Method and Data-Acquisition Workflow for Rock-Type Definitions in the Lower Carboniferous Resource Play, NW England*

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Abstract

The Lower Carboniferous shales of Northern England are currently under the early stages of exploration. Lithological heterogeneity, both lateral and vertical, is a major challenge to prediction of reservoir and completion design. We here present a method and a workflow for data acquisition and effective characterization of rock types based on data collected from two newly drilled exploration wells.

The two exploration wells penetrated the Namurian section before terminating in the Visean Carboniferous Limestone Supergroup. A comprehensive data-acquisition program was carried out to fully characterize the lower Namurian section and the underlying prospective Visean limestone facies. The wireline log-suite acquired included elemental spectroscopy logs, dipole sonic and image logs, in addition to standard wireline logs. In both wells, sections of the Namurian stratigraphy were cored and a comprehensive work program was conducted including shale source-rock specific petrophysical core analysis, geomechanical studies and source-rock evaluation as well as XRD and XRF data acquisition. XRD and XRF measurements on rotary sidewall cores and cuttings were also conducted.

Use of rigorous mathematical solutions allows us to simplify the range of lithologies and to develop data-derived rock type characteristics. This approach, combined with facies analysis and depositional system modeling, also allowed us to predict rock properties and to selectively sample the formations. Ten rock types were defined ranging from calcareous, quartzose/siliceous, mixed and to argillaceous types. The rock types exhibit a strong stratigraphic distribution. The distribution reflects facies changes related to different depositional systems and the large-scale controls on those systems. Understanding this relationship can assist in the future with subsequent lithostratigraphic correlations and enhanced horizontal well placement, once additional data are acquired on existing and new wells.

The prospective parts of the stratigraphy that have optimal properties including high TOC and brittleness have been related to specific rock-type ranges. The essential compositional characteristics for these rock types have been defined, facilitating identification via multi-element

fingerprinting. Future work will continue to improve the model and develop a robust framework for assessing lithological heterogeneity and geomechanical properties of the Lower Carboniferous resource play.

Introduction

The Lower Carboniferous resource play in Northern England is a target for hydrocarbon exploration across central Britain (Andrews 2013). It is critical to target predominantly marine organic-rich, low-clay, fine-grained rock types with high hydrocarbon content in which a large fracture network can be induced (i.e. Bustin and Bustin 2012). We here present data from two exploration wells.

Geological Setting

The Lower Carboniferous shales in the North West were deposited in rift basins formed by crustal extension between early Devonian (pre rift) to late Namurian (post rift) (Figure 1). The basin morphology and sedimentation patterns (including thickness) were controlled by basin bounding faults, resulting in the accumulation of relatively thick sequences of basinal shales and turbidites, with thinner platform carbonate sequences deposited on highs (Waters et al. 2009). Inversion occurred during the Variscan Orogeny when up to 5 km of uplift occurred in some areas. Sedimentation comprises a variety of carbonate, and clastic facies, which were deposited under the influence of glacio-eustasy and tectonic events. The initial Dinantian fill comprises up-to 1400-m-thick sequence of shales, siltstones and thin limestones deposited in a relatively deep water, sometimes anoxic, setting. The late Namurian fill of coarse-grained clastics and shales was deposited by a deltaic system that prograded from the NE towards the SW. Local subsidence and faulting also created complex depositional patterns and lateral heterogeneity. Despite this complexity, lithological variations generally reflect two main depositional settings: hemipelagic mudstone associated to carbonate platforms and hemipelagic mudstone associated to the deltaic system.

Method and Data-Acquisition Workflow

The two exploration wells penetrated the Namurian section before TD in the Visean Carboniferous Limestone Supergroup. A comprehensive data-acquisition program was carried out to fully characterize the early Namurian section and the underlying prospective Visean limestone facies. The wireline log-suite acquired included elemental spectroscopy logs, dipole sonic and image logs, in addition to standard wireline logs. In both wells, sections of the Namurian stratigraphy were cored and a comprehensive work program was conducted including shale source rock specific petrophysical core analysis, geomechanical studies and source-rock evaluation as well as XRD and XRF data acquisition. XRD and XRF measurements on rotary sidewall cores (RSWCs) and cuttings were also conducted.

The following methodology was developed:

- Step 1: Develop rock-typing characterization by PCA.
- Step 2: Perform advanced petrophysical log analysis in order to characterize the formation.

