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Total Organic Carbon Evaluation of the Bowland Shale Formation in the Upper Bowland of the Widmerpool Gulf.

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1 Abstract

Widmerpool Gulf is one of the basins in the carboniferous Bowland Hodder shale in Central Britain. The area of interest in the Widmerpool Gulf is the Bowland Shale Formation within the Upper Bowland. This paper focuses on evaluating the total organic carbon (TOC) from Rempstone 1 and Old Dalby 1 both penetrating the Bowland Shale Formation using Passey's delta Log R method. TOC is an essential property needed to have a productive shale gas play - accurate characterisation of TOC is critical in evaluating the potential of shale gas reservoirs because it closely relates to the amount of kerogen and therefore total gas content. Passey's method involves the use of well logs to obtain the organic richness i.e. TOC. It relies on the response of well logs to organic matter using an overlay of porosity logs and resistivity logs. Which causes a separation i.e. a delta Log R separation. The reasons for the delta Log R separation in an organic rich reservoir/non reservoir rocks is due to the presence of low density, high transit time kerogen and the presence of formation fluid i.e. oil, gas or water. Immature source rocks also observe a separation but only from the porosity log whilst non source rocks observe no separation. Rempstone 1 and Old Dalby 1 well logs were exported on Interactive Petrophysics to analyze the lithology of the intervals before been exported to Microsoft Excel to evaluate the parameters of Passey's equation to enable TOC determination. TOC estimates for the Upper Bowland Shale section in the

Widmerpool Gulf and was found comparable to estimates obtained from British Geological Society (BGS) RockEval core analysis report. This method proved to be a suitable way of estimating the total organic carbon using simple well logs.

2 Abbreviation

Tmax (deg C), Maximum Temperature for thermal release of hydrocarbon

3 Keywords: Total Organic Carbon; Widmerpool Gulf; Bowland Shale Formation; Passey delta Log R; Shale Gas; Unconventional Reservoirs.

4 Introduction

Shale reservoirs are described as unconventional reservoirs because commercial rates of hydrocarbons cannot be achieved without hydraulic stimulation. Shale is not a rock type rather it is a term widely used to describe rocks i.e. mudstones that contain extremely fine grains typically less than 4µm in diameter. Some shales could also contain different amount of silt size particles which are up to 62.5µm. However conventional sandstone rocks are composed of grains which can vary between 62.5µm and 2000µm in diameter . These shales contain a variety of mineral grains e.g. clay, quartz, feldspar, and heavy minerals like pyrite . The composition of these minerals will be more heterogeneous in mudstones compared to sandstones. Adequate characterisation of a shale gas formation is needed to have a productive and commercial play. The work carried out by reported key properties necessary to have productive shale gas play are illustrated on (Table 1).

Table 1: Essential and Desirable Property of a Shale Gas Play

Essential Property	Desirable Property
Organic Richness	Brittleness/Mineralogy
Thermal Maturity	Permeability

Organic matter type	Natural fractures
Free gas	
Gas in place	
Shale thickness	
Low water saturation	
Reservoir Pressure	

The identification of sweet spots increases the success of the hydraulic fracture process. Sweet spots are locations on the shale play which possess the essential and desirable properties. They are notably characterised by low clay volume, mid to high kerogen content (organic richness), high effective porosity, low water saturation, high Young's Modulus and Low Poisson's Ratio . A petro physical model is then necessary to obtain a complete evaluation of a shale formation. It typically consists of open-hole log data calibrated with laboratory core data to build a representation of the shale gas formation .

This paper focuses on evaluating the total organic carbon (TOC), for the Bowland Shale Formation in the Upper Bowland using conventional well logs (sonic and resistivity logs) from two wells namely, Rempstone 1 and Old Dalby 1 (Table 2) using Passey's delta Log R method proposed by . The results will then be compared to laboratory core results to validate the study.

