The Effect of Directional Net Stresses on the Directional Permeability of Coal

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ABSTRACT

Many researchers have found that coal permeability is strongly inversely proportional to the net stress levels. However, most of the supporting lab data was gathered with hydrostatic/isotropic external stresses, quite unrepresentative of in situ conditions. It is well known that the in situ stress vectors are quite anisotropic, with the maximum principal stress (usually horizontal tectonic) being as much as 50% greater than the minimum principal stress (whether horizontal or vertical). Also, most coal basins exhibit face cleat orientation parallel to the maximum principal stress. The inferred stress-shear strain relationship poses the question of how would the directional permeability of a coal seam be affected by changing directional external net stresses, when these are parallel, perpendicular or oblique to the face cleats or other directions?

This paper addresses the question and summarises tests done on Permian age coal from China’s Sunan Basin and Australia’s Bowen Basin, utilising a True Triaxial Stress Coal Permeameter. This test facility delivers three independently controlled external stresses on cubic or prismatic specimens, with flow along any one of the three specimen axes. Investigations were carried out on 40, 80 and 200 mm cubes and on an 80x80x160 mm prism. Our results indicate that an increase of the net stress along the flowing face cleat direction actually increases cleat permeability significantly. An increase of the net stress in the butt cleat direction generally reduces face cleat permeability at an exponential rate, while an increase in the vertical net stress generally results in a mild increase in both face cleat and vertical permeability.

An important conclusion is that laboratory investigations of coal permeability need to provide for the orientation of the maximum principal stress and the orientation of face cleats corresponding to the in situ condition for the coal reservoir under study. The resulting more accurate profiling of permeability behaviour over time can be applied to aid exploration, to engineering design of well trajectories and to forecasts of gas drainage, production profiles and reserves, including reservoir modelling.

INTRODUCTION

Directional stresses

Close, 1993 refers to evidence by other researchers that the majority of USA coal basins exhibit a strong correlation between face cleat orientation and the direction of the maximum horizontal stress, usually paleotectonic. This provides a solid explanation for coal’s anisotropic permeability, as the face cleats develop a longer run length to the butt cleats, due to higher loading. The butt cleats develop

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orthogonally to the face cleats because they are parallel to the minimum principal stress vector; they also develop a shorter run length due to lower loading.

There are several coal basins that highlight the conclusions by Close of the correlation between face cleat orientation and orientation of the maximum horizontal stress. A very good example of this is recent work by Bell and Labonte, 1998, of the Canadian Geological Survey, on the Alberta basin, reproduced here as Figure 1. It can be seen that the principal stress trajectory, orthogonal to the Mesozoic deformation front, is quite parallel to the face cleat orientation (determined from wellbores and coal mines). Other examples of mostly parallel orientation are the Black Warrior Basin of Alabama (Pashin and Carroll, 1999), the Raton Basin of Colorado/New Mexico (Close, 1993) and the Bowen Basin of Queensland (Pattison and Fielding, 1996). Close does acknowledge that there are exceptions to this general correlation; sometimes there are large variances in the face cleat strike between seams in the same coal measure.

Deriving principal stress direction from borehole deformation or “breakout” is now being practised on both sandstone and coal reservoirs (Bell, 1998). A schematic of this interpretation is shown in Figure 2, being a plan view of a deformed borehole (exaggerated scale). This approach gives the direction of the neotectonic maximum stress, not necessarily the paleotectonic stress which would have controlled the face cleat formation during coalification.

![Figure 1- Correlation of face cleat and principal stress orientations, Alberta Basin (from Bell and Labonte)](image)

