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Porosity and permeability characterization of coal: a micro-computed tomography study

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ABSTRACT

A unique contrast agent technique using X-ray micro-computed tomography (micro-CT) was developed for studying micrometer-sized features in coal. The technique allows for the visualization of coal fractures not visible with conventional imaging methods. A Late Permian medium volatile bituminous coal from Moura coal mine was imaged and the resulting three-dimensional coal cleat system was extracted for fluid flow simulations. The results demonstrate a direct relationship between coal lithotype and permeability, i.e. bright coals offer more permeability than dull coals. However, there was no direct relationship between porosity and permeability for any given lithotype. Scanning electron microscope and energy dispersive spectrometry (SEM–EDS) together with X-ray diffraction (XRD) methods were used for identifying mineral matter at high resolution. After segmentation of the micro-CT image, mineral phase was removed from the segmented data and it was found that permeability was significantly improved by increasing cleat void space and connectivity; suggesting that enhanced recovery methods could target de-mineralization techniques. Overall, only the epigenetic mineral phases in the bright band influenced permeability while lithotype had a stronger impact on permeability than porosity. Coal lithotype and mineralization are important evaluation criteria when considering coal seam gas development sites.

1. Introduction

Coal is a dual porosity system containing micropores and a network of natural fractures known as cleats. Whereas the micropores account for most of the porosity in coal, the cleat network offers the permeability for fluid flow (Clarkson and Bustin, 1996; Moore, 2012; Puri et al., 1991). Cleats are characterized by two main orthogonal sets of fractures "face" and "butt" cleats that, in most instances, are perpendicular to the bedding (Close, 1993; Close and Mavor, 1991; Laubach et al., 1998; Ting, 1977). Intrinsic and extrinsic forces in coal create cleats (Su et al., 2001) with endogenetic and exogenetic origins. Face cleats are the dominant, well-developed through-going cleats formed first, cutting across the bedding surface while butt cleats are formed later and generally are short, discontinuous and terminating at the intersection with face cleats (Ting, 1977; Laubach and Tremain, 1991; Laubach et al., 1998). In some coals, a third set of cleats are developed perpendicular to the bedding intersecting the face and butt cleats (Gamson et al., 1993). Cleat properties are affected by many factors including coal rank, layer thickness, composition and *in-situ* stress regimes (Laubach et al., 1998; Su et al., 2001; Ting, 1977). The dependence of cleat properties on these factors and their inter-relationships are not well understood. Cleat network structure varies noticeably with coal composition and is among the most important factors affecting permeability in coal (Flores, 2014). It has been observed that, in general, coal cleat frequency increases from lignite to medium-to-low volatile bituminous coal (Ammosov and Eremin, 1963; Law, 1993; Su et al., 2001; Ting, 1977; Tremain et al., 1991). However, after this point, vitrinite reflectance of 1.3–1.5%, coals have shown different behaviors in terms of cleat frequency; decreases (Ammosov and Eremin, 1963; Ting, 1977), stays unchanged (Laubach et al., 1998; Su et al., 2001), decreases slowly and then stays constant (Su et al., 2001). This behavior of coals suggests that cleat frequency increases until a vitrinite reflectance of about 1.3–1.5% but it is less predictable in coals of higher ranks. Therefore, coal rank plays an important role in coal permeability since, regardless of other factors; coals with a vitrinite reflectance closer to 1.3–1.5% are more likely to encompass a well-developed cleat network.

Many researchers have investigated coal porosity and permeability through different methods and conditions (Clarkson and Bustin, 1997; McKee et al., 1988; Paterson et al., 1992; Puri et al., 1991; Rodrigues and Lemos de Sousa, 2002). Porosity of coals is principally related to

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coal composition and rank (Flores, 2014). Macropores are normally dominant in low-rank coals whereas high-rank coals mainly contain micropores (Flores, 2014; Parkash and Chakrabartty, 1986). Vitrinite maceral, e.g. vitrain lithotype, mainly composed of micropores and inertinite, e.g. fusain macrolithotype, mostly contains mesopores and macropores (Flores, 2014; Harris and Yust, 1976; Lamberson and Bustin, 1993; Mastalerz et al., 2008). Permeability of coal, as the most important parameter in gas recovery, mainly depends on the dimensions, spacing, connectivity, and degree of mineralization of cleats (Clarkson and Bustin, 1997; Laubach et al., 1998). Laboratory testing of core plugs is commonly used as an indicator of potential seam permeability, however, the highly heterogeneous and stress-dependent nature of coal makes laboratory measurements difficult to perform and the results difficult to interpret. Consequently, permeability in coal is poorly understood. A better understanding of coal permeability and the factors that control it will depend on a better understanding and detailed characterization of the cleat system. Smyth and Buckley (1993) and Clarkson and Bustin (1997) experimentally measured the permeability of different coals and they indicated that vitrite-rich (bright) coals are more permeable than inertite-rich (dull) coals. They mentioned that the cleat network governs the permeability and cleat spacing is a function of bed thickness and coal rank. However, they were not able to perform a systematic measurement on the cleat spacing of the examined coals. Smyth and Buckley (1993) did not examine the effect of mineral matter on coal permeability and Clarkson and Bustin (1997) were not able to obtain the mineral content for each sample precisely since they measure it petrographically through visual point count methods.

Different methods have been used for mineral identification in coal demonstrating that carbonates, quartz, clays, and sulfides are common cleat or fracture infillings (Ward, 2002). The most common occurring infillings of cleats or fractures are epigenetic minerals, which form after coal formation; hence they are generally perpendicular to the coal bed (Flores, 2014). The minerals in coal reduce the reservoir performance, and decrease the internal surface area of the coal through mineralizing pores and cleats (Flores, 2014).

