Drilling induced fractures in coal core from vertical exploration well: a method to determine cleat azimuth, and the angle between cleat and maximum horizontal stress, and its application

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DRILLING INDUCED FRACTURES IN COAL CORE FROM VERTICAL EXPLORATION WELLS: A METHOD TO DETERMINE CLEAT AZIMUTH, AND THE ANGLE BETWEEN CLEAT AND MAXIMUM HORIZONTAL STRESS, AND ITS APPLICATION

David Titheridge

ABSTRACT: Drilling induced fractures that have been described from cored sandstone, mudstone and limestone, also occur in many coal cores. This paper outlines a method of using petal and related fractures in coal core to determine the angle between face cleat and the principal horizontal stresses. The method also enables determination of the azimuth of cleat, in wells in which the apparent dip of cleat on a scanner image is vertical. As the angle between face cleat and the principal horizontal stresses can have a major influence on initial permeability, the method has application in coal bed, coal mine, and enhanced coal bed methane.

INTRODUCTION

The value of interpreting stress azimuth from induced fractures in the bore wall is well known to the petroleum industry. The angle between (effective) principal horizontal stresses (S_H, S_h), and the strike of natural fractures is an important one in petroleum production, for those fractures close or parallel to S_H (and perpendicular to S_h), have the widest oil-filled apertures and dominate permeability pathways. The same principle has applications for Coal Mine Methane (CMM; production/utilization and/or drainage/ventilation to atmosphere), Coal Bed Methane (CBM) production, and Enhanced Coal Bed Methane (ECBM; combined methane production with concurrent sequestration of CO_2 in coal).

In recent years there has been increasing reliance on image logs from sonic and resistivity scanners to obtain orientation and dip of fractures and sedimentary structures with low to high dip. However, in the case of near vertical exploration drill-holes, the apparent dip of cleat in a scanner image may be vertical, and if so, it is not possible to obtain the azimuth of cleat.

This paper offers a geometrical method to determine the angle between cleat and S_H (and S_h) as well as their azimuths. It is based on the presence of drilling induced petal (and related) fractures in coal core, and breakout azimuth from a scanner log.

STRESS, CLEAT AND PERMEABILITY

Stress regimes

The state of stress in rocks can be described by three orthogonal principal stress directions. The maximum, intermediate and minimum principal stress directions (S_1>S_2>S_3) in rocks can be either vertical (S_V) or horizontal (S_H, S_h). There are three stress regimes associated with fault formation (Figure 1). The type of fault formed in the geological past may not have any relationship to the present day stress. The nature of drilling induced tensile fractures has some dependence on stress regime.

Cleat, stress, the angle between S_H and cleat, and permeability

The stress that acts on cleat has both tectonic and pore pressure components (Figure 1). It is well established that minimum principal effective stress, S_p-Pore Pressure (PP, Figure 1) plays a major role in the initial permeability of coal prior to production/drainage (review by Bell, 2006 with examples from Australia). Matrix shrinkage and increase in cleat aperture during desorption (production) is associated with an increase in permeability (Gray, 1987; Levine, 1996).
Face cleat is the main permeability pathway in coal, though butt cleat and other fractures may contribute. In some coals there is not a dominant face cleat, and both sets may abut the other (Figure 2). Cleat properties of coals, and particularly those that contribute to interconnectedness of cleat, (spacing, height, width, aperture, development of butt or secondary face cleat, and paucity or abundance of mineralisation), all contribute to permeability.

