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The nature of porosity in organic-rich mudstones of the Upper Jurassic Kimmeridge Clay Formation, North Sea, offshore United Kingdom

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ABSTRACT

Analyses of organic-rich mudstones from wells that penetrated the Upper Jurassic Kimmeridge Clay Formation, offshore United Kingdom, were performed to evaluate the nature of both organic and inorganic rock constituents and their relation to porosity in this world-class source rock. The formation is at varying levels of thermal maturity, ranging from immature in the shallowest core samples to mature in the deepest core samples. The intent of this study was to evaluate porosity as a function of both organic macerals and thermal maturity.

At least four distinct types of organic macerals were observed in petrographic and SEM analyses and they all were present across the study area. The macerals include, in decreasing abundance: 1) bituminite admixed with clays; 2) elongate lamellar masses (alginite or bituminite) with small quartz, feldspar, and clay entrained within it; 3) terrestrial (vitrinite, fusinite, semifusinite) grains; and 4) *Tasmanites* microfossils. Although pores in all maceral types were observed on ion-milled surfaces of all samples, the pores (largely nanopores with some micropores) vary as a function of maceral type. Importantly, pores in the macerals do not vary systematically as a function of thermal maturity, insofar as organic pores are of similar size and shape in both the immature and mature Kimmeridge rocks. If any organic pores developed during the generation of hydrocarbons, they were apparently not preserved, possibly because of the highly ductile nature of much of the rock constituents of Kimmeridge mudstones (clays and organic material).

Inorganic pores (largely micropores with some nanopores) have been observed in all Kimmeridge mudstones. These pores, particularly interparticle (i.e., between clay platelets), and intraparticle (i.e., in framboidal pyrite, in partially dissolved detrital K-feldspar, and in both detrital and authigenic dolomite) are noteworthy because they compose much of the observable porosity in the shales in both immature and mature samples.

The absence of a systematic increase in organic porosity as a function of either maceral type or thermal maturity indicates that such porosity was probably unrelated to hydrocarbon generation. Instead, much of the porosity within mudstones of the Kimmeridge appears to be largely intraparticle and interparticle (adjacent to inorganic constituents), so the petroleum storage potential in these organic-rich mudstones largely resides in inorganic pores.

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1. Introduction

Intense research on mudstones (shales) in recent years, particularly those containing abundant organic carbon, has been driven by the desire to better characterize these fine-grained rocks in order to gain a more comprehensive understanding of them as unconventional petroleum (gas, oil, or natural gas liquids) reservoirs. Technological advances have resulted in the successful completion of thousands of wells in the last few years that now produce petroleum from these low porosity/low permeability unconventional reservoirs, also referred to as shale gas or shale oil reservoirs. In fact, in the United State, the volume of proven reserves of natural gas increased 11% between 2008 and 2009, largely due to the development of shale gas (Energy Information Administration, 2010). Furthermore, oil and natural gas liquids (e.g., propane, butane, etc.) are increasingly being produced from mudstones. Overall, petroleum exploration in these

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fine-grained, unconventional reservoirs has expanded worldwide in an attempt to exploit these self-sourced reservoirs (Fishman et al., 2011).

Petroleum production from mudstones has outpaced their characterization, especially the mechanism(s) by which petroleum is stored in them. Mudstone petroleum reservoirs typically have low porosity (Hill et al., 2008), so any process that increases porosity in these rocks would serve to enhance their storage potential and, thereby, potentially improve productivity. A recent hypothesis suggests that porosity is created within kerogen as a result of the volume change it undergoes during and after petroleum generation (Jarvie et al., 2007). Should such a mechanism result in the development of secondary pores, and if that porosity is available to store petroleum in mudstone petroleum reservoirs (Loucks et al., 2009, 2010, 2012; Slatt and O'Brien, 2011), then organic porosity would be considered a key, and possibly a necessary component of shale petroleum systems. There have been some excellent papers published recently regarding porosity and pore networks in mudstones and claystones (e.g., Bernard et al., 2012; Curtis et al., 2012; Desbois et al., 2009; Heath et al., 2011; Keller et al., 2011; Loucks et al., 2012; Lu et al., 2011). Nevertheless, there has been no comprehensive test of the hypotheses that 1) increasing thermal maturity, with attendant petroleum generation, results in a systematic and progressive increase in secondary porosity in organic macerals; and 2) development of secondary porosity in organic macerals with maturation is a function of maceral type, although Loucks et al. (2012) and Schieber (2010) did suggest that the type of organic material may play a role in the formation of pores as a function of thermal maturity.

