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# Characterizing coal cleats from optical measurements for CBM evaluation

S. Weniger [1], P. Weniger [2], R. Littke *

*Institute of Geology and Geochemistry of Petroleum and Coal, Energy and Mineral Resources Group (EMR), RWTH Aachen University, Lochnerstrasse 4-20, Haus B, 52056 Aachen, Germany*

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In this study we apply fracture characterization techniques, common to many other reservoir rocks, to coals. Additionally, the data gathered from this technique is used to determine fracture permeability and porosity based on a cubic relationship between permeability and porosity, as a function of aperture and spacing. However, these data are in an unconfined stress state. To relate this information to the subsurface, which is in a confined state, the results are then compared and calibrated to permeability data determined from laboratory triaxially confined samples, using the same sample material. A 1D scanline technique is used to gather data on cleat aperture, spacing, height, and frequency. Sixteen different coals from several European basins were examined, creating a large dataset (>8000 individual data measurements). This data was gathered from blocks of coals and from polished sections. The polished sections were digitally scanned under the microscope to create an image of the whole section. As a result, we examined a range of scales from micrometers to centimeters. Maximum, minimum and median values are determined for each attribute. To clearly define the limits of resolution of the data, a practical pore resolution is applied to a power law function of the data. Cleat attributes were further examined to determine a relationship with cleat type, e.g., face or butt, and lithotype. Power law distributions of butt cleat attributes are similar to the distributions found in lithotype. It was concluded that butt cleats are more strongly related to lithotype, and thus bed thickness and mechanical strength of the bed, than face cleats. Cleat aperture and spacing depend on cleat type. A face to butt cleat ratio of 5:1 given an aperture of about 12 μm was found. This is similar to a published anisotropy in permeability, where face cleats are five times more permeable than butt cleats. Cleat porosity from aperture and spacing is several times greater than cleat porosity calibrated to laboratory permeability (under stress). The calibrated porosity ranged from 0.01% to 1.8% and agrees with published values of in-situ cleat porosity. Thus aperture width due to an increase in stress is predicted to decrease four times. This data can be used to calibrate reservoir simulators for CBM production.



## 1. Introduction

Fluid flow properties of coal seams control the transport of water, gas and petroleum (liquid and gaseous hydrocarbons). Knowledge of these properties is important for gas extraction prior to coal mining activities as well as for production of coalbed methane (CBM) in un-mined areas. Fluid transport in coal can be simplified into two processes: a slow, diffusion controlled flow through microporous coal matrix and a faster, pressure driven 'Darcy' flow through an interconnected network of fractures (Close, 1993; Gash, 1991; Gray, 1987a). Coalbed methane is mainly stored as adsorbed gas on micropore surfaces in the coal matrix and to a lesser extent exists as free gas in pores and fractures. During gas extraction operations water and free gas are produced from interconnected pores and fractures. This results in pressure decrease that leads to desorption of adsorbed gas, which then diffuses through the coal matrix to the connected pore and fracture network from where it can be extracted (Cui and Bustin, 2005; Harpalani and Chen, 1997). Systematic fractures in coal beds are very common and have been called cleats since miners adopted the term in the early 19th century (Kendall and Briggs, 1933). Cleats are of fundamental importance to well bore stability, mining, and coal bed methane production (Laubach et al., 1998). CBM is an important source for unconventional gas resources. Of all the factors that can affect gas transport during coalbed methane development, the permeability of cleat systems has the most significant influence (Roadifer et al., 2003).

A better understanding of the cleat structure is important in determining the economics for CBM exploration and development. Cleats that are open or well connected provide pathways for hydrocarbon and water flow during draw down in the wellbore. This has been observed in many wells and core samples in the laboratory (Gray, 1987a, 1987b). In laboratory experiments, coal cores without a viable cleat system only allow for a minimal transport of fluids over a long period of time or are essentially impermeable (Han et al., 2010). Some drill

* Corresponding author.
*E-mail address:* Ralf.Littke@emr.rwth-aachen.de (R. Littke).
[1] Present address: Wintershall Holding GmbH, Friedrich-Ebert-Strasse 160, 34119 Kassel, Germany.
[2] Present address: Federal Institute for Geoscience and Resources (BGR), Stilleweg 2, 30655 Hannover, Germany.

