Total Organic Carbon in the Bowland-Hodder Unit of the southern Widmerpool Gulf: a discussion.

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Abstract

This review of the article by Kenomore et al. (2017) on the total organic carbon (TOC) evaluation of the Bowland Shale Formation in the Widmerpool Gulf sub-basin (southern Pennine Basin, UK) reveals a number of flaws, rooted mostly in an inadequate appreciation of the local mid-Carboniferous stratigraphy. Kenomore et al. use the ΔLog R, the 'Passey' method after Passey et al. (1990), to evaluate the TOC content in two boreholes in the Widmerpool Gulf: Rempstone 1 and Old Dalby 1. We show here that Kenomore and co-authors used maturity data, published by Andrews (2013), from different formations to calibrate their TOC models of the Bowland Shale Formation (Late Mississippian–Early Pennsylvanian); the Morridge Formation in Rempstone 1 and the Widmerpool Formation in Old Dalby 1. We contest that this gives viable TOC estimates for the Bowland Shale Formation and that because of the location of the boreholes these TOC models are not representative over the whole of the Widmerpool Gulf. The pyrite content of the mudstones in the Widmerpool Gulf also surpasses the threshold where it becomes an influence on geophysical well logs. Aside from these stratigraphic and lithologic issues, some methodological flaws were not adequately resolved by Kenomore and co-authors. No lithological information is available for the Rock-Eval samples used for the maturity calibration, which because of the interbedded nature of the source formations, has implications for the modelling exercise. We recommend that more geochemical data from a larger array of boreholes covering a wider area, proximal and distal, of the basin are collected before any inferences on TOC are made. This is necessary in the complex Bowland Shale system where lithological changes occur on a centimetre scale and correlations between the different sub basins are not well understood.

1. Introduction

The Pennine Basin is a Carboniferous depocentre that underlies most of northern England and consists of a patchwork of fault-bounded basins separated from each other by carbonate blocks (Figure 1a). In recent years, the Pennine Basin has received renewed attention from the research and industrial community because some of its successions, in particular the Bowland Shale Formation and its lateral equivalents (e.g. the Morridge Formation), were identified as potentially prospective targets for shale gas and oil (Selley, 1987; Smith et al., 2010). One of the sub-basins, the Widmerpool Gulf, is the subject of a recent study by Kenomore et al. (2017) with the remit of:

'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 using Passey's ΔLog R method proposed by Passey et al. (1990)' (Kenomore et al. 2017, p.137).

There is a relative paucity of organic geochemical (including TOC) data for the Bowland Shale in the public domain. For example, the Andrews (2013) report for the Pennine Basin in its entirety only contains 109 Rock-Eval pyrolysis data points (17 boreholes; 1028.25m of core). Kenomore et al. (2017) had potential to be a valuable addition to the sparse dataset characterizing this potentially important source of indigenous energy in the UK. However, a detailed analysis of the paper revealed many misconceptions and shortcomings. Taken together, these observations ultimately result in the misleading conclusion that:

'Passey's method is a suitable method to estimate TOC as the value bears a close resemblance to estimates obtained from British Geological Survey (BGS) Rock-Eval core analysis report (*sic*).' (Kenomore et al., 2017, p.143).

We believe these shortcomings stem from an incomplete understanding of the complex local stratigraphy in the Widmerpool Gulf combined with an oversimplified representation of the ΔLog R method to assess TOC in the Bowland Shale Formation. These are the main reasons for the conception of the current manuscript. As pointed out, but inadequately referenced, on p. 138 in Kenomore et al. (2017), the ΔLog R method (colloquially called the 'Passey technique', following Passey, 1990) was used before to assess TOC values of Jurassic shales of the Weald Basin (Gent et al., 2014 in Andrews, 2014) but was hitherto not applied to the Carboniferous data set from the Pennine Basin.

To eradicate some of the misconceptions, we present below the necessary stratigraphic background in the Widmerpool Gulf (Section 2), the assumptions inherent to and limitations of the ΔLog R (Passey) method when applied to the Carboniferous Widmerpool Gulf succession (Section 3), a reinterpretation of the well logs using the ΔLog R method of Rempstone 1 and Old Dalby 1 with a short discussion highlighting the aforementioned uncertainty (Section 4), followed by concluding remarks and suggestions for future research (Section 5).

2. Stratigraphic and palaeogeographic notes

In the context of studying the organic rich Carboniferous mudstones identified as the most prospective intervals for unconventional hydrocarbons (Selley, 1987; Smith et al., 2010), it is necessary to review the local stratigraphy of the Pennine Basin. The Widmerpool Gulf is the southernmost sub-basin of the Pennine Basin, and is one of many fault-bounded sub-basins that formed during the Chadian–early Arundian and late Asbian–Brigantian rift-driven fragmentation of Early Palaeozoic deposits (Fraser et al., 1990; Gawthorpe, 1987). Under the influence of the thermal sag phase of basin development, an epi-continental sea transgressed the Pennine Basin with the Southern Uplands and Wales-Brabant High still emerging (Figure 1) (Leeder, 1982; Leeder and McMahon, 1988). During the course of the Namurian (Serpukhovian–Bashkirian), these basins were filled in with deltaic successions originating from the emerging land masses. However, the deltaic deposits are interspersed by intervals rich in ammonoid and bivalve fauna that have been termed ‘marine bands’ (Bisat, 1923). These depositional intervals representing maximum flooding surfaces (Gross et al., 2014) with an estimated periodicity of 111 kyr (for the Pendleian–Arnsbergian) (Waters and Condon, 2012) reflecting glacio-eustatic sea level fluctuations (Isbell et al., 2003; Stephenson et al., 2008; Veevers and Powell, 1987). In the Namurian as a whole, 60 marine bands with an average duration of 180 kyr, have been recognized (Martinsen et al., 1995) of which 46 correspond to the occurrence of a key goniatite species (Bisat, 1923; Holdsworth and Collinson, 1988; Ramsbottom, 1977; Ramsbottom et al., 1962).

