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A Geological Evaluation of Jurassic Shale Oil Plays in Southern England.

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Summary

Recent drilling results have highlighted the potential for the development of Jurassic source rocks of southern England as a shale oil play. Sustained natural oil flows have been reported by UKOG (2015) from the tight, Lower Kimmeridge limestones in the Horse Hill-1 well. According to the operator, this discovery is naturally fractured and can be produced without hydraulic fracture stimulation.

The occurrence of shale gas in the UK has been known of since the nineteenth century, but development of this resource attracted very little interest until recent years (Selley, 2012; Andrews, 2014). The first exploration well in the United Kingdom that was specifically drilled for shale gas was Preese Hall-1 in northwest England in 2010. This well was hydraulically fractured in the Bowland Shale, but operations were suspended following reports of repeated seismicity caused by the injection of fluid during hydraulic fracture treatment (Green et al., 2012). Assessments of the Carboniferous shale gas potential of northern England and Scotland and of the Jurassic shale oil potential of southern England have been published by the BGS/DECC (Andrews, 2013, 2014; Monaghan, 2014). These studies listed the various criteria for evaluation of shale plays and provided broad descriptions and resource estimates for the Carboniferous and Jurassic shale plays in the United Kingdom.

This paper presents the results of an integrated petrophysical and geological assessment of the Jurassic sequence in the south of England. The study area stretched from the Weald and Vale of Pewsey Basins in the north to the onshore parts of the Portland–Isle of Wight Basin on the Dorset coast in the south (Figure 1). The evaluation focused on the Kimmeridge Clay Formation, the Oxford Clay Formation, the Downcliff Clay Member, Charmouth Mudstone Formation and the Blue Lias Formation.

The stratigraphic framework used for the study is based on the extrapolation of the well-known outcrop stratigraphy on the Dorset Coast to the study wells. Wireline log data and new sedimentological core description results were used to constrain facies mapping. Detailed sedimentological core description was carried out on three of the twelve study wells. From the trends observed in the wireline log data, the lithofacies and level of oxygenation, 14 initial facies associations were assigned over the cored intervals ranging from restricted shallow marine through shoreface to shelfal environments. These facies associations were grouped into seven combined facies associations which were used as input for the electrofacies analysis and facilitated the extrapolation of facies to intervals that lacked core data Additionally this workflow provided a useful template for estimating Total Organic Carbon TOC from logs using the CARBOLOG® equation and this resulted in a significant improvement in the correlation between the laboratory measured TOC values and the log-based TOC estimates. Results from the mineralogical analysis of core and cutting samples were utilised to calibrate and improve the petrophysical interpretations and to assess the elastic properties of the rocks in the intervals of interest. The petrophysical data, elastic properties and the facies interpretations were used to evaluate and map the development potential of the Jurassic source rock intervals as unconventional reservoirs.