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stem tests of Fruitland coals in the San Juan basin resulted in no fluid flow to the wellbore due to closed cleats and no interconnection (Close and Mavor, 1991; Close, 1993; Mavor et al., 1991). Subsequent core samples from these coal intervals revealed that cleats were essentially closed and not well connected (Close, 1993). The relationship between well cleated cores and high fluid flow and productivity from the associated wells has been observed in many CBM reservoirs (Ammosov and Eremin, 1963; McCulloch et al., 1974; Close, 1993).

A cleat network can be simply classified into two orthogonal fractures (face and butt cleats). Cleats commonly show little shear offset and are, therefore, opening-mode fractures (Laubach et al., 1998; Solano-Acosta et al., 2007). Both face and butt cleats are oriented perpendicular to bedding, but butt cleats usually “abut” against face cleats. Thus, face cleats are through-going, while butt cleats end at intersections with face cleats (Fig. 1). The abutting fractures, i.e. butt cleats, in this type of orthogonal relationship are interpreted as being younger than the face cleats (Hancock, 1985; Laubach et al., 1998). Cleats form in response to the physical and chemical processes during coalification (Laubach et al., 1998; Solano-Acosta et al., 2007). These opening-mode fractures retain little evidence of the loading paths that caused them, because they form in rocks with low tensile strength, e.g. coals (Laubach et al., 1998). Fracture growth modeling shows that this orthogonal relationship can arise under biaxial extension (Olson, 1993), a circumstance that can accompany the conditions under which cleats form (Laubach et al., 1998). Laubach et al. (1998) give a thorough review on the origins of cleats as well as a discussion of cleat forming mechanisms.

Cleats can be further classified by their size, spacing, connectivity, aperture, degree of mineral fill, and preferred orientation (Close, 1993; Laubach et al., 1998). Some of these cleat parameters can be related to coal rank and type. Levine (1993) showed that cleat spacing was found to increase with rank from lignite to bituminous coal and then decrease in the high rank range through anthracite. Cleat spacing is also greater in dull coal than in bright coal lithotypes (Tremain et al., 1991; Close and Mavor, 1991; Gamson et al., 1993, 1996). Pattison et al. (1996) noted that cleats are usually restricted to a single lithotype, whereas fractures can cross different lithotypes. Fractures that cross-cut beds are termed master cleats (Dawson and Esterle, 2010; Laubach and Tremain, 1991) and are shown in Fig. 1. Cleat spacing was found to increase linearly with cleat height (Dawson and Esterle, 2010; Grout, 1991). However, these historical works on cleat spacing measurements often did not take into account the size distributions encountered, or the criteria used to measure spacing is ambiguous. Laubach et al. (1998) note that a clear relationship between cleat spacing and bed thickness was only found for those cleats that span the entire thickness of the bed, also known as primary cleats, and thus neglecting secondary and tertiary cleats. Secondary and tertiary cleats are those contained within a bed, but they do not span the entire thickness (Tremain et al., 1991). Moreover, the relationship held up for beds less than 10 to 20 cm thick and those whose bed thickness was clearly defined by non-coal interbeds (Tremain et al., 1991). Where such clearly defined coal bed thickness is lacking, as in the Adaville coals in Wyoming, a spacing to bed thickness relationship becomes unclear (Laubach et al., 1998).