In this paper, mature source rocks consists of the rock matrix, solid organic matter, and the fluid type contained in the pore space . An immature source rock consists of the rock matrix, solid organic matter and water contained in the matrix . Non-source rocks consists of the matrix and formation water within the matrix.

Previous study using this method to evaluate TOC was carried out on the Jurassic Shales of the Weald Basin but no study was done on the Carboniferous Bowland Shale hence the need for this paper.

Table 2: Specified intervals of interest

Well	Depth Interval MD (m)	Bowland Hodder Unit	Basin Located
Old Dalby 1	1270 – 1300	Upper Bowland Shale Unit	Widmerpool Gulf
Rempstone 1	750-800	Upper Bowland Shale Unit	Widmerpool Gulf

5 Methods and Materials

1. Well log data were obtained from Rempstone 1 and Old Dalby 1 as they both penetrated the Bowland Shale Formation in the Upper Bowland. These logs were exported on Interactive Petrophysics to analyze the lithology of the intervals before been exported to Microsoft Excel to evaluate the parameters of Passey's equation to enable TOC determination (A).
2. Thermal maturity value for the Bowland Shale Formation through Rempstone 1 were not available. However, , provided Tmax values of five samples (at an average of 437C) at different depths within the Morridge Formation of Rempstone 1 in the Upper Bowland. Therefore, this value of 437C was assumed for the Bowland Shale Formation within the Upper Bowland. Using (Equation 1), Ro was estimated to be 0.71. This resulted in a level of Maturity (LOM) of 9.33 using (Equation 3).

3. In Old Dalby 1, the thermal maturity of the Bowland Shale Formation was assumed to be 0.6 (a lower estimate) based on the range between 0.6 and 0.7 suggested by . This resulted in a Level of Maturity (LOM) of 8.45 using (Equation 3).
4. The baseline sonic and resistivity values were fixed for both wells at $70\mu s/ft$ and $7\Omega m$ respectively. The baseline sonic travel time was chosen arbitrarily as a minimum for both wells based on the sonic travel times across the specified intervals. This was because, it was impossible to determine the baseline intervals from the well log data. The challenge sometimes, in defining the baseline interval needed to implement Passey's method was also highlighted by .
5. The cut-offs applied by in the British Geological Society (BGS) Bowland study for thermal maturity were also used in this paper i.e. R_o values greater than 0.6 indicates thermal maturity for oil and thermal maturity greater than 1.1 indicates thermal maturity for gas. Depths less than 1500m were also assumed to be immature for gas generation based on criteria.

6 Theory

The shale intervals considered in this paper were from Rempstone 1 and Old Dalby 1 which penetrate the Bowland Shale Formation in the Widmerpool Gulf (or trough) (Figure 1). According to British Geological Society (BGS) reports, the Widmerpool Gulf, generally exhibit high TOC's (> 3wt. %) compared to other basins within the Bowland Hodder Shale.

Figure 1: Location of basins and wells within the Bowland Hodder Shale

The depth intervals of interest all exhibited high gamma ray signatures and correlation from , (Figure 2)

Figure 2: Bowland Shale Formation across Rempstone 1 and Old Dalby 1

These shales typically began as organic rich muds which are deposited in marine environments, in lakes, or in swamps and mires along sea or lake margins . The presence of organic matter make shales source rocks - source rocks like shales¹ contain appreciable amounts of organic matter, up to 50wt%, while non-source rocks also contains some organic matter but are not significant i.e. less than 1wt%

The amount of organic matter in a source rock is described as the total organic carbon content. The type of organic matter will determine what type of fluid can be produced or found in the source rock when burial and thermal maturation occurs (Table 4). Accurate characterisation of TOC is critical in evaluating the potential of shale gas reservoirs because it closely relates to the amount of kerogen and therefore the total gas content as organic content contains both adsorbed and free gas. . TOC along with thermal maturity and organic matter type are important parameters which determine whether a rock will be a good source rock. Not accounting for kerogen content (TOC) will result in a gross underestimation of porosity and hence gas content. Hydrogen to Carbon ratios and Oxygen to Carbon ratios are used to determine the type of organic matter in the form of the van Krevelen Diagram - though a good source rock should have high TOC (Table 3), the more hydrogen associated with the carbon, the more hydrocarbon can be generated .