**Previous findings**

Many previous laboratory researchers found an exponential inverse relationship between net (effective) stress and permeability (Lingard, 1984, Dabbous, 1992, Gray, 1992, McKee, 1992, McElhinney, 1993, Enever, 1997, Harpalani, 1997, St George, 1997, Wold, 1999, Barakat, 1999). However, most tests were conducted with isotropic stresses, where a hydrostatic bath is applied to the whole core to replicate external stresses. Given coal’s high compressibility, isotropic stresses will indeed close all flow paths (Massarotto, 2002). An isotropic net stress masks out any distinctions that could be observed with separate stresses in each of the three axial directions. Where a triaxial test rig was used, the results were sometimes different. Unfortunately, a benchmark study on Leichhardt Colliery 50 mm cores, which was
performed in a triaxial Hoek cell, had equal axial and radial stresses, ie the cell was used isotropically (Gray, 1992). The Leichhardt data showed a drop in permeability of 2 to 4 orders of magnitude for a 10 MPa increase in net stress (in Massarotto et al, 2001). This data was later built into the data sets of Enever et al, 1997, for Australian coals. A key conclusion from all this previous work was for the CBM industry to expect severe reductions in permeability as the reservoir pressure is depleted. A further basis for this was a big assumption that external stresses acting on the coal seam are constant; thus the coal seam would face an ever increasing net stress environment. The combination of incomplete knowledge of coal’s complex character and the constant stress assumption may have delayed the development of the Australian CBM industry by several years.

A significant departure from the above research was contained in the data gathered by Lingard et al, 1984, on West Cliff Colliery cores (Massarotto et al, 2001). Several of their specimens exhibited an increase, or at least no decrease, in vertical permeability as the axial stress was increased, while the radial stress was held constant. This data, and the observations by Close, led one of the authors (Massarotto) to postulate that indeed the direction of the principal stress can have significant implications for the long term behaviour of directional permeability of in situ coal. This same suspicion was shared by two of our supporting CBM company geologists, Roger Fisher from Texaco E&P and Ashley Edgar from Oil Company of Australia.

**Correspondence principle**

We have concluded from our research that it is very important to use the actual direction of stresses and the actual orientation of the face cleat, both as correspond to the in situ situation of the coal reservoir under study. This has been coined the “correspondence principle” (Massarotto, 2002), for relevant laboratory testing of permeability. A companion paper at this year’s Symposium presents complementary research findings on the basic anisotropic behaviour of coal permeability (Massarotto et al, 2003).

**TECHNICAL APPROACH**

**Equipment**

In order to do a comprehensive study of directional stresses and their effect on directional permeability, a “true” triaxial stress cell is required, where three independently-set and mutually-orthogonal stresses can be developed. This compares to the conventional “triaxial” stress cell, where really only two directional stresses are developed: an axial stress and a radial stress perpendicular to this. A normal triaxial cell could be used for the comprehensive study but would be limited in the variations that can be explored. It would also require triplicate specimens cut into the face cleat, butt cleat and the vertical directions of the coal seam. The single deviatoric stress would be the axial stress and would always be in the direction of flow (in standard Hoek cells).

The world-first True Triaxial Stress Coal Permeameter was developed at The University of Queensland in support of a comprehensive coal permeability research program. It has been previously described at the International Coalbed Methane Symposium (Massarotto et al, 2001). It was designed specifically for this directional stress research, capable of testing cubic coal specimens of 40, 80, and 200 mm cube and 80x80x160 mm prisms. External stresses can be as high as 40 MPa (on the 40
mm cell), and the test cells are capable of handling 14 MPa of inlet pore pressure for test gases. A picture of the TTSCP facility is shown in Figure 3.

![Figure 3-TTSCP: Pressure vessel with top cover on test bench, showing overhead crane and gas meters](image)

**Specimens**
The specimens investigated are sourced from Permian age coal. The China coal was sourced at the TaoYuan mine in the Sunan Basin, Anhui Province. The large block samples were spot analysed for mean vitrinite reflectance, with $V_r$ ranging from 0.87% to 0.9%. Blocks were sourced from 500m depth in the mine and were preserved for transportation in cellophane, covered by fibreglass and surrounded by expandable foam in the shipping barrels. Only one block has been opened fully and the sample was intact on opening. Preparation details were covered in a previous paper (Massarotto et al, 2001). A picture of one of our specimens, showing well developed face and butt cleats and their run length, tortuosity and connectivity, is shown in Figure 4.

![Figure 4- Bl II, Sp 3, 80x80x160 mm, coal specimen, showing highlighted cleats and ply microfractures; main 80x160 face is “bottom”](image)

The Bowen Basin specimens were sourced from three locations: two
exploration wells, yielding 61 mm cores recovered from approximately 550m depth. The fixed carbon content on one well was reported at between 59% and 66%; for the second well, at 62% to 70%. Mean vitrinite reflectance on samples from the second varied from 0.61% to 0.81%. Unfortunately, by the time we sourced the cores, they had air dried in storage for some two years and were thus more brittle than the TaoYuan fresh coal, making it difficult to cut whole cubes. The other Bowen Basin samples were freshly-cut large blocks from the Newlands Coal underground mine in Queensland. The later 40 mm cubes, an 80mm cube and a 200 mm cube were cut from these and tested.