![Figure 1 - Stress, shear structures (faults), and natural and drilling induced tensile fractures](image)

![Figure 2 - Two types of cleat systems](image)

It is self-evident from a horizontal 2D perspective that if face cleat is perpendicular to $S_{H}$ (and parallel to $S_{h}$), initial permeability will be low. Recent measurements of coal permeability under laboratory triaxial stress conditions have confirmed this (Massarotto, et al., 2003). On the other hand, also from a 2D perspective, if face cleat is parallel to $S_{H}$ (and perpendicular to $S_{h}$), initial permeability is likely to be relatively high. However when the three 3D states of stress are considered, this is only be true for normal and strike slip fault regimes, and only if $S_{h}$ is small. In a thrust fault regime, even if face cleat is...
parallel to \( S_H \) (and perpendicular to \( S_V \)), permeability is unlikely to be high, as \( S_3 \) is vertical (Figure 3). In general, the prevailing stress regime in Eastern Australian coal basins at coal mining depths, is the thrust fault stress regime. It is invariably associated with low permeability. Normal and strike slip fault regimes with horizontal minimum stress (\( S_{3h} \)), are a prerequisite for high permeability. Their presence is related to local geology.

If face cleat is parallel or orthogonal to the principal horizontal stress, then the magnitude of normal stress acting on cleat is the orthogonal principal horizontal stress magnitude. If cleat is at an acute angle to \( S_H \) and \( S_V \), then the normal stress magnitude acting on cleat is between that for \( S_H \) and \( S_V \). Permeability can be expected to reflect the normal stress magnitude acting on cleat.

**Figure 3 - Angle between face cleat and \( S_H \), and predicted permeability based on relative magnitudes of fault stress regimes**

<table>
<thead>
<tr>
<th>Stress Regime</th>
<th>Permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>Potentially HIGH perm if ( \sigma_2 = \sigma_3 = \text{low} )</td>
</tr>
<tr>
<td>Strike-slip</td>
<td>LOW PERM ( \sigma_2 = \sigma_3 )</td>
</tr>
<tr>
<td>Thrust</td>
<td>( \sigma_3 = \sigma_4 )</td>
</tr>
</tbody>
</table>

**Origins of variation between the azimuths of \( S_H \) and face cleat**

It is widely accepted that cleat is a tensional joint in coal, and that its development occurs during early coalification, with loss of moisture and other volatiles. Face cleat generally develops parallel to \( S_H \) and perpendicular to \( S_V \) at the time of early coalification. This applies to normal, strike-slip and thrust fault regimes (Figure 1). There are many basins world-wide where the azimuth of \( S_H \) has remained the same since early coalification so that face cleat and principal horizontal stress have the same orientation e.g. SW Alberta, Canada (Bell and Bachu, 2003).

However there are also many instances where the relationship between face cleat and stress azimuths departs from this situation of similarity, as a result of regional changes in stress direction over time since cleat formation, or local perturbations of the regional stress field in the vicinity of folds and faults (Barton and Zoback, 1994; Rippon, *et al.*, 2006; Yale, 2003). A more comprehensive review is in Titheridge, 2012.

**Orientation of core and determining azimuths of cleat**

Prior to recent developments in acoustic and resistivity scanner imaging, determination of the orientation of core for sedimentary fabrics, tectonic structures and stress and strain states was entirely via retrieval of oriented core (Nelson, *et al.*, 1987). Orientation of core has also been achieved by paleo-magnetic methods (e.g. Lackie and Schmidt, 1993; Van Alstine and Butterworth, 2002).

Analysis of bore wall images from acoustic and resistivity measurements is now the prevalent means of obtaining directional data of sedimentary and structural features. The basis of determining dip and strike of planar inclined bedding and faults, is the sinusoidal trace of a planar feature on a circular image of the bore wall. The amount of dip is determined from the amplitude of the sinusoidal trace, and the dip azimuth is the minima of the sinusoidal trace. The latter can be read off the horizontal axis of a scanner log scaled from 0 to 360 degrees (Figure 4).

The azimuth of cleat in coal can also be determined where the apparent dip of cleat is not vertical from a full sinusoidal trace, or interpolation of a maxima or minima if the full trace is truncated (Figure 4b-4d). However if the apparent dip of cleat is vertical, or very near vertical, as is common for many exploration
well, there is no sinusoidal trace, or maxima or minima to determine dip and strike (Figure 4e-4k). In this instance cleat azimuth needs to be determined from a combination of core and scanner data.