Table 3: Guideline for TOC .

Quality	TOC (wt. %)
Poor	<0.5
Fair	0.5 to 1

Good	1 to 2
Very good	2 to 4
Excellent	>4

Table 4: Characteristics of the main types of Kerogen .

Kerogen Type	H:C Ratio	O:C Ratio	Origin of Organic Material	Fluid Type
Type I	1.7-0.3	0.1-0.02	Algal sources in lakes and lagoons	Light high quality oil
Type II	1.4-0.3	0.2-0.02	Mixture of plant debris, phytoplankton and bacteria in marine sediments	Main and common source of crude oil.
Type III	1.0-0.3	0.4-0.02	Land plants in coaly sediments	Predominantly natural gas
Type IV	0.45-0.3	0.3-0.02	Oxidised plant remains and charred wood from forest fires	No petroleum potential

The Bowland Shale Formation across both wells i.e. Rempstone 1 and Old Dalby 1 were generally classified as containing Type II Kerogen. These shales are deposited in marine conditions and typically contain large quantities of uranium, which is a good indicator of organic richness. The high uranium content contributes to very high gamma ray intensity ($> 200\text{API}$ was observed in the specified intervals of interest) in Type II shales). As hydrocarbons can be generated from these shales, they are described as source rocks - all the oil/gas trapped in conventional reservoirs around the world have been generated from these source rocks. For shale gas reservoirs, the gas is unable to migrate to conventional traps for various reasons:

- The ultra-low permeability nature tends to limit migration
- Absence of migration path due to regional geological processes (**Figure 3**)

Figure 3: Extensive sections of the shale source rock have no migration

6.1 Thermal Maturity (R_o)

Thermal maturity represents an essential property necessary to identify a productive shale gas play. It indicates the maximum temperature reached by a source rock during burial over time as well as the thermal stress on the kerogen over time which controls the rate of organic matter transformation to hydrocarbons. "Vitrinite reflectance is the most common method of evaluating thermal maturity and is performed through microscopic inspection of kerogen and analysis of the reflectivity of the particles using a photomultiplier".

Another method to evaluate thermal maturity is the RockEval Tmax which can be converted into a Vitrinite reflectance equivalent value (Equation 1).

$$T_{max}eq\%Ro = 0.018(T_{max}) - 7.16 \text{ [where } T_{max} \text{ is in } ^\circ\text{C]}$$

(Equation 1)

'Ro values from 1.1 – 3.5% are widely accepted as the 'gas window' (Figure 4) .

Figure 4: Thermal Maturity

6.2 Passey's Delta Log R Method

Passey's method simply involves the use of well logs to obtain the organic richness. It relies on the response of well logs to organic matter using an overlay of porosity logs and resistivity logs. This method showed that a combination of sonic curve and resistivity curve provided the best results as the sonic log is not severely affected by in-hole conditions compared to the density or neutron readings. An overlay of sonic and resistivity curve over a mature organic rich intervals causes a separation i.e. a

delta Log R separation occurs (Equation 2) (Figure 5). The delta Log R separation is directly proportional to TOC and is a function of maturity (Equation 3 and 4). This means that the separation can be converted to TOC providing the Level of Maturity (LOM) is known – the latter is dependent on estimating thermal maturity through Tmax or Ro (Equation 3).

$$\Delta \text{Log } R_{\text{sonic}} = \log_{10} \left(\frac{R}{R_{\text{baseline}}} \right) + 0.02 \times (\Delta t - \phi t_{\text{baseline}})$$

(Equation 2)

Level of Maturity (LOM)

$$= 0.0989 * Ro ** 5 - 2.1587 * Ro ** 4 + 12.392 * Ro ** 3 - 29.032 * Ro^2 + 32.53 * Ro - 3.0338$$

