SPE 14UNCV-167776-MS

Unlocking the Resource Potential of the Bowland Basin, NW England

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This paper was prepared for presentation at the SPE/EAGE European Unconventional Conference and Exhibition held Vienna, Austria, 25–27 February 2014.

Abstract

The Bowland Basin of NW England is a key part of the Pennine Carboniferous Petroleum System which is estimated by the British Geological Survey to hold over 1300 TCF of total original gas in place (TOGIP) of shale gas resource. The basin is a Lower Carboniferous (Dinantian) extensional basin which underwent at least two major phases of rifting and intrabasinal tectonics. The basin was inverted in late Carboniferous times and subsequent burial continued until mid or late Cretaceous time. The gas-bearing shale section is extremly thick (>6000 ft) intensly naturally fractured and relatively complex structurally. Ongoing geoscience studies are focussed on addressing the the intrabasinal sedimentary architecture of the Bowland Basin, structural configuration, reservoir properties and the current stress regime. The Preese Hall-1 shale gas discovery well provides an opportunity to assess the shale gas characteritics of the Bowland Basin and its resource potential. Based on extensive core and log data the shale gas resource is estimated to be approximately 1 TCF per square mile (29 BCM per square kilometre). The gas is methane rich with little carbon dioxide and the less thermally mature parts of the succession includes significant wet gases. The gas density (gas per unit volume) in the Bowland Basin compares favourably with producing shales in North America, however, the gas saturated succession is significantly thicker.

In this preliminary contribution we describe some of the basic properties of the basin including the stratigraphy and structure, rock properties and structural configuration along with our approach to the modelling the petroleum system and estimation of TOGIP. The gas resources of the Bowland Basin alone could make a significant contribution to UK energy supplies. Unlocking this resource potential requires understanding of the complex set of geological variables and devising a development strategy compatible with the social issues surrounding shale gas development.

Introduction

The UK Pennine Carboniferous Petroleum System (PCPS) was recently reported to have over 1300 TCF of shale gas resources in place by DECC/BGS (Andrews, 2013). This system comprises a number of linked, Lower Carboniferous fault bounded extensional basins characterized by thick accumulations of hemi-pelagic calcareous mudstones and related marine facies. The Bowland Basin (Figure 1) probably contains a total thickness of up to three kilometres of Dinantian and Namurian sediments. The key boundary faults are the Craven Fault System to the North and the Pendle Lineament to the south and east. These faults mark steep depositional ramps with associated boulder beds and talus deposits which provide abrupt lateral facies changes with the adjacent block areas.

The four key elements within the Bowland Basin in terms of shale gas resources are the Hodder Mudstone, The Lower Bowland Shale, Upper Bowland Shale and the Sabden Shale Group (Figs, 2,3). The Hodder Mudstone (corresponding largely to the Arundian and lower part of the Holkerian sub-Stages) is restricted entirely to the basin and comprises hemi-pelagic mudstones and limestone turbidites with associated massive limestones deposited on shallower water highs. The Lower Bowland (mainly Asbian and Brigantian sub-Stages) is also entirely marine and comprises a mixture of fine grained calc turbidites, fine grain detrital siliciclastic facies and hemipalagic clay-rich facies. The Upper Bowland Shale is Pendleian (Serpukhovian) in age and corresponds to a major marine flooding event which deposited organic rich shales over much of the UK, western and central Europe.

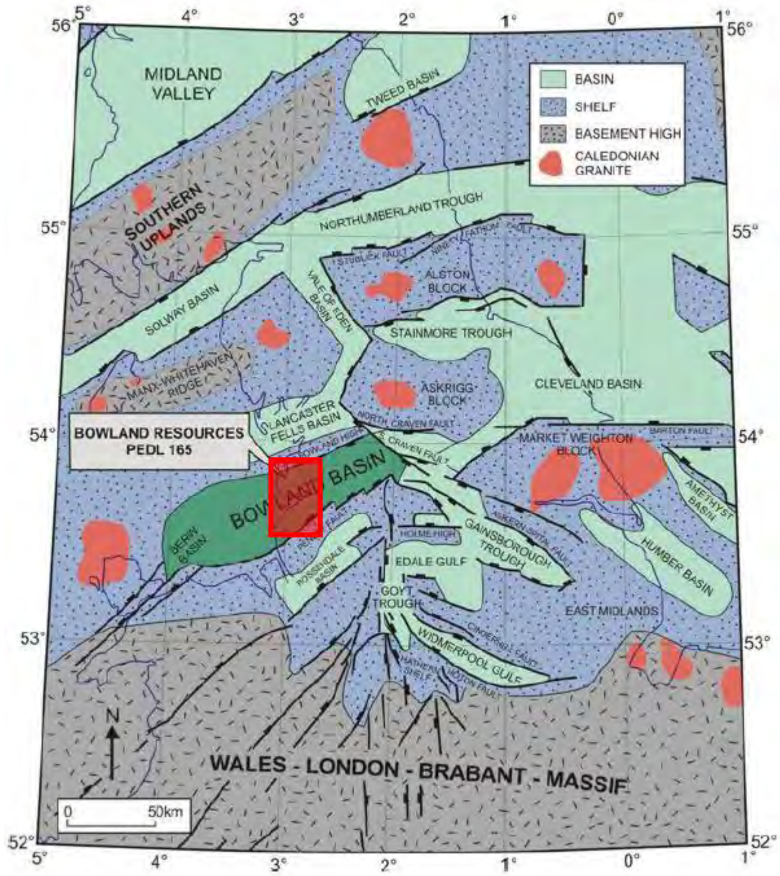

Fig. 1. -Carboniferous basins of the Pennine Petroleum System showing the location of the Bowland Basin and PEDL165 the first dedicated shale gas licence in the UK (shaded red) (modifield from Fraser and Gawthorpe (2003).