2.1 Carboniferous deposits in the Widmerpool Gulf

The Carboniferous stratigraphy of the Widmerpool Gulf, summarized in Figure 2, reflects the palaeogeographic changes the area underwent: a fault-bounded rift topography created during the Late Devonian was gradually infilled during the Visean, punctuated with transgressions in the Namurian and evolved to a richly forested fluvial plain giving rise to extensive coal horizons by the Pennsylvanian (Aitkenhead et al., 2002). A complete overview of all the Carboniferous deposits proven in the Widmerpool Gulf are given by Waters et al. (2007) and Waters et al. (2009). For the purposes of this manuscript it suffices to highlight the composition and palaeogeography of the Widmerpool, Bowland Shale and Morridge Formations and the Millstone Grit Group.

The Widmerpool Formation, formally defined by Aitkenhead and Chisholm (1982), consists of dark to pale brown, calcareous or carbonaceous, locally pyritic, fissile mudstones, interbedded with turbidites consisting of quartzose/calcareous siltstone and sandstones (Waters et al., 2009). This formation is a predominantly turbiditic deposit with southerly-sourced sediments mainly derived from the Wales-Brabant High (Aitkenhead et al., 2002)

The upper part of the Craven Group is represented by the Bowland Shale Formation (in this area, formerly termed the 'Edale Shales', Waters et al., 2007), which has a highly diachronous upper boundary across the sub-basins of the Pennine Basin: early Pendleian in the Craven Basin (Riley, 1990); Kinderscoutian in the Widmerpool Gulf (Figure 2; Waters et al., 2007) and Yeadonian in North Wales (Davies et al., 2004; Waters et al., 2007). In the Widmerpool Gulf, the Bowland Shale Formation passes laterally southwards into the sandstone dominated Morridge Formation (Millstone Grit Group) which accumulated along the northern margin of the Wales-Brabant High (Waters et al., 2009).

The Morridge Formation was introduced as a distinct unit by Waters et al. (2009) to highlight the different source area for the fluvio-deltaic successions from the rest of the Millstone Grit Group found in the more northern parts of the Pennine Basin. The Morridge Formation contains pale protoquartzitic sandstone intervals sourced from the Wales Brabant High while the terrestrial material for the remainder of the Millstone Grit Group is sourced from the north. Lithologically, the Morridge Formation consists of interbedded dark grey, shaly mudstones and pale protoquartzitic silt- to sandstones interpreted as turbiditic sand bodies and shallow-water fluvio-deltaic facies (Waters et al., 2009).

2.2 The Bowland-Hodder Unit

Andrews (2013) introduced the informal stratigraphic unit 'Bowland-Hodder unit' (BHU) in the Bowland Basin, referring to the seismically defined unit of Fraser et al. (1990). The base of this informal unit broadly equates to the top of the Chadian carbonates identified in the Widmerpool Gulf while the top of the unit corresponds to the base of the sandstone dominated Millstone Grit (Figure 3). Because of the progradational nature of the Millstone Grit, the top of the Bowland-Hodder is highly diachronous (Aitkenhead et al., 2002; Waters et al., 2007). Andrews (2013) subdivided the BHU into two parts:

1) a lower unit comprising syn-rift sediments (Chadian–Brigantian) deposited during the formation of the Pennine sub-basins (see above). This unit contains slumps, debri-flows and turbidites and laterally passes to limestone deposited over the highs (Gawthorpe and Clemmey, 1985; Riley, 1990).
2) an upper unit composed of post-rift sequences (latest Brigantian–Pendleian, locally Arnsbergian, proving its highly diachronous nature) deposited during the period of thermal sag and periodic transgression of an epicontinental sea in combination with deltaic sequences that became more important (Fraser et al., 1990). This unit was informally termed the 'upper Bowland Shale' (see also Aitkenhead et al., 2002).

The boundary between these two parts has been taken as the onset mudrocks with a characteristic high gamma response on downhole geophysical logs, which has been equated to the Visean–Namurian

(Brigantian–Pendleian) boundary and in terms of biostratigraphy generally coincides with the *Emstites leion* marine band (Andrews, 2013).

2.3 The Rempstone 1 and Old Dalby 1 boreholes

The two boreholes discussed by Kenomore and co-authors are Rempstone 1 (national grid reference SK 58212 24053; BGS reference number SK52SEBJ39) and Old Dalby 1 (national grid reference SK68143 23703; BGS reference number SK62SEBJ14), both located in the most southern part of the Widmerpool Gulf, close to the northern margin of the Wales-Brabant High (Figure 1). The schematic lithological logs of Yeadonian and older deposits in the boreholes are depicted in Figure 3c following Andrews (2013) and Pharaoh et al. (2011). These logs have been coloured to reflect the lithology in function of the informal BHU introduced in section 2.2 and indicated the intervals for which Kenomore et al. (2017) applied the ΔLog R method (black) and the intervals for which Rock-Eval data was published by Andrews (2013). Analysis of Figure 1 and Figure 3 raises two issues:

1. Rempstone 1 and Old Dalby 1 are located in the southernmost part of the Widmerpool Gulf, which makes them unrepresentative for the basin as a whole as they are subject to proximal deposition with a high proportion of siliciclastic input. This is reflected in the lithostratigraphic successions (Figure 3): the Bowland Shale Formation laterally passes into the Morridge Formation, it is expected to find thicker deposits of Bowland Shale in the centre and more to the north of the Widmerpool Gulf (Section 2.1). This is apparent in the Duffield 1 core (national grid reference SK 34280 42170, BGS reference number SK34SWBJ5, Aitkenhead, 1977) where a greater proportion of shale is proven than in either Rempstone 1 and Old Dalby 1 (Figure 3).

2. Kenomore et al. derive TOC values for the Upper Bowland Shale using the ΔLog R technique, and restrict themselves to the Bowland Shale Formation. They then compare the obtained results to the Rock-Eval results published in Andrews (2013) to conclude their measurements are comparable to the pyrolysis results. However, it is important to note that in Rempstone 1 the Rock-Eval results originate from samples from the upper part of the Morridge Formation and in Old Dalby pyrolysis was performed on samples from the Widmerpool Formation. These two formations are very different from the Bowland Shale Formation (see Section 2.1), and therefore a direct comparison is invalid and is a cause of confusion.

