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Volumetric imaging and characterization of natural fracture networks

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Abstract
The three-dimensional geometry of the fracture network was obtained using a Wood's metal injection method to capture the interconnected fracture geometry under reservoir conditions. An auto-correlation analysis was performed to examine the anisotropy and stationarity of the two-dimensional spatial correlations in the fracture network with depth in the sample. Visualization of the auto-correlation function in successive planes indicate that the spatial correlation among fractures within a network is anisotropic and non-stationary. These results imply that extension of two-dimensional fracture maps to the third dimension may not accurately represent the structure of the fracture network.

Introduction

The difficulty in characterizing and imaging natural fracture networks in rocks arises because the three dimensional networks are imbedded in a rock matrix that is opaque to almost all probes. Real fracture networks are often only observed as two-dimensional planes or cross-sections, such as in rock outcrops, tunnel or excavation walls, or as thin sections after destruction of the rock sample. The three-dimensional interconnectivity of a fracture network is a key feature in the analysis of the structural integrity and the hydraulic permeability of a rock mass. The interconnectivity defines the rock blocks that have the potential to damage an engineering structure and controls the movement of contaminants and other fluids through rock. While the seismic visibility of fractures in rock has been studied as a means of remote non-destructive detection of fractures [Pyrak-Nolte et al., 1990], more information is needed to reconstruct the complex network geometry for use in network flow modeling.

The transport of fluids through a fractured rock mass is intimately related to the geometry of the fracture network. Numerical models for simulating fluid flow through fracture networks in three-dimensions require some form of data on the geometry of the network, such as spatial correlations, interconnectivity, fracture length, or fracture orientation (Long et al., 1985; Tsang et al., 1988; Karasaki, 1993; Cacas et al, 1988). While these network models are fairly sophisticated, data on the three-dimensional topology of fracture networks have been lacking. Input sets for these simulators are often based on two-dimensional observations of the fracture network. Two-dimensional data sets yield information on the distribution of fractures but do not yield information on the three-dimensional connectivity or three-dimensional spatial correlations of the network.

To bridge this gap in the understanding of fracture networks, Wood's metal injection and computerized x-ray tomography were used to image the geometry of natural fracture networks in coal under *in-situ* stress conditions. The results of this process is the generation of data sets that permit the quantitative visualization and analysis of three-dimension fracture networks.

Samples

Two coal cores were drilled from blocks of coal collected from Seam #1 of the Sundance Pit at the La Plata Coal Mine, New Mexico to study the three-dimensional interconnected geometry of fractures in coal. Core AA was drilled perpendicular to the bedding plane. Core BB was drilled parallel to the bedding planes and parallel to the dominant fracture set (face cleats). The dimensions and porosity of the samples are listed in Table 1.

TABLE 1. Data from Wood's metal injection experiments on coal samples AA and BB from seam #1 in the Sundance Pit at the La Plata coal mine, New Mexico.

Sample Number	AA	BB
Dimensions (cm)		
Diameter	8.89	8.89
Length	4.41	11.18
Bulk Volume (cm^3)	274	694
Fracture volume measured (cm^3)	0.22	0.64
Effective Fracture Porosity (%)	0.082 ±0.002	0.094 ±0.002
Minimum aperture accessed	1.22 ±0.59	1.37 ±0.65

Experimental Procedure

A Wood's metal injection technique was used to capture the interconnected fracture network geometry in coal. Wood's metal injection was first used by Dullien (1969) to capture the pore geometry of voids in sandstones. Since, it has been used to capture the void geometry and contact area distribution in single natural fractures (Pyrak-Nolte et al., 1987), crack growth under compressive stress (Zheng, 1989), and the distribution of two-phases in the pores of sandstone (Yadav et al, 1986). The advantages of Wood's metal over traditional resin techniques are that the high-surface tension of Wood's metal allows the size of aperture accessed to be controlled and that the metal leaves a detailed cast of the fracture surfaces.

The experimental set-up is shown in Figure 1. The coal sample is placed in a hydrostatic pressure vessel and subjected to confining pressures representing reservoir conditions. Core AA and BB were subjected to confining pressures of 4.89 MPa and 5.54 MPa respectively. The apparatus is heated to approximately 95 °C. During heating, a nitrogen back pressure (0.44-0.49 MPa) is used to prevent oxidation of the coal during heating (Nelson, 1989) and to provide a constant pressure front to the invading metal. Molten Wood's metal is injected into the sample and is allowed to solidify. After injection, X-ray computerized tomographic (CT) scans are taken

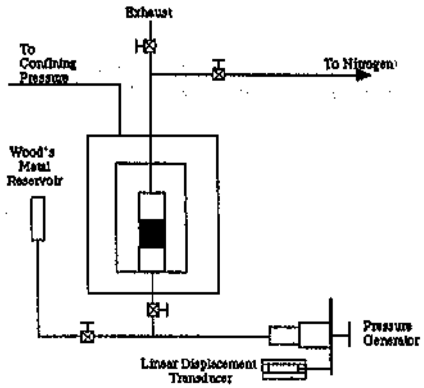

FIGURE 1. Schematic of Wood's metal injection system.

to delineate the metal-filled fractures. From the two-dimensional scans, the three-dimensional fracture network geometry can be reconstructed (Pyrak-Nolte & Montemagno, 1994).