Figure 4 - Examples where cleat can and cannot be determined from a scanner log: a) small scale fault b) and c) cleat with apparent dip and full sinusoidal trace on scanner image, and in core (same well within 8m) d) cleat with maxima only (due to truncation of cleat), maxima of sinusoidal trace can be interpolated e) apparent dip of cleat is vertical on scanner image, cleat azimuth cannot be determined f) and g) hypothetical cleat on bore wall and on scanner image h,i,j,k) four interpretations of “g” indicating no unique solution without sinusoidal trace where apparent dip of cleat on scanner image is vertical

Drilling induced failures (breakout) and tensile fractures in the borewall

Borehole breakout is due to localised failure of rock around a bore wall. It forms as a result of local concentration of horizontal hoop stress exceeding the strength of the rock (Bell, 1996; McGregor, 2003). It manifests as two zones of borehole enlargement at 180 degrees to each other that can be detected on an image from an acoustic or resistivity bore-hole scanner image. Breakout has the same azimuth as \( S_h \) and the apex of petal fractures on the core perimeter, and is at 90 degrees to \( S_h \). Breakout is often a common feature of bore wall images at coal mining depths.

Drilling induced tensile fractures may also occur in the bore-wall. They form parallel to \( S_h \) and at 90 degrees to breakout. They form when circumferential tensile stress exceeds the tensile strength of the well-bore wall. They are common in deep petroleum wells and often present at 90 degrees to breakout. They have the same orientation as centre-line fractures seen in sandstone core.

Drilling induced tensile fractures in coal core

Drilling induced tensile planar and curvi-planar fractures in coal core include petal, core edge, and saddle fractures, as well as discing (Figure 5). A new descriptive category, namely incipient core edge fractures, is recommended for those small fractures confined to the core perimeter. They may be present when none of the other fractures listed above, are not.
Curvi-planar drilling induced fractures are known as “petal fractures”. The origin of the name arises from their resemblance to petals attached to a stem when they coalesce with centreline fractures.

Figure 5 - Drilling induced fractures in coal core and sandstone: a) Petal-centreline fractures (from Lacazette, 2000) in sandstone. b,c) Petal fractures top and side views. d) Curved petal fractures in side view (white arrows), cleat with calcite (yellow pointer). e) Incipient core edge fractures f,g) Saddle fractures, same core. h,i) Discing in coal.

Petal fractures in coal have not been observed in association with centreline fractures (cf. sandstone, Figure 5a). Curvature of petal fractures in coal occurs in their upper part (cf. the lower part of some sandstones, Bell, 1996). Petal fractures generally enter coal core at relatively low angles and steepen downwards towards the centre of the core where they become planar or near planar. In other instances, petal fractures only penetrate about a third of the core diameter from the core exterior and commonly terminate before becoming vertical. The trace of the top of petal fractures in a bore wall scanner image is flattened as a result of their curvi-planar shape (Lacazette, 2000; cf. the sinusoidal maxima of planar fractures.)
features intersecting the bore wall). Curvi-planar petal fractures are rarely observed in coal on scanner images of the bore wall.

Petal fractures appear as linear features in bedding plane sections but curved when observed perpendicular to the long axis of core. The relationship of the azimuths of borehole break-out, $S_{th}$, centre-line fractures, petal fractures, and the location of petal fracture apices, in a horizontal bore-hole cross section is illustrated in Figure 6. Observations to date indicate that petal fractures only form in the more competent dull coal lithotypes with sparse bright bands and sparse cleat.

![Figure 6 - Petal and related fractures in core (RHS) and on the bore wall (LHS)](image)

The orientation of apices and strike of petal fractures are very consistent and measurable to about ±2°. This contrasts with the wide azimuthal range of breakout, where it is necessary to visually estimate the central position of breakouts 180 degrees apart. In some instances, petal fractures in coal occur on diametrically opposite sides of the core; if that is the case the apices of petal fractures on the core perimeter are always at 180 degrees.