3. The ΔLog R (Passey) methodology

To evaluate the conclusions of the Kenomore et al. (2017) study, we applied the ΔLog R methodology to the same wireline data used by these authors. The TOC was calculated using the ΔLog R method inbuilt into the Senergy Software Interactive Petrophysics™ TOC calculator. The methodology employed in the current paper follows the general method outlined by Gent et al. (2014) in their TOC calculation in the Jurassic shales of the Weald Basin. In the ΔLog R method, scaled sonic and resistivity curves overlay in a 'lean shale' defined as a non-source shale. When overlain correctly, the TOC curve was well calibrated with the measured TOC from Andrews (2013). As highlighted by Kenomore et al. (2017), the lean shale point is difficult to establish when just considering two wells with limited core data. For this study the lean shale point was chosen to fall in the central part of the Morridge Formation for both Old Dalby 1 and Rempstone 1 (~1250 m and ~690 m respectively).

The density and neutron overlay plots were used to verify those of the sonic log. Sonic slowness is preferentially used as it is least susceptible to inaccuracies arising from poor borehole conditions often encountered when drilling shales.

A key parameter in the Passey equation for calculating TOC is the level of maturity (LOM), originally derived to calculate coal rank (Passey et al., 1990). The LOM can be calculated from vitrinite reflectance values (Ro) (Hood et al., 1975) (Equation 1; obtained from Schlumberger's Techlog™ software):

$$LOM = 0.0989 \times Ro^5 - 2.1587 \times Ro^4 + 12.392 \times Ro^3 - 29.032 \times Ro^2 + 32.53 \times Ro - 3.0338 \quad (1)$$

The output TOC curves were calculated first using the expected maturity. The maturity parameters were then adjusted according to variations in the Rock-Eval and vitrinite reflectance data to the maximum and minimum values (Table 3). Shading on the TOC curve in the graphical log plots displays this uncertainty (shading in Figures 4 and 5), where higher maturity values give lower TOC values for a given set of logs and vice versa.

Reservoir intervals have to be removed from the calculated TOC curve as the Passey method only accounts for source rocks. This was achieved by applying a volume of clay (VCl) discriminator based on the gamma ray response. Over the Bowland Shale this has no effect as it is in its entirety considered as a shale for the purposes of this calculation. In the overlying Morridge Formation and underlying Widmerpool Formation the shales are interbedded with significant thicknesses of limestone and sandstone, which have been removed, leaving null values in the calculated TOC curve (Figure 4).

The vertical resolution of the calculated TOC is limited by the resolution of the logging tools. Therefore, for example, sharply varying TOC values across thinly interbedded shale, coal and sand intervals may be indistinguishable and is likely to be presented as a smoother TOC curve response (Passey et al, 2010). By contrast, each TOC measurement from core or cutting samples represent a single point in the succession.

In addition to these points, it is important to highlight the influence of pyrite on petrophysical logs, discussed by amongst others Clavier et al. (1976) and Kennedy (2004). Kenomore and co-authors (p. 140) suggest only a completely pyritised section (with a density of 5 g/cm^3) will influence measurements and because none of the cores reach that density they conclude pyrite content is negligible. We contest this and in the Morridge Formation pyrite content is so abundant (up to 7.6%; in Carsington Dam Reconstruction Borehole C3, Hennissen et al., 2017) to the point where it influences vitrinite reflectance analysis (Paul C. Hackley, written communication, 2017). For the Bowland Shale Formation similar values (up to 6.7 wt%; Hennissen et al., 2017) have been recorded from the Edale Basin. These values exceed the 5 wt% threshold where a steep decline in resistivity due to pyrite influence has been reported (Clavier et al., 1976; Clennell et al., 2010) and therefore it can be expected that the results of the Passey method as applied by Kenomore and co-authors will have been influenced by the pyrite presence.

4. The ΔLog R method on Rempstone 1 and Old Dalby 1

The methodology detailed in Section 3 was applied to the geophysical logs of Rempstone 1 and Old Dalby 1 to produce Figure 4. To calibrate the TOC calculations, we use vitrinite reflectance data from Coombes et al. (1986) in Rempstone 1 (Table 1) and T_{max} calculated Ro data from Andrews (2013) in both boreholes (Table 2) to determine the LOM presented in Table 3. Also included in Figure 4 are the results presented by Kenomore and co-authors.

Analysis of Figure 4 clearly shows:

1. Kenomore et al. (2017) calibrated Rempstone 1 and Old Dalby 1 TOC outputs with calculated maturity values from intervals outside the stratigraphic limits of the Bowland Shale Formation. In the Rempstone 1 Borehole they used a fixed average calculated Ro of 0.71 (Tmax of 437°C) based on the 5 measurements from Andrews (2013) in the Morridge Formation (Table 1) while in Old Dalby 1 these authors used the lower estimate of 0.6 for Ro.
2. In Figure 4a, we present a curve calibrated using additional vitrinite reflectance measurements from the end of well report from Rempstone 1 (Coombes et al., 1986). These measured vitrinite reflectance values are taken to be more reliable than the T_{max} equivalent Ro (T_{max} eq. Ro) from Andrews (2013) as they are a direct measurement: T_{max} eq. Ro is acquired using the Jarvie et al. (2001) equation, calibrated for the Barnett Shale, which may introduce errors when used in a different setting (e.g. Wüst et al. 2013). Here, we find an increase in TOC with larger uncertainties, especially in the Bowland Shale Formation (purple curve, Figure 4a). However, the results from Kenomore et al. (2017) seem to correlate better with this calculated curve rather than the Rock-Eval calculated values from Andrews (2013) (blue curve in Figure 4a).
3. Calibration of the calculated TOC curves in Old Dalby 1 is very difficult. The interbedded nature of the Widmerpool Formation (the source of the Rock-Eval data) do not represent a thick shale sequence preferred when calibrating the calculations.

These three points show the influence of the original Rock-Eval data on the outcome of the calculated TOC. None of these measurements from Andrews (2013) were performed on the interval targeted by Kenomore et al. (2017). Given the highly interbedded nature and sedimentologically diverse character of both the Widmerpool Formation and the Morridge Formation (Section 2), where the Rock-Eval measurements were made, it is unlikely these represent the same depositional environments reflected by the Bowland Shale Formation. Therefore, we believe that the statement by Kenomore et al. (2017) that the results of the study correlate well with the average values of previously published BGS data is misleading. Moreover, it is important to note that the Passey method was intended for identifying and calculating TOC in organic-rich rocks (Passey et al., 1990), but not for resource play evaluation (see also Lecompte and Hursan, 2010).