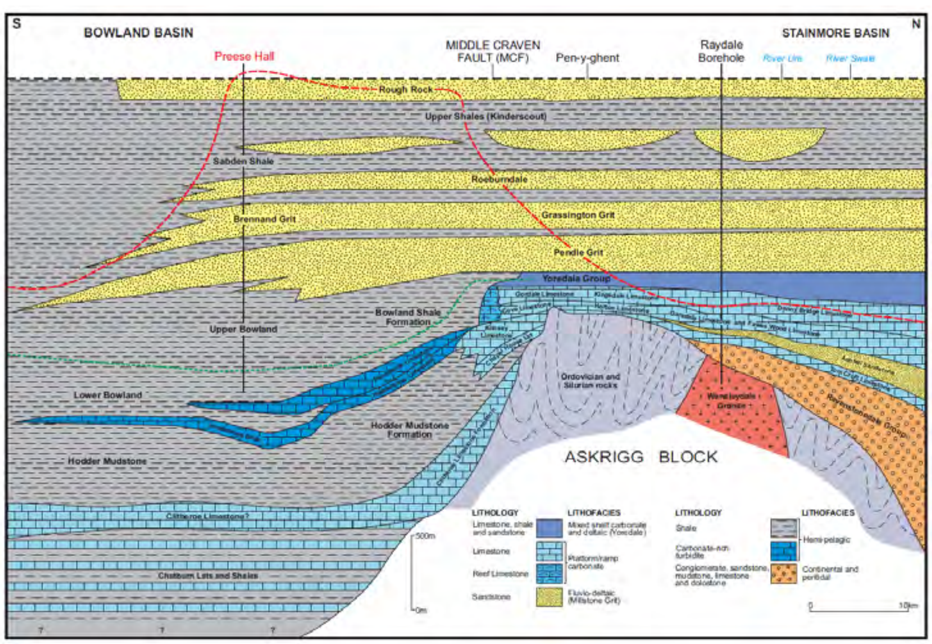

Fig. 2. -Schematic cross section from the Askrigg Block to the northern part of the Bowland Basin with the Preese Hall-1 well projected on. The red dashed line shows the projected position of the Variscan Unconformity and the amount of sediment removed during the Variscan Orogeny (modified from Waters and Davies, 2006).

The Sabden Shale Group comprises of a series of black organic and clay-rich shale interbedded between more massive gritstone bodies. The thick and varied nature of the basin presents a number of key issues which are familiar in shale gas developments. These include:

1. Stratigraphy and basin architecture
2. Rock properties
3. Present day structural configuration and stress regime
4. Modelling the petroleum system and gas in place

Preese Hall-1 Shale Gas Discovery Well

Preese Hall-1 (LJ/06-5) was spudded on August 16th 2010. The well is located on the Fylde coast of NW Lancashire in the Bowland Basin. It was the first dedicated unconventional shale gas well drilled in the UK. It is located approximately 2.2 miles east of the outer limits of Blackpool and approximately 2.8 miles west of the Elswick gas producing site.

Previous exploration in the area has been carried out by a number of companies and, in particular the joint venture between BP/BG (Gas Council). In this campaign the Thistleton-1 well was drilled in 1988 which lies some 1.4 miles east of Preese Hall -1 on strike of a 2D seismic line which connects the two wells (Figure 4). This well was expected to test a combined fault and dip-closed structural high at Permian and Carboniferous levels. The Thistleton-1 well penetrated a thick sequence of Namurian/Dinantian shales including the Bowland Shale Formation. These shales were gas-bearing and Thistleton-1 thus became a key offset well for the shale gas exploration programme in the Bowland Basin.

Structurally Preese Hall-1 is located on the western flank of the Elswick Dome and the top of the Bowland Shale, the target formation, was encountered at a depth of 6540ft MD (6492ft TVDSS) and the well was drilled to a total depth of 9100 ft MD (8906 TVDSS). Gas desorption/geochemical studies were undertaken on site and initial estimates show a number of prospective shale horizons including the Sabden and Bowland Shale Formations. Maturity data show that most of the section is in the thermal gas window.

At the time of drilling palynology was used for the biostratigraphy but unfortunately poor preservation and resolution hampered reliable results throughout the Carboniferous shale formation. As such formation tops, in the most part, were picked from knowledge of thicknesses encountered from field outcrops. Following the completion of drilling Preese Hall-1 the core collected underwent a full biostratigraphic review by the British Geological Survey. It was concluded that the Preese Hall-1 well reached TD within the Lower Bowland Shale Formation of Brigantian age. Therefore Preese Hall-1 did not intersect any formations in the Worston Shale Group, including the Pendleside Limestone, Hodder Mudstone and Clitheroe Limestone Complex, which are all considered as prospective in the basin. Within the Lower Bowland Shale two thick (<150ft) strata of calcareous turbidites were encountered and have been given the informal name of Preese Hall Limestone and Weeton Limestone respectively. Formation tops for Preese Hall-1 are provided in Figure 3.