The axes of saddle fractures are parallel to $S_{th}$ (Bell, 1996; Figures 5f and 5g). Whilst no directional stress information can be obtained from discing in core (Figures 5h, 5i) it is likely that their presence indicates the principal horizontal stresses are similar in magnitude and greater than the vertical stress (thrust fault regime). Transitional forms between saddle fractures and discing exist.

The origin of petal and saddle fractures and discing of core (Figure 5), has been attributed to the re-distribution and concentration of compressive stresses around the cutting edge of a drill bit. Finite Element Method (FEM) modelling of stress trajectories indicates that petal (and saddle-shaped) fractures strike in the direction of maximum horizontal compression (Lorenz, et al., 1990; Li and Schmitt, 1997, 1998). Drill bit pressure ($= S_{V}$ at the core bit) produces tensile fractures in core ahead of the drill bit. The orientation and type of tensile fractures (petal, saddle and discing) induced by drilling, shows some dependence on the type of fault stress regime and the $S_{V}/S_{th}$ ratio (Li and Schmitt, 1998). Petal fractures develop in normal and strike-slip fault stress regimes. Saddle shaped fractures are most likely to develop in strike-slip fault stress regimes. Discing of core can form in any of the fault stress regimes but is most likely to occur in a thrust fault stress regime (Figure 1).

**METHOD AND PROCEDURE**

**Preparation**

It is essential to be able to restore sections of the core to their original orientation with respect to each other. The best way to do this is to paint parallel lines of different colour on the core, and parallel to the axis of the core after removal of one of the inner tube splits, prior to placement of core in a core tray or
gas desorption canister. Consistent use of different colours will indicate up and down directions of the core. This is generally standard practice for exploration drilling. It is often possible to restore core from different drill runs by matching ends but where coal has been purposefully broken to fit coal core into a canister or core box, this is often impossible. If core has petal fractures, the angle between the arbitrary lines and the petal fracture apices in the same drill run can be determined. The notional location of petal fracture apices can then be transferred to adjacent lengths of core without petal fractures where cleat is to be measured (Titheridge, 2012).

Overview of calculation

The process from data collection/input to azimuth and angle results is summarised in Figure 7a.

![Diagram of data source and output](image_url)

**Figure 7 - (a) Data source and output and (b) axioms to support calculation**

It is impractical and cumbersome for many reasons to measure cleat and stress directions and angles on the bedding plane of core (Titheridge, 2012). The reasons include the existence of incipient core edge fractures that develop on the core perimeter, that are a useful source of information when none of the other types of drilling induced fractures are present. The solution is to use the location of the apex of petal fractures and cleat intersections on the core parameter. The basis of the method of determination is that the azimuth of apices of curvi-planar drilling induced petal (and related) fractures on the core perimeter is the same as the azimuth of breakout on the borewall (Figure 6). $S_h$ is transposed to the notional centre of the core as it is orthogonal to breakout and the apex of petal fractures. The cleat chords are transposed to the centre of the core. The transposition is based on six axioms of geometry (Figure 7b). This procedure reduces the task of measurement, to obtaining two angles between a petal fracture apex and each of the two intersections of a cleat chord with the core circumference. Angular measurements around the perimeter of the core can be made clockwise or anti-clockwise but must be consistently recorded as positive or negative looking down-hole.

**Measurement**

The angle between petal fracture apices and cleat intersections of the core perimeter can be measured with a circular protractor that fits the diameter of the core, or a flexible wrap around protractor. Circumferential distances obtained with dress makers tape can easily be converted to degrees. On many occasions it will be necessary to extrapolate a cleat on a bedding plane to the core perimeter with a straight edge and china-graph pencils. It will also be necessary to extrapolate the location of petal fracture apices along the same piece of core (or same drill run) to a bedding plane section with cleat to be measured.