- Step 3: Measure geomechanical properties of the rock to correlate the logs to the rock. Leeb hardness tests were performed, alongside fluid compatibility tests to characterize the 'reactivity' of the rock type.
- Step 4: Analyze each rock type with respect to correlation with mechanical properties and the potential reactivity with the fracturing fluid.
- Step 5: Conduct fracture modeling to estimate the extent of the stimulated rock volume and the type of fractures that could be created.

Rock Type Classification by PCA

Principal Component Analysis (PCA) was used to define the rock types because this multivariate approach can be used to develop a mathematical expression of the key differentiators between the various lithologies (Esbensen 2010, Schovsbo et al. 2015). PCA was also used to develop a simplified range of lithologies. PCA was performed on both XRF and XRD data, as well as on wireline log readings. PCA transforms a matrix of measured data (N samples, P variables), X, into sets of projection sub-spaces delineated by Principal Components (each a linear combination of all variables), which display variance-maximized interrelationships between samples and variables respectively. PCA score plots display groupings, or clusters, between samples based on compositional similarities, as described by the variable correlations (shown in accompanying loading plots), and also quantify the proportion of total data-set variance that can be modeled by each component. All data analyses in this work are based on auto-scaled data [X-X(avg)/std].

From the variable loading plot (Figure 2), the main lithological components were identified from the correlations between elemental spectroscopy log readings. These included quartz, carbonate, clay, and organics. The rock types were defined in a series of PCA steps by slicing the PCA-1 and PCA-2 score space. The PCA-defined rock types were further calibrated with core description, and mud-log data to provide the lithological descriptions (Figure 3). The definition of rock type is an iterative process in which the rock types are re-evaluated following further data acquisition. The ultimate goal is to resolve PCA-based rock types as mineralogically consistent categories with discrete descriptions and connections to clay species, TOC, porosity, and gas saturation. Furthermore, this simplified rock-type approach has been used to predict rock properties and selectively sample the formations.

Compositional Variance of Rock Types, and Stratigraphical and Geographic Distribution

Average total clay content is the main compositional variable between rock types. Rock type 10 (carbonate to calcareous sandstone) has the lowest average clay content, and rock types 15-19 (argillaceous types) have the highest average clay content. Rock types 11-14 (quartzose/siliceous and mixed types) have intermediate average clay content.

The rock types exhibit a strong stratigraphic distribution (Figure 4). In Well A, the Visean and early Namurian stratigraphy is dominated by quartzose/siliceous and mixed types (types 11-14) whereas the late Namurian stratigraphy is dominated by argillaceous types (type 15-19). In Well B, the early Namurian stratigraphy is dominated by rock type 15 (mixed) whereas the late Namurian stratigraphy is dominated by rock types 18 and 19 (argillaceous). In addition, five of the rock types occur in both wells (types 10, 11, 14, 16 and 18), whereas four are unique to Well A (rock types 12, 13, 15, and 17) and one is unique to Well B (rock type 18). These differences reflect facies changes related to different depositional systems and the large-scale controls on those systems and can assist in the future with subsequent lithostratigrahic correlations which can enhance horizontal well placement, once additional data is acquired on existing and new wells.

Conclusions

A method and workflow for rock-type definitions and the prediction of associated rock properties, based on log and/or XRF data, has been developed for Lower Carboniferous strata in North West England. We have successfully applied a specific rock-typing methodology, (PCA of XRF rock composition and wireline log characteristics) to recognize 10 rock types in this heterogeneous succession, to which we can associate specific geomechanical properties. The simplified range of 10 lithologies within the Lower Carboniferous resource play includes calcareous rocks (type 10), quartzose/siliceous rocks (type 11-13), mixed composition rocks (type 14), and argillaceous rocks (15-19). The prospective parts of the stratigraphy that have optimal properties including high TOC and brittleness have been related to specific rock-type ranges.

The essential compositional characteristics for these rock types in exploratory wells have been defined, facilitating identification via multi-element fingerprinting. This method allows for “quick-look” rock-type identification using a hand-held XRF scanner, applicable in the lab or at the drill site. In combination with facies analysis and depositional system modeling, this approach allows us to predict rock properties. Consequently, selective sampling of key formations for both routine analysis and specialised rock-mechanics analysis is possible. This ensures a cost effective programme for future data acquisition, aiding exploration decision making. Future work will continue to improve the model and develop a robust framework for assessing lithological heterogeneity and geomechanical properties of the Lower Carboniferous resource play.

