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Multi-scale x-ray computed tomography analysis of coal microstructure and permeability changes as a function of effective stress

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ABSTRACT

Gas permeability (k) and porosity (φ) are the most important parameters in CBM/ECBM and CCS in deep unmineable coal seams. k and φ depend on the coal microstructure, and k and φ significantly change with varying effective stress. However, how the coal microstructure is related to such permeability and porosity changes is only poorly understood. We thus imaged sub-bituminous coal samples at two resolutions (medium - 33.7 μm and high - 3.43 μm voxel size) in 3D with an x-ray micro-computed tomography as a function of applied effective stress; and investigated how cleat morphology, k and φ are influenced by the changes in effective stress and how these parameters are interrelated. In the images, three phases were identified: microcleats (void), a mineral phase (carbonate) and the coal matrix. When effective stress increased, the cleats became narrow and closed or disconnected. This resulted in a dramatic permeability drop with increasing effective stress, while porosity decreased only linearly.

1. Introduction

Gas permeability is a key factor in coal bed methane (CBM) and enhanced coal bed methane recovery (ECBM), and carbon geo-sequestration in deep unmineable coal seams (Pekot and Reeves, 2002; Moore, 2012). It is well established that gas permeability is highly sensitive to effective stress (Harpalani and Chen, 1992; Palmer and Mansoori, 1996; Karacan and Okandan, 2000; Connell et al., 2010; Cai et al., 2014). This is directly relevant for field production processes, e.g. in ECBM another gas (e.g. nitrogen) is frequently injected to increase the reservoir pore pressure (and thus reduce effective stress) to release methane; or during CBM production reservoir pressure is depleted and effective stress increases. In this context it has been shown that permeability increases by matrix shrinkage due to methane desorption, or permeability decreases by cleat compaction due to pore pressure loss (Harpalani and Chen, 1997; Kumar et al., 2012). It also has been well documented that permeability decreases drastically with depth (because the overburden stress and thus effective stress increase), and it has been suggested that this is caused by fracture closure (Enever et al., 1999). However, most investigations on coal permeability change focus on the coal swelling effect during gas injection (e.g. CO_2: e.g. Reeves, 2004; Larsen, 2004; Siriwardane et al., 2009) or water encroachment (e.g. Zhang et al., 2016; Stevens et al., 1998); while the influence of effective stress on permeability and associated coal microstructural changes are still poorly understood.

Traditionally dual coal porosity and permeability sets are distinguished, one for the coal matrix and the second set for the natural fracture (cleats) network. The permeability of the coal matrix is much lower than that of the cleats network, thus the cleats network effectively controls the overall permeability of the coal seam (Harpalani and Chen, 1992; Karacan and Okandan, 2000; Connell et al., 2010). Furthermore cleats can be subdivided into butt cleats, which are orthogonal to the coal bedding, and face cleats, which are perpendicular to the coal bedding (Laubach et al., 1998). Cleat properties such as size, structure, orientation and connectivity all significantly affect permeability (Laubach et al., 1998; Flores, 2013). It has been thought that the cleats change when the in-situ stresses change (Chen et al., 2011). However, the variation of the microstructural morphology associated with such changes,

Table 1
Physical properties of the coal studied.

ρ (g/cm^3)	M_{ad} (%)	V_{daf} (%)	A_{ad} (%)	C_f (%)	E (GPa)	υ
1.35 (±0.03)	6.90 (±0.50)	36.00 (±1.00)	4.20 (±0.20)	54.00 (±2.00)	2.60 (±0.40)	0.31 (±0.1)

Note: ρ is the bulk density; M_{ad} is the moisture content; V_{daf} is the volatile matter; A_{ad} is the ash yield; C_f is the fixed carbon content; E is Young's Modulus; and υ is Poisson's ratio. All properties were measured using Chinese Standard GB/T 212-2008.