5. Conclusions

In reviewing the study published by Kenomore et al. (2017) we uncovered several flaws which mostly reflect poor consideration of the geological setting of the Carboniferous deposits in the Widmerpool Gulf. These can be subdivided into geological and methodological concerns:

Geological concerns:

1) The thermal maturity utilised to calibrate the TOC calculations in the Passey methodology for the Bowland Shale Formation were from different formations. In the Rempstone 1 Borehole, Rock-Eval measurements from the Morridge Formation while in Old Dalby 1 Rock-Eval measurements from the Widmerpool Formation were used.

2) Both wells investigated by Kenomore and co-authors were located in the southernmost part of the Widmerpool Gulf. Only a very thin interval of Bowland Shale was proven in these boreholes making them unsuitable datapoints representing of the Widmerpool Gulf as a whole.

3) Pyrite is a major component in the Carboniferous mudstones of the Widmerpool Gulf surpassing the 5 wt.% threshold where it has shown to have an influence on the well log responses.

Methodological concerns:

1) The Rock-Eval data used for the calibration of the maturity comes from interbedded formations and no information of the lithology of these samples is known; the Morridge and Widmerpool formations are heterolithic mudstone-sandstone successions. The provenance of the organic material and the TOC as a whole in the mudstones and sandstones is different and these changes occur at a higher resolution than the resolution of the geophysical logs.

2) No robust geochemical data set is available to calibrate the calculation.

We recommend that more geochemical data is collected to calibrate the TOC models and that this occurs in the formations that are the subject of the modelling exercise. This should then be repeated for more wells and over a larger area within the Widmerpool Gulf, in order to make the extrapolations credible. It is important to realise the limitations of the ΔLog R methodology. We believe the ΔLog R method could be used as a steering tool to identify intervals of interest but because of the heterogeneous nature of the Carboniferous deposits it falls short to perform a meaningful assessment of the potential resource and more traditional multi-proxy approaches need to be applied (e.g. Rock-Eval, palynofacies analysis, X-ray diffraction and carbon isotope analysis). This is mostly due to the onus being placed on the level of maturity (LOM) in its derivation. Because of the variable lithology and with it, variable organic content and character, we believe the ΔLog R methodology is not a viable replacement for traditional TOC determinations (eg. Rock-Eval pyrolysis) in the Widmerpool Gulf.

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Figure Captions

Figure 1: Mississippian paleogeography of the UK (A) and a focus on the Widmerpool Gulf and adjacent areas with the boreholes discussed in the text.

Figure 2: Stratigraphic column in the Bowland Basin, Edale Basin and Widmerpool Gulf plotted, with the Bowland Shale Formation highlighted, against the local (Holliday and Molyneux, 2006) and global (Davydov et al., 2012) chronostratigraphy (modified after Hennissen et al., 2017).

Figure 3: The informal Bowland-Hodder Unit (BHU); A: Schematic diagram of the BHU in a fault-bounded sub basin of the Pennine basin (modified after Andrews, 2013); B: idealized succession through the Millstone Grit and Bowland Hodder unit (modified after Andrews, 2013); C: schematic logs of four key Widmerpool boreholes, Duffield (following Gross et al., 2014), Carsington Dam composite (followingAitkenhead, 1991; Aitkenhead et al., 2002), Rempstone 1 (following Pharaoh et al., 2011) and Old Dalby 1 (following Pharaoh et al., 2011).

Figure 4: Comparison of the ΔLog R methodology applied to the Rempstone 1 borehole. Note the position of the cored intervals which form the bases of the Rock Eval analysis presented in Andrews (2013). Shaded envelopes in curves 5a and 5b represent uncertainty intervals for the calculated TOC.

Figure 5: Comparison of the ΔLog R methodology applied to the Old Dalby 1 borehole. Note the position of the cored intervals which form the bases of the Rock Eval analysis presented in Andrews (2013). Shaded envelopes in curves 5a and 5b represent uncertainty intervals for the calculated TOC.

Figure 6: A crossplot of TOC and S2, indicative of hydrocarbons formed during thermal decomposition, in Widmerpool Gulf samples. Data from Hennissen et al. (2017) and Andrews (2013).

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Figure Captions

Figure 1: Mississippian paleogeography of the UK (A) and a focus on the Widmerpool Gulf and adjacent areas with the boreholes discussed in the text.

Figure 2: Stratigraphic column in the Bowland Basin, Edale Basin and Widmerpool Gulf plotted, with the Bowland Shale Formation highlighted, against the local (Holliday and Molyneux, 2006) and global (Davydov et al., 2012) chronostratigraphy (modified after Hennissen et al., 2017).

Figure 3: The informal Bowland-Hodder Unit (BHU); A: Schematic diagram of the BHU in a fault-bounded sub basin of the Pennine basin (modified after Andrews, 2013); B: idealized succession through the Millstone Grit and Bowland Hodder unit (modified after Andrews, 2013); C: schematic logs of four key Widmerpool boreholes, Duffield (following Gross et al., 2014), Carsington Dam composite (followingAitkenhead, 1991; Aitkenhead et al., 2002), Rempstone 1 (following Pharaoh et al., 2011) and Old Dalby 1 (following Pharaoh et al., 2011).

Figure 4: Comparison of the ΔLog R methodology applied to the Rempstone 1 borehole. Note the position of the cored intervals which form the bases of the Rock Eval analysis presented in Andrews (2013). Shaded envelopes in curves 5a and 5b represent uncertainty intervals for the calculated TOC.

Figure 5: Comparison of the ΔLog R methodology applied to the Old Dalby 1 borehole. Note the position of the cored intervals which form the bases of the Rock Eval analysis presented in Andrews (2013). Shaded envelopes in curves 5a and 5b represent uncertainty intervals for the calculated TOC.

Figure 6: A crossplot of TOC and S2, indicative of hydrocarbons formed during thermal decomposition, in Widmerpool Gulf samples. Data from Hennissen et al. (2017) and Andrews (2013).