X-ray micro-computed tomography (micro-CT) is a non-destructive three-dimensional imaging technique, which has been extensively applied in various geological applications (Mees et al., 2003; Wildenschild and Sheppard, 2013). Many researchers have used micro-CT images of coal for fracture characterization (Karacan and Okandan, 2000; Mazumder et al., 2006; Montemagno and Pyrak-Nolte, 1999; Pyrak-Nolte et al., 1997; Wolf et al., 2008; Heriawan and Koike, 2015; Mostaghimi et al., 2015), evolution of the coal structure (Li et al., 2012), investigation of fracture/permeability evolution under cyclic loading (Cai et al., 2014), analysis of coal damage at different pressures (Viljoen et al., 2015), studying gas adsorption and desorption (Karacan and Okandan, 2001; Vega et al., 2014; Karacan and Mitchell, 2003), macerals distribution determination (Verhelst et al., 1996), and evaluation of coal heterogeneity and spatial distribution of pores, fractures and minerals (Golab et al., 2012; Yao et al., 2009). In a recent study, Heriawan and Koike (2015) used micro-CT imaging to identify micro-fractures of coal and observed a relationship between the properties of micro-fractures and coal quality. They also correlated the coal quality with the regional geological structures. To enhance the contrast of a micro-CT image, the sample can be saturated with an attenuating fluid with a large atomic number such as xenon (Maylotte et al., 1986), sodium iodide (Withjack, 1988) and/or Wood's metal (Montemagno and Pyrak-Nolte, 1999; Pyrak-Nolte et al., 1997). However, studies investigating the role of minerals and lithotypes in coal porosity and permeability are still insufficient. Also, no attempt has been made to quantify the effect of mineral phase on coal permeability.

Herein, we report a novel framework based on micro-CT imaging to evaluate the porosity and permeability of coals and characterize the effects of lithotype and mineralization on coal permeability. The method uses micro-CT imaging to generate 3D images of coal at dry and wet (saturated with X-ray attenuating fluid) conditions (Golab et al., 2012; Golab et al., 2010). The dry and wet imaging facilitates the identification and subsequent segmentation of coal cleat systems from the digital images that would otherwise be unobtainable. To further assist in the digital analysis of coal images, scanning electron microscope and energy dispersive spectrometry (SEM–EDS) together with X-ray diffraction (XRD) data was collected and registered to the micro-CT data to provide information on mineral content and high-resolution structural information of coal cleats. The presented technique provides a means to evaluate how and why coal permeability, at the centimeter to micrometer length scale, is influenced by coal lithotype, porosity, cleat structure, and mineralization. High-resolution digital images of coal provides insight into the structural and functional properties of coal that are paramount for engineering coal seam gas reservoirs for improved gas recovery.

2. Materials and methods

2.1. Coal sample

Six samples with various ranks and lithotypes were obtained from the Bowen Basin of Australia, then sets of rapid low quality micro-CT scans were carried out on the samples. From the six samples, one coal sample containing approximately similar proportions of bright and dull lithotypes with a well-developed cleat network was chosen. Bright and dull band coals were identified based on megascopic criteria (Thomas, 2002; Hower et al., 1990). The sample was a Late Permian medium volatile bituminous coal, vitrinite reflectance of 1.15%, from Moura coal mine. The Moura mine, is currently called Dawson Mine, located 185 km southwest of Gladstone, Queensland, Australia. The first independent commercial production of coal seam gas in Australia started in 1996 in the Moura mine feeding into the Wallumba–Gladstone gas pipeline (Dicks et al., 2004).

Moura mine (Qhh) lies in the Baralaba Coal Measures on the southeastern of the Bowen Basin Formation (Fig. 1). The Bowen Basin contains vast coal resources and is one of the world largest deposits of bituminous coal. It was an area of shallow water or terrestrial sedimentation for most of the Permian (Dicks et al., 2004). Coal accumulations have occurred throughout almost all of this period, primarily around the margins and in isolated locations, spreading to cover nearly the entire basin in the latest Permian (Dicks et al., 2004). The coal geology of the Bowen Basin has been discussed in detail by Hawthorne (1975) and Mallett et al. (1995).

Baralaba Coal Measure Formation was deposited during latest Permian times under fluvio-deltaic conditions (Dicks et al., 2004; Korsch et al., 1998). The geological structure of the Moura coal field has become progressively more complex and more faulting has been measured toward the northern end (Dicks et al., 2004; Korsch et al., 1998). The Baralaba Coal Measure Formation encompasses a higher amount of sandstone in comparison to other coal mines in the Bowen Basin (Dicks et al., 2004). The faulting and inter-bedded sandstones may have acted as channels for the penetration of surface water, at least in some parts of the Moura coal seams (Dicks et al., 2004). Moura coal geology is more specifically explained in Mallett et al. (1980).

A summary of the sample specifications, including proximate and ultimate analyses, is provided in Table 1. The ultimate and proximate analyses were performed on a sister core of the sample according to the Australian Standard (AS1038.3–2000) providing percentages of the four basic constituents: fixed carbon, volatile matter, moisture, and ash yield of coal. The relative density of the sample was also calculated together with proximate analysis. This procedure determines coal quality, which has a determinative impact on coal as a reservoir (Bustin and Clarkson, 1998; Carroll and Pashin, 2003; Levine, 1993).