for this study given the age of many of the wells.

The Wessex area data indicate the presence of producible oil, with a large number of samples having an OSI > 100 mgHC/gTOC, particularly within the Lower Lias (Figure 42a). The average OSI for the organic-rich (TOC > 2%) shales of the Jurassic in the Wessex area is 65 mHC/gTOC. The Oxford Clay, Upper Lias and Middle Lias all have OSI < 100 mgHC/gTOC (even after correcting for evaporative loss), suggesting the free oil component in these formations is negligible. This is in agreement with the predicted immaturity of these formations surrounding the well locations for which S1 data is

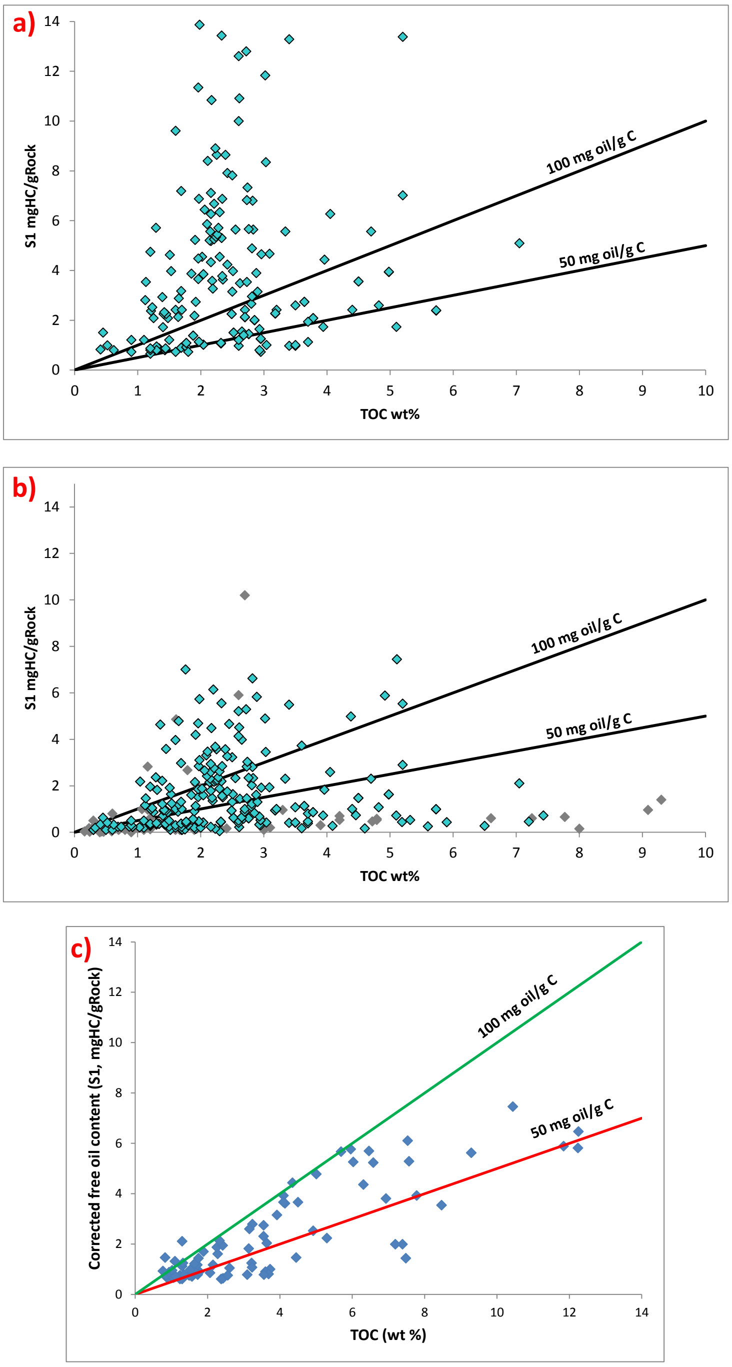


Figure 42. a) S1 vs TOC for the Wessex area. Blue = Lower Lias, grey = all other data. b) S1 corrected for evaporative loss vs TOC for the Lower Lias in the Wessex area (not including data from West Compton 1 – see text for discussion). c) Corrected S1 vs TOC for all Jurassic shales in the Weald Basin, from Andrews (2014).

available (for these intervals). A maximum OSI of 378 mgHC/gTOC is found in one sample of an oil shale from outcrop in the Kimmeridge Clay, but is not reflective of its maturity.

The Lower Lias has a maximum of 279 mgHC/gTOC found in one sample from the Blue Lias interval, although all shale intervals in the Lower Lias have samples with OSI > 100 mgHC/gTOC in the Portland 1 stratigraphic test, and the Down Barn 1 and West Compton 1 hydrocarbon wells. However, the validity of this data is questionable, particularly for the West Compton 1 well which is located north of the Purbeck-Isle of Wight Disturbance, and away from the 'core mature area' for the Lower Lias. The immaturity of the Lower Lias interval at West Compton 1 is supported by the lack of hydrocarbon shows within the well, with only traces of methane and ethane gas reported. Anomalously high S1 values may be due to the presence of migrated oil or contamination by drilling mud (Peters & Cassa, 1994). All three wells were drilled with oil-based mud so this may, at least in part, explain the anomalous S1 measurements. Jiang et al. (2016) found that invasion of drilling mud within shale cores from the Duvernay and Nordegg formations of the Western Canada Sedimentary Basin may account for over 20% of the S1 peak in some samples. However, Portland 1 and Down Barn 1 are both located in the area where it is thought the Lower Lias has reached maturity for oil generation so elevated S1 peaks would be anticipated.