Acknowledgment

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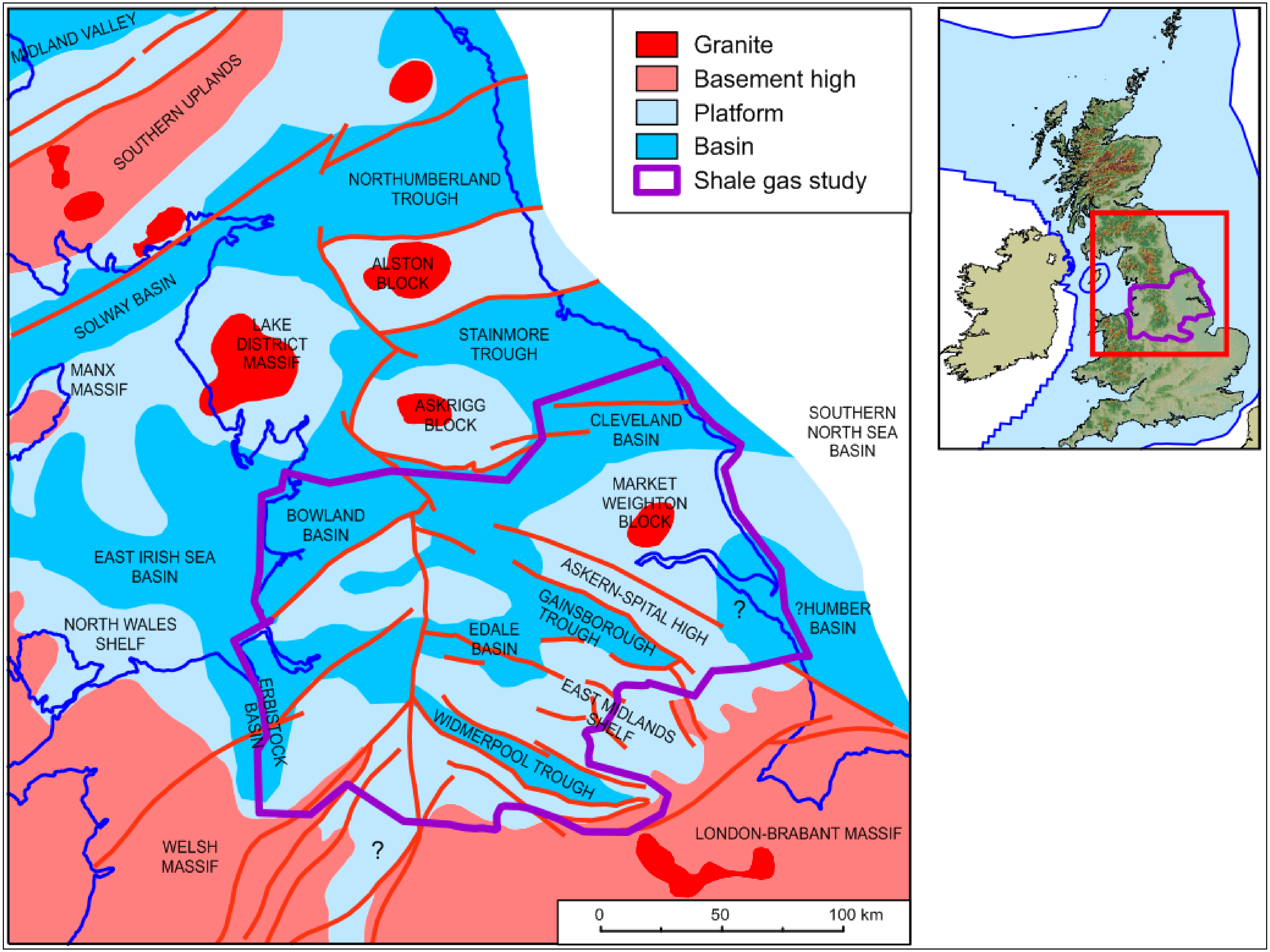

Figure 1. The Early Carboniferous basins and platforms of central Britain (from Andrews 2013).

