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High-resolution three-dimensional imaging of coal using microfocus X-ray computed tomography, with special reference to modes of mineral occurrence

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A B S T R A C T

Samples of coal from the Sydney and Bowen Basins of eastern Australia have been imaged at high resolution using a large-field, 3D microfocus X-ray computed tomography (μCT) system, with special but not exclusive attention to evaluating the modes of occurrence of the mineral matter within the coal. The samples imaged were 110 mm, 25 mm, 19 mm, 10 mm, and 4 mm in size, yielding voxel dimensions of 54, 30, 12, 6, and 3 μm respectively. Data collection was carried out using a helical stage, providing images with $>2000^2$ voxels in the horizontal (X–Y) plane and up to 3500 voxels high. Three-dimensional image blocks derived from the scans were examined as cross-sections along orthogonal planes and as perspective images, manipulated to be viewed from any angle. Imaging after saturating the coal with X-ray attenuating brine was also carried out to highlight the distribution of connected micro-pores and cleats, and improve the detail of features seen within the samples.

Features evaluated within the coals included the size and three-dimensional distribution of siderite nodules, and different types of mineral infillings in petrifactions of maceral components. Individual macerals could also be identified within the coal, based partly on X-ray density and partly on the associated porosity and structure. In some cases high-resolution images enabled the nature of individual plant particles to be identified within the coal samples. Mineral-filled cleats and open fractures were also evaluated, including the origin of radiating fracture patterns around siderite nodules in vitrinite. In some cases several generations of cleat and/or fractures could be distinguished, and the sequence of their formation and infilling was interpreted.

Complementary analyses of the mineral matter in the samples were carried out using X-ray diffraction, as well as examination of polished sections by optical microscopy examination. Images obtained from the μCT scans were also registered against SEM–EDX and QemSCAN images of polished sections prepared from the same samples after scanning, providing a more definitive basis for identifying the different components and for integrating μCT data with results from other petrographic and electron microscope studies.

1. Introduction

X-ray micro-computed tomography (μCT) is a technique that yields high-resolution three-dimensional X-ray images of solid opaque objects quickly and non-destructively (Carlson et al., 2003). It is similar to medical CT scanning, but carried out on a smaller scale and with greatly increased resolution (down to 2 μm is possible). Use of such imaging is of value in a variety of applications, including examination of clastic (Golab et al., 2010) and carbonate (Arns et al., 2005b) reservoir rocks in petroleum geology, as well as three-dimensional studies of coal (Mazumder et al., 2006), paper (Roberts et al., 2003), biomaterials (Knackstedt et al., 2006), bones (Zezabe et al., 2005), and volcanic ash (Ersoy et al., 2010), and materials for palaeontology (Long et al., 2006), soil science, meteoritics, and geotechnics (Ketcham and Carlson, 2001; Mees et al., 2003). Digital 3D imaging of core material at the pore scale using μCT, for example, allows improved understanding of petrophysical response, multiphase flow properties and geological heterogeneity in petroleum reservoir evaluations (e.g., Arns et al., 2005a).

The intensity recorded in the pixels (2D) and voxels (3D) obtained in μCT analysis represents the relative radio density, or relative attenuation, of X-rays through individual segments of the imaged material (Novelline, 1997). The X-ray attenuation of any material is a function of both the electron density and effective atomic number of the species (Van Geet et al., 2001b). Within the tomogram, the X-ray opacity of the material in each individual segment determines its brightness, allowing a three-dimensional image to be reconstructed from sections viewed at different angles. Voids are usually represented as black in such images due to their low X-ray opacity, Fe-bearing minerals are usually light grey or white due to high X-ray opacity, and Si- and Al-bearing

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Table 1
Coal samples and tomographic resolution used in the study.

Sample site	Site location	Specimen size	Number of voxels	Voxel size (resolution)
Ulan	Western Sydney Basin	110 mm	2048^3	53.7 μm
		19 mm	1024^3	21.0 μm
		19 mm	$2048^2 \times 3800$	14.6 μm
		10 mm	2048^3	5.5 μm
		4 mm	$2048^2 \times 3000$	3.0 μm
Tahmoor	Southern Sydney Basin	19 mm	2048^3	11.7 μm
		4 mm	$2048^2 \times 3300$	3.0 μm
Newcastle	Northern Sydney Basin	25 mm	1024^3	29.7 μm
South Walker Creek	Northern Bowen Basin	19 mm	2048^3	10.0 μm

minerals are usually medium-grey due to intermediate X-ray opacity. Although apparent opacity is a guide to effective atomic number, the physical density is also a factor in determining overall X-ray attenuation.

The direct identification of minerals in tomographic images generally relies on contrasts in X-ray attenuation. For example, attenuation contrasts have been used to estimate the degree of Mg–Fe substitution in iron–magnesium rich silicates with sufficiently differing iron contents, and CaAl–NaSi substitution in plagioclase solid solutions (Tsuchiyama et al., 2000). However, the X-ray attenuation of minerals with similar characteristics may overlap (e.g., quartz and alkali feldspar, Tsuchiyama et al., 2000), making identification in tomograms more difficult. Although features such as crystal habit, cleavage or alteration textures can be used to assist mineral identification, the most definitive solution is to integrate mineralogical data from 2D images (e.g. SEM–EDS) to extend the mineral identification capacity of μCT studies.

