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Significance of sedimentary organic matter input for shale gas generation potential of Mississippian Mudstones, Widmerpool Gulf, UK

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ABSTRACT

Carboniferous mudstones in central and northern England are shale gas prospects but the controls on the amount and composition of organic matter are not well understood, even though these parameters define the volumes of gas generated in fine-grained sediments. Organic matter in samples from basinal late Mississippian (Arnsbergian) mudstones in the Widmerpool Gulf was characterised by using semi-quantitative ($n = 58$) and quantitative palynofacies ($n = 16$) analyses, sporomorph counts and bulk rock geochemistry (total organic carbon, $\delta^{13}C$ of bulk organic matter, Rock-Eval Pyrolysis).

The results of this study suggest that most organic matter at this location was delivered to the sediment–water interface as aggregates of a granular translucent type of amorphous organic matter (AOM_{Gr}, mean = 66.7% ± 19.3%) via hemipelagic suspension settling. AOM_{Gr} represents fragments of algal material with subordinate inclusions of small plant fragments and pyrite framboids held together by microbial colonies. AOM_{Br} (brown granular amorphous organic matter) is the second most abundant group (mean = 15.6% ± 8.5%) comprising similar microbial colonies that grew on suspended land plant-derived fragments in the water column. Palynofacies components representing clearly terrestrial organic matter are much less abundant and include gelified organic matter (G, mean = 9.6% ± 12.6%), black phytoclasts (Ph_{Bl} mean = 2.7% ± 4.7%), brown phytoclasts ($Ph_{Br,}$ mean = 3.3% ± 3.6%) and sporomorphs (mean = 1.4% ± 1.3%). Sediment delivery processes influence the balance between terrestrial organic matter and AOM_{Gr}. During low sea-level times, turbidity currents and debris flows delivered terrestrial organic matter (representing 12% to 40% of the palynofacies). Kerogen composition varies between Type II and III. In contrast, thin-bedded carbonate-bearing mudstones deposited during rising and high sea-level contain up to 95% AOM_{Gr} and these high abundances correspond to higher total organic carbon. Carbonate and AOM_{Gr} were generated by high bioproductivity in the water column. Type II (oil- and gas-prone) kerogens are dominant in these mudstones and therefore these intervals represent the best potential targets for thermogenic shale gas.

1. Introduction

The hydrocarbon source rock potential of fine-grained sediments is largely controlled by the original amount and composition of sedimentary organic matter buried with the sediment. Understanding small-scale variations of organic matter in relation to sedimentary processes and changes in depositional environment is crucial for identifying prolific source rock intervals, particularly in prospective gas shales (e.g., Passey et al., 2010; Aplin and Macquaker, 2011). This is important because gas concentrations are not evenly spread in shale gas reservoirs, unlike in conventional, buoyancy-driven oil and gas fields where hydrocarbons fill intergranular pore spaces as a homogenous phase across a reservoir (Tissot and Welte, 1984; Mann et al., 1997).

Early Namurian (Mississippian) basinal mudstones present in subsurface and outcrop in the Pennine province of Central and Northern England are regarded as potential targets for onshore shale gas exploration (Department of Energy and Climate Change, 2010; Roche, 2012; Selley, 2012). Specifically, the Upper Bowland Shale Formation and Edale Shale Group mudstones are believed to represent source rocks for conventional hydrocarbon finds in this region (e.g., Fraser et al., 1990; Smith et al., 2010); however, detailed studies determining the depositional controls of oil and gas producing intervals are lacking. The re-evaluation as shale gas reservoirs requires refined investigations of the distribution and composition of organic matter (OM) within these mudstone-dominated successions.

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In this study, we present organic geochemical and palynological data from mudstones obtained from one fully cored borehole located in the Widmerpool Gulf, Derbyshire, UK. We describe the variability of organic matter present in these mudstones and relate the OM content to sedimentary processes and changing depositional environment. The findings presented here contribute to current understanding of how biological input affects the shale gas source rock potential of fine-grained sediments.

Previous studies of Mississippian mixed shallow marine to deltaic deposits in the Northumberland Basin and the Alston Block revealed that amorphous organic matter (AOM) and land plant fragments (phytoclasts) are the main organic matter constituents and the ratio between these determines the overall characteristics of the bulk OM. Because AOM is dominant in samples from marine limestone horizons (Stephenson et al., 2008) and their equivalent clay-rich marine bands in the Pennine Basin (Hawkins et al., 2013), with mean bulk organic $\delta^{13}C$ around −28.5‰ (Lewan, 1986), it has been interpreted to originate from marine phytoplanktonic and other algae. In contrast, land-derived phytoclasts characterise the terrestrially influenced fluvio-deltaic intervals (Frank and Tyson, 1995; Stephenson et al., 2008). Bulk terrestrial OM can also be distinguished by its average $\delta^{13}C$ of −23.5‰ (Peters-Kottig et al., 2006). This isotopic pattern has been used in several studies conducted on bulk OM of Carboniferous age (e.g., Maynard, 1981; Wenger et al., 1988; Stephenson et al., 2008; Davies et al., 2012), although absolute $\delta^{13}C$ levels of these end members vary through this period in response to global changes in atmospheric CO_2 (Stephenson et al., 2010). Similar studies, however, have not been undertaken for the mudstone-dominated successions deposited in the deeper water basins of the southern Pennine province during the early Namurian. Several studies suggest that partly fossiliferous mudstones, including the marine bands contain more total organic carbon (TOC) than fossil-barren intervening mudstones (e.g., Spears and Amin, 1981; Kombrink, 2008; Smith et al., 2010); however, no specific links between sedimentary processes and depositional environment with OM content and composition have been reported.

