Marine and Petroleum Geology 71 (2016) 198–210

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

Geochemical and lithological controls on a potential shale reservoir: Carboniferous Holywell Shale, Wales

Leo P. Newport*, Andrew C. Aplin, Jon G. Gluyas, H. Chris Greenwell*, Darren R. Gröcke

Durham University, Department of Earth Sciences, Science Labs, Durham, DH1 3LE, UK

A R T I C L E I N F O

Article history:
Received 3 July 2015
Received in revised form
14 October 2015
Accepted 30 November 2015
Available online 8 December 2015

Keywords:
Bowland Shale
Mudstone
Source rock
Shale gas
Lithofacies
Organofacies
Carboniferous
Petrography

A B S T R A C T

The Holywell Shale is part of the Carboniferous Bowland Shale Formation, identified as the main potential shale gas system in the UK. Here, we report geochemical and petrographic data from five outcrops of the Lower and Upper Holywell Shale across northeast Wales. At outcrop, the Holywell Shale is immature to early oil mature and has total organic carbon (TOC) values ranging between 0.1 and 10.3 wt %, with a mean of 1.9 wt %. Carbon isotope data clearly differentiate terrestrial and marine organic matter and show that both occur throughout the Holywell, with terrestrial sources (Type III/IV) dominating the Upper Holywell and marine sources dominating the Lower Holywell (Type II/III). Trace element data indicate that bottom waters were oxygenated, resulting in poorly preserved organic matter, supported by C/N and HI data. A range of silt- and clay-rich lithofacies occur, which show no relationship to either the amount or type of organic matter. We interpret the data in terms of a mixed supply of terrestrial and marine organic matter to marine depositional environments in which there was sufficient hydrodynamic energy to transport fine-grained sediment as bed load. The resulting mudstones exhibit a range of sedimentary textures with millimetre- to centimetre-scale silt–clay bed forms which show almost no relationship to organic matter type and amount. The small-scale variability and heterogeneity of both organofacies and lithofacies means that the reservoir quality of the Holywell Shale is inherently difficult to predict.

1. Introduction

Over the past decade the production of hydrocarbons from unconventional sources has increased significantly, specifically with the development and exploitation of mudstone source-rock reservoirs where hydrocarbons have been generated *in-situ* (Hart et al., 2013). A key shale gas target in the UK is the Carboniferous Bowland-Hodder Formation of the Pennine Basin (Andrews, 2013). The present study focuses on the Holywell Shale deposits of northeast Wales, part of the Bowland Shale Formation, and investigates the way in which a complex interplay of sediment supply, depositional environment and provenance and preservation of organic matter influences the source-rock reservoir quality of this major mudstone unit.

The Carboniferous basins of northern England, including the Pennine Basin in which the Holywell Shale was deposited (Fig. 1), were formed during the Dinantian (359.2–326.4 Ma) by a phase of rifting that was dominated by N–S extension acting along pre-existing NW–SE and NE–SW post-Caledonian weaknesses to create asymmetrical half-graben structures. Subsequent Namurian sedimentation (326.4–314.5 Ma) occurred during a period of post-rift thermal subsidence which created sufficient accommodation space for the accumulation of up to 2 km of sediments, including the Holywell Shale (Fraser and Gawthorpe, 1990; Williams and Eaton, 1993). The type-section for the Holywell Shale is contained within the Abbey Mills borehole with a maximum thickness of 152 m (Davies et al., 2004; Waters, 2009).

Namurian sedimentation in northern England generally occurred in a shallow epicontinental seaway within a series of connected basins stretching across the UK and Ireland (Fig. 2; Davies et al., 1999). Sediment was supplied from the north into deltaic systems and shallow seas and deposited in water depths of less than 100–200 m (Fig. 2; Wells et al., 2005). Sea levels in the late Mississippian and early Pennsylvanian were also strongly influenced by a series of glacioeustatic cycles which resulted in global sea level variations of 60–100 m (Rygel et al., 2008) which

* Corresponding authors.
E-mail addresses: leo.p.newport@gmail.com (L.P. Newport), chris.greenwell@durham.ac.uk (H.C. Greenwell).