The corrected S1 versus TOC for the Lower Lias (not including data from West Compton) is shown in Figure 42b. For the Weald, even when the S1 values are corrected with an evaporative factor of 2.42 (the P10 case used in Appendix A), the average oil saturation index is well below the 'producible oil' value, even in extremely organic-rich shales (Figure 42c; Andrews, 2014); the correlation between TOC and S1 suggests that most of the 'free oil' is bound within the kerogen. The average present-day S1 values within the 'core mature area' of the Wessex area for organic-rich shales (TOC > 2%) were used as the P50 input in the Monte-Carlo simulation (Table 3).

Source rock unit	Average present-day S1 in all samples in study area (mgHC/gRock)	Average present-day S1 in organic-rich shales in the 'core mature area' (mgHC/gRock)	Estimated average original S1 (mgHC/gRock)	Average oil yield using Jarvie et al (2007) bbl/acre-ft	Average oil yield using Michael et al (2013) bbl/acre-ft
Kimmeridge Clay	2.36	2.93	5.86	128.3	151.4
Oxford Clay	0.35	0.13*	0.26	5.7	6.7
Upper Lias	0.25	0.2*	0.40	8.8	10.3
Middle Lias	0.72	0.79*	1.58	34.6	40.8
Lower Lias	1.55	1.87	3.74	81.9	96.6
Kimmeridge Clay	1.40	1.21	2.42	53.0	62.6
Oxford Clay	1.10	1.16	2.32	50.8	60.0
Upper Lias	1.00	1.07	2.14	46.8	55.4
Middle Lias	0.90	0.88	1.76	38.5	45.5
Lower Lias	1.00	0.28	0.56	12.3	14.5

*Table 3. S1 values used for the Monte Carlo simulation (top = this study, bottom = Weald study (Andrews, 2014)). *denotes average values taken from all data, due to limited data for samples with TOC > 2%.*

The gross mature rock volumes for the units of interest were determined using depth cut-offs equivalent to oil maturity of R_o = 0.6% and R_o = 1.1%, after Charpentier & Cook (2011). Type II and III kerogens (present in the Wessex area) may start generating oil at values of R_o > 0.5% (Tissot & Welte, 1978), but a higher cut-off of R_o = 0.6% is used in this study for consistency with previous shale oil-in-place evaluations (Andrews, 2014; Monaghan, 2014) and gives a reasonable match to the data, when corrected for maximum burial (Figure 43). The equivalent depths for R_o = 0.6% are 7000-8000 ft (2130-2440 m) and for R_o = 1.1% are 12000-13000 ft (3660-3990 m). These depth-maturity surfaces are a regional simplification and as such do not fully account for the complex variation particularly in areas which are highly faulted; 3D basin modelling incorporating the full burial and erosion history would be needed to resolve maturity on a more local scale.

The gross rock volumes were then upwards truncated at two alternative levels below the surface – firstly at a depth of c. 3950 ft (1200 m), which is the minimum burial depth below protected areas defined in the Infrastructure Act 2015, and secondly at a depth of c. 5000 ft (1500 m) as proposed by Charpentier & Cook (2011). Net mature shale volumes were then determined from the estimated percentage of shale with TOC > 2% within the interval (or with TOC > 1% for the Upper and Middle Lias due to lack of data).

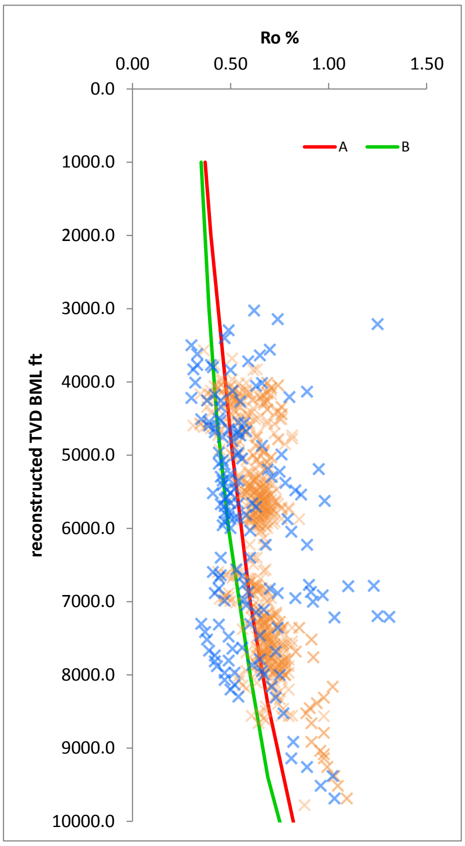


Figure 43. Measured vitrinite reflectance (blue crosses) and vitrinite reflectance derived from T_{max} (orange crosses) for the Wessex area, plotted against maximum burial depth. The two trend lines were derived from maturity data in the Weald Basin (Andrews, 2014), but show a good fit to the maturity data from the Wessex area. Trend A (red line) has R_o = 0.6% at 7000 ft (2130 m) and trend B (green line) has R_o = 0.6% at 8000 ft (2440 m).