Figure 1

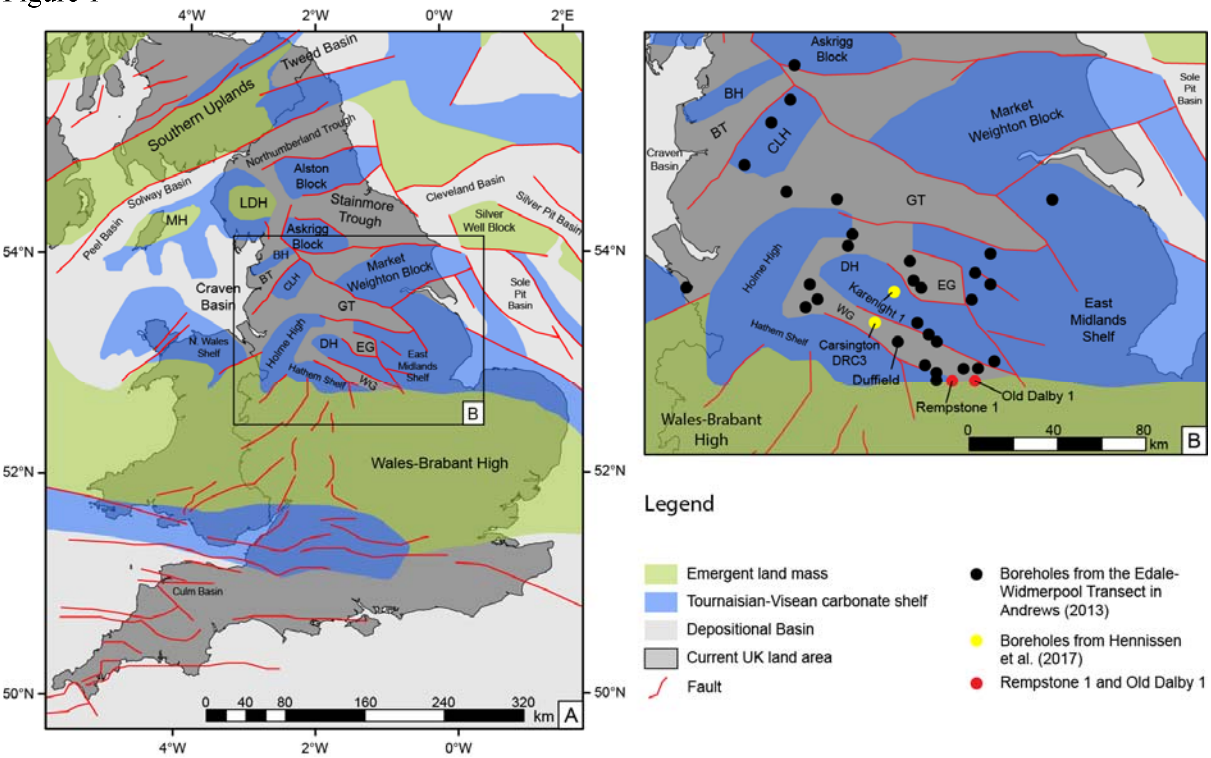


Figure 2 (next page)