Specimens were cut with smooth, diamond-impregnated bronze rock cutting blades, and machined square in a mill with diamond-tipped flat bits. Initial specimens were then polished; this was discontinued after it was found that the machining process yielded very smooth sides at lower speeds. Some moisture was adsorbed during the rough cutting process, but this was mainly shallow penetration; the samples quickly dried out and no free moisture was evident on any surface after machining. All specimens were tested at inherent moisture levels, to preserve the *in situ* character. Permeabilities are thus at residual water saturation, with the inherent blockage of some mesopores.

**RESULTS**

*Introduction*

The results of the “correspondence principle” experiments are presented below in groups where the maximum stress is either parallel, perpendicular or both parallel & perpendicular to the cleat direction. The latter occurred when we determined the vertical permeability of the specimen (ie flowing through both face and butt cleats): in this case, a maximum stress in the horizontal direction can be parallel to the face cleat and perpendicular to the butt cleats, or *vice versa*. Most of the tests were conducted with maximum stress parallel to the face cleat, as this is the corresponding situation for some 70% of coal basins in the USA (Close, 1993).

The deviatoric stress ratio, defined as the net stress level of the maximum stress vector divided by the average net stress of the specimen, was generally limited to between 1.0 and 1.5, though some experiments started as low as 0.5. Due to limitations of some test conditions, it was not possible to gather results for all tests up to 1.5 deviatoric stress ratio. Some of our specimens failed at 1.5; specimens were then evaluated visually for apparent strength and to what limit we thought they could be safely taken.

Increased levels of net stress in any direction were achieved generally by increasing the external stress in that direction, keeping the other two external stresses constant via automatic control. At times these did drift, due to several factors. Occasionally, small leaks in the hydraulic control valves occurred and due to the wider band on the target set-points, a drift occurred before set-point was achieved. More often, the changing net stress state of the specimen allowed more (or less) gas to flow through, as the permeability increased (or decreased). This then reduced (or increased) the mean pore pressure in the sample and thus increased (decreased) the net stress for all directions. Increased net stresses were also achieved by decreasing the gas pressure. Net (effective) stress is the external stress less the mean gas pressure across the specimen.
Because permeability is measured in the flow direction and in our tests gas flows vertically through the test cell, the measured permeability is designated $K_z$ and the stresses are referenced $\sigma_x$, $\sigma_y$, and $\sigma_z$ relative to this axis. This keeps standard nomenclature for the facility, in whatever direction the specimen is mounted in the test cells. Thus, results are presented as $K_z$ versus deviatoric stress ratio.

Tests were usually started with helium, to initially determine absolute permeability, with no risk of adsorption. Test sequencing then called for testing anisotropy and directional stress effects with nitrogen, as it is a less costly fluid. Methane (highest cost due to its 99.99% purity) was normally reserved for methane effective permeability, both static and dynamic; the latter measures the adsorption- and desorption-induced permeability effect. Notwithstanding, directional stress results were obtained with any of the three gases; we do not expect the general results and correspondence conclusions to be highly influenced by the type of fluid used, though the effective permeability is of course different.

**Maximum stress parallel to cleat direction**

**Face cleat permeability-**

Our investigations focused on situations where the maximum net stress is parallel to the face cleat direction, representing a horizontal maximum stress in the reservoir. The individual results in this group represent tests done on 40 mm cubes (TaoYuan mine and Bowen Basin coals), an 80x80x160 specimen (TaoYuan) and the 200 mm cube (Newlands' Bowen Basin mine).

The first group is of two tests of 40 mm cubes cut from Bowen Basin well cores and one 40 mm cube from TaoYuan (Figure 5). There was a sharp rise in nitrogen face cleat permeability for test 43 with the increase in parallel net stress. Results of test 38 showed a slight increase of helium permeability, then a slight decrease. Test 32 showed an increase in helium permeability also, but only covered an initial base deviatoric stress ratio at 1.05, followed by a group of results at 1.4 to 1.47.

