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# Stresses in Sedimentary Strata, including Coals, and the Effects of Fluid Withdrawal on Effective Stress and Permeability

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# STRESSES IN SEDIMENTARY STRATA, INCLUDING COALS, AND THE EFFECTS OF FLUID WITHDRAWAL ON EFFECTIVE STRESS AND PERMEABILITY

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*ABSTRACT*: This paper describes the methods which can be used to determine the in-situ stresses in sedimentary strata including coals. It also examines the changes in effective stresses brought about by fluid withdrawal such as that caused by gas and water drainage. These changes in effective stress are brought about directly by changing fluid pressure and, in the case of coals, by the effects of shrinkage as the coal releases gas and if it dries out.

As the permeability of coal is very significantly affected by its effective stress the drainage of coals is dependent on the state of effective stress. Coal permeability may either increase or decrease during drainage. Permeability frequently shows some initial decline as fluid pressure decreases before shrinkage effects cause an increase. In some cases though, the overall trend is for a continuing decline in permeability. Under these circumstances no amount of stimulation to induce drainage will work and some other means must be sought to de-stress the coal. This has typically been by working an adjacent seam which is more amenable to being mined.

## INITIAL STRESSES IN COALS

Determining the initial stress in the coal is important because it represents the starting level of stress before varying fluid pressures and coal shrinkage changes the stress levels. The importance of knowing initial stress is so that the initial value of the coal's mechanical behaviour may be assessed at the correct stress level. Mechanical behaviour specifically refers to the non-linear stress strain behaviour of coal and to the stresses at which coal may fail. It is also important to know the initial stresses so that it is possible to determine whether coal is de-stressed.

The measurement of stress in coals is, however, not simple because coal is generally fractured and weak. This means that hydrofracturing in coals usually only reveals the stress level normal to the cleat direction closest to being perpendicular to the normal principal stress. For the same reasons the process of overcoring cannot be used in coals as they break up. It is however possible to measure stress in competent strata surrounding the coal seam and make an estimate of the stress in the coal itself. The most accurate procedure for this is to use overcoring. Hydrofracture is a second option while some rather less accurate measurements may be made by examining borehole breakout trends or hole ovality. Overcoring requires that the rock should remain in an elastic state through the process. The extraction of information on the major principal stress from hydrofracture test data also requires that the rock is elastic though the minimum stress may be determined in rock with more plastic behaviour. Borehole breakout requires that the rock should have passed any elastic situation and to have actually failed.

Overcoring is a process where a pilot hole is drilled at the end of a larger hole and a tool is inserted to measure either strain on the wall of the pilot hole or the diameter of that hole. The equipment includes some means to orient the tool and then the core is cut over the top of the tool while the deformations of the pilot hole are measured (Gray, 2000). The tool is retrieved in the core and the information downloaded from it and the rock sample taken for measurement of Young's modulus and Poisson's ratio. A pictorial view of the overcoring process is shown in Figure 1 while examples of the diameter traces during the overcore are shown in Figure 2. Figure 3 shows the best fit of a theoretical pilot hole deformation to the measured deformations.

The stresses measured in sedimentary rocks will vary significantly through the strata. This variation is substantially due to the varying stiffness of the rock. Having obtained stress measurements in some of the strata surrounding the coal seam it is necessary to consider how these are distributed through sequence and to obtain an estimate of the stresses which may exist in the coal. To do this, it is necessary to develop a suitable model.