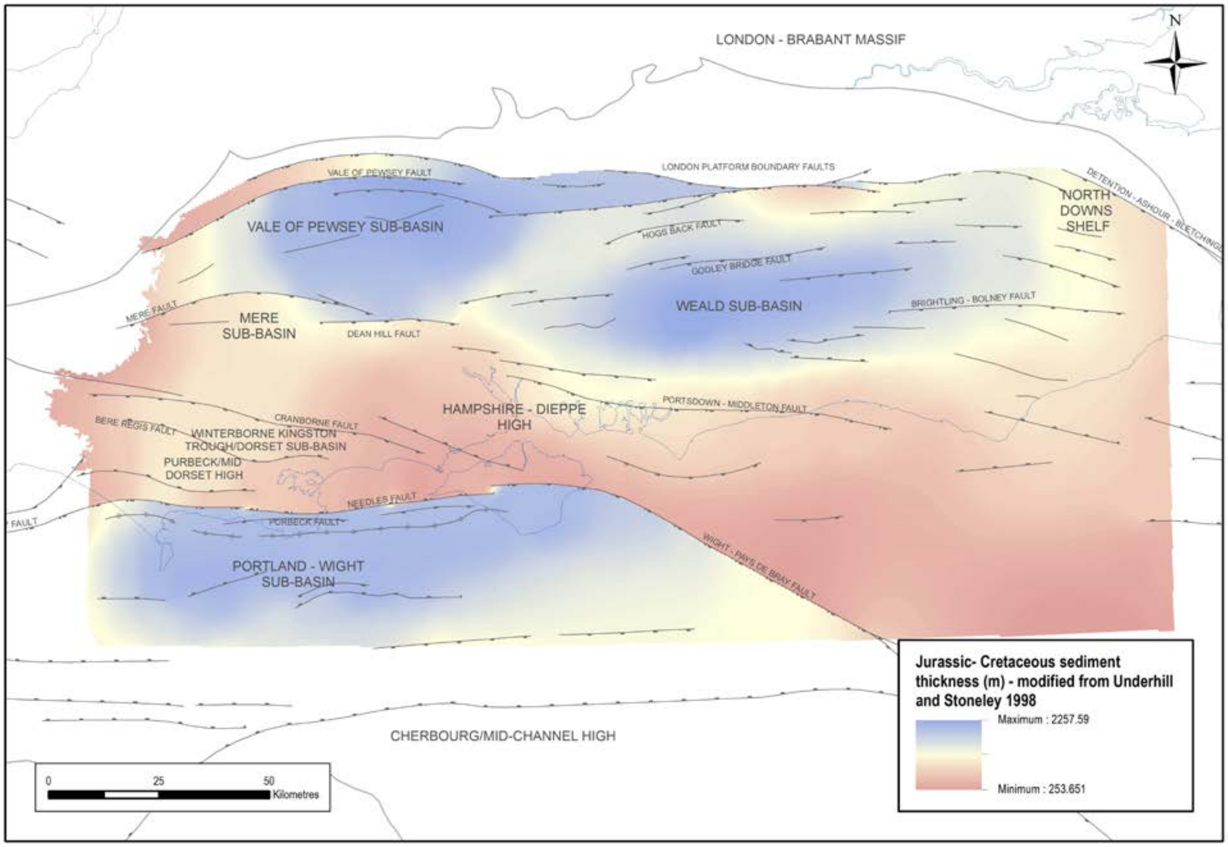

Figure 1: Location map of study area showing the main structural elements and sub-basins

An extensive geochemical database was combined with new analyses to characterise the source rocks. This data was integrated into 1-D basin models to identify and map effective source kitchen areas. The organic matter in the analysed interval is dominated by Type II kerogen, with significant input of Type III kerogen towards the London-Brabant Massif. The Upper Jurassic Kimmeridge Clay and the Oxford Clay are within the early oil window, while the Lower Jurassic Downcliff Clay Member, Charmouth Mudstone Formation and the Blue Lias Formation have reached peak oil maturity in the deeper parts of the Weald Basin. The source richness and kerogen types were combined with the maturity maps to create generation risk maps.

The risk for ground water contamination from hydraulic fracturing was also evaluated. These results were combined with the reservoir and generation risk maps to produce common risk segment maps in order to identify the sweet spots in the study area.

Regional geology

The earliest natural gas production in the Weald Sub-basin was from Heathfield-1 (at depths of about 100m). The well was drilled in 1896 by the London, Brighton and South Coast Railway Company (Andrews, 2014; Selley, 2012). The gas production rate reached up to 1000 SCF/day (Hawkes et al., 1998). The study area contains the Wytch Farm Field which is the largest onshore field in the UK, producing 18,000 barrels of oil equivalent per day (Andrews, 2014).

The present day basin geometry is a result of the interaction of Mesozoic and Tertiary basin forming processes overprinted by Alpine Compression (Buchanan, 1998). The study area is divided into the Channel, Vale of Pewsey and Weald Sub-basins and the Winterborne Kingston Trough (Lake, 1985). The stratigraphy and the main tectonic events for the basin are summarised in Figure 2.