Previous researchers have used medical CT, and more recently micro-CT techniques, for: quantitative characterisation of fractures in coal (e.g. Karacan and Okandan, 2000; Mazumder et al., 2006; Montemagno and Pyrak-Nolte, 1999; Pyrak-Nolte et al., 1997; Van Geet and Swennen, 2001; Wolf et al., 2008), with particular application to developing an improved understanding of coal seam gas flow. Other authors have used micro-CT to study gas adsorption and desorption in coal (He et al., 2010; Karacan and Mitchell, 2003; Karacan and Okandan, 2001), and the three-dimensional distribution of macerals (Verhelst et al., 1996), especially vitrinite (Van Geet et al., 2001a), and minerals such as pyrite (Simons et al., 1997). The technique has also been used to investigate coal drying (Mathews et al., 2011), pyrolysis and gasification (Maylotte et al., 1986), and the swelling and strain distribution associated with CO_2 injection (Karacan, 2007; Pone et al., 2009, 2010), as well as to investigate the heterogeneity and spatial distribution of pores, fractures and minerals in coals of varying rank levels (Yao et al., 2009).

2. Samples and analysis techniques

2.1. Tomographic instrumentation

The present study is part of a programme aimed at using a new, high-resolution, large-field μCT instrument developed at the Australian National University in Canberra (Varslot et al., 2010, 2011), which has previously been applied to a range of other materials (Arns et al., 2005b; Golab et al., 2010; Knackstedt et al., 2006; Long et al., 2006; Zezabe et al., 2005), to evaluate the three-dimensional constitution of coal at different scales. Particular reference is given in the present paper to the distribution of mineral and maceral components, and the evaluation of micro-cleat and fracture patterns in a range of Australian coal samples. The system used for this study is the only facility in the world with a capacity to perform helical μCT imaging, for example of cylindrical core samples. X-rays from a micro-focus source were used to probe the samples, and an X-ray camera was used to record a series of X-ray transmission radiographs at different viewing angles by moving the position of the rotation stage relative to the X-ray camera, as described by Sakellariou et al. (2004). The samples were evaluated using the methodology described by Varslot et al. (2010, 2011),

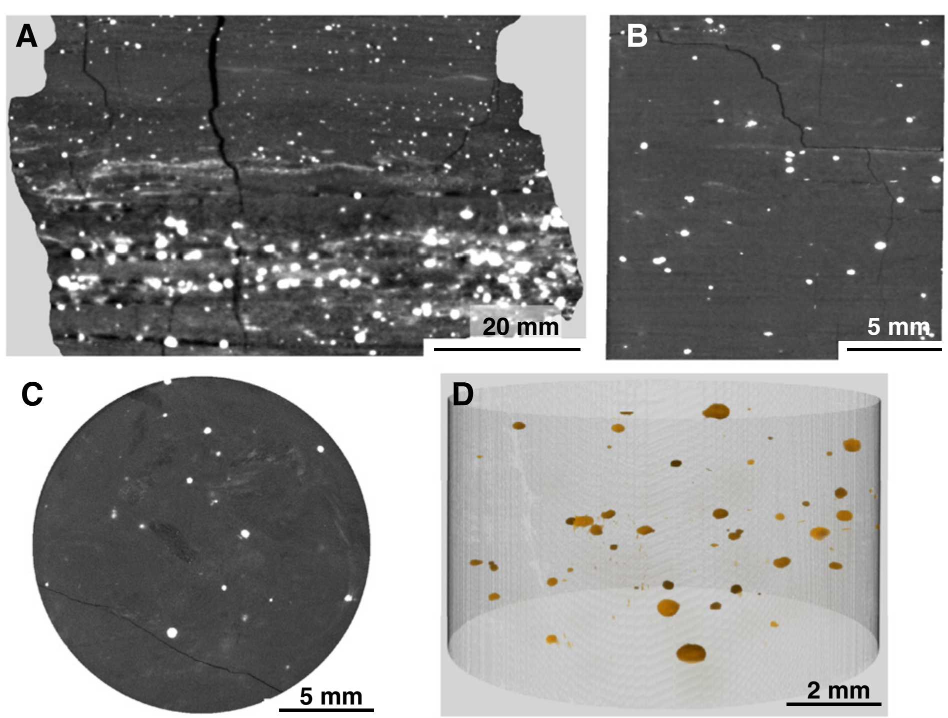

Fig. 1. Tomographic images of Ulan coal samples: A) vertical section (X-slice) through tomogram of a 110 mm hand specimen, voxel size 53.7 μm; B) vertical section (X-slice) through tomogram of a 19 mm core sample, voxel size 21 μm; C) bedding plane section (Z-slice) through 19 mm core tomogram, voxel size 21 μm; D) perspective view of 3D visualisation of 10 mm core tomogram, showing distribution of siderite nodules (orange) within the organic and clay mineral matrix.