The second example is from the 80x80x160 prism cut from TaoYuan coal blocks (Figure 6). This shows the helium face cleat permeability increasing slowly as the horizontal deviatoric net stress is varied from some 0.75 to 1.13.
The third example is drawn from the results of three tests on the Newlands Coal 200 mm cube, using helium, methane and nitrogen (Figure 7). As can be seen, the helium and methane tests showed an initial increase in permeability, followed by a slow decline. The nitrogen curve shows a steady slow rise in permeability up to the last test point.

The fourth example is the group of 40 mm cubes cut from Newlands coal blocks, with helium and methane as test fluids (Figure 8). Four of these tests show a flat or slightly increasing permeability with increased deviatoric stress in the flowing direction. A fifth test (test 9) shows an initial solid increase in permeability, followed by an asymptotic decline after the deviatoric stress ratio reached 1.15. The sixth test, on specimen NS2-3 exhibited a traditional exponential drop-off in permeability, as if the stress state were isotropic. However, during later anisotropic testing, the butt cleat permeability was found to be some 2 ½ times the face cleat permeability (both at 3.5 MPa net stress). We concluded then that our interpretation of which was the face cleat was in error (this can be easily done on the 40 mm cube specimens with little expression of surface cleats, as was with this specimen). Thus in the above, the maximum stress was applied not parallel to the erroneous face cleat but actually orthogonal to the real face cleat, and thus closing up high-flow cross channels.

The broad parallel-stress category also includes the situation when the vertical stress may be the maximum stress acting on the specimen; this stress is also parallel to the face cleats. Two tests yielded results in this investigation, including the 80x160 mm specimen from TaoYuan (Figure 9) The effective nitrogen permeability for test 13a showed excellent correlation of increasing with a corresponding net stress increase. It is noted, however, that this was performed in the 0.5 to 0.92 region.
In test 4C (Figure 10), the nitrogen effective permeability showed a steady and proportional rise with an increase in the deviatoric stress ratio, in the range of 1.1 to 1.25.

**Butt cleat permeability**
We were interested to determine the effects when the maximum stress was parallel to the butt cleats, anticipating mixed results as the resulting shear strain would tend to close off the face cleats. These provide needed-continuity during cross flow to the next butt cleat. One example is the combined results of Newlands tests 2, 3 and 15 (Figure 11). As can be seen, this group presents mixed results, with tests 3 & 15 showing decreases, as expected; however, test 3 shows a later increase at deviatoric stress ratio of 1.1 to 1.3. These two tests show that any gain in the butt cleat direction is more than offset by loss of connecting permeability in the face cleat direction, as the maximum stress is acting against the latter. Test 2 with helium, in contrast, showed a steady increase in butt cleat permeability. This is compatible with the observation that specimen NS 2-3 was quite stress sensitive.

Results from testing the Newlands 200 mm cube (Figure 12) present a dual effect: first, an increase at the lower stress ratio, as the butt cleats open up slightly; then, a decrease as the closure of cross-flowing face cleats takes effect.
The case where maximum stress is acting in the vertical or overburden direction relative while measuring butt cleat permeability has been analysed with the 200 mm cube in test 5E (Figure 13). This showed an initial decrease with a flattening out at a stress ratio of about 1.2. This contrasts with the positive effect on face cleat permeability from an increase in the vertical stress. The interpretation is that the connecting pathways from butt cleat to butt cleat are closing up faster than the butt cleats are opening.

**Maximum stress perpendicular to cleat direction**

**Face cleat permeability**-
The investigation of maximum stress being orthogonal to the face cleat direction was performed in test 13c(i) with the TaoYuan 80x160 mm prism (Figure 14). This shows a logical steep decline in face cleat permeability with the deviatoric stress increasing at right angles to the face cleats. Since face cleats transport generally 2 to 5 times more fluid in coal seams (see companion paper, Massarotto et al, 2003), this character of coal seams is very important for exploration of promising CBM reservoirs. If the tectonic stress has changed over time to be orthogonal to the face cleats, permeability loss over time can be quite significant.