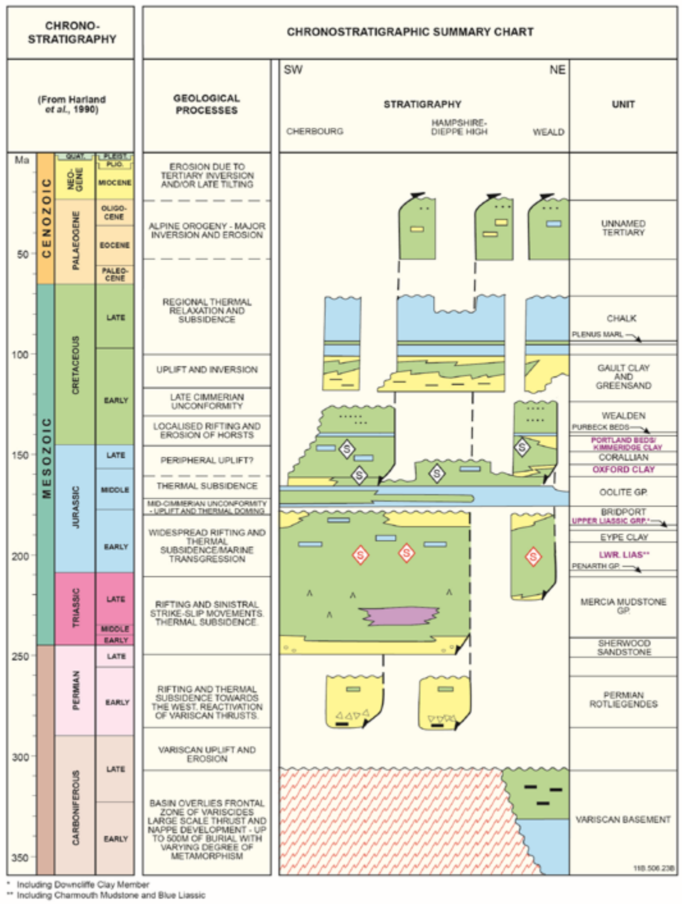

Figure 2: Stratigraphic summary chart of study area

The principal source rocks in the study area are as follows:

Formation	Age
Kimmeridge Clay Formation	Early Kimmeridgian to Tithonian
Oxford Clay Formation	Middle Callovian-Late Oxfordian
Downcliff Clay Member	Toarcian
Charmouth Mudstone Formation	Sinemurian to early Pliensbachian
Blue Lias Formation	Hettangian to Sinemurian

The Jurassic in northwest Europe was characterised by warm, humid climates. Palaeogeographic reconstructions show that the study area was located in a variably oxygenated shallow seaway (<200m paleo-water depth) that covered much of Northwestern Europe, with clastic sediment input from emergent areas. Sedimentation was influenced by syn-depositional movements along E-W trending faults. Subsidence rates were low close to the stable London Platform, but in the central part of the Weald Sub-basin rapid and continued subsidence resulted in the deposition of thick Jurassic sequences prior to the shallowing of the basin in the Late Jurassic.

The Lias Group was deposited from the Latest Triassic into the Middle Jurassic at a palaeo-latitude of about 35° N. It consists of rhythmically interbedded limestones, marls and shales with the rhythm probably reflecting astronomically-induced climatic cycles. The Lias sequence is an important oil-prone source rock interval in Wessex Basin. Source quality is affected by higher terrestrial input derived from the London Brabant High into the Weald Basin.

Further carbonate units were deposited from the middle Jurassic (Oolite Groups) as well as shallow marine clay units (Oxford and Kimmeridge Clay Formations). The Kimmeridge Clay also consists of rhythmically bedded marine mudstones and limestones. From the Late Jurassic into the Late Cretaceous reactivation of extensional faults occurred. Rifting and sedimentation led to burial of Jurassic source rocks at sufficient depths for maturation to occur. The closure of Tethys triggered the Alpine Orogeny at the end of the Maastrichtian which caused uplift and inversion.