Permeability in coal is affected by the nature and attributes of the cleats, e.g. spacing, aperture, height, or connectivity. A high cleat density, which is the number of cleats per length or area, is suggested to favor a better fluid flow for CBM production (Cui and Bustin, 2005; Somerton et al., 1975). Karacan and Okandan (2000) studied three coal seams in Turkey and found two to be more intensely fractured than the third. The authors proposed that intense fracturing may have a positive effect on gas production due to a faster diffusion from the matrix. Solano-Acosta et al. (2007) also suggested that very small fractures (microcleats) in the matrix aid in transporting fluids from the coal matrix. Cleat apertures between 4 μm and 50 μm may be optimal for CBM production, based on San Juan Basin coals, while larger apertures may lead to very high permeability coefficients, but also to high water production that is detrimental to economic production (Scott, 2002). Philip et al. (2005) found that permeability is more sensitive to fracture length distributions than it is to aperture, especially in a poorly connected fracture network. Long and Witherspoon (1985) showed that as fracture length increases, so does the degree of interconnection. Thus, aperture might not be the only attribute influencing permeability.

Quantifying cleat attributes, such as spacing, aperture, or height, can be challenging at best. Logging data in the wellbore can provide a direct indication of cleat density under in-situ stress (Chatterjee and Paul, 2013; Close and Mavor, 1991). Nevertheless, cleat attributes determined from non-stressed samples can also be used as a guide to identify sweet spots with a favorable production potential (Mavor et al., 1994). Different methods have been used to visually determine cleat attributes. Mazumder et al. (2006) measured cleat spacing and aperture distributions at a millimeter scale using X-ray computed tomography and automated image analysis. The automated detection of cleat attributes is hindered by noise and artifacts in the binary image. Wolf et al. (2008) used CT scans to verify cleat angle distributions determined from artificial fragments and drilling cuttings. A magnifying glass and ruler have been used to determine cleat geometries, such as spacing or height, in coalmines and hand samples (Dawson and Esterle, 2010; Paul and Chatterjee, 2011). Software, like geographic information system, GIS, have been used to spatially reference the orientation of cleats and analyze their connectivity (Rodrigues et al., 2014).

Measurement of the smallest cleats depends on the applied visual method and its resolution. X-ray tomography applied to rocks can resolve pixel with an area equal to about 0.2 $mm^2$ to 0.78 $mm^2$ (Bertels

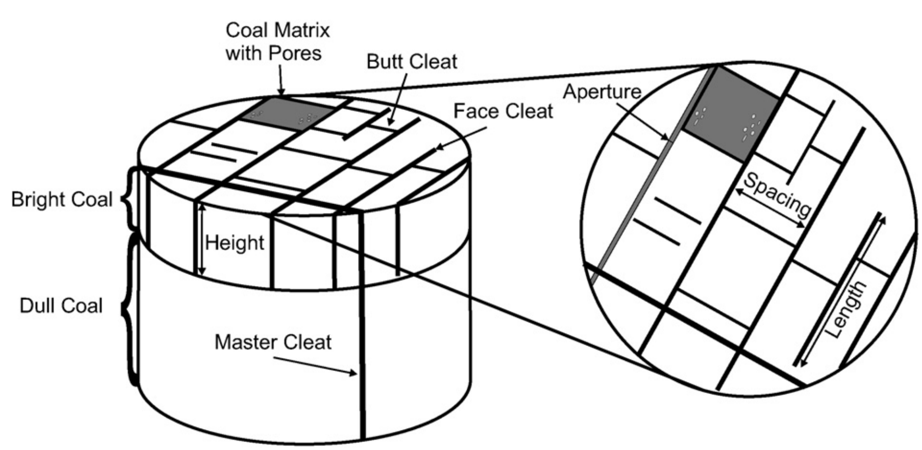


**Fig. 1.** Schematic of coal cleat attributes; a. coal core with bright lithotype being more highly cleated than dull lithotype; change in lithotype designates a bedding plane in sketch; b. plan view; aperture is a dimension perpendicular between opposing fracture walls; spacing is a distance between two cleats of the same set at right angles to cleat surface; length is a dimension parallel to cleat surface and parallel to bedding; height is a dimension parallel to cleat surface and perpendicular to bedding.