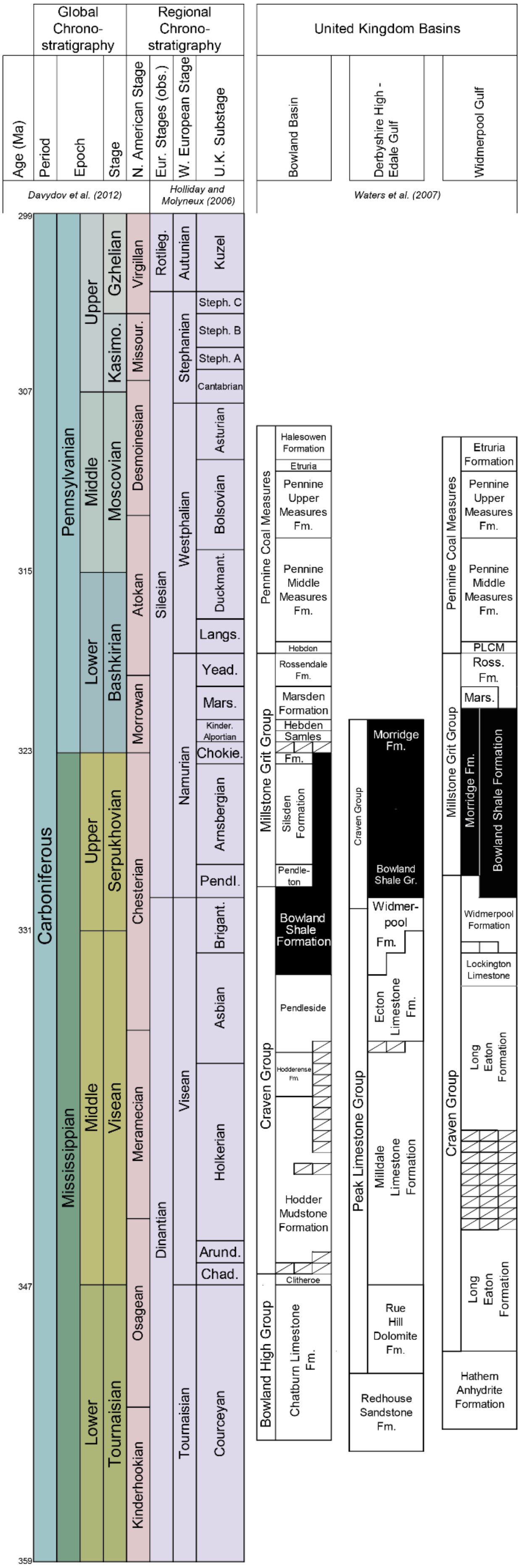

Global Chrono-stratigraphy
Regional Chrono-stratigraphy
United Kingdom Basins
Age (Ma)
Period
Epoch
Stage
N. American Stage
Eur. Stages (obs.)
W. European Stage
U.K. Substage
Bowland Basin
Derbyshire High - Edale Gulf
Widmerpool Gulf
Davydov et al. (2012)
Holliday and Molyneux (2006)
Waters et al. (2007)
299
307
315
323
331
347
359
Carboniferous
Pennsylvanian
Mississippian
Upper
Middle
Lower
Gzhelian
Kasimo.
Moscovian
Bashkirian
Serpukhovian
Visean
Tournaisian
Virgillan
Missour.
Desmoinesian
Atokan
Morrowan
Chesterian
Meramecian
Osagean
Kinderhookian
Rotlieg.
Silesian
Dinantian
Autunian
Stephanian
Westphalian
Namurian
Visean
Tournaisian
Kuzel
Steph. C
Steph. B
Steph. A
Cantabrian
Asturian
Bolsovian
Duckmant.
Langs.
Yead.
Mars.
Kinder.
Alportian
Chokie.
Arnsbergian
Pendl.
Brigant.
Asbian
Holkerian
Arund.
Chad.
Courceyan
Pennine Coal Measures
Halesowen Formation