System	Series	Regional substage	Lithostratigraphy	Depth (ft) MDRT
Triassic	Middle		Mercia Mudstone	Surface
	Lower		Sherwood sst	680
			Sherwood St Bees sst	1390
Permian	Upper		Manchester Marl	3380
	Lower		Collyhurst sst	3840
Pensylvanian		Langsettian	Lower Coal Measures	4090
	Bashkirian	Yeadonian	Rough Rock	4198
		Marsdenian	Upper Shales	4402
		Kinderscoutian	Kinderscout Group	4890
		Chokierian/Alportian	Sabden Shale Group	5240
Mississippian	Serphukhovian	Arnsbergian	Roeburndale Fm	5380
		Pendleian	Brennand Grit	5880
			Pendle Grit Fm	6090
			Upper Bowland Shale	6540
	Visean	Brigantian	Lower Bowland Shale	8220
			Preese Hall Lst	8225
			Weeton Lst	9004

Fig. 3 -Table of the stratigraphy encountered in Preese Hall-1. The well reached a total measured depth of 9100ft in the Lower Bowland Shale Formation.

Structural Evolution of the Bowland Basin

To the NW of the Basin Carboniferous rocks out crop at surface within the Ribblesdale Fold Belt, a series of NE-SW trending en echelon folds about 25km wide and extending ENE-WSW over at least 80km. To the WSW the fold belt disappears down dip and is overlain unconformably by a thick Permo-Triassic sequence which was deposited following the Variscan Orogeny. Similar Carboniferous sections can be traced further west through the East Irish Sea and to the Clare Basin in western most Ireland.

The Bowland Basin formed by active rifting during late Devonian-Dinantian times (Leeder, 1982, Arthurton, 1984). The Pennine Carboniferous basins formed in a major zone of dextral transform faulting in the Canadian Maritimes and extending NE into the British Isles (Dewey, 1982). The fold structures formed during Chadian-Pendleian times and resulted from deformation of the 16000ft thick cover with varying degrees of right lateral convergence along the transform system.

The northern margin of the Bowland Basin is now represented by the Craven Fault System which broadly delineates the Askrigg Block from the basin itself. The middle Craven fault appears to have been the active syn-depositional fault (Arthurton 1984). Westwards the basin margins are not clear but the SE margin is now marked by the Pendle Lineament. This is a NW dipping fault associated with the Pendle Monocline. There are very marked thickness variations across the fault and the Pendle Lineament appears to have been one of the major extensional basin margin faults. Active extension appears to have ceased in early Namurian times and the basin entered a thermal sag phase (Fraser and Gawthorpe, 2003). High angle reverse faults that terminate at the base of the Millstone Grit Group are stong evidence that the first pulse of inversion may have occurred in earlier Namurian time following the end of Upper Bowland Shale deposition. During the Namurian and Westphalian a thick sequence of deep water turbidites, pro-delta shales (Sabden shale group) and fluvio-deltaic sand bodies (Millstone Grits) were deposited. Inversion of the basin took place during the Variscan Orogeny in Late Carboniferous (Stephanian) times. Inversion along the Pendle lineament resulted in the formation of the Pendle Monocline and although the Carboniferous was deeply eroded at this time there are remnants of Westphalian strata in place (Corfield *et al.,* 1996).

The Bowland Basin fill contains up to 5km of interbedded shales, calcareous mudstones, limestones, siltstones and sandstones (Riley, 1990, Fraser and Gawthorpe 1990, 2003). The evolution of the Bowland Basin has been evaluated using surface outcrops, and previously drilled wells including the Preese Hall-1 exploration well drilled by Cuadrilla Resources. Some of the structural elements discussed here can be observed in the legacy 2D seismic shot in the basin such as line GC83-352 shown in Figure 4.