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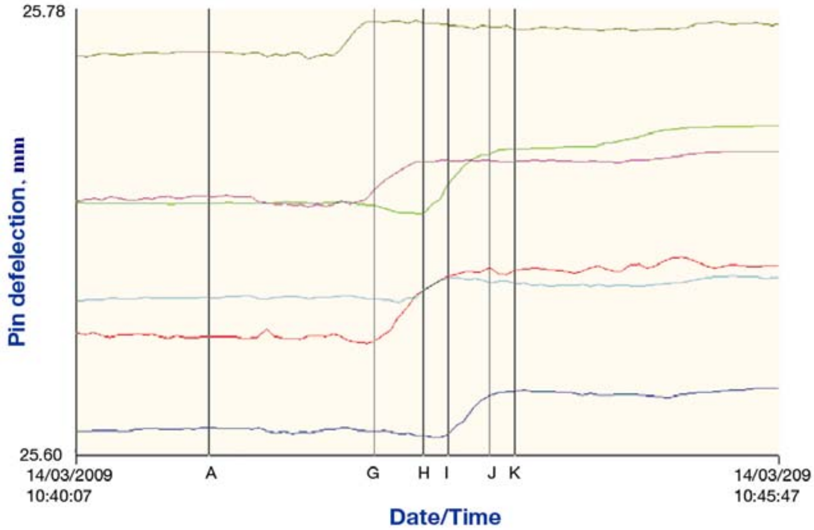


**Figure 1 - Pictorial view of overcoring operation** **Figure 2 - Example of diameter change with time during overcoring**

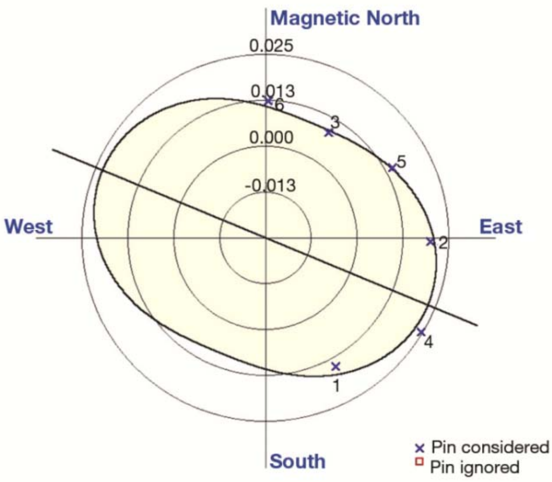


**Figure 3 - Example of best theoretical deformation fit to real diameter change points**

Sedimentary strata is generally laid in marine or lacustrine environments and built up as a series of layers. Where the strata remains fairly horizontal and not too contorted or faulted, the vertical stress ($\sigma_v$) is essentially due to self-weight and can be calculated on the basis of 0.025 MPa/m depth or an effective stress of 0.015 MPa/m depth. Assuming the rock is laterally constrained, such that there is no allowable strain in the horizontal plane, the horizontal effective stress due to self-weight ($\sigma'_{h/sw}$) can be calculated using the following Equation (1):

$$\Delta\sigma_{h/sw} = \Delta\sigma_v \left(\frac{v}{1-v}\right) \qquad (1)$$

In practice, the horizontal stresses are very seldom equivalent to this. Part of the reason is that this equation represents a simplified elastic model which does not account for creep processes. More generally, there are other components which result from horizontal effective tectonic stress ($\sigma'_{h/tec}$), generated by tectonic movements. This may be due to tectonic plate loading, but is more frequently due to local structural conditions such as anticlines and synclines.

The major and minor principal effective tectonic stresses, $\sigma'_{h/tec/1}$ and $\sigma'_{h/tec/2}$, are calculated using Equations 2 and 3:

$$\sigma'_{\mathrm{h/tec/1}} = \sigma_1 - \sigma_{h/sw} \quad (2)$$

$$\sigma'_{\mathrm{h/tec/2}} = \sigma_2 - \sigma_{h/sw} \quad (3)$$

It is desirable, regionally, to consider the strain caused by tectonic movements, rather than focusing on stress fields. Stresses vary with the modulus of the rock; the stiffer the rock, the more stress it carries for a given strain. Using the values of tectonic stress calculated from Equations 2 and 3, the components of tectonic strain can be calculated as follows in Equations 4 and 5.