Etruria
Pennine Upper Measures Fm.
Pennine Middle Measures Fm.
Hobdon
Millstone Grit Group
Rossendale Fm.
Marsden Formation
Hebden
Samles
Fm.
Silsden Formation
Pendle-ton
Bowland Shale Formation
Craven Group
Pendleside
Hodderense Fm.
Hodder Mudstone Formation
Clitheroe
Bowland High Group
Chatburn Limestone Fm.
Craven Group
Morridge Fm.
Bowland Shale Gr.
Widmer-pool Fm.
Ecton Limestone Fm.
Peak Limestone Group
Milldale Limestone Formation
Rue Hill Dolomite Fm.
Redhouse Sandstone Fm.
Etruria Formation
Pennine Upper Measures Fm.
Pennine Middle Measures Fm.
PLCM
Ross. Fm.
Mars.
Millstone Grit Group
Morridge Fm.
Bowland Shale Formation
Widmerpool Formation
Lockington Limestone
Craven Group
Long Eaton Formation
Long Eaton Formation
Hathem Anhydrite Formation

Figure 3

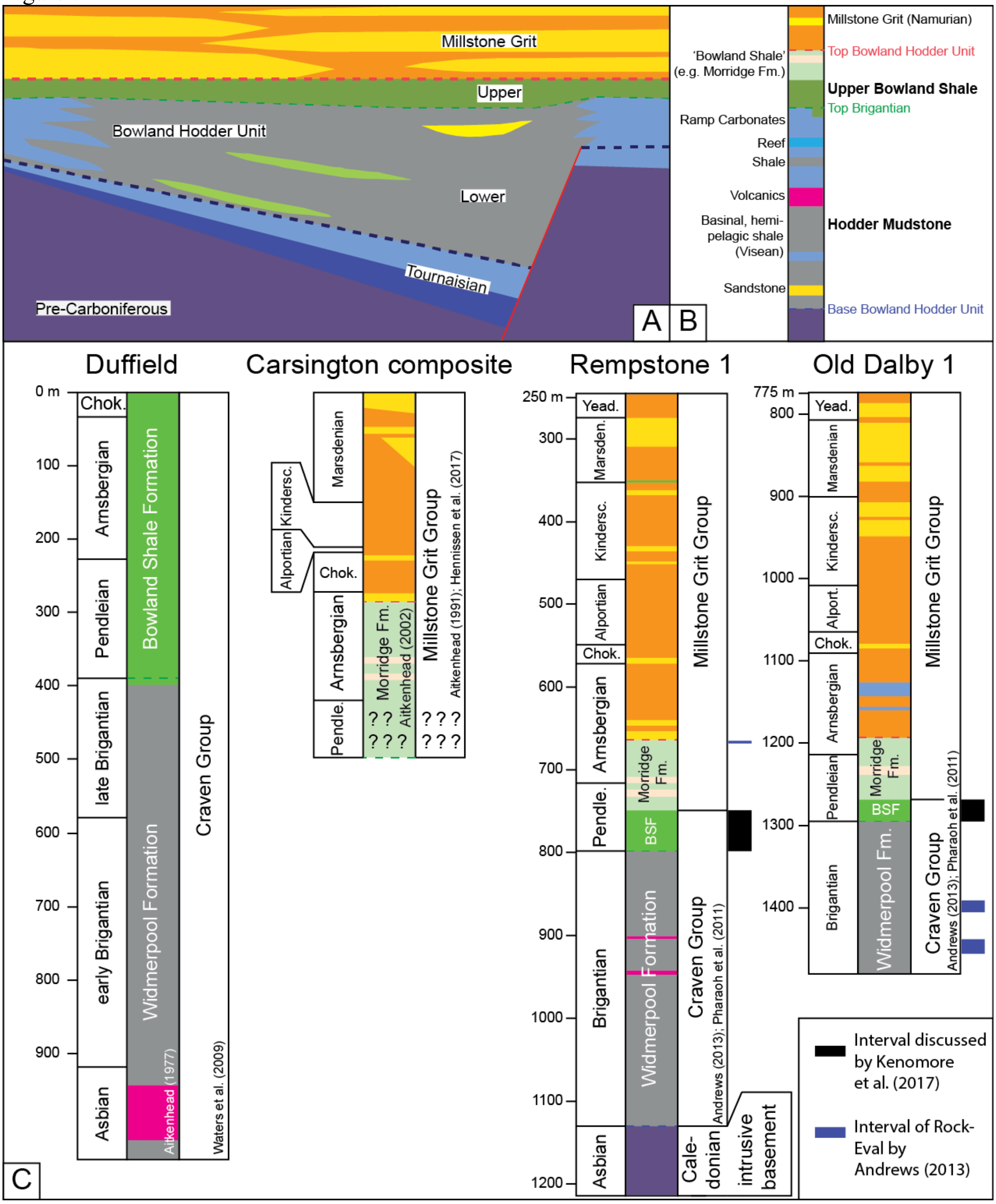
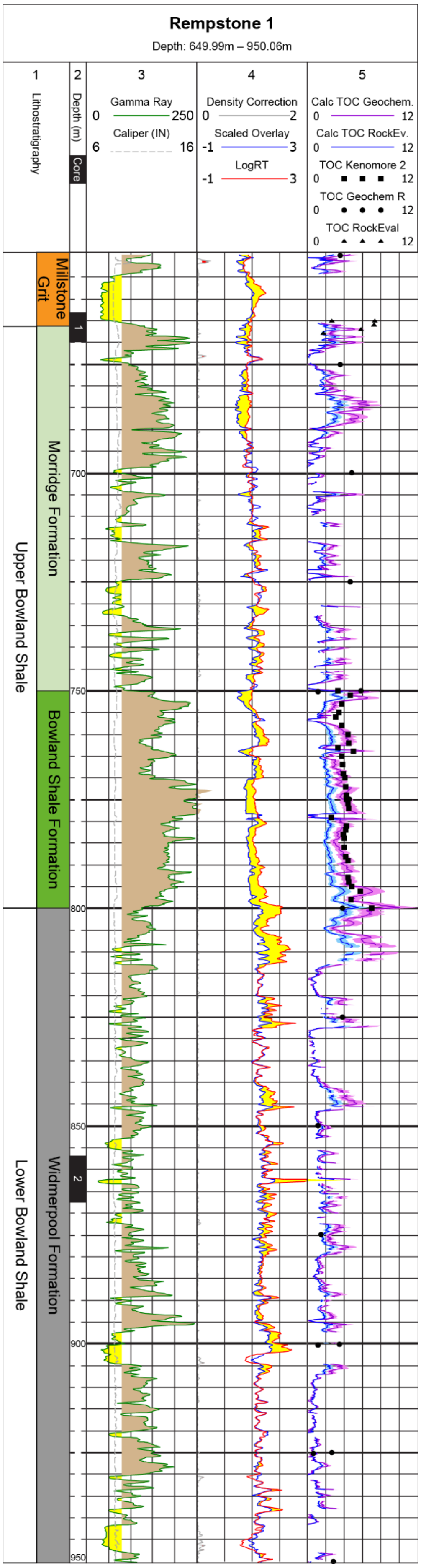
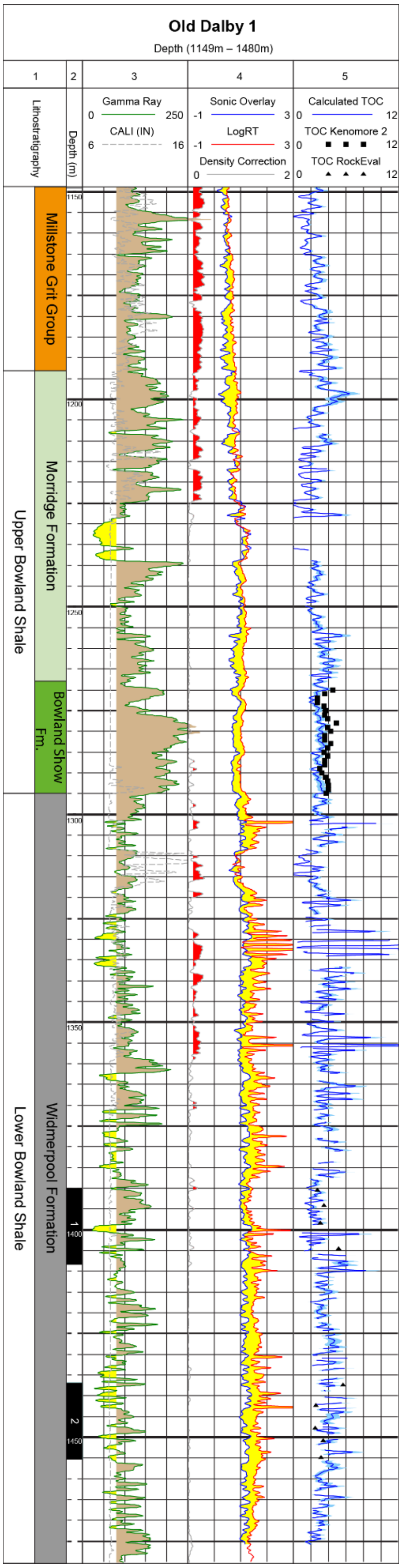