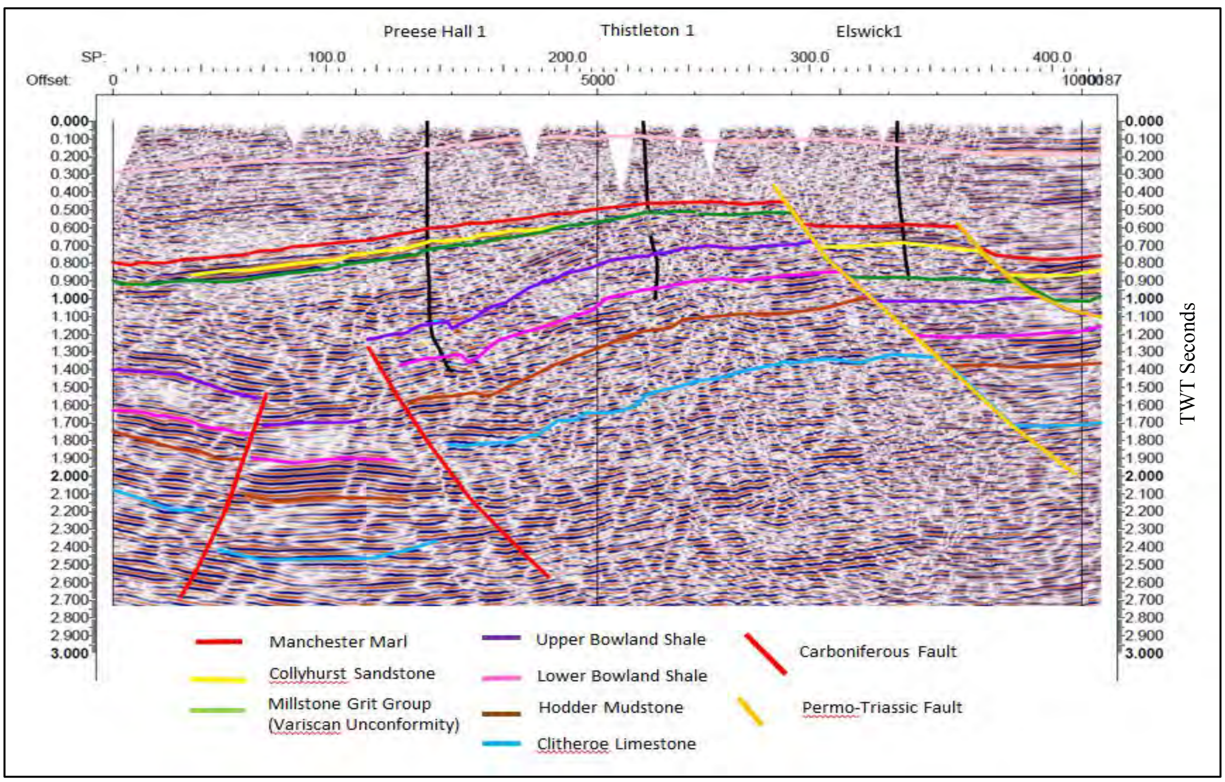

Fig. 4.-Seismic cross section view shown in two way time (seconds) at roughly 1:1 scale looking due North through the centre of the Bowland Basin and PEDL 165. 2D seismic line GC83-352.

Two distinctifly different faulting types can be observed within the Bowland basin 2D seismic. Regional Carboniferous faulting observed in seismic reflection data and at outcrop (Figure 4), shown as the red faults. This normal faulting is associated with Dinantian rifting which is believe to of had later regeneration and accomedted strong inversion during the Variscan orogeny, as well as possible early Namurian times. These Carboniferous fault trends reflect the influence of Caledonian basement structures across the northern UK that came before. Such faults are restricted to the Palaeozoic part of the geological section and do not cross either the Variscan unconformity or the regional seal and overburden.

The second main style of faulting observed is the Permo-Triassic normal faulting, show in figure 4 as the yellow faults. These normal faults such as the larger Thisteton fault which is antithetic to the regional Woodsfold fault allowed syndepositional growth of the Permian formations such as the Collyhurst Sandstone and Manchester Marl. These Permo-Triassic faults off set the regional seal formation which is the Manchester Marl but as the Elswick Permian Collyhurst sandstone resivoir is gas charged and is proximal (<0.6 mile) may suggest these faults are sealing in nature. These Permo Triassic faults are reletivly low angle (roughly 50^{o}) with throws in excess of 1000ft and offset the older Carboniferous faults and formations.

Rock Properties and Lithology

The cuttings and core samples from Preese Hall-1 were analysed using a combination of standard x-ray diffracion and thin section petrographic techniques. The lithological classification scheme used is based on that originally devised by Larese and Heald (1977). In this scheme the total clay comprises the combined clay minerals, illite, kaolinite and chlorite. There are only minor amounts of mixed layer illite-smectite in the Bowland and none recorded in the well studied. The compositional plot shows a very diverse range of lithologies; all the formations have a dominant clastic component and all claystones are silty. It is also noteworthy that calcareous and highly calcareous lithologies including limestones are more abundant in the Lower Bowland Shale. The younger formations (Upper Bowland Shale and Millstone Grit) have a dominant clastic component. The main point of emphasis is that the Bowland Basin is a mixed clastic-carbonate succession.

The Lower Bowland Shale is a highly variable formation and comprises a wide range of lithologies (Figure 5). Calcareous mudstones, siltstones and even sandstones are relatively abundant. The Upper Bowland Shale (Figure 5) is poorer in carbonate components. The main lithologies are high and low-silt mudstones with occasional clay-rich mixed mudstones and occasional thin sandstones and dolomitized limestones. The lithological composition is an important control on TOC. The highest TOC lithologies plot consistently near the clastic line indicating the probable influence of clastic input on organic carbon deposition. Thin section photomicrographs illustrating the Upper and Lower Bowland Shale are shown in Figure 6.

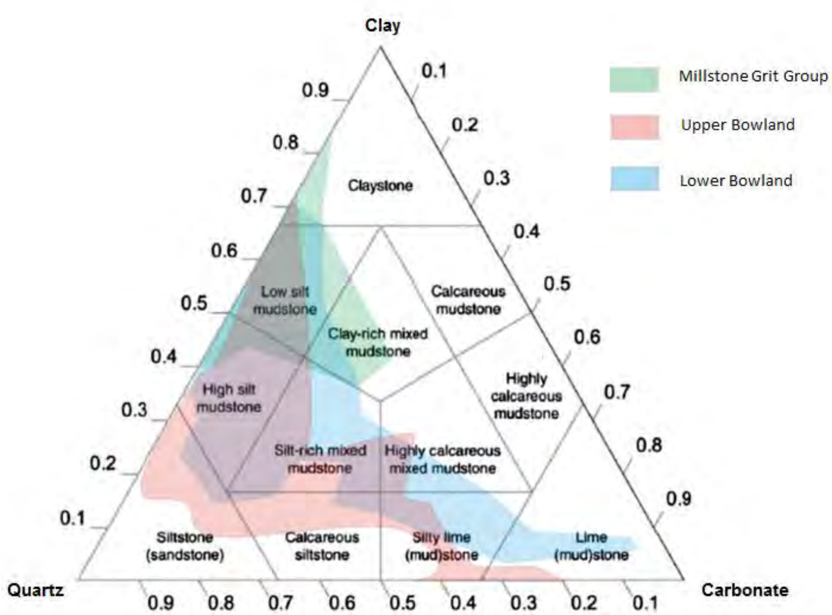

Fig. 5. -Ternary plot of both core and cuttings samples collected through out the Carboniferous section Preese Hall-1 showing the plotting area of XRD mineralogy results within the Cuadrilla classification scheme. The Sabden Shale (Millstone Grit Group Shales) plots on the quartz to clay line with almost no carbonate influence. Upper Bowland is marked by the red shaded area near the quartz pole and Lower Bowland indicated by the blue shaded area shows increasing carbonate component.