OGA (formerly DECC) have not previously estimated the shale oil-in-place volumes for the Wessex area, and no unconventional drilling has taken place. There are no published estimates of shale oil-in-place resource for the Wessex area. The U.S. EIA evaluated the technically recoverable shale resource for the Lias of the Wessex and Weald study areas collectively in 2013, reporting an unrisked oil-in-place volume of 54 billion bbl (USEIA, 2013). England (2010) estimated up to 913 million m^3 of oil and 242 billion m^3 of gas have been expelled from the Lower Lias in the Portland-Wight sub basin kitchen (including offshore) from a volumetric calculation from basin modelling. The methodology applied in this study tends to underestimate oil-in-place volumes compared with using a basin modelling approach (Al Fraser, personal communication).

The results of the two maturity scenarios, including the cut-offs described above, are presented in Table 4. This study estimates that the total oil-in-place resource for the Jurassic shales in the Wessex study area is 0.2-1.1-2.8 billion bbl (32-149-378 million tonnes) (P90-P50-P10). A range of values is presented based on a Monte Carlo analysis to give a measure of uncertainty in the resource estimation (Figure 44). Significant volumes of shale gas are not thought to be present within the Jurassic shales of the study area. Even when combined with the oil-in-place volumes determined for the Weald, which had a P10 value of 8.6 billion bbl for all shale intervals (Andrews, 2014), the volume predicted from this study is considerably smaller than that predicted by the U.S. EIA. At least some of the discrepancy is due to the difference in methodology used for the volumetric determination and differences in input parameters.

	Total oil in-place estimates (billion bbl)		**Total oil in-place estimates (million tonnes)**	
	With top of oil window at 7000 ft (2130 m) maximum burial depth	**With top of oil window at 8000 ft (2440 m) maximum burial depth**	**With top of oil window at 7000 ft (2130 m) maximum burial depth**	**With top of oil window at 8000 ft (2440 m) maximum burial depth**
Kimmeridge Clay	0.00 – 0.01 – 0.04	0.00 – 0.00 – 0.00	0.24 – 1.50 – 4.77	0.00 – 0.00 – 0.00
Oxford Clay	0.00 – 0.01 – 0.03	0.00 – 0.00 – 0.00	0.20 – 1.17 – 3.52	0.01 – 0.06 – 0.19
Upper Lias	0.00 – 0.00 – 0.01	0.00 – 0.00 – 0.00	0.12 – 0.39 – 1.00	0.03 – 0.09 – 0.20
Middle Lias	0.01 – 0.03 – 0.08	0.00 – 0.01 – 0.02	1.31 – 4.38 – 11.53	0.38 – 1.21 – 2.93
Lower Lias	0.52 – 1.34 – 2.70	0.22 – 0.55 – 1.08	71.5 – 182.8 – 368.4	30.0 – 75.2 – 147.3
All Jurassic clay units	**0.2 – 1.1 – 2.8**		**32 – 149 - 378**	

Table 4. Estimates of the total potential in-place shale oil resource for the Jurassic in the Wessex study area. P90, P50 and P10 values are given for each unit, where P10 is the most optimistic scenario. This estimate only covers unconventional oil, and excludes volumes in potential tight conventional or hybrid plays.