Stratigraphy and facies interpretation of the Wessex Basin

The stratigraphic framework used for the study is based on the extrapolation of the well-known outcrop stratigraphy on the Dorset Coast to the study wells. A detailed sedimentological evaluation was carried out on 3 wells for which a total of 130m of core was available. The observed trends in the wireline logs and cores led to the identification of 14 initial facies associations ranging from restricted shallow marine through shoreface to shallow shelf environments. These facies associations were grouped into seven combined facies associations which were used as input for the electrofacies analysis and provided the framework for the petrophysical analysis. The electrofacies were calibrated using the gamma ray (GR), neutron porosity (NPHI), density (RHOB) and compressional sonic (DT) logs. Cross plots of these logs showed very good discrimination of the identified facies associations and enabled the mapping of the facies associations across the study area (Figure 3). The distribution of the identified facies associations is discussed in the following paragraphs.

The Blue Lias consists of carbonate-dominated facies fringing the London-Brabant Massif which extends westwards to the northern part of the Vale of Pewsey Sub-basin. Restricted shallow marine silt-dominated, oxic shelf conditions were established in the southern part of the Vale of Pewsey Basin while in the Winterborne Kingston Trough and the southern part of the part of the Portland-Isle of Wight Sub-basins, oxic to anoxic silt-dominated shelf conditions prevailed.

In the eastern part of the Weald Sub-basin, the Charmouth Mudstone Formation consists predominantly of oxic silt-dominated shelf to restricted shallow marine carbonate passing westwards and southwards into mixed oxic and anoxic silt-dominated facies in the Vale of Pewsey Sub-basin. In Winterborne Kingston Trough and the Portland-Isle of Wight Sub-basins the Charmouth Formation consists of anoxic silt-dominated facies.

The facies distribution for the Downcliff Clay Member in the Weald Sub-basin shows a prevalence of oxic silt-dominated shelf facies, grading westwards to mixed oxic and restricted shallow marine facies. Localised sand and silt-dominated shelf facies have been recognized in some wells on the western flank of the Weald Sub-basin. Anoxic to oxic silt-dominated shelf facies are prevalent in the Vale of Pewsey Sub-basin and extend southwards into the Winterborne Kingston Trough and the Portland –Isle of Wight Basin.

The facies distribution for the Oxford Clay is variable in the Weald Basin and appears to be controlled by an East-West trending high, with deposition of silt-dominated oxic shelf to restricted shallow marine facies on the high. Wells on the flanks of this high indicate predominantly silt-dominated, anoxic shelf facies with localised carbonate development. Localised sand and silt-dominated shelf facies interbedded with anoxic shelf facies have been identified towards the western margin of the Weald Sub-basin. Silt-dominated anoxic shelf facies are prevalent in the Vale of Pewsey Sub-basin and extend southwards to the Winterborne Kingston Trough and Portland-Isle of Wight Sub-basin.

Sedimentation in the Weald Basin was controlled by a structural high trending approximately East-West during the deposition of the Kimmeridge Clay Formation. The Lower Kimmeridge Clay Formation shows a mixture of shoreface and offshore transition zone to restricted marine facies associations in the Weald Sub-Basin, localised sand input in the central part of the Weald Sub-basin. Anoxic silt-dominated shelf facies are prevalent in the rest of the study area, outside the Weald Sub-Basin. The Upper Kimmeridge Clay Formation consists mainly of anoxic silt-dominated shelf to shoreface facies in the Weald Sub-basin, with a slightly more mixed oxic to anoxic shelf facies on the margins of the London-Brabant High. Elsewhere in the study area, the Upper Kimmeridge Clay Formation is thin to absent.