Here we use a detailed palynofacies scheme (Table 1) to track changes in the composition of particulate OM through a vertical borehole section. The relative abundance of the palynofacies groups, obtained from point counts, is compared with bulk total organic carbon, organic $\delta^{13}C$ and microlithofacies data compiled in Könitzer et al. (2014). Thus, we examine the variation of organic matter content with respect to sediment delivery processes and depositional environment. This study also represents one of the first transmitted light microscopic investigations of Carboniferous organic matter attempting to distinguish different types of AOM and to critically consider the possible origin and processes of these types. Finally, we discuss the hydrocarbon source rock properties, obtained from Rock-Eval parameters, for all lithofacies and OM types present.

2. Geological setting

The Widmerpool Gulf is one of several small, linked marine basins in the southern Pennine province which acted as depocentres for fine-grained sediments of the Edale Shale Group during the Visean to Namurian. This area was located between the northern Pennine province, which was influenced by regional supply of siliciclastic material from fluvio-deltaic systems from the northeast (Collinson, 1988; Waters and Davies, 2006) and the emergent Wales–London–Brabant High in the south (Fig. 1). Sedimentation in the basins was characterised by the accumulation of dark, fissile mudstones in a continuously submerged setting in water depths of a few hundred metres (Collinson, 1988; Aitkenhead et al., 2002). Significant rises in sea-level are recorded by (in places) fossiliferous mudstone successions. These include 'marine bands', intervals which contain diagnostic ammonoid fauna used for biostratigraphic subdivision and correlation (Ramsbottom, 1977; Holdsworth and Collinson, 1988; Davies, 2008) and are interpreted as maximum flooding surfaces (e.g., Hampson et al., 1997). During sea-level regressions, mudstones barren of macrofossils were deposited with interbedded silt- and sandstone turbidites delivered from delta slopes fringing the Wales–London–Brabant High (Trewin and Holdsworth, 1973; Aitkenhead, 1977; Chisholm et al., 1988; Collinson, 1988).

Sea-level fluctuations are thought to have been driven by glacio-eustatic forcing (Ramsbottom, 1977; Holdsworth and Collinson, 1988; Hampson et al., 1997; Stephenson et al., 2010; Waters and Condon, 2012). The first glacial phase C1 of significant ice sheets in the southern hemisphere during the late Pendleian to mid-Arnsbergian (Fielding et al., 2008) induced high-frequency and high-magnitude sea-level fluctuations following ca. 110 ka and 400 ka Milankovitch eccentricity rhythms (Waters and Condon, 2012). The E_{2a3} (*Eumorphoceras yatesae*) marine band present in the studied succession (Fig. 1C) is considered to

Table 1
Palynofacies scheme based on observed organic particle properties under transmitted white and incident UV light (after Combaz, 1980; Venkatachala, 1981; Batten, 1983, 1996; Highton et al., 1991; Tyson, 1995; Ercegovac and Kostić, 2006; Sebag et al., 2006; Stephenson et al., 2008).

Category	Group		Description
Amorphous organic matter (AOM)	AOM_{Gr}	Granular translucent AOM	Heterogeneous, colourless to dark grey particles with diffuse edges and inclusions of other particles Moderate to strong patchy fluorescence
	AOM_{Br}	Brown AOM	Similar to granular translucent AOM, but with inner gelified aspect Moderate patchy fluorescence
Gelified organic matter	G	Gelified OM (including vitrinite)	Black, dark brown or amber lustrous particles, lacking internal structure. Dull irregular or smooth edges Weakly fluorescent
Phytoclasts (Ph_{total})	Ph_{Bl}	Black opaque phytoclasts	Opaque angular clasts or laths Non-fluorescent
	Ph_{Br}	Brown phytoclasts	Brown sharp-edged fragments with remnant biostructure: pitted features, cross-hatching or thickenings Weak or no fluorescence
		Membranes	Light brown or grey non-cellular, angular sheets Non-fluorescent
		Cuticles and other translucent fragments	Brown to colourless sheets with cellular or fibrous structures Strongly fluorescent
Algae remains	A	Prasinophycean phycomas, e.g., Leiosphaeridia Acritarch cysts	Discrete folded, circular or spinose entities Very strong fluorescence
		Undifferentiated algal remains	Light brown to colourless tube-like filaments, yellow translucent non-cellular folded sheets Strong to very strong fluorescence
Sporomorphs	S	Spores and Pollen	Miospores 30–100 μm Monosaccate pollen 150–300 μm Very strong fluorescence