$$\varepsilon_{tec/1} = \frac{\sigma'_{h/tec/1} - \nu\, \sigma'_{h/tec/2}}{E} \quad (4)$$

$$\varepsilon_{tec/2} = \frac{\sigma'_{h/tec/2} - \nu\, \sigma'_{h/tec/1}}{E} \quad (5)$$

To examine the average tectonic strain for a group of stress measurements it is necessary to rotate the principal strains into direct N-S and E-W strain and shear strain components to find the mean of these. The principal tectonic strains and their direction may be calculated from these three mean strains. If tectonic strains are relatively uniform between adjacent stress measurements they may be used to calculate stresses in rock of varying stiffnesses and Poisson's ratios in locations stress measurements have not been made. This process is the reverse of that used to derive the tectonic strain.

In these cases, the horizontal stress due to overburden is calculated according to Equation 1. The effective stresses due to tectonic strain may be calculated using Equations 6 and 7.

$$\sigma'_{h/tec/1} = \frac{-E}{1-\nu^2}\left(\varepsilon_{tec/1} + \nu\, \varepsilon_{tec/2}\right) \quad (6)$$

$$\sigma'_{h/tec/2} = \frac{-E}{1-\nu^2}\left(\varepsilon_{tec/2} + \nu\, \varepsilon_{tec/1}\right) \quad (7)$$

The principal effective stresses are calculated by adding the horizontal stress due to self-weight to the above figures.

Figure 4 illustrates a theoretical example of a layered sedimentary strata with varying stiffness and Poisson's ratios. The rock is subject to gradually varying tectonic strains. The major tectonic strain, increasing with depth, indicates some features of a possible anticline, while the minor tectonic strain shows the reverse trend. The stiffness of the strata varies considerably and so, correspondingly, do the stresses.

Vertical variation in tectonic strain is indicative of unconformities. Faulting may often be detected by lateral variations in tectonic strain. Faults are invariably locations of stress relief, and normally faulted zones generally show very low to negative tectonic strain, though not tensile stress.

The tectonic strain model fairly frequently provides a good basis for understanding the stress distribution within strata. It is a useful analytical technique for understanding the stress distribution. Departures from this model need to be considered as the abnormal and deserving of further study. They may be due to unconformities or extreme plasticity of the rocks.

A good example of even tectonic strain across major variations rock properties is gained from a borehole drilled in the Surat Basin in Queensland. Here two stress measurements were taken adjacent to each other in quite different material and the tectonic strain was calculated and found to be almost identical. This is presented below in Table 1. A similar case is presented from a proposed mine in the Bowen Basin in Table 2. Here the major tectonic strains are very similar while the minor tectonic strains show more variation.

It should be noted that tectonic strains can be quite variable as they are influenced by local geological features.