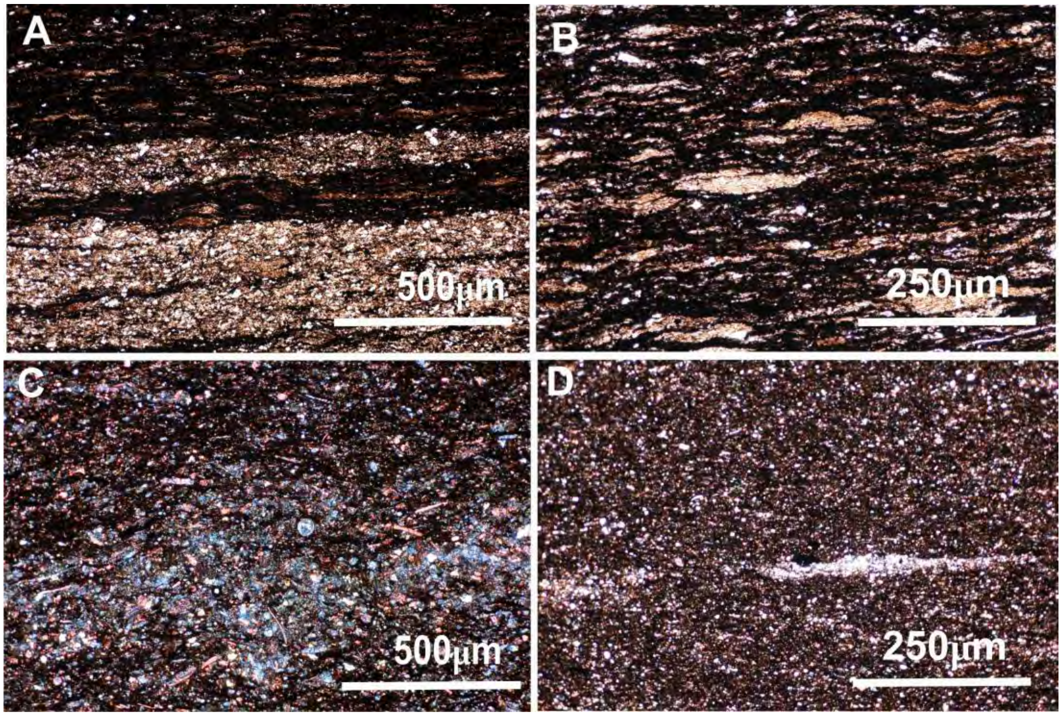

Fig. 6. -Thin section photomicrographs of typical Bowland Shale lithofacies. A Upper Bowland Shale showing interbedded distal turbidite siltstones and high-TOC mudstones. B. Upper Bowland slightly silty Claystone. The irregeular bodies are organic material including megaspores and *Tasmanites*-like bodies which have been diagenetically altered, C. Lower Bowland calcareous turbidite facies (packstone) with organic-rich clay matrix, D. Slightly calcareous high-silt claystone with discontinuous fine silt laminae. This facies is one of the key reservoir lithologies of the Lower Bowland Shale

Natural fractures and Present day structural configuration and stress regime

The present-day stress regime has been determined as strike slip where Shmax>Sv>Shmin as observed in the Preese Hall 1 well bore.The orientation of the maximum horizontal principal stress (Shmax) has been determined from drilling induced tensile fractures and borehole breakouts. These were interpreted from resistivity image log data for the Preese Hall-1 well bore using the methods outlined in Barton and Moos (2010). Drilling-induced tensile fractures, interpreted at multiple depth intervals, are shown in Fig. 7 and indicate the direction of Shmax around the well bore with an average azimuth of 353-173^{o}. These results, depict a N-S direction of the SHmax, which are roughly consistent (within 20^{o}) with other measurements in northern England.

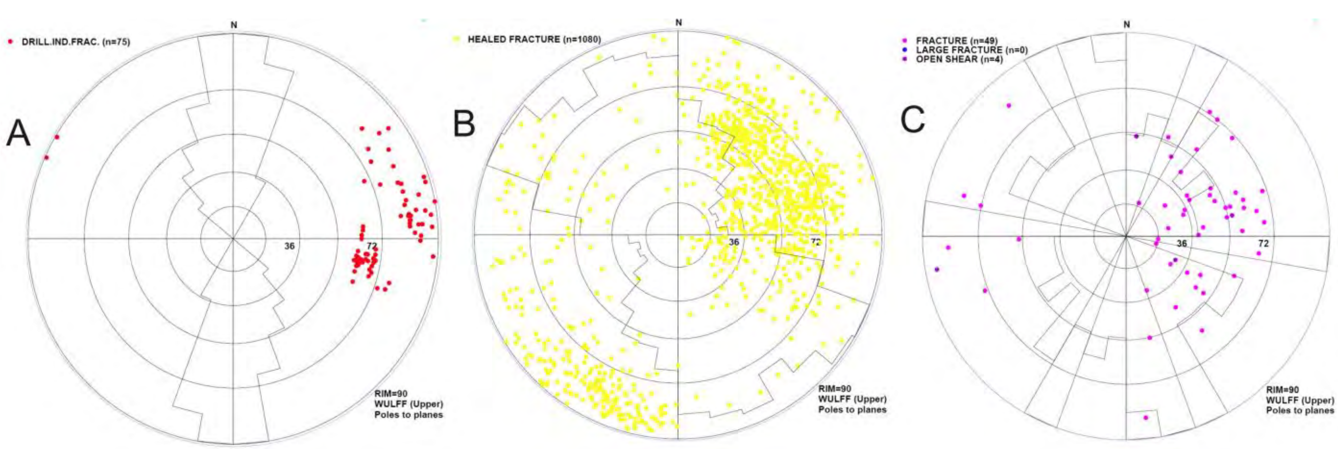

Fig. 7. - Wullf nets (upper hemisphere) showing poles to planes and rose diagrams A. Drilling induced tensile fractures B. Healed natural fractures. C. Open natural fractures and shears.