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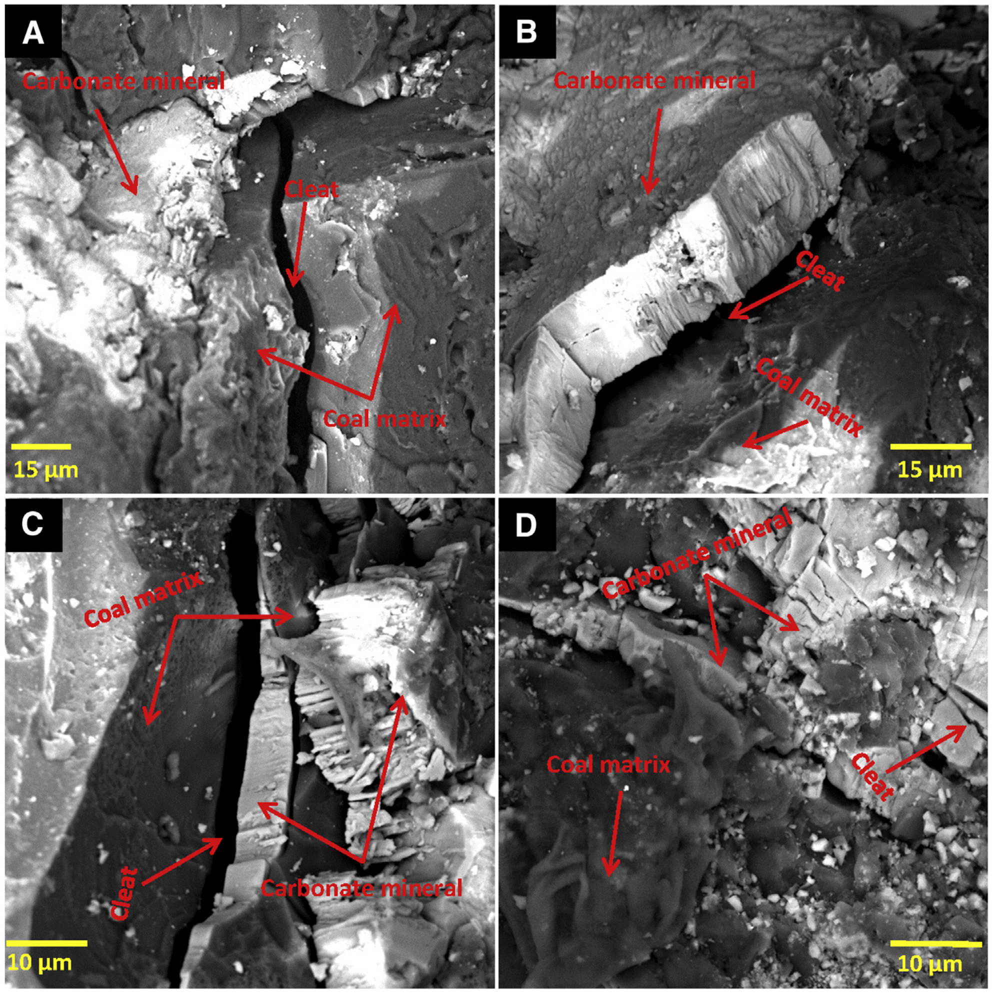

Fig. 1. SEM images of the coal sample's surface, where the coal matrix, mineral phase and cleats were clearly identified. (A) cleat inside the coal matrix; (B) cleat between the coal matrix and the mineral phase; (C) minerals filled in the cleat (D) cleat inside the mineral phase.

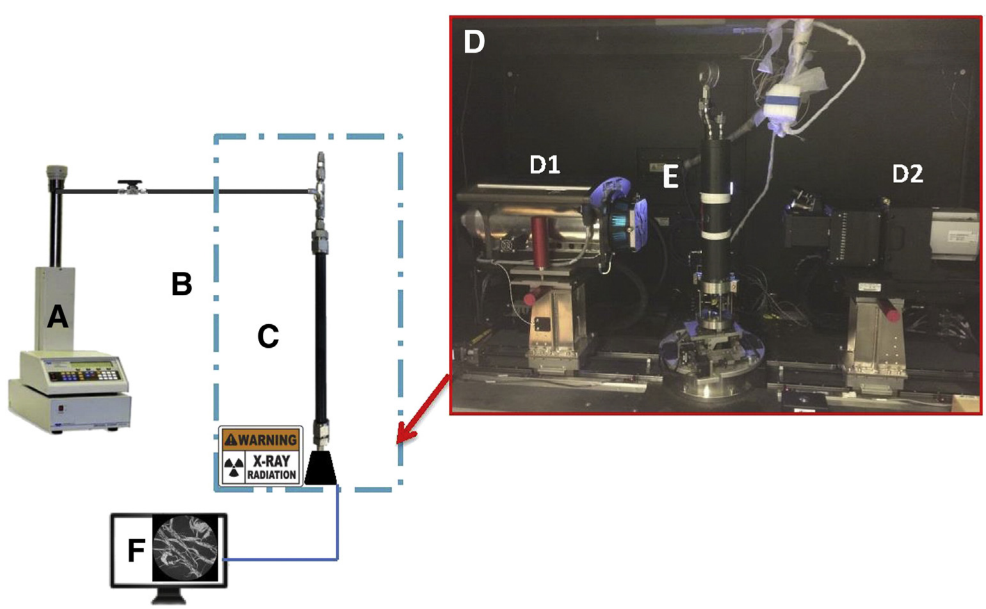

Fig. 2. Experimental microCT coreflooding apparatus, (A) confining pressure pump, (B) microCT, (C) core holder for small plug sample (plug diameter = 5 mm), (D) microCT inside view, D1 is the x-ray source, D2 is the x-ray detector, (E) is the core holder for large plug samples (plug diameter = 38 mm), (F) images output and processing.