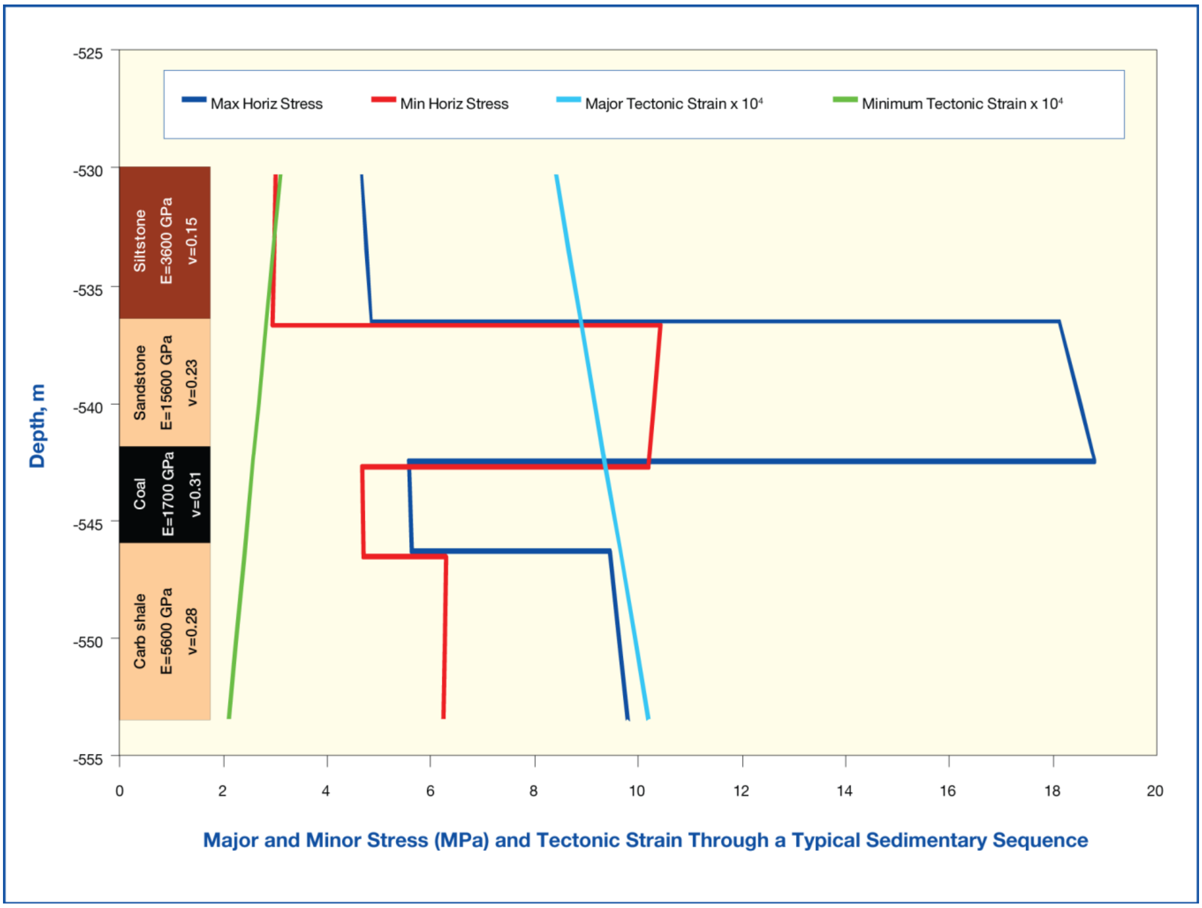


**Figure 4 - Theoretical stress distribution through a typical sedimentary sequence showing monotonically varying tectonic strain and the induced stresses in rocks of varying stiffness**

**Table 1 - Stresses and tectonic strains in Juandah coal measures in the Surat Basin Queensland**

| Depth | Young's Modulus (MPa) | Poisson's Ratio | Principal Stresses | | Tectonic Strains | |
|---|---|---|---|---|---|---|
| | | | Major | Minor | Major | Minor |
| 507.49 | 1315 | 0.09 | 1.13 | 0.79 | 3.14E-04 | 3.66E-05 |
| 508.89 | 31646 | 0.17 | 11.72 | 5.01 | 3.02E-04 | 5.32E-05 |

It should be noted that tectonic strains can be quite variable as they are influenced by local geological features.

With the benefit of stress measurements in rocks it is possible to calculate tectonic strains and to apply these values to other strata which have not had stress measured using the known mechanical properties of the rock. This includes the coal seams. There are however some problems with this in that the determination of the coal's mechanical properties is not easy and that the coal has undergone some chemical changes following deposition in the coalification process. It does however provide a first estimate of the stresses and their direction. This may be clarified further by hydrofracture testing to confirm minimum stress levels within the coal.

The processes to arrive at the initial stress calculations in coal are useful. Lacking such information, however, it is possible to estimate the initial stress and focus on the stress changes.