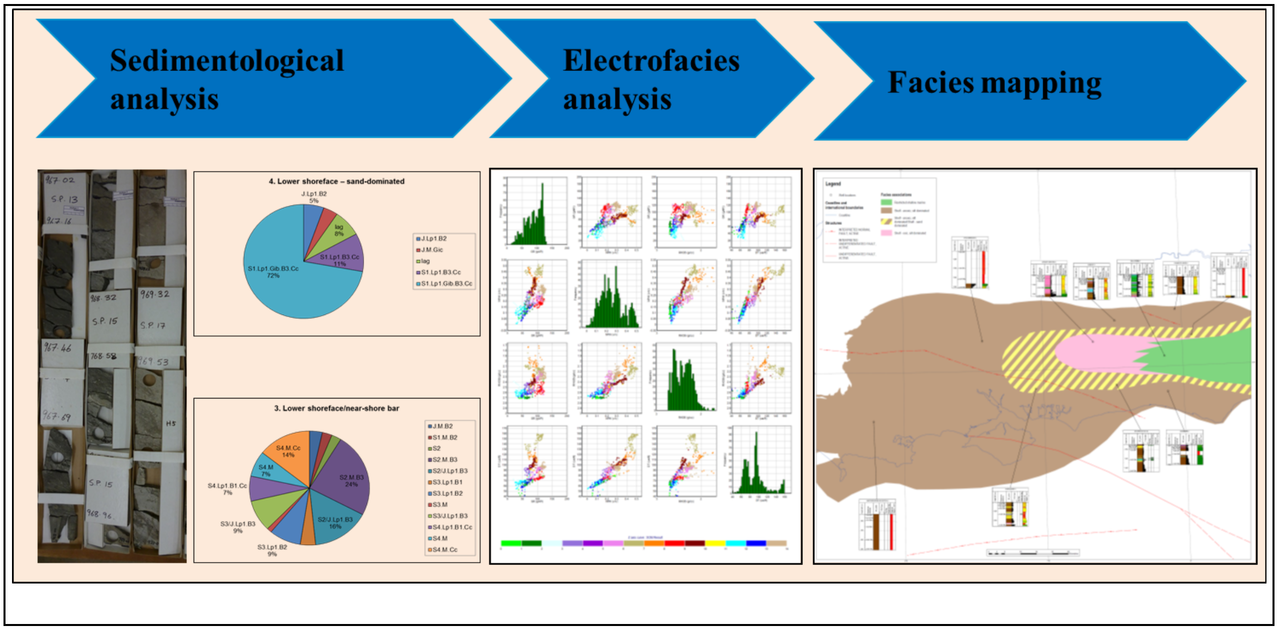

Figure 3: Workflow for facies mapping based on integration of sedimentological data and electrofacies. Detailed facies interpretations from core descriptions were grouped into facies associations and used as training datasets for the electrofacies analyses. The identified electrofacies showed very good correlation with the sedimentological facies facilitated the extrapolation of the sedimentological interpretations to well intervals without core data and enabled the regional mapping of the facies .

Automated Mineralogy

Automated Mineralogical analysis of 149 samples from 4 wells was undertaken using a QEMSCAN® 650F system comprising a scanning electron microscope combined with two energy dispersive spectrometers (EDS), which integrate the scanned data to provide information on the chemical, textural and mineral compositions of the samples. The results show a mixed carbonate/clay system with local increases in clastic material within the analysed wells (Figure 4).

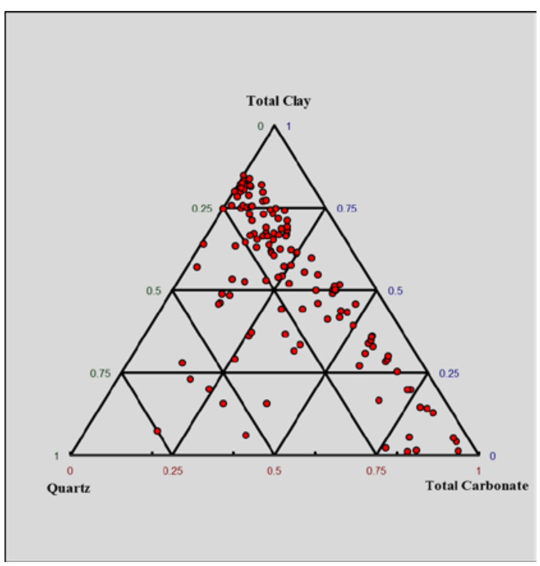

Figure 4: Bulk mineralogical compositions from the 149 samples taken from four wells.