There are a wide variety of natural fractures throughout the Bowland Basin with variations in vertical and lateral density. Previous authors have studied the orientation of these fractures and their relation to larger scale structural features in the areas surrounding the Bowland basin (Moseley and Ahmed, 1967, Fairburn and Ferguson, 1992). Here the natural fractures have been studied using image logs, core data and petrographic analysis of the fracture materials. The orientation and fracture density distribution of partially healed and open fractures is shown in Figure 7. The partially healed fractures provide important reservoir permeability in the Bowland Shale. Core samples immersed in water at reservoir temperature commonly show gas issuing from partially healed fractures (Figure 8A)

The orientation of the natural fractures show a larger range then that observed in the drilling- induced fractures. The dominant orientation 325º-145º is consistent with strike of maximum horizontal shortening in the Variscan orogeny. It would also be expected that when hydraulically stimulated the interaction between hydraulic fractures and natural fracture will give rise to a highly complex fracture network. The fractures fills are dominated by calcite with minor amounts of dolomite and occasionally quartz. A key feature of the Bowland fractures is that they occur with a distinctive two-phase fill. Figure 8B shows a typical non-ferroan fracture. The boundary between the two phases is arrowed and it is this which may provide one of the natural permeable conduits in the Bowland Shale.

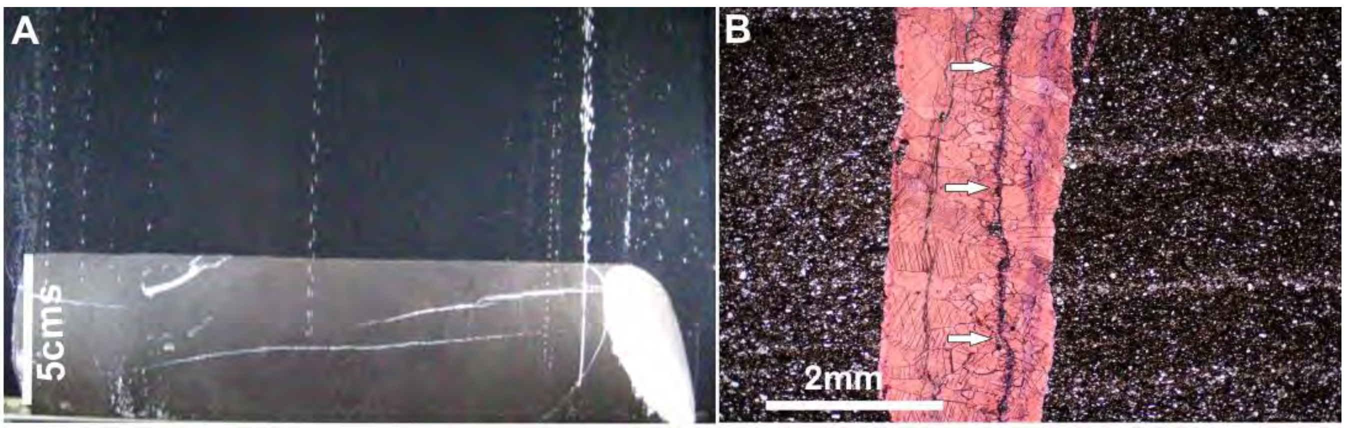

Fig. 8. –A. Core sample immersed in water at reservoir temperature showing gas production from partially healed calcite fractures. B. Thin section photomicrograph of a typical calcite filled fracture. The boundary between the two growth phases is arrowed.

Reservoir Properties and Total Gas in Place

The Preese Hall-1 well was the first shale gas well in the Bowland Basin (and the UK), and hence a comprehensive wire-line coring program was designed and carried out with collection of cuttings samples between cored intervals. Based on mud log data obtained while drilling, the shales stratigraphy from about 5000 ft (>1500 m) through to total well depth of about 9000 ft (>2700 m) is gas charged. The reservoir properties including hydrocarbons in place was determined utilising a comprehensive log suite, extensive core analyses and, in non-cored analyses, cuttings analyses. The work flows for the total hydrocarbons in place and composition are summarized in Figure 9.

The maturity of tested section in the Presse Hall-1 well as defined by Tmax and vitrinite reflectance ranges from the upper part of the oil window (Tmax ≈450ºC) in the Marsdenian Upper Shales (5000 ft; 1524 m) through to dry gas in the Brigantian Lower Bowland Shale (Tmax >470ºC). The integrated gas composition from canister desorption correlates well with the maturity with wet gas in the upper part of the tested interval (>40% C_2+) to 95% C_1 at the base of the cored section at 9000 ft (2740 m). The natural gas liquids in the upper part of the section have not been quantified.