Data

An example of the geometry of the fracture network observed in the CT scans after image processing is illustrated in Figure 2. The metal-filled fractures are

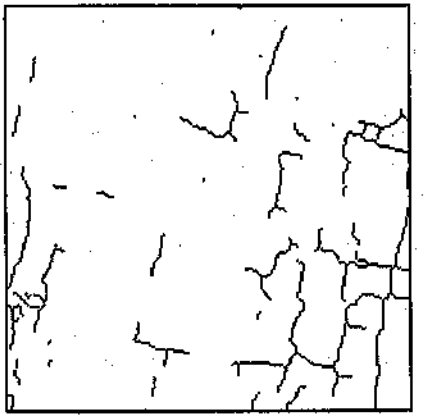

FIGURE 2. Fracture pattern from an image processed CT-scan of core BB.

clearly visible in this 63 mm by 63 mm section of core BB. The fractures in this core appear planar and rectilinear.

Auto-Correlation Analysis

Spatial correlation analysis can yield several parameters describing pore (Berryman, 1985) or fracture geometry, such porosity, specific surface area, fracture spacing, length and width of the fracture. An auto-correlation analysis was performed to determine the anisotropy and stationarity of the two-dimensional spatial correlations in a fracture network with depth in the samples. Ninety and forty-two CT scans were used in the analysis for cores BB and AA, respectively. To analyze the spatial correlations in the networks, the auto-correlation function for each CT scan was determined using equation (1). The auto-correlation function is computed from

$$S(\vec{\lambda}) = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\vec{k})\, F^{*}(\vec{k}) \exp(i\vec{k}\cdot\vec{\lambda})\, d\vec{k} \qquad \text{(EQ 1)}$$

the inverse Fourier Transform of the Fourier Transform times the complex conjugate of the Fourier Transform. After calculating the auto-correlation function for each slice of the image, the auto-correlation slices were used to reconstructed a volumetric image of the spatial correlations with depth in the sample.

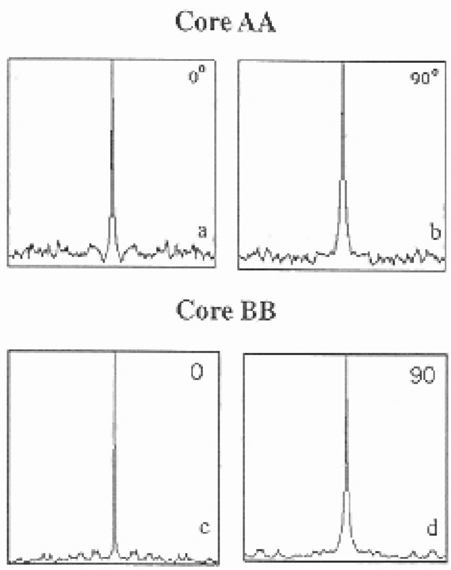

FIGURE 3. Auto-correlation function for cores AA and BB illustrating the anisotropy of the fracture network with direction.

Discussions

The spatial distribution of the fractures within a single plane from the CT scans can be examined with one-dimensional graphs (Figure 3) or two-dimensional images (Figure 4). Figure 3 shows the auto-correlation function for both cores for orientations of 0° and 90°. Because the fracture network is anisotropic, the spatial correlation functions for 0° and 90° are different for both cores. The width of the correlation functions (which is related to the length of the fractures) is larger for the 90° orientation. For the 0° orientation, the spacing between fractures can be observed from the oscillations in the auto-correlation function. The anisotropy is also evident in the two-dimensional visualizations of the correlation functions in Figure 4. If the network was isotropic the correlation functions would appear as a circle in this figure.

The non-stationarity in the spatial correlation among fractures is observed by examining the change in correlation function with depth in the sample. In Figure 4 the spatial correlations functions for two different depths (approximately 20 mm apart) in the sample are shown.The fact that the spatial correlations vary with depth illustrates the non-sationarity of the structure of the fracture network. This analysis indicated that the fracture network was

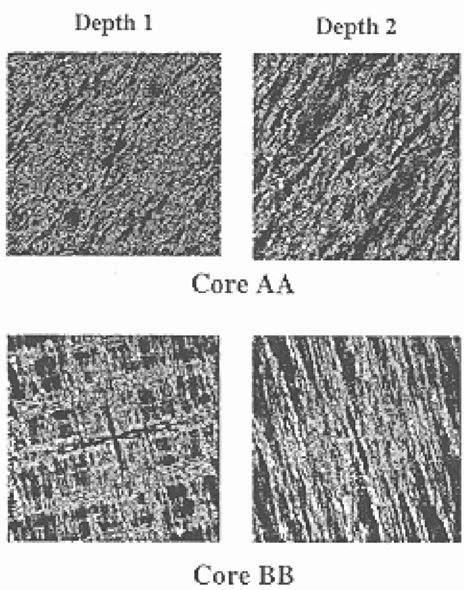

FIGURE 4. Two-dimensional auto-correlation for cores AA and BB at different depths illustration the non-stationarity of the fracture

stationary only for increments of distance of less than 5 mm. Non-stationarity can arise from changes in maceral (coal minerals) distribution during formation of the coal and from lithostatic stresses in the Earth that increase with depth.

Summary

Spatial correlations in a natural fracture network in coal are observed to be anisotropic and non-stationary. This indicates the difficulty in extending two-dimensional data sets from rock outcroppings or borehole samples to the third dimension.

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