Figure 4 (next page)



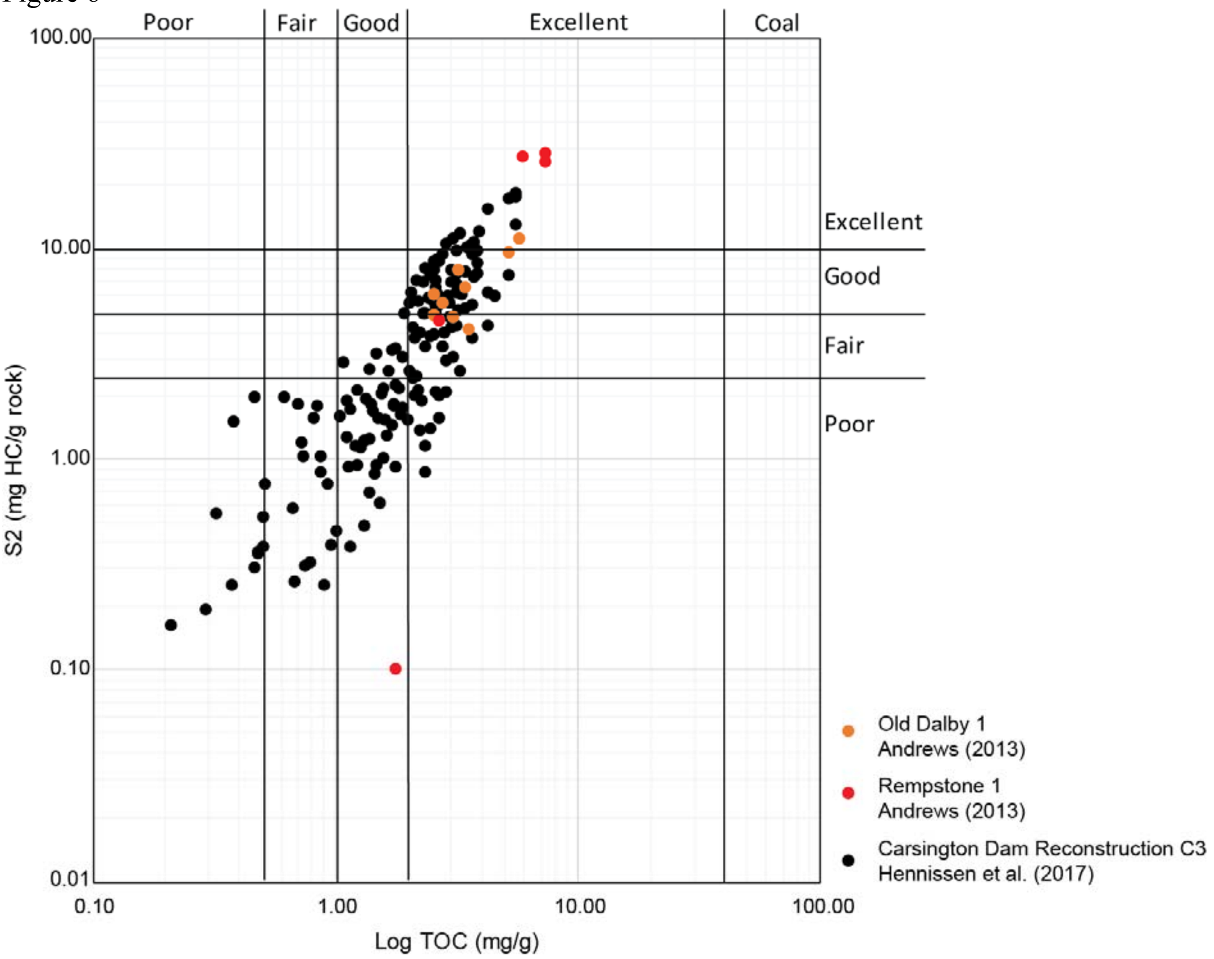
Rempstone 1
Depth: 649.99m – 950.06m
1
Lithostratigraphy
2
Depth (m)
Core
3
Gamma Ray
0 250
Caliper (IN)
6 16
4
Density Correction
0 2
Scaled Overlay
-1 3
LogRT
-1 3
5
Calc TOC Geochem.
0 12
Calc TOC RockEv.
0 12
TOC Kenomore 2
0 12
TOC Geochem R
0 12
TOC RockEval
0 12
Millstone Grit
Upper Bowland Shale
Morridge Formation
Bowland Shale Formation
Lower Bowland Shale
Widmerpool Formation
1
2
700
750
800
850
900
950

Figure 5



Old Dalby 1
Depth (1149m – 1480m)
1
2
3
4
5
Lithostratigraphy
Depth (m)
Gamma Ray
0
250
CALI (IN)
6
16
Sonic Overlay
-1
3
LogRT
-1
3
Density Correction
0
2
Calculated TOC
0
12
TOC Kenomore 2
0
12
TOC RockEval
0
12
Millstone Grit Group
Morridge Formation
Upper Bowland Shale
Bowland Show Fm.
Widmerpool Formation
Lower Bowland Shale
1150
1200
1250
1300
1350
1400
1450
1
2

Figure 6



Poor
Fair
Good
Excellent
Coal
100.00
10.00
1.00
0.10
0.01
S2 (mg HC/g rock)
Excellent
Good
Fair
Poor
Old Dalby 1
Andrews (2013)
Rempstone 1
Andrews (2013)
Carsington Dam Reconstruction C3
Hennissen et al. (2017)
0.10
1.00
10.00
100.00
Log TOC (mg/g)

Tables

Tables

Table 1: Rock-Eval and vitrinite reflectance results from Coombes et al. (1986) in the Rempstone 1 borehole

Rempstone 1		
Coombes et al. (1986)		
Depth (m)	TOC (%)	%Ro
650	3.6	0.5
675	3.6	
700	4.8	
725	4.7	
750	5.8	0.5
775	4.6	
800	3.8	
825	3.8	
850	1.2	0.46
875	1.5	
900	3.5	
925	2.7	
950	2.8	0.44

Table 2: Rock-Eval results from Andrews (2013) in the Old Dalby 1 and Rempstone 1 boreholes

Rempstone 1					Old Dalby 1				
Depth (m)	Depth (ft)	TOC (wt. %)	T_{max} (°C)	T_{max} R_o	Depth (m)	Depth (ft)	TOC (wt.%)	T_{max} (°C)	T_{max} R_o
665.0	2181.8	2.66	437	0.71	**1390.6**	4562.3	2.73	436	0.69
665.3	2182.7	7.31	437	0.71	**1394.3**	4574.5	3.53	433	0.63
666.0	2185	7.29	438	0.72	**1398.5**	4588.3	3.06	434	0.65
667.0	2188.3	5.87	437	0.71	**1404.6**	4608.3	5.12	432	0.62
668.0	2191.6	1.77	431	0.60	**1437.5**	4716.2	5.65	435	0.67
					1442.5	4732.6	2.55	434	0.65
					1447.8	4750	2.54	436	0.69
					1450.8	4759.8	3.40	438	0.72
					1455.0	4773.6	3.18	436	0.69
Average:		4.98	436	0.69	Average:		3.53	435	0.67

Table 3: Level of Organic Maturity (LOM) and equivalent vitrinite reflectance values and sources used in the TOC calculation. The error margins are represented by blue shading on the graphical log plot (Figure 4). *Ro calculated from Tmax using the following equation following Jarvie et al. (2001) $Ro = 0.0189 \times Tmax - 7.16$ Where Tmax is in degrees Celsius.

	Bowland Shale & Morridge Formation		Widmerpool Formation	
	Vitrinite Reflectance (Ro)	Level of Maturity (LOM)	Vitrinite Reflectance (Ro)	Level of Maturity (LOM)
Rempstone 1				
Rock-Eval and Ro data (Coombes et al., 1986)	0.51 ±0.04	7.5 ±0.5	0.56 ±0.05	8.0 ±0.5
Rock-Eval data (Andrews, 2013)	0.69 ±0.07*	9.2 ±0.5	0.73 ±0.07*	9.5 ±0.5
Old Dalby 1				
Rock-Eval data* (Andrews, 2013)	0.61 ±0.05*	8.5 ±0.5	0.66 ±0.06*	9.0 ±0.5