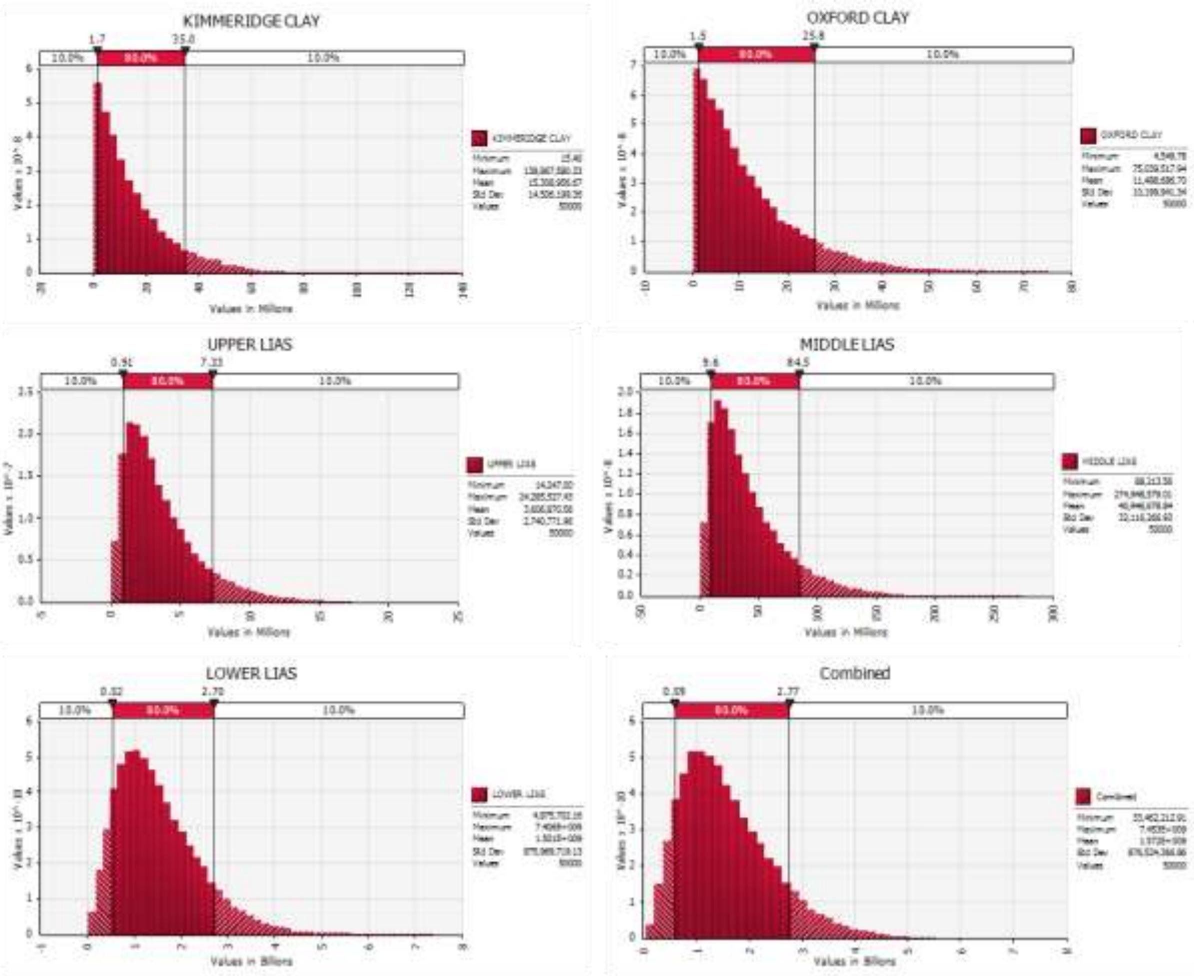


Figure 44. Probabilistic distribution and cumulative probability curve representing the result of a Monte Carlo analysis for the in-place resource estimation of shale oil for all Jurassic shale intervals, with a maturity cut-off of 2130 m.

9 Synthesis and Conclusions

This study presents a preliminary estimate of oil-in-place resources for the Jurassic shales of the Wessex area, determined following the methodology present in Andrews (2014). Estimated oil-in-place volumes for the five intervals considered in this study range from 0.2 – 1.1 – 2.8 billion bbl (32 – 149 – 378 million tonnes) (P90 – P50 – P10). Volumes associated with tight conventional and hybrid plays are not included in the calculation. No significant shale gas resource is recognised with the study area.

The Lower Lias appears to be the only interval with shale oil potential, albeit with relatively small volumes in a localised area largely south of the Purbeck-Isle of Wight Disturbance, where a full Jurassic section is preserved (Figure 45, 46, 47). Major erosion at the Base Greensand Unconformity