Petrophysical interpretation and rock typing

The automated mineralogical data from the sample analyses have been used to calibrate the petrophysical interpretations. The results of these analyses have been used to determine rock properties based on definitive lithology measurements throughout various zones of interest within the wells. In conventional petrophysical analyses, assumptions are made on a number of rock properties. The Automated Mineralogy results distinguish between Feldspars, Micas and Quartz and also to determine exact clay mineral composition. This allowed a more precise determination of shale and matrix properties at the measured points and eliminates the need to make assumptions for these properties.

With the data available from the Automated Mineralogy analyses more precise values for matrix density (ρ_{matrix}) and clay density (ρ_{clay}) have been calculated for use in the porosity estimation. These were combined with predicted TOC values from logs to correct the estimated porosity values for the presence of organic carbon within the formations.

Synthetic TOC logs were created using the improved Carbolog equation of Sun et al. (2013):

$$TOCCarb = a\Delta t + bR^{-1/2} + c$$

The TOC laboratory measurements were linked to groups of electrofacies. The Carbolog equation constants were derived for each electrofacies group using a Compressional Sonic and Resistivity cross plot. The TOC estimates from the logs showed good correlation with the values obtained from laboratory measurements ($r^2 = 0.7$). Synthetic TOC logs were created using electrofacies and extrapolated away from cored intervals.

Elastic properties were estimated for the study wells. Shear velocity data were unavailable for any of the study wells. Synthetic shear sonic logs were computed using the Greenberg-Castagna relationship (Greenberg and Castagna, 1992). The derived elastic properties indicated presence of significant brittle intervals associated with carbonate bands which would be amenable to hydraulic fracturing. In outcrops and wells along the Dorset Coast, naturally fractured bands of limestone and marl ranging from a few centimeters up to as much as 1m thick have been observed in the Kimmeridge Clay Formation (Morgans-Bell *et al*., 2001).

Source rock quality and maturity

Data from over 1100 samples from multi-client databases as well as published sources (Andrews 2013; Akande, 2012 a, b; Scotchman, 2001 and Ebukanson and Kinghorn, 1985, 1986.) were assessed to determine the source rock quality and maturity. The available data included TOC and rock-eval pyrolysis data. The inferred kerogen types from the pyrolysis data were confirmed by microscopic kerogen analyses performed on a number of samples. The source quality and organic richness show marked variation with facies.

The most optimal conditions for source rock deposition and preservation occurred during the deposition of the Kimmeridge Clay Formation. The available data show very good quality source intervals, rich in sapropelic organic matter and showing high TOC values. Minor input of terrestrial organic matter was observed in a few samples from more proximal facies in the Weald Sub-basin, probable derived from the London- Brabant High. The Oxford Clay Formation showed lower TOC and Hydrogen Index HI values. Increased terrestrial influence in the Weald Sub-basin resulted in higher amounts of type III kerogen. More oxygenated shallow marine conditions prevailed during the deposition of the Downcliff Clay Member, Charmouth Mudstone Formation and Blue Lias particularly in the Weald Sub-basin and they all show lower TOC values and higher proportions of type III kerogen than the Kimmeridge Clay Formation.

The source quality and maturity data were integrated into 1-D basin models which were created in order to obtain an accurate estimate of Jurassic sourced hydrocarbon generation, timing and location. The modelling results have been used to constrain the kitchen maps in the Kimmeridge Clay Formation, Oxford Clay Formation, Upper Liassic, Middle Liassic and Lower Liassic. A total of four sections were modelled in the study area, comprising three drilled well sections and one synthetic section.