http://dx.doi.org/10.1016/j.marpetgeo.2015.11.026
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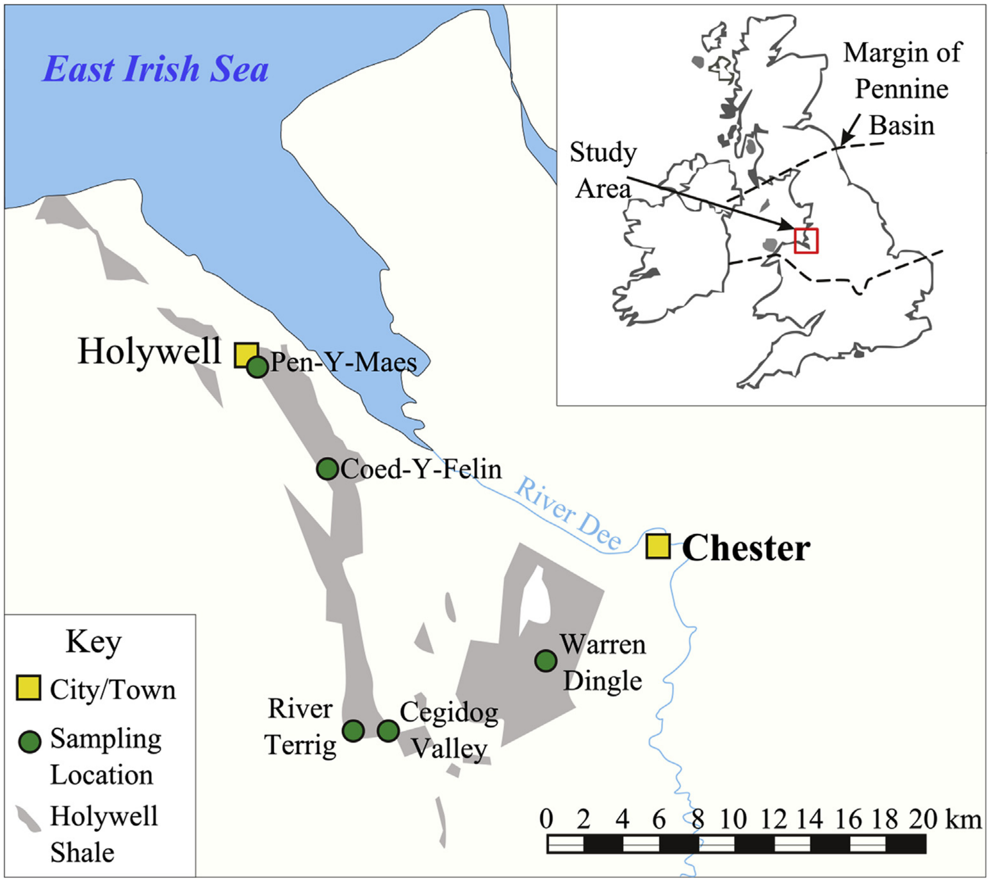

Fig. 1. Map of the study area with the wider location (inset image), showing the extent of the Holywell Shale (grey) and the main outcrop locations studied.

are well recognised in the UK Namurian (Armstrong et al., 1997; Bott and Johnson, 1967; Church and Gawthorpe, 1994; Hampson et al., 1996; Jerrett and Hampson, 2007; Martinsen et al., 1995; Ramsbottom, 1977; Wright et al., 1927). The Holywell Shale was thus deposited as a succession of marine, brackish and non-marine mudstones on the southwest edge of the Pennine Basin (Fig. 2; Collinson, 1988; Davies et al., 2004; Guion and Fielding, 1988). Maximum flooding surfaces are represented by a series of ammonoid (goniatite) marine bands up to several metres thick, which contain assemblages of both benthic and planktonic fauna and which represent a range of fresh water to saline environments (Waters et al., 2009). These marine bands allow the Holywell Shale to be dated biostratigraphically (Fig. 3; Davies et al., 2004; Ramsbottom, 1974, 1978; Waters and Condon, 2012).

Organic carbon contents of Namurian mud-rich sediments in northern England typically range from 1 to 3%, with values up to 8% (Andrews, 2013). Palynological and carbon isotope studies show that the organic matter is derived from both marine and terrestrial sources (Stephenson et al., 2008; Davies et al., 2012). Previous work suggests that at least parts of the Lower Holywell Shale (E1c age; Fig. 3) has petroleum potential and may have sourced oils in the Douglas and Lennox oilfields in the East Irish Sea (Armstrong et al., 1997).

The quality of shale reservoirs relates to both their gas/oil storage potential and the rate at which that petroleum can be delivered to a wellbore from matrix pores to a fracture network induced by hydraulic fracturing. These factors relate in turn to the nature and amount of organic matter in the rocks, and also their lithology and mineralogy (e.g. Passey et al., 2010). In a depositional system like the Holywell Shale, in which both water depth and the supply of both sediment and organic matter changed over short periods of geological time, controls on shale reservoir quality will be complex in both space and time, and thus difficult to predict. In this context, we look here at a series of samples from both the Lower (Pendleian to Arnsbergian) and Upper (Marsdenian to Yeadonian) units of the Holywell Shale to determine whether there are relationships between the sedimentology and mineralogy of the rocks and the nature and amount of organic matter.

2. Methods

2.1. Sample site description

Samples were collected from outcrops of the Holywell Shale. Outcrop access was restricted due to the limited exposure of the Holywell Shale within northeast Wales (Fig. 1). The outcrops sampled consisted of narrow sections (<1 m) within stream cuttings, where samples were taken from an area of ~0.5 m^2. In the case of River Terrig and Pen-Y-Maes, which were more extensive, multiple sites were sampled along the exposures and therefore, represent a more significant range in stratigraphy (Fig. 3). Due to faulting, the River Terrig location does not represent a continuous sequence of deposition and the stratigraphic placement of this location is difficult as the E2b3 pelagic goniatite fauna (*Cravenoceratoides nititoides*) is only reported as present on the north side of the fault (RTS2 sampling site, with RTS3, RTS5, RTS6 sampling