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The coal cleat system: A new approach to its study

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ABSTRACT

After a general analysis regarding the concept of coal "cleat system", its genetic origin and practical applications to coalbed methane (CBM) commercial production and to CO_2 geological sequestration projects, the authors have developed a method to answer, quickly and accurately in accordance with the industrial practice and needs, the following yet unanswered questions: (1) how to define the spatial orientation of the different classes of cleats presented in a coal seam and (2) how to determine the frequency of their connectivites. The new available and presented techniques to answer these questions have a strong computer based tool (geographic information system, GIS), able to build a complete georeferentiated database, which will allow to three-dimensionally locate the laboratory samples in the coalfield. It will also allow to better understand the coal cleat system and consequently to recognize the best pathways to gas flow through the coal seam. Such knowledge is considered crucial for understanding what is likely to be the most efficient opening of cleat network, then allowing the injection with the right spatial orientation, of pressurized fluids in order to directly drain the maximum amount of gas flow to a CBM exploitation well. The method is also applicable to the CO_2 geological sequestration technologies and operations corresponding to the injection of CO_2 sequestered from industrial plants in coal seams of abandoned coal mines or deep coal seams.

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1. Introduction

The coal fracture system has been investigated since the earliest days of coal mining operations, and the first descriptions and speculations on fracture origin dated back to the late 19th century, aiming to determine the design of mine workings (Pattison et al., 1996). Such studies consisted in general descriptions of the appearance of the fractures and measurements confined to their orientation, which are considered important issues in designing coal mines so as to maximize extraction efficiency and to improve safety conditions.

In the past, coalbed gas was considered mostly as a hazard (Flores, 1998) due to the effect of both fire-damps and gas outbursts. Many studies were also carried out in the scope of mine safety related to these phenomena, i.e. coal fracturing and tectonics (Alpern, 1963, 1967, 1970). An account of more recent investigations was given by Cao et al. (2001), Jin et al. (2003), Ryan (2003), and Solano-Acosta et al. (2007, 2008), respectively.

Coalbed gas corresponds nowadays almost to a resource commodity through the commercial exploitation of CBM deposits, and the study of coal fracturing is again considered crucial. In fact, as stated by several different authors (Gamson, 1994; MacCarthy et al., 1996; Ayers, 2002; Durucan and Shi, 2009), the prerequisite to obtain economical and technical viable projects in coalbed gas recovery as well as in CO_2 injection is intimately related to coal permeability which, in turn, depends on coal fracturing.

Many terms were used over the years to designate the natural fracturing of coal. However, the term "cleat", used for the first time in 1925, was the one retained by the current miners, geologists, and engineers as the general designation for a variety of fractures commonly found in coal, usually as a result of the coalification process and basin regional tectonics. In fact, cleats in coal have been described as equivalent to joints in competent rocks or as closely spaced, pervasive fractures originated from an almost imperceptible movement associated with an extensional opening. After the

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work of Macrae and Lawson (1954), Nickelsen and Hough (1967), Ting (1977), Karacan and Okandan (2000), and Wolf et al. (2001), the formation of cleat appears to be influenced by shrinkage occurring during the process of coalification, stress release, and extensional strain. It was also documented that, in general terms, a cleat system is present in coal ranging from lignite to anthracite, being commonly well developed in low volatile bituminous coals. This is justified by the fact that the increases of heat and pressure, usually associated with metamorphism, produce plastic flow that destroys the original cleat structure. This fact was more recently confirmed by Su et al. (2001).

Many hypotheses exist concerning the origin of cleats in coal. However, authors like Ting (1977) and Close (1993) believed that cleat genesis can be effectively classified in three main processes: dehydration, devolatilization, and tectonics. The first process consists of dehydration caused by mechanical compaction of plant fragments when water is expelled from peat induced by overburden. This process is easily understandable since coal, at the very beginning of its formation, has a high moisture content, which progressively decreases as rank increases. Consequently, coal suffers considerable changes in volume that lead to fragments being rearranged due to inter-granular slippage, compaction, and the collapse of cellular cavities. As a result, coal fractures tend to increase as dehydration increases. The devolatilization effect consists in the loss of volatile matter during the coalification process and after the loss of moisture has already been completed. This mechanism also produces a decrease in coal volume which, once more, induces fracture formation.

Tectonics apparently controls cleat orientation in coal in a process somewhat similar to jointing observed in other rocks. It is common to relate the strike directions of cleats to major structures such as folds in many basins, although local and lateral disturbances, such as faults, folds, and stresses, induced by differential compaction and produced by underlying non-coal material, tend to complicate the coal cleat system. Another aspect that must be pointed out is that, locally, cleats can be rotated and deviated from the settings resulting from the stress field. In order to avoid this effect, it is necessary to study a set of samples strategically positioned, depending on the spatial basin geometry, in the coalfield to permit a real representative stress field study.