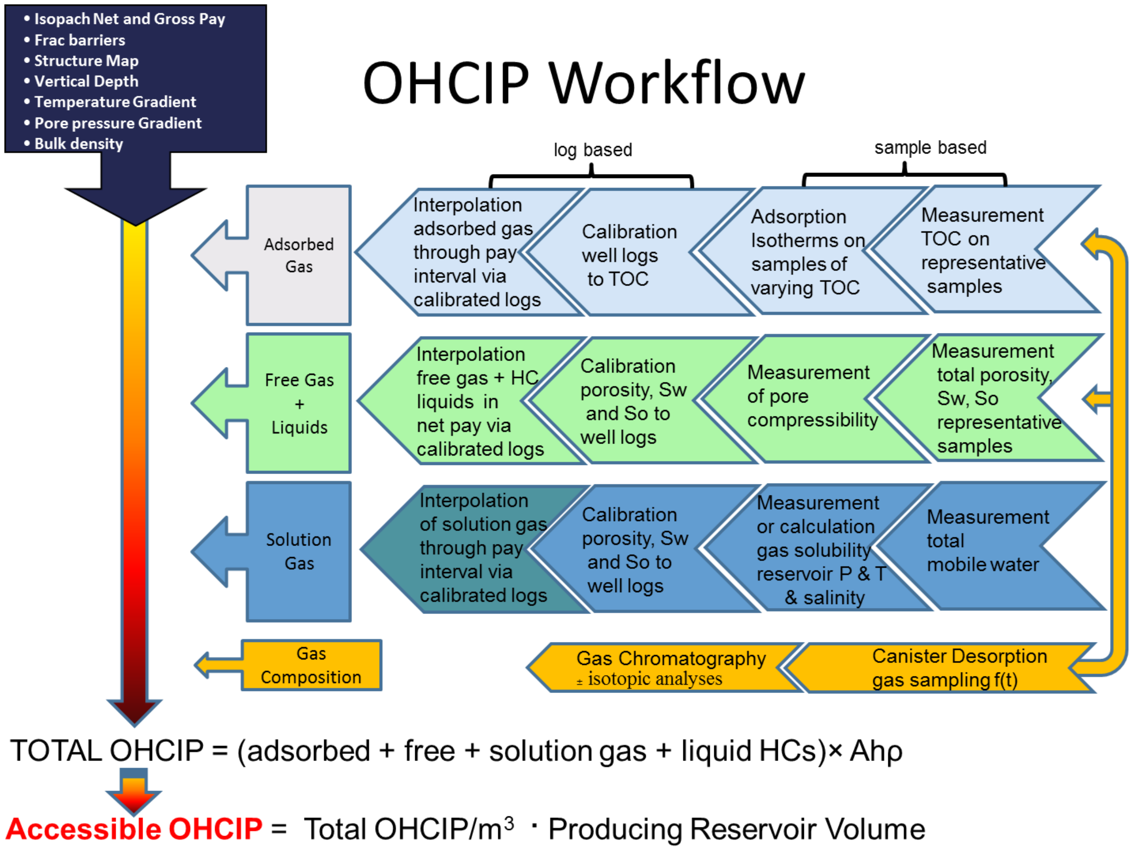

Fig 9. -Work flow utilised in this study for determining total hydrocarbons in place.

The isotope composition of the produced gas during short term tests of the Lower part of the Bowland Shale averages -39.7 $\delta^{13}CH_4$ and -136 δD-CH_4. The isotope composition of the heavier hydrocarbons ranges from -31.9 $\delta^{13}C_2H_4$ through to -21.5 n-C_5H_{12}. There is a very poorly defined trend to increase in desorbed gas content from the top of the tested section to the base with most values between 20 and 50 scf/tonne (0.6 cubic metres to 1.5 cubic metres/tonne) As anticipated there is also a general trend between total organic carbon content and desorbed gas however this trend is in part masked by the trend of increased adsorbed gas with pressure (depth).

The total organic carbon content varies through the stratigraphy with the highest values in the Bowland shale. The average total organic carbon content of the cored intervals ranges from 1 to 7% and averages 2.65% and in the cuttings samples average 2.2%. For the most part the kerogen is too mature to type by Rock-Eval pyrolysis. Petrographically there is significant humic material (Type III) however the wetness of the gas at the organically less mature top of the sampled section implies Type I/II kerogen which are less obvious microscopically. The effective porosity of the samples through the section averages 2.8% and the water saturation averages 25%. The average matrix permeability is $1E^{-5}$ md and there is a good correlation between gas filled porosity and unconfined matrix permeability.

The total gas in place was determined from a combination of adsorption isotherms on representative samples of varying total organic carbon content, lab determination of the total free gas charged porosity and solution gas. The free gas porosity was corrected for volume of adsorbed gas. The desorbed gas from canisters provides a minimum gas composition in as much as significant problems were encountered in core retrieval leading to unusually long lost gas times. The gas in place in non-sampled areas was interpolated based on log calibration. Fracture porosity was not considered in the volumetric analyses although the reservoir is highly naturally fractured. An example adsorption isotherm together with calculated solution gas and free gas (from effective porosity) is shown in Figure 10 for the Upper Bowland Shale.