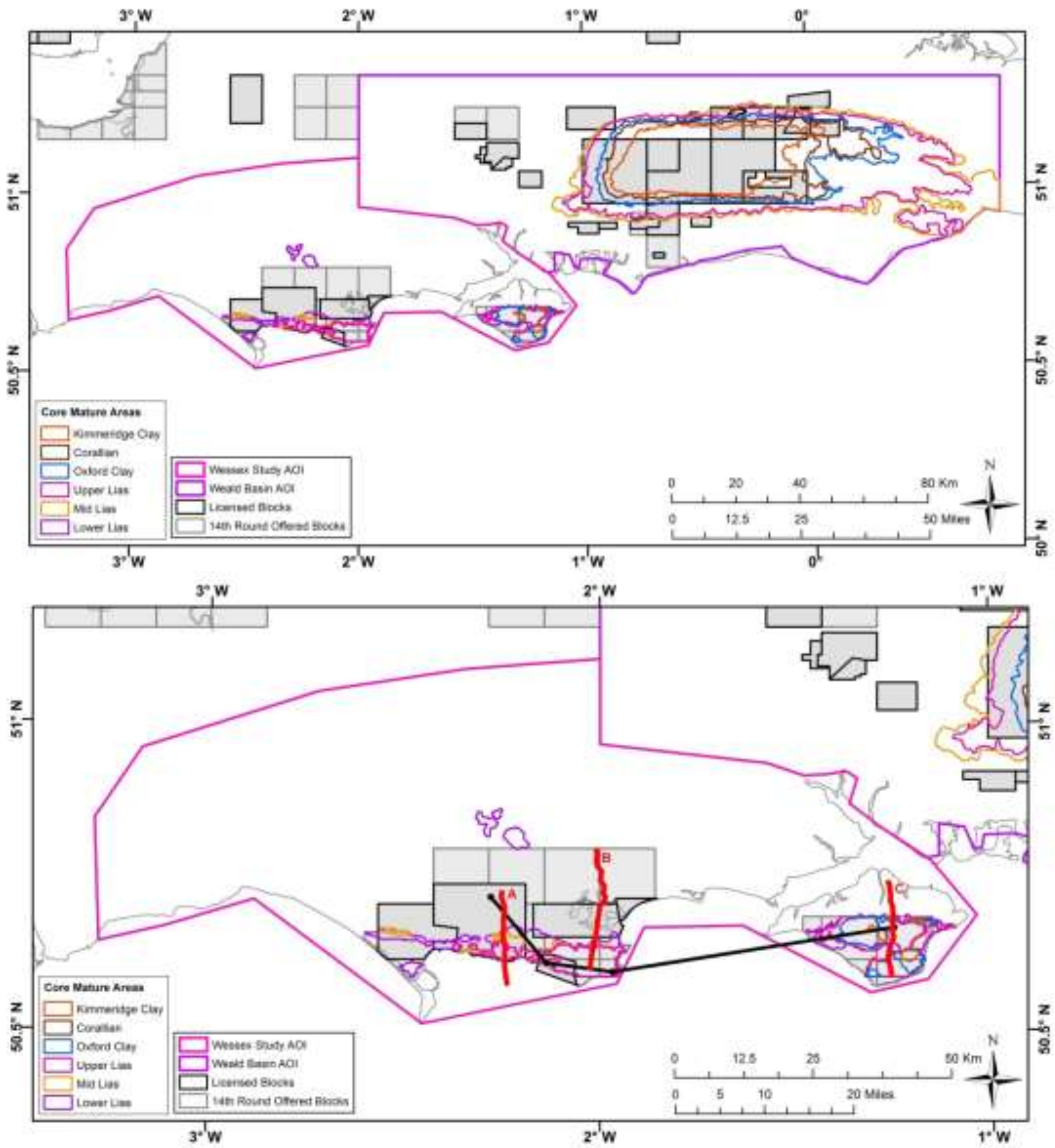


Figure 45. (Top) Core mature areas for the Jurassic shale intervals of the Weald and Wessex areas. (Bottom) Zoom-in of Wessex area. Location of the seismic sections in Figure 46 (red lines) and the well correlation panel in Figure 47 (black line) also shown.

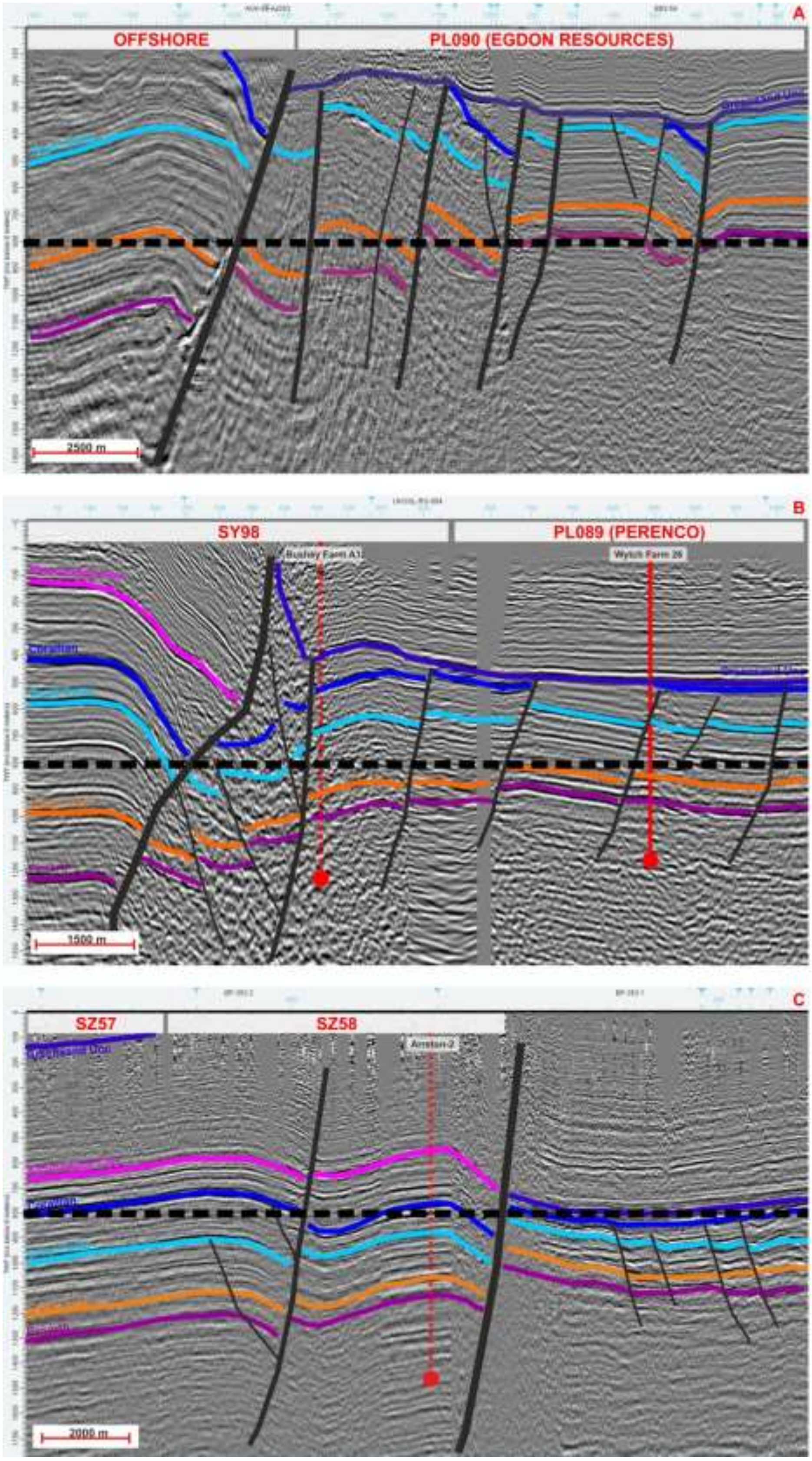


Figure 46. Interpretation of three north-south seismic lines with horizons mapped in this study. (A) Line AUK-94-AJ053 & B92-54, (B) UKOGL-RG-004, (C) BP-353 1 & BP-353 2. Dashed black line is approximately 1200 m (c. 3950 ft) below surface. Seismic data provided by UKOGL. Location of lines shown in Figure 45.