**Butt cleat permeability**-
The case of an orthogonal maximum stress acting while measuring butt cleat permeability has been investigated with the Newlands 200 mm cube, test 5D (Figure 15). The initial reduction is compatible with butt cleats starting to close up; however, the flattening out implies the gain from cross-connecting face cleats offsets the initial direct loss of butt cleat permeability.
**Vertical (FC + BC) permeability**

This last section looks at a group of tests where vertical permeability was measured while varying vertical stress (Figure 16). These three tests were done on 40 mm cubes cut from Bowen Basin cores. A steady increase in permeability is observed in tests 37 and 39, as was expected: the aperture of both face and butt cleats reacts favourably to the shear strain imposed by the vertical stress.

The results of test 46 with nitrogen show an initial drop, followed by an increase. The drop in permeability seems illogical at first glance; it may be caused by a temporarily contributing horizontal fracture along the ply, or by a very small by-pass occurrence (though not probable, since the permeability was already quite low at 0.8 mD range) or by some other unknown phenomenon (testing error on the lowest point?).

**Isotropic net stresses**

We subjected several specimens to an isotropic stress field, to derive conventional inverse relationships between permeability and the average net stress. Results are shown in the following Figures 17, 18 and 19.

Tests 14b and 26 exhibit the traditional exponential fall-off in permeability with increases in the isotropic stress field. Several other tests for anisotropic permeability had early or late periods during the tests where a similar strong reduction in permeability occurred when the three stresses were increased equally.
Test 2B with the 200 mm cube shows an anomalous behaviour. This test was conducted by increasing the mean gas pressure flowing through the specimen, while keeping the external stresses constant. Thus the experiment progressed with a reducing isotropic net stress. The normal expectation would be for an increase in permeability, but only one such point was observed. The key observation is that the stress range is possibly too narrow to be meaningful.

![Graph](image)

**Figure 19**

### APPLICATIONS

That directional stresses can significantly affect the directional or anisotropic permeability of coal is a significant finding for several applications. For coal mine demethanation, this knowledge will yield a much more accurate assessment of gas flow rates and drainage times to get below threshold or shut-down levels of methane concentration in the mine. Also, knowing when the maximum principal stress is perpendicular to the face cleats should lead to denser drain-hole spacing than when it is parallel. Zones of high mean stress will also drain less and should receive denser spacing of drain-holes.

For CBM explorers, an assessment of the magnitude and current direction of the principal underground stresses needs to be coupled with knowledge of face and butt cleat behaviour in this environment, to define the risk of severe permeability loss, or the potential of significant improvement, over time. The overall assessment would point to whether the coal reservoir is a good candidate for a CBM development project. This type of information about a coal seam may also be useful in designing well stimulation programs. This behaviour of coal seams should now be built into the leading-edge reservoir simulators of CBM projects to greatly improve their accuracy.

Other applications where directional fluid flow and stress-related behaviour may be important are underground coal gasification and CO$_2$ geologic sequestration into coal seams.

### CONCLUSIONS

1. Our numerous investigations have shown that directional stresses have a profound effect on the directional, anisotropic permeability of coal.

2. The strongest correlations are a positive effect on directional permeability when the maximum principal stress is parallel to this direction, whether this is the face cleat or vertical direction.

3. When the principal stress is aligned with the butt cleat direction, there may be a small initial positive effect on butt cleat, but mostly there occurs a reduction
in face cleat permeability, resulting in an overall loss in average seam permeability.

4. An important conclusion is that laboratory investigations of coal permeability need to integrate the real orientation of the maximum principal stress and the orientation of face cleats corresponding to the in situ condition for the coal reservoir under study.

5. A true triaxial stress coal permeameter, testing cubic or prismatic specimens at in situ conditions of external stress and pore pressure, is an ideal apparatus for investigating the effect of directional stresses on the directional permeability of coal. It can be used to collect important permeability characterisation to input into various methane drainage and CBM reservoir models, to increase their relevancy and accuracy.

The implications of these findings are that exploration for CBM will be more successful in basins or sub-basins where the neo-tectonic stresses are parallel to the face cleat direction. This implication is considered valid notwithstanding the author’s view that coal reservoirs act more like constant volume chambers than constant external stress chambers. Even when the reservoir initially behaves as a constant volume chamber, later in the life of the reservoir there will be a tendency for a partial increase in net or effective stress, either if the desorption and associated shrinkage do not occur as quickly or if the flexural strength limit of the overburden has been reached.

A corollary conclusion is that explorers should stay away from areas with an orthogonal correspondence between face cleat and neo-tectonic principal horizontal stress.

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REFERENCES