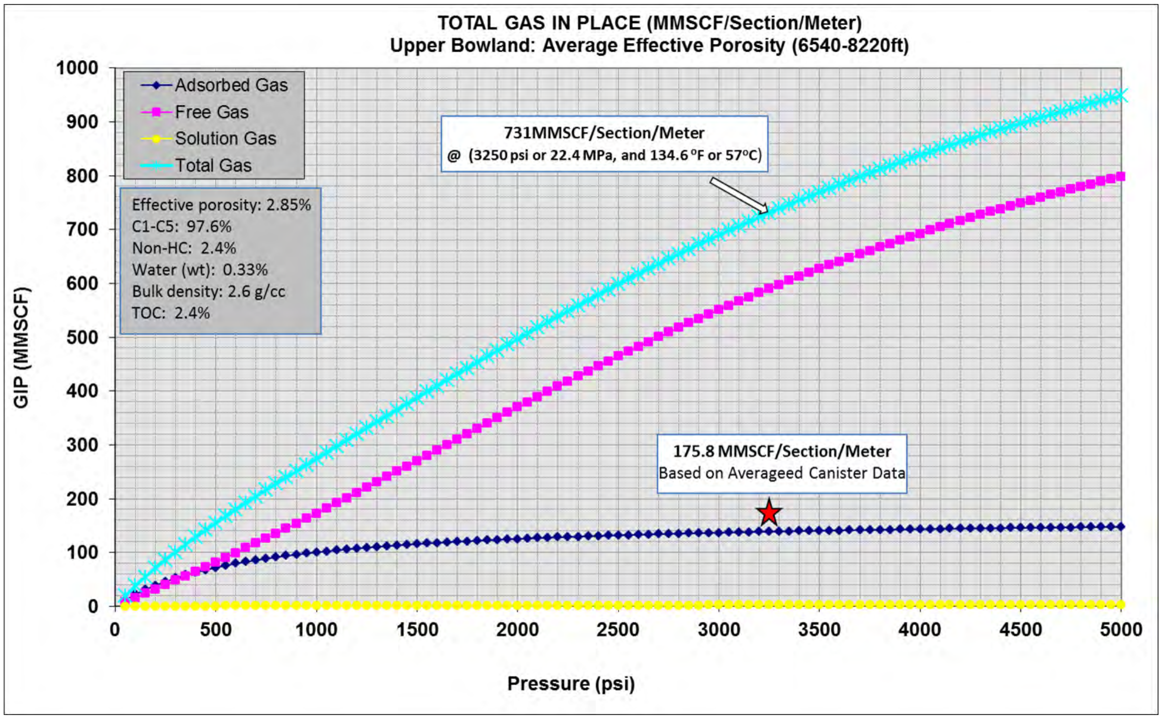

Fig. 10. -Quantification of the total gas in place based on adsorption isotherm, solutions gas and free gas filled porosity. The canister desorbed gas is plotted (red star) at the reservoir pressure (22.4 MPa) for comparison and compares favorably with laboratory determined adsorbed gas content. The effective porosity to gas is corrected for the adsorbed gas volume based on the density of the sorbate.

At reservoir pressure and temperature the gas density in the example in figure 10m is 732 MMSCF/Section/meter (≈ 223 MMSCF/Section/ft or 0.73 BCF/Section/meter or 8 BCM/metre/kilometre) with about 20% of the gas occurring in the adsorbed state and the balance as free gas in porosity. Through the shale stratigraphy the gas density varies from a low of 360 MMSCF/Section/meter (≈ 110 MMSCF/Section/ft) to a high of 1500 MMSCF/Section/metre (≈ 457 MMSCF/Section/ft). When the total gas charged section is taken into consideration, the total gas resource through the stratigraphy approaches 1 TCF per section (square mile). The natural gas liquids were not quantified in the Preese Hall-1 well.

Fig 11- . Lower Bowland shale core sample immersed in water at reservoir temperature after retrieval by wireline coring. Methane actively bubbles from the rock matrix, bedding planes and fractures.

Modelling the petroleum system and gas in place

The resource analyses performed on all wells utilized core and cuttings samples (where core was not available) through the prospective gas shale zones, using industry established shale gas protocols. Well site testing was conducted and follow up laboratory analyses that included a protocol for total gas in place determination (TOGIP), a typical core sample can be seen in Figure 11. The resource analyses protocol was devised to establish the adsorbed, free and solution gas through the prospective intervals. We mostly used wireline retrieved core which was used to sample representative intervals. We also extrapolated the sample data to non sampled intervals using wireline log correlations with gas saturations being ground truthed using cuttings analyses and formation evaluation log data. These procedures are standard in the industry where it is not possible, nor practical, to core the entire section of interest. In all the wells coring was challenging, nevertheless an adequate sample suite was obtained in the key intervals. Extrapolating the cored interval data via wire line logs, however has proved challenging. The cored intervals are invariably washed out and hence the log response of the cored intervals are difficult to compare and extrapolate to non-cored intervals. In such intervals however cuttings samples were collected, desorbed and analysed and hence provide confirmation of the distribution and volume of gas in place.

Based on the log responses and the data sets in hand, a combination of deterministic and probabilistic approaches was taken to calculating total gas-in-place. P10, P50 and P90 values were approximated, or determined for porosity, adsorbed gas, solution gas and reservoir pressure and temperature where sufficient measurements were available and the total volume of gas-in-place on a per metre basis was calculated and on volume per metre/section basis. The net pay through each interval was than determined based on taking into consideration wire line log responses, mud log gas, cuttings and canister desorption data. In intervals where little data were available conservative estimates were made from measurements of like strata with similar desorption gas contents.

The reservoir characteristics including gas in place, mineralogy and rock moduli of the shales in the Bowland Basin compare favourable with producing shales in North America and particularly the producing Marcellus and Fayetteville shales. One of unique features of the shales in the Bowland Basin is the extra ordinary thickness of hydrocarbon saturated shales and hence gas volume per unit area. This thick interval provides the opportunity to drill horizontal wells in different stratigraphic intervals from a single pad, increasing the amount of producible gas per pad while maintaining a minimal surface footprint.

Acknowledgements

We would like to thank Cuadrilla Resources Ltd, AJ Lucas Group Ltd, and Centrica for permission to publish this paper and the valuable input from Bernard Besly on the shale classification scheme.

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