(Equation 3)

$$\text{TOC} = (\Delta \log R) \times 10^{(2.297 - 0.1688 * \text{LOM})}$$

(Equation 4)

Prior to overlaying the curves, the curves need to be appropriately scaled such that 1 resistivity cycle corresponds to $-50 \mu\text{s}/\text{ft}$ ($-164 \mu\text{s}/\text{m}$). After scaling, the curves also needs to be base lined – a baseline condition occurs when the curves directly overlies each other or track each other in a fine grained non-source rock over a significant depth range. A baseline interval is an interval with approximately zero or minimum TOC (~ 0.8 wt. %). In this paper, the background TOC of (~ 0.8 wt. %) were not added to the TOC value estimated.

There are two reasons for the delta Log R separation in an organic rich reservoir/non reservoir rocks;

1. The porosity curve responds to the presence of low density, high transit time kerogen;
2. While the resistivity curve respond to the formation fluid i.e. oil or gas.

In an immature organic rich rock with no hydrocarbons generated, a separation also occurs but only from the porosity curve(Figure 5).

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Figure 5: Bowland Shale Formation Delta Log R separation in Rempstone 1 (top) and Old Dalby 1 (bottom)

The original empirical equation developed by Passey in 1990 (Equation 4) was calibrated for source rocks in the oil maturity window i.e. for R_o values between 0.6-0.9 and Level of Maturity (LOM) 6-10.5. Therefore, using this equation in over mature intervals i.e. Level of Maturity (LOM) >10.5 or R_o >0.9 can lead to underestimation of TOC.

A correction multiplier greater than or equal to 1 was proposed by to account for the original limitation. Core data is needed to evaluate the magnitude of the multiplier.

6.2.1 Log response to shale gas reservoirs

There are key signatures which needs to be observed from the well logs before implementing the Passey delta Log R method (**Table 5**).

Table 5: Logging tool response in organic rich reservoirs

Logging Tool	Response in Shale Gas Reservoirs/Organic rich intervals
Gamma Ray Log	High Gamma Ray values often greater than 70API.
Density Log	In organic rich intervals, low density readings will be observed compared to the surrounding rock matrix.
Sonic Log	Increased transit time is observed in organic rich intervals.
Neutron Log	Organic matter increases the apparent neutron porosity – increased hydrogen

	content.
Resistivity Log	Organic matter is not conductive therefore resistivity increases in the presence of TOC. As maturation increases, resistivity increases rapidly (e.g. in gas).

6.2.2 Anomalous Delta Log R Separation

6.2.2.1 Influence of Pyrite

When Pyrite is present in the organic rich intervals, TOC is underestimated using Passey's method . This is because Pyrite is conductive and reduces the resistivity of the rock and subsequently reduces the Delta Log R term hence TOC declines . Pyrite has a very high density approximately 5g/cm^3 and no density up to 5 g/cm^3 was observed in the intervals studied across the two wells in this paper.

6.2.2.2 Reservoir Intervals

Sandstone intervals can sometimes show a high gamma ray intensity due to the presence of feldspar or mica which can be mistaken for the presence of organic matter. However absence of high transit times (greater than $230\mu\text{s/m}$) tend to suggest the absence of organic matter. In this situation, neutron-density cross plot or other log methods can be used to distinguish between organic rich or lean zones. In this paper, only organic rich shale zones were considered.

6.2.2.3 Poor Boreholes

Poor boreholes can cause cycle skipping which would result in anomalous delta log R values. When transit times exceed approximately $150 \mu s/ft$ ($500 \mu s/m$). This transit time value is also applicable to uncompacted shales. No value exceeding $150 \mu s/ft$ ($500 \mu s/m$) was observed in this paper (A).

6.2.2.4 Low Porosity Intervals

When the porosity of the formation is less than 3-4%, the resistivity increases greatly because of the absence of electrically conducting fluid - hence delta log R separation can be very high and should not be used. According to , these low porosity intervals can easily be identified by their short transit times, around, $50-55 \mu s/ft$ or $164-180 \mu s/m$. In this paper, no transit times were used within that range (A).