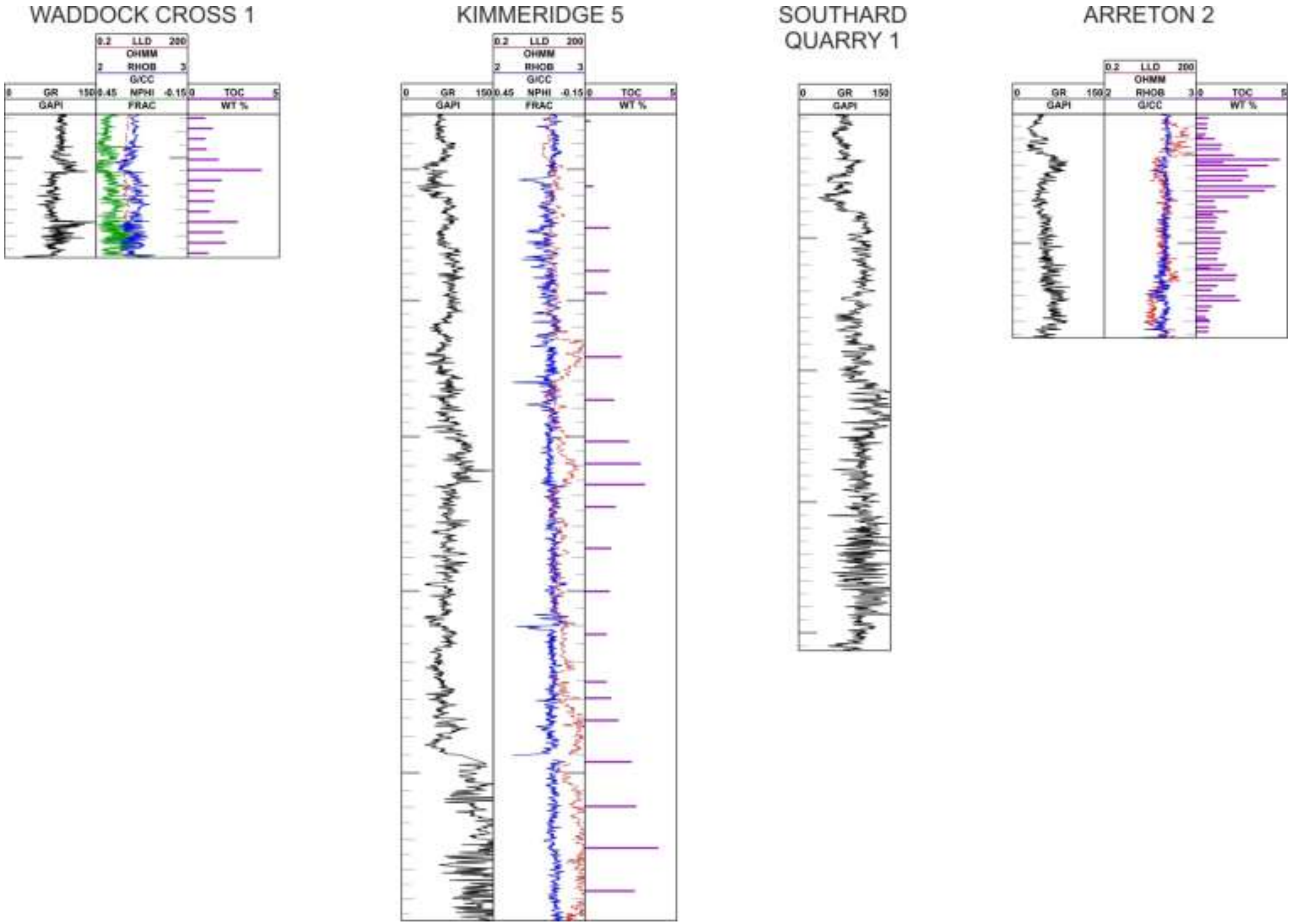


Figure 47. Correlation of the Lower Lias section demonstrating the significant increase in thickness of this interval south of the Purbeck-Isle of Wight Disturbance. Location of wells shown in Figure 45.

(to the north of the Purbeck Isle of Wight Disturbance) and in the Tertiary has limited the present-day extent and maximum burial depth of the Oxford Clay and Kimmeridge Clay (Figure 48). Within the study area, oils from the four oil fields (including Wytch Farm, the largest onshore oil field in Europe) and from shows and seeps have all been correlated to a Lower Lias source, with the kitchen to the south of the Purbeck-Isle of Wight Disturbance, demonstrating the presence of a mature oil-prone source within this interval.