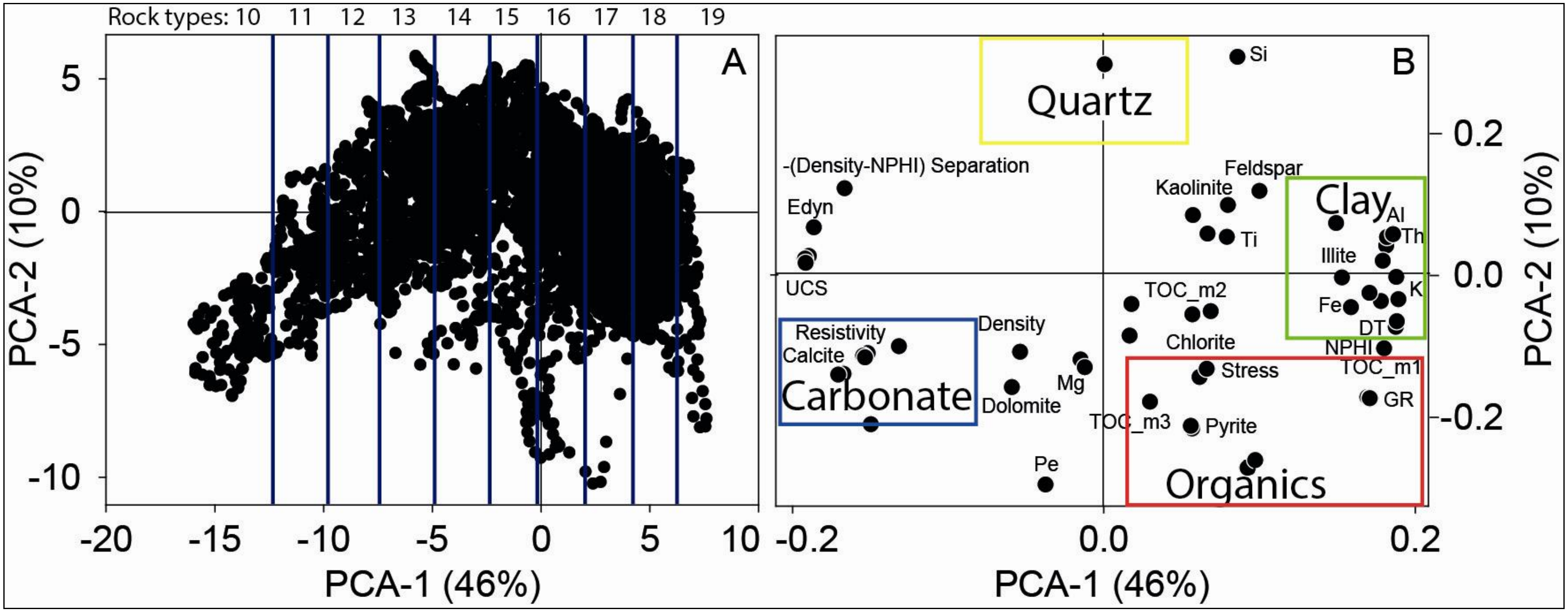

Figure 2. Results of multivariate data analysis, principal component analysis (PCA), based on wireline log data including various calculated properties from one well. A) Score plot, B) Loading plot of the first and second PCA components. The first two principal components model 56% of the total variance. In A) Rock types (RT10-RT19) are defined by slicing the PC-1 axis into 10 consecutive groupings (shown in a simplistic manner in A). In B) the main variable correlations responsible for this lithological division are identified. Main lithotypes include quartz, carbonate, clay and organics.

Rock Type	Description	Color code
10	Limestone to carbonate-cemented sandstone	
11	Sandstone/siltstone with low carbonate content /carbonate stringers	
12	Quartz rich siltstone with biogenic silica and silicified shale	
13	Quartz rich siltstone with biogenic silica and silicified shale	
14	Siltstone	
15	Siltstone/silty mudstone	
16	Silty mudstone	
17	Mudstone	
18	Argillaceous mudstone	
19	Argillaceous mudstone	

Figure 3. PCA-defined rock types that have been calibrated with core description and mud-log data to provide the lithological descriptions. Note that some rock types have similar descriptions. More data and further analyses should help resolve lithological differences.

Stratigraphy		10	11	12	13	14	15	16	17	18	19
		ROCK TYPES									
		Calcareous	Quartzose/siliceous			Mixed	Argillaceous				
Well A	Late Namurian III	-	-	-	-	m	M	m	m	-	-
	Late Namurian II	-	-	-	-	-	m	M	M	M	-
	Late Namurian I	-	-	-	M	M	-	-	-	-	-
	Early Namurian II	-	-	m	m	m	M	M	M	-	-
	Early Namurian I	M	m	M	-	-	-	-	-	-	-
	Visean	m	-	M	-	-	-	-	-	-	-
Well B	Late Namurian II	m	m	-	-	-	-	m	-	M	M
	Late Namurian I	m	M	-	-	m	-	-	-	-	-
	Early Namurian I	m	m	-	-	M	-	-	-	-	-
	Visean	M	m	-	-	-	-	-	-	-	-

Figure 4. Relative abundance of rock types. Legend: M= major occurrence; m=minor occurrence. For lithostratigraphy, see Waters et al. (2009).