7 Results and Discussions

7.1 Rempstone 1

In this paper, an average TOC value of 4.2 wt. % was obtained for Rempstone 1 using Passey's delta log R method compared an average TOC value of 5 wt. % from British Geological Society (BGS) RockEval core analysis (Figure 6) – this represented a 0.8wt. % difference compared to the value obtained from core analysis. This variation was because the thermal maturity used in core analysis was from a shallower depth (Morridge Formation) within the Upper Bowland (Figure 2) and was then assumed to be the same for the depth interval considered in this paper. Owing to the multiple subsidence and inversion experienced in the Bowland Hodder Shale, the linear relationship between R_o and depth does not always hold across the area hence thermal maturity could have been higher or lower. Another reason for the difference could be associated with the shallower depths (665m to 668m) from which the samples used were obtained for core analysis compared to depth interval (750m to 800m) used in this paper using Passey's method hence there could have been some maturation of organic matter which reduced the value obtained using Passey's method.

Of the sixteen selected wells chosen for TOC analysis by British Geological Society (BGS), the wells i.e. Rempstone 1 and Old Dalby 1 within the Widmerpool Gulf exhibited higher TOC values compared to other basins (Figure 6).

Figure 6: Core analysis TOC values from the British Geological Society (BGS)

7.2 Old Dalby 1

The value obtained for Old Dalby 1 from Passey's method in this paper was 3.7 wt. % compared to the core analysis estimate of 3.5 wt. % obtained from British Geological Society (BGS) RockEval core analysis (Figure 6) – this represents a minor difference between both methods. It is important to note that the average value of TOC from core analysis was predominantly from the Lower Bowland at a greater depth (1390m to 1455m) compared to depths of 1270m to 1295m from the Upper Bowland used in this paper hence maturation in the lower section could have resulted in the reduction of organic carbon content. The thermal maturity value for Old Dalby 1 was also assumed (see section 2) which might have had an influence on the results.

The final summary of results from this paper are shown on Table 6. For the full set of data used to obtain the data on Table 6, please see appendix A

Table 6: Final summary of results

Well Name	Baseline Values	Thermal Maturity	TOC Range (wt. %)	Average TOC (wt. %)
Rempstone 1	70 μ s.ft , 7ohm-m	0.71	2.61 - 7.04	4.2
Old Dalby 1	70 μ s.ft , 7ohm-m	0.60	2.71 - 4.48	3.7

The maximum TOC obtained for upper Bowland in the Widmerpool Gulf (or Trough) in this paper was 7 wt. % similar to a maximum of 8 wt. % obtained by British Geological Society (BGS). Results from this paper showed that Passey's method is a suitable method to estimate total organic carbon as the value bears a close resemblance to estimates obtained from core analysis by British Geological Society (BGS).

8 Conclusion

Based on the findings observed from this paper, the following conclusions were evident;

1. The TOC values obtained for the Bowland Shale Formation through both wells were both in the range of "very good to excellent" based on the guidelines by in section 3.
2. The average TOC obtained for the Bowland Shale Formation in the Upper Bowland between 3.7wt. % - 4.2wt %. A maximum of 7 wt. % was observed

compared to 8 wt. % observed by British Geological Society (BGS) for the Bowland Shale.

3. Passey's method, yet simple, poses a challenge when attempting to find the baseline interval needed to estimate TOC.
4. Passey's method provided a good and economic alternative to obtaining total organic carbon content in the absence of core analysis.