We have undertaken a study of the Upper Jurassic Kimmeridge Clay Formation, in the offshore United Kingdom (Fig. 1), to test the hypotheses that porosity in organic material (i.e., kerogen) systematically increases with thermal maturation, and that maceral type may control the nature and amount of secondary porosity developed with maturation. The Kimmeridge is a world-class petroleum source rock, and is the principal source of oil and gas produced from the North Sea (e.g., Chew and Stephenson, 1986; Gautier, 2000; Klemme and Ulmishek, 1991; Peters et al., 2007). This study focused on a suite of cores drilled through parts of the Kimmeridge, where the cores span a distance of about 120 km in a northwest-southeast direction (Fig. 1). In these cores, the Kimmeridge is at variable levels of thermal maturity (Fig. 1), ranging from immature (vitrinite reflectance (R_o) is <0.5%) to mature (R_o ~1.3%). Much of the analyses presented below are from three wells, where attention was focused because in these wells the Kimmeridge is at different levels of thermal maturity (see below). The wells are: 1) 21/23B-3, referred to as the low maturity well; 2) 21/18-2AS1, referred to as the intermediate maturity well; and 3) 22/28a-1, referred to as the high maturity well (Fig. 1).

The emphasis of the results presented herein has been on 1) systematic documentation and comparison of the nature of organic macerals in the various cores; 2) characterizing the presence and nature of porosity, both inorganic and organic, and 3) comparing the characteristics of pores observed in the Kimmeridge Clay Formation across the study area. The intent of this investigation was to establish porosity characteristics for the Kimmeridge in the region of study. Caution should be exercised in extrapolating these results and interpretations to the Kimmeridge in other regions, as well as to other mudstone petroleum reservoirs, without careful consideration of similarities and differences to the Kimmeridge studied here.

2. Geologic setting

The Upper Jurassic Kimmeridge Clay Formation (Fig. 2) is one of the thickest and most extensively distributed marine mudstone successions in Europe (cf. Wignall, 1991; Ziegler, 1990). The formation consists of several hundreds to in places more than 1400 m of clay-rich lithologies with intercalated sandstone units toward the margins of individual sub-basins and graben structures (Richards et al., 1993). Although locally, coccolith limestones and diagenetic limestone and dolomite beds are interbedded with the shales (Williams et al., 2001), the formation is mud-dominated (Fig. 3). Internally, the

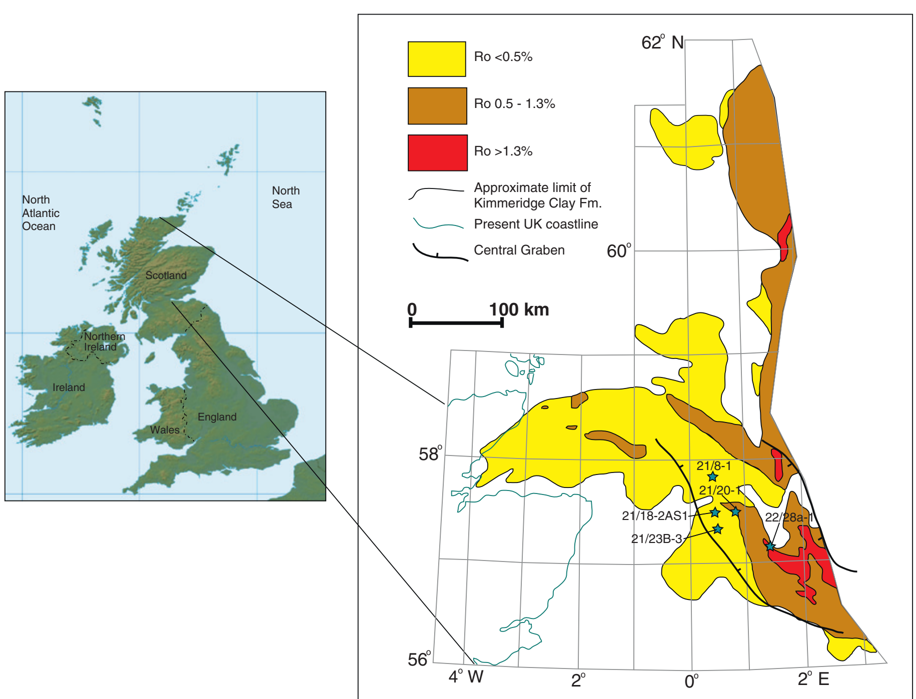

Fig. 1. Map showing location of cores used in this study from offshore United Kingdom (UK). Core identification numbers also shown. Complete data sets (e.g., mineralogy, geochemistry, petrography, etc.) are presented herein for cores 21/23B-3, 21/18-2AS1, and 22/28a-1, whereas observational data only are presented for cores 21/8-1 and 21/20b-3. Extent of thermal maturation data on top of Kimmeridge Clay Formation modified from Johnson et al. (2005). Approximate position of the Central Graben also shown.