## CHANGES IN STRESS BROUGHT ABOUT BY FLUID REMOVAL

Effective stress is the total stress minus the product of fraction (close to unity in a cleated coal) and the fluid pressure as shown in Equation 8.

$$\sigma' = \sigma_T - \beta * p \quad (8)$$

The tendency for coal lumps to change dimension is associated with gaining or losing gas from coal. This can be measured mechanically. The general trend is for the coal to swell with absorption and shrink with loss of gas. The shape of the strain curve induced by gas pressure may sometimes, but not always, be considered to be similar to the shape of the sorption isotherm curve. An example of such a strain curve is shown in Figure 5. Here the x-axis shows the sorption pressure while the y-axis displays the strain. This example shows a change of 1600 microstrain over a sorption pressure change of 3 MPa.

**Table 1 - Stresses and tectonic strains at a proposed mine site in the Northern Bowen Basin**

| | | | |
|---|---|---|---|
| Sigra IST (Test Ref) | 101.021 | 103.021 | |
| Depth, m | 241.10 m | 247.30 m | |
| Location to Seam | Leichhardt Seam Roof | Leichhardt Seam Roof | |
| Material Description | Fine Grain Sandstone with Dark Grey Siltstone Banding | Fine Grain Sandstone with Dark Grey Siltstone Banding | |
| Young's Modulus, MPa | 11765 | 34762 | |
| Poisson's Ratio | 0.12 | 0.23 | |
| Unconfined Compressive Strength | 28.6 | 100.3 | Mean Roof Values |
| Angle of Maximum Principal Effective Stress (degrees E of Magnetic North) | $33.12^0$ | $30.82^0$ | $31.17^0$ |
| Maximum Tectonic Strain | 7.07E-04 | 6.22E-04 | 6.65E-04 |
| Minimum Tectonic Strain | 3.57E-04 | 7.47E-05 | 2.16E-04 |
| Max Principal Effective Stress, MPa | 9.46 | 24.58 | |
| Min Principal Effective Stress, MPa | 5.77 | 9.10 | |
| Ratio of Maximum Effective Stress over UCS | 0.33 | 0.25 | |

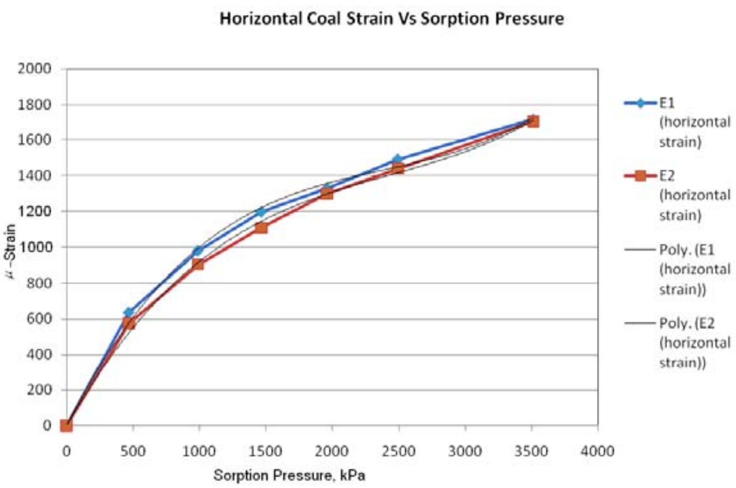


**Figure 5 - Example of coal's dimensional change with gas pressure**

The stresses in coal during fluid production are a function of the initial total stress in the coal and the changing fluid pressure and changes in stress brought about by shrinkage of the coal as it gives up gas and dries out. Shrinkage by removal of moisture is reported by Pan *et al*. (2008). However, whether actual removal of moisture to achieve drying and related shrinkage occurs in a commercial gas production situation, is of some doubt, though the effect is widely recognized in coals that are drained from underground.