9 Acknowledgements

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10 Appendix A

Table of Results for Old Dalby 1

Depth (m)	Sonic us/ft.	Resistivity (ohm-m)	Delta Log R	TOC wt. %
1270	91.6874	10.2714	0.600279602	4.48428892
1271	89.8771	8.4765	0.480660526	3.59069451
1272	79.4791	10.4365	0.363038837	2.712021248
1273	71.4778	15.3735	0.371230712	2.773217286
1274	75.8588	15.6039	0.465311118	3.476029311
1275	80.0399	13.7966	0.495472033	3.701341408
1276	83.6214	11.2297	0.477698114	3.568564304
1277	86.005	11.2416	0.525830088	3.928126208
1278	85.5928	12.0574	0.548011629	4.093829717
1279	88.7749	9.9505	0.528244864	3.94616539

1280	89.7601	10.382	0.566384985	4.231084816
1281	85.7537	10.1105	0.474748594	3.546530399
1282	87.3383	9.5782	0.482951861	3.607811546
1283	86.9258	11.7923	0.565016479	4.220861625
1284	82.121	13.3657	0.523313669	3.909327717
1285	76.9171	15.1473	0.473579187	3.537794542
1286	85.2898	11.6678	0.527686936	3.941997482
1287	88.2718	9.1125	0.479975501	3.585577145
1288	89.2572	8.6328	0.47619764	3.557355256
1289	88.6454	7.5287	0.404529952	3.021973717
1290	85.2383	9.528	0.438669708	3.27700909
1291	87.2219	9.8223	0.491553155	3.672066077
1292	88.4068	10.0901	0.52693343	3.936368543
1293	88.3937	10.3833	0.539111362	4.027341756
1294	87.7819	10.6853	0.53932668	4.028950252
1295	77.788	15.7372	0.507589424	3.791862362

Table of Results for Rempstone 1

Depth (m)	Sonic (us/ft.)	Resistivity (ohm-m)	Delta Log R	TOC wt. %
750	93.9611	9.8491	0.627520507	3.329844269

751	106.667	9.7256	0.876158364	4.649204088
753	103.2289	7.7317	0.707754954	3.755596436
755	87.5398	13.5578	0.637887183	3.384853495
756	80.651	16.1406	0.575841635	3.055618018
758	87.8866	15.8278	0.712054514	3.778411408
760	80.5315	28.9258	0.826817339	4.387383277
762	75.6959	37.5516	0.843448406	4.475633562
763	86.0427	13.9973	0.621800231	3.299490474
764	109.2029	10.1328	0.944689431	5.012854006
765	95.1128	11.0421	0.700209636	3.715558325
767	86.972	16.952	0.723562904	3.839478968
769	80.7835	23.419	0.740140307	3.927444492
770	82.563	23.1457	0.77063228	4.089245614
772	100.392	10.45	0.78185825	4.148814558
774	97.3705	12.447	0.79737665	4.231160636
775	97.9786	12.2616	0.803021104	4.261112096
776	98.9368	12.5432	0.832046307	4.415130019
777	98.8651	13.269	0.855042154	4.537154062
779	77.1984	15.6095	0.492258952	2.612098939
781	81.6273	26.4181	0.80934954	4.294692997
782	94.9801	13.395	0.781446678	4.14663061
783	93.5974	12.9858	0.74031867	3.92839095

784	98.1938	10.718	0.748891713	3.973882527
786	94.8936	12.5919	0.752865226	3.994967385
788	95.0061	13.4175	0.782695564	4.153257638
789	91.5293	17.7336	0.834284868	4.427008611
793	94.239	15.7375	0.836617703	4.439387452
794	94.1194	16.2927	0.849283021	4.506594077
795	92.5199	20.0116	0.906581773	4.810641389
796	91.4575	31.5033	1.082408009	5.743637165
798	90.611	21.1525	0.892483664	4.735831866
800	74.8339	118.6324	1.325783276	7.035071837

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- Passey's delta Log R method can be used to evaluate total organic carbon using simple logs in the absence of core geochemical results.
- Accurate selection of the baseline values in the Passey's method is essential in obtaining accurate results.
- The Bowland Shale Formation had a very good to excellent source rock quality based on the estimates of total organic carbon content obtained.
- Results from Passey's method was found comparable to core analysis estimates and was deemed suitable in estimating total organic carbon.