The cleat system, as it is currently understood, is theoretically characterized by two main sets of sub-parallel fractures (“face cleat” and “butt cleat”), both mostly orthogonal to bedding. Face cleats are usually dominant, with individual surfaces almost planar, persistent, laterally extensive, and widely spaced. Butt cleats constitute a poorly defined set of natural fractures, orthogonal or nearly orthogonal to face cleats. Face cleats are continuous throughout the coal seam, while butt cleats tend to be discontinuous, non-planar, commonly ending at the intersection with face cleats. However, in practical terms, detailed cleat characteristics of a coal seam are far more complex than the two main fracture sets as described above. This fact is on the basis of different detailed cleat classifications in literature, e.g. Ammosov and Eremin (1963), Tremain et al. (1991), and Gamson et al. (1993). In 1998, Laubach et al. (1998) defined the following detailed cleat characteristics: orientation, spacing, aperture, height, length, and connectivity as crucial indices to classify the cleat system in a coal basin.

2. The need for a new approach to study coal cleat system

Since the very first studies on the coal cleat system process, several authors have been interested in introducing a correct and adequate methodology to quantitatively characterize coal cleat networks. However, up to date, it was only possible to obtain quantitative results by a rather expensive and time-consuming method, similar to the one used in micro-tectonics which is a direct response of regional and local tectonic settings (Ting, 1977; Close, 1993; Levine, 1993; Pyrak-Nolte et al., 1993; van Krevelen, 1993; Laubach et al., 1998; Montemagno and Pyrak-Nolte, 1999; Morris et al., 1999; Mazumder et al., 2006).

In the present work, a new, semi-automatic, fast, accurate, and statistically based optical method, aiming to obtain more reliable results in order to satisfy the current industrial practice and needs, was developed. In this regard, it should be mentioned that, more recently, Alpern and Lemos de Sousa (2002) have proposed, to adapt to CBM problems, an alternative mechanical degradation test that was developed to study the outburst prediction (Alpern, 1963) through which it has been possible to define a “fracturability index” in correlation with gas circulation.

In fact, it is well known that the natural network of fractures presented in coal allows the drainage of CBM from coal seams to the production wells through the cleat system. Furthermore, in a classical approach, exploitation methods include additional fracture opening induced by stimulation with injection of various fluids. However, even when using more advanced technologies that are applied in several basins, such as open-hole cavity completion method, the gas production advantage revealed to be either successful or unsuccessful depending on the basins and/or the coal seams (see also Ayers (2002)). This means that only in very favorable cases it is possible to obtain advantageous economic levels of CBM production.

Therefore, what really matters in the authors’ opinion is, in each case, to know (i) the spatial orientation of the different classes of fractures (cleat) and (ii) the frequency of their connectivity, in order to make possible a right orientated hydraulic fracturing injection of fluids (water, gas, or combining both fluids) under pressure to open the cleat system, thus allowing the highest amount of gas release. In fact, the cleat families of highest connectivity frequency are those that define the gas circulation network to the production well, and are, therefore, the most favorable ones to be opened by fluids, although they must be injected in the correct direction. Taking this fact into account, drilling a higher number of holes does not solve *per se* the problem of gas production from coal seams. The method must be applied with extreme care, otherwise it may lead to misleading conclusions. One limitation in this method is related with the availability of the core samples needed to this kind of studies.

Other options, like the televiewer method, considered as the best solution to study *in situ* the cleat system mostly in terms of orientation, do not, in the authors’ opinion, allow to study the microfractures, only the meso and macrofractures. Additionally, the presented method is able to statistically describe in detail the characteristics of the studied samples, also in terms of spacing, aperture, height, length, filling, and connectivity.

It should also be noted that, although the coal cleat system also depends on the local and regional tectonics, the cleat network cannot be inferred using conventional regional micro-tectonics studies. Indeed, in terms of mechanical properties, coal has a very particular rheologic behavior; the deformation threshold is totally different from the other rocks presented in the local stratigraphic column, even considering strata directly contacting with coal seams, i.e. the roofs and floors. This particular rheologic behavior occurs due to its microlitotypes composition, i.e. if one is dealing with a rich liptite coal, one will certainly have difficulties in observing a pertinent fracture network, since liptite has a high elasticity behavior and this performance will be more complex when liptite is strongly interstratified with the other microlitotypes whose behaviors are totally different. Additionally, in most basins that correspond to CBM deposits, the ellipsoid of effective tectonic stress is more or less constant, i.e. there are no changes in amount

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