Stress changes in coals are brought about by the removal of fluids. In laterally extensive environments the horizontal dimension remains the same while the ground level drops. Thus the horizontal strain remains constant whilst a reduction in vertical strain occurs. Using Equation 3 and assuming that β is unity (consistent with bedding plane fractures) then the increase in effective vertical stress can be expected to be exactly the same as the reduction in fluid pressure as per Equation 9.

$$\Delta\sigma'_v = -\Delta P \qquad (9)$$

This change in vertical stress causes a corresponding change in horizontal stress given by Equation 10, which is similar to Equation 1.

$$\Delta\sigma'_{h/sw} = \Delta\sigma'_v \left(\frac{v}{1-v}\right) \qquad (10)$$

The effects of fluid pressure reduction on effective horizontal stress are given in Equation 11. They are a combination of the direct effect of reducing fluid pressure (as in the horizontal form of Equation 9), and the effects brought about by the Poisson's effect as given in Equation 10.

$$\Delta\sigma'_h = -\Delta P(1+\left(\frac{v}{1-v}\right)) \qquad (11)$$

If, however, shrinkage occurs then the effects need to be taken into account as described in Equations 12 and 13.

The horizontal stress changes brought about by shrinkage are:

$$\Delta\sigma_{sh/1} = \frac{E}{1-v^2}\left(\Delta\varepsilon_{sh/1} + v\,\Delta\varepsilon_{sh/2}\right) \qquad (12)$$

$$\Delta\sigma_{sh/2} = \frac{E}{1-v^2}\left(\Delta\varepsilon_{sh/2} + v\,\Delta\varepsilon_{sh/1}\right) \qquad (13)$$

Therefore the net effective changes in horizontal stress caused by fluid removal are given in Equations 14 and 15:

$$\Delta\sigma'_{h/1} = \Delta P(1+\left(\frac{v}{1-v}\right)) - \frac{E}{1-v^2}\left(\Delta\varepsilon_{sh/1} + v\,\Delta\varepsilon_{sh/2}\right) \qquad (14)$$

$$\Delta\sigma'_{h/2} = -\Delta P(1+\left(\frac{v}{1-v}\right)) - \frac{E}{1-v^2}\left(\Delta\varepsilon_{sh/2} + v\,\Delta\varepsilon_{sh/1}\right) \qquad (15)$$

Without shrinkage effects, a reduction in fluid pressure will bring about an increase in effective horizontal stress (per Equation 11). If shrinkage effects occur, then Equations 14 and 15 describe the combined effect. In some cases horizontal effective stress will increase while in others it will decrease

If one of the effective horizontal stress levels in the coal drops to a low enough value compared to either the other effective horizontal stress, or to the vertical effective stress then the potential for a small scale localised failure may occur. Otherwise this horizontal stress may drop to zero whereupon further shrinkage will lead to direct opening of the cleat.

The equations presented in this paper are formulated in terms of linear elastic parameters for Young's modulus (*E*) and Poisson's ratio ( $v$ ). It should be appreciated that coal is a inhomogeneous rock which may undergo stresses which take it into a non-linear range of behaviour. It is therefore essential in the analysis of the effects of stress change to take into account this behaviour by proceeding with step wise calculations for each increment in fluid pressure change, using as far as can be determined, the tangent values of *E* and $v$ at the appropriate stress levels.

Figure 6 shows the stiffness versus effective stress behaviour of a coal under hydrostatic loading. This is highly non linear. Coals also frequently show a significant difference between vertical and horizontal stiffness.

## A STRESS PATH CALCULATION

Information has been used from the proposed Northern Bowen Basin Mine site in the Bowen Basin of Queensland to calculate the stress path. The initial effective stress in the seam has been calculated from the tectonic strains, using an appropriate secant Young's modulus and Poisson's ratio. The stress path is shown in Figure 7 and has then been calculated based upon desorption as soon as the fluid pressure is lowered. The calculation uses the shrinkage curve shown in Figure 5.