Much of the area considered potentially prospective is already licensed for exploration, or has been offered for award following the 14th onshore bid round (Figure 49). The oil-in-place volume is limited in part due to the requirement of a minimum depth of 1200 m below surface for hydraulic fracturing in protected areas, which cover a large part of the 'core mature area' (Figure 50). The interpreted seismic sections (Figure 46) and cross-sections (Figure 48) show how this cut-off intersects the five shale intervals evaluated in this study. The predicted oil-in-place volumes without this restriction would not increase substantially to north of the Purbeck-Isle of Wight Disturbance (due to insufficient maximum burial depth to attain oil maturity), but may impact the volumes to the south. Estimates of recoverable shale oil volumes are not calculated as there have been no production tests for the Jurassic shales of the Wessex area to provide the required data.

Figure 48 (Next page). Generalised cross-section through the Wessex and Weald study areas showing the relationship between the present-day depth of the shale intervals with the oil window and top-down truncation.

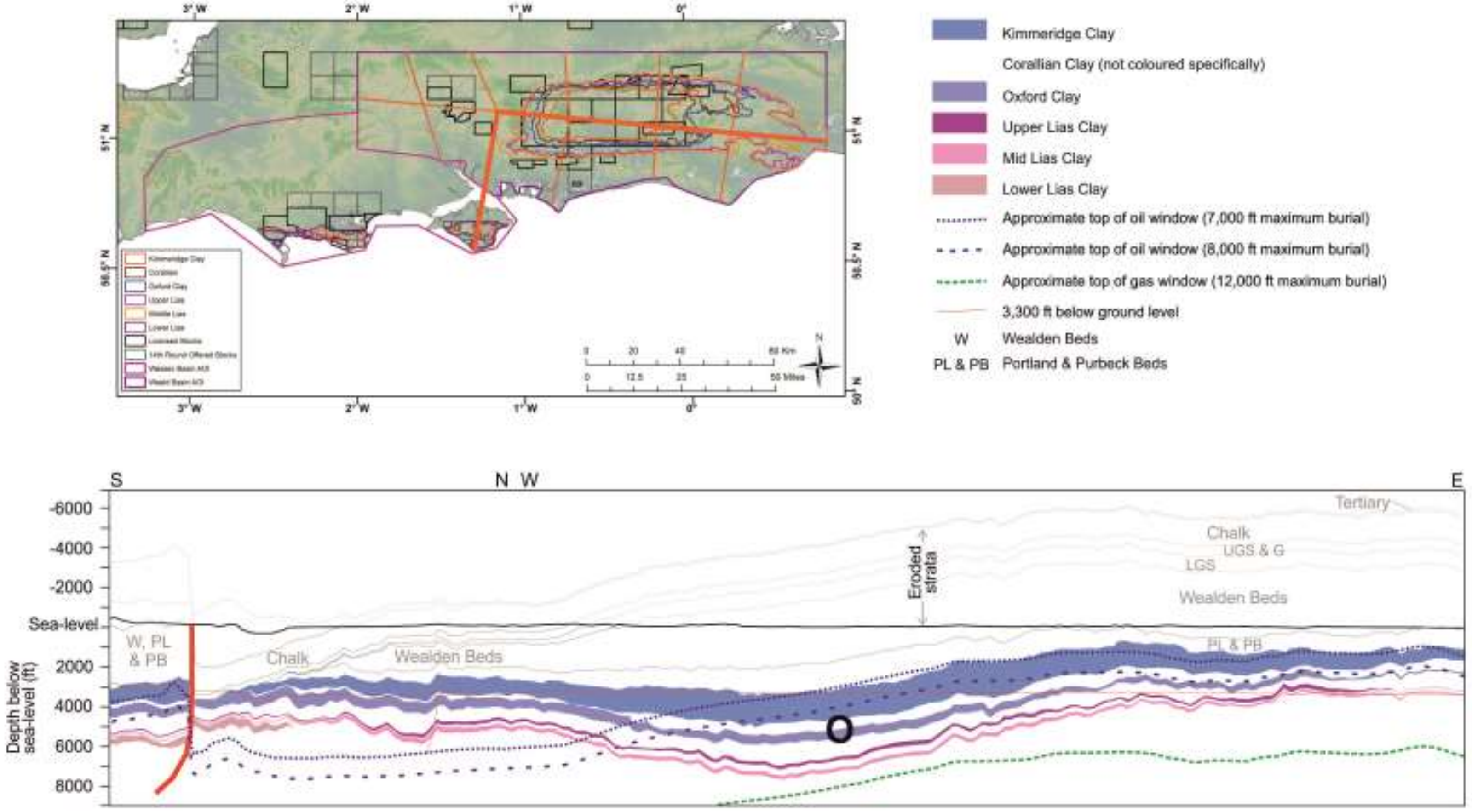

3° W
2° W
1° W
0°
51° N
50.5° N
50° N
Kimmeridge Clay
Corallian Clay (not coloured specifically)
Oxford Clay
Upper Lias Clay
Mid Lias Clay
Lower Lias Clay
Approximate top of oil window (7,000 ft maximum burial)
Approximate top of oil window (8,000 ft maximum burial)
Approximate top of gas window (12,000 ft maximum burial)
3,300 ft below ground level
W
Wealden Beds
PL & PB
Portland & Purbeck Beds
S
N W
E
-6000
-4000
-2000
Sea-level
2000
4000
6000
8000
Depth below sea-level (ft)
W, PL & PB
Chalk
Wealden Beds
Eroded strata
Tertiary
UGS & G
LGS
PL & PB

Figure 49. Core mature areas with a 1200 m (c. 3950 ft) below ground level cut-off applied for each shale interval evaluated in this study. Contains Ordnance Survey data © Crown copyright and database right (2016).