**Geometrical construction and calculation**

The steps involved in calculation are: (i) transpose $S_h$ to the centre of the core (90 degrees to the apex of the petal fracture), and (ii) transpose cleat to the centre of the core (Figure 8).
Limitations of the method

The limiting factor of the method is that petal and related drilling induced fractures are often rare or absent from some coal cores. For example in the Southern Coalfield, NSW, the Bulli Seam, has abundant drilling induced fractures (predominantly dull coal). In contrast, in the working section of Wongawilli Seam about 30 metres below the Bulli Seam, drilling induced fractures in coal are absent. The Wongawilli Seam contains abundant bright bands and abundant cleat.

Application

Knowledge of face cleat/stress angles can also assist with CO$_2$ sequestration via the ECBM method. This may determine placement of injection and production holes depending on production objectives (Figure 9a).

Knowledge of the angle between stress and cleat is critical to planning the orientation of hydro-fracs in areas of low permeability due to unfavourable face cleat/stress angle (Figure 9b).

The method can also potentially improve the interpretive value of plots of log permeability vs effective stress (Figure 10). Traditionally the stress plotted has been $S_{3h}$-PP ($\sigma_3$). This assumes that $S_{3h}$ is perpendicular to face cleat. However, if at any location, $S_{3h}$ is perpendicular, or at a moderate to high acute angle to (face) cleat, the plotted effective stress parameter needs to be $S_{h}$-PP. The calculated effective normal stress is based on the magnitudes of both $S_{3h}$ and $S_{h}$, and the angle between cleat and $S_{h}$. If $S_{3h}$-PP is plotted, any outliers (assuming valid permeability and magnitude tests) could include data where $S_{3h}$ is perpendicular or at a high acute angle to face cleat. If $S_{h}$-PP is plotted, any outliers are most likely to have geological causes (Figure 10).
SUMMARY

i) The presence of petal and related drilling induced fractures in coal core, and breakout information from scanner logs, can be used to determine the angle between $S_h$ and face cleat direction, as well as cleat azimuth (where this cannot be obtained from a scanner log).

ii) Whilst face cleat is often parallel to $S_h$, there are many instances where it is not due to post-cleat rotation of the regional stress field, or local perturbations of the regional stress field, that is often related to faulting and folding.

iii) A knowledge of the angle between face cleat and $S_h$ (and $S_h$), together with stress magnitude measurements, assists the interpretation of anomalies on permeability vs stress plots.

iv) The method can be applied to CMM, CBM, and ECBM/CO$_2$.

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Figure 9 - Conceptual CO$_2$ migration in coal and optimal direction for in-seam fracturing when $S_h$ is perpendicular to cleat. (a1) $S_h$ and CO$_2$ migration parallel to face cleat. Short time to CH$_4$ production with small extent of CO$_2$ replacement. (a2) $S_h$ parallel to face cleat but CO$_2$ migration perpendicular to face cleat. Longer time to CH$_4$ production with large extent of CO$_2$ replacement. (b) $S_h$ is perpendicular to face cleat direction, hence low permeability. Red hole: optimal hole stability and maximum intersection of cleats but fracs same orientation as hole. Green hole: RHS may have wall failure but fracturing achievable.

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Figure 10 - Application of stress/cleat angle and stress magnitude data in detecting permeability anomalies. a) Calculated normal stress acting on face cleat at all angles with constant $S_h$ and variable $S_h$. b) Hypothetical log k vs effective minimum principal stress ($\sigma_N$). Numerous outliers. c) Same hypothetical permeability data with log k vs effective normal stress ($\sigma_N$). Many outliers from plot above now fall on general trend leaving two residual anomalies, A1(??mineralisation of cleat, very high CO$_2$ % and gas content) and A2(?? zone of secondary tectonic fracture)
REFERENCES