The sections were compiled using available well data and structural information from multi-client databases and public sources. The palaeo-water depth was provided from in-house plate model and paleogeographic reconstructions. The sediment water interface temperature (SWIT) has been calculated via the Auto SWIT method and the heat flow via the McKenzie (1978) heat flow model function. The most critical factor in simulating the maturity history of the source rocks is the magnitude of the Cenozoic uplift which varies significantly for the Weald Sub-basin and for the Wessex Basin. The model was constrained using temperature calibration data abstracted from well reports and vitrinite reflectance measurements measured for this study. It calculates values using the "Easy%Ro" method of Sweeney and Burnham (1990).

In order to create maximum depth of burial maps present-day structural depth maps derived from well tops have been combined with uplift maps for the Weald Sub-basin (Andrews, 2014) and the Wessex Basin (Holford et al., 2009). These burial maps were then integrated with the results of the 1-D basin modelling to define the maturity limits of the Jurassic source intervals prior to the Cenozoic uplift event.

The basin modelling results indicate that all the analysed source intervals in the Vale of Pewsey Sub-Basin are immature. The Kimmeridge Clay and Oxford Clay Formations are early oil mature in the Weald Sub-basin and immature elsewhere in the study area. The Liassic source rocks; Downcliff Clay Member, Charmouth Mudstone and the Blue Lias Formations are in the early to peak oil window in the Weald Basin and in the early oil window in the Winterborne Kingston Trough. The only mature source rock in the Portland – Wight Sub-basin is the Blue Lias Formation.

Risk mapping

The geochemical, mineralogical, petrophysical and geomechanical properties of the Jurassic source rocks were assessed including the source rock thickness, quality and maturity, lithology, mineralogy, effective porosity and mechanical properties. These parameters were used to create three risk maps for each play as follows:

- Source risk
- Reservoir risk
- Environmental risk

Play fairway mapping and 'sweet spot' definition was performed for each of the plays by combining the above risk maps using a common risk segment mapping approach. All the plays show good shale oil potential in the Weald Sub-basin while the main potential in the Winterborne Kingston Trough and Wight-Portland Sub-basin is in the Liassic interval. Organic-rich source rocks exist throughout the study area and the extent of the play fairways are mainly limited by source rock maturity. The mineralogical data and the mechanical data show that although the target source rocks are clay rich, they display sufficient brittleness for exploitation as hybrid shale plays with naturally fractured carbonate bands as proven by the success in Horse Hill development area. In the play fairways, the risk of ground water contamination is mitigated by fact that the shale targets are separated by at least 400m from viable aquifers that are used for domestic and industrial water supply.

Conclusions

- The presence of a proven shale play has been identified in the Kimmeridge Clay Formation in southern England, and has been established by recent drilling in the Weald Basin.

- Older source rock intervals showing potential as shale plays include the Oxford Clay Formation, the Downcliff Clay Member, Charmouth Mudstone Formation and the Blue Lias Formation

- A very good match was obtained between the sedimentologically-defined facies and electrofacies and this was used to extrapolate facies interpretations to intervals in the study wells that had no core data and enabled the mapping of the facies association for the source intervals under consideration across the study area.

- The application of the electrofacies classification helped in defining the constants used in the CARBOLOG equation and significantly improved the correlation between the estimated TOC from wireline logs and the laboratory measurements.

- Available geochemical data shows the presence of high TOC, type II and type II/III source rocks. These source rocks reached oil window maturity prior to the Alpine uplift event during the early Cenozoic.

- The automated mineralogy results were integrated with log derived TOC used to constrain the petrophysical analyses.

- Log derived elastic properties show the presence of brittle intervals suitable for hydraulic fracturing.

- The risk of ground water contamination during hydraulic fracturing is mitigated by the >400m separation between the identified shale plays and the groundwater sources for domestic and industrial use.

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