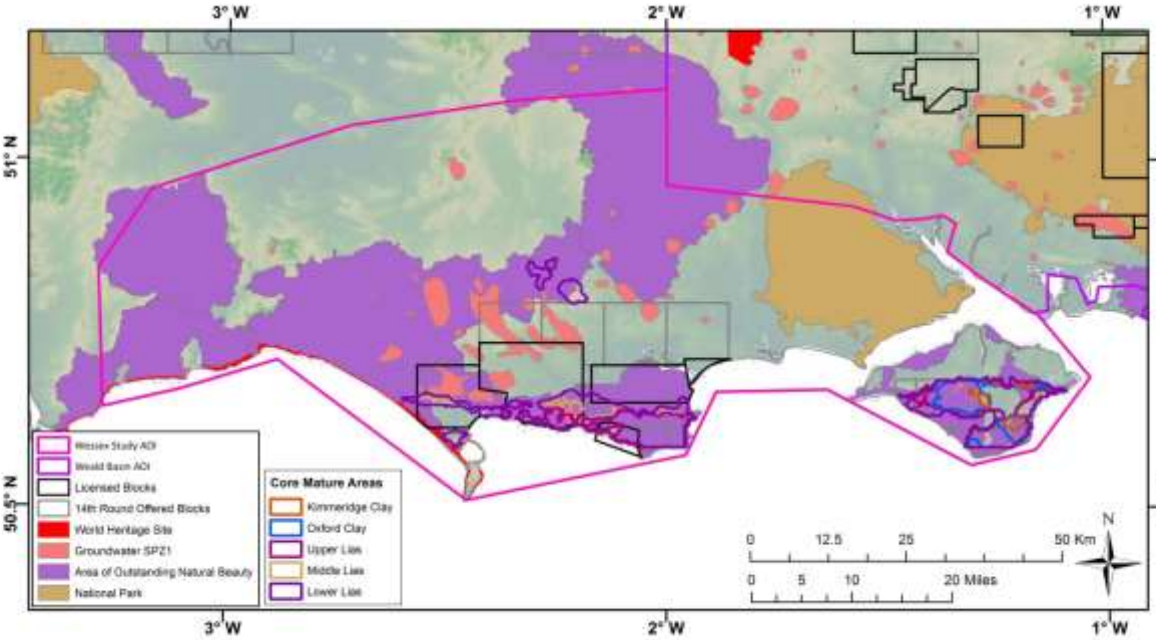


Figure 50. Core mature areas with a 1200 m (c. 3950 ft) below ground level cut-off applied for each shale interval evaluated in this study with protected areas as defined in the Infrastructure Act 2015. Background is hill-shaded topography.

10 Glossary

Unit/abbreviation	**Full name**
API	standard (American Petroleum Institute) measure of natural gamma radiation typically in a borehole, or of oil gravity
bbl	barrel (of oil)
bcf	billion (10^9) cubic feet
ft	foot/feet
ft^3 or scf	(standard) cubic foot/feet
GIIP	gas initially in place
HI	hydrogen index = [S2*100]/TOC. It is a measure of the ratio of H to C.
HI_o	original hydrogen index
HI_{pd}	present-day hydrogen index
km	kilometre(s)
km^2	square kilometre(s)
m	metre(s) (1 m = 3.28084 ft)
m^3	cubic metre(s) (1 m^3 = 35.31467 ft^3)
Ma	million years before present
$mile^2m$	a volume occupying an area of 1 square mile with a thickness of 1 metre (1 $mile^2m$ = 2,589,988 m^3)
mmbo	million (10^6) barrels of oil
mmcf	million (10^6) cubic feet of gas
OI	oxygen index = [S3*100]/TOC. It is a measure of the ratio of O to C.
OIIP	oil initially in place
R_o	vitrinite reflectance (in oil) (%)
S1	the amount of hydrocarbons volatalised during the first stage of Rock-Eval pyrolysis (in milligrams of hydrocarbon per gram of rock, mgHC/gRock)
S2	the amount of hydrocarbons generated through thermal cracking of non-volatile organic matter during Rock-Eval pyrolysis (mgHC/gRock)
ss	sub-sea level
STOIIP	stock-tank oil initially in place (at surface temperature and pressure)
tcf	trillion (10^{12}) cubic feet
tcm	trillion (10^{12}) cubic metres
T_{max}	the temperature (°C) at which the maximum release of hydrocarbons from cracking of kerogen occurs during Rock-Eval pyrolysis (top of S2 peak). It is a measure of maturity.
TOC	total weight percent of organic carbon (% or wt%)
$\delta^{13}C$	an isotopic signature; a measure of the ratio of carbon stable isotopes ^{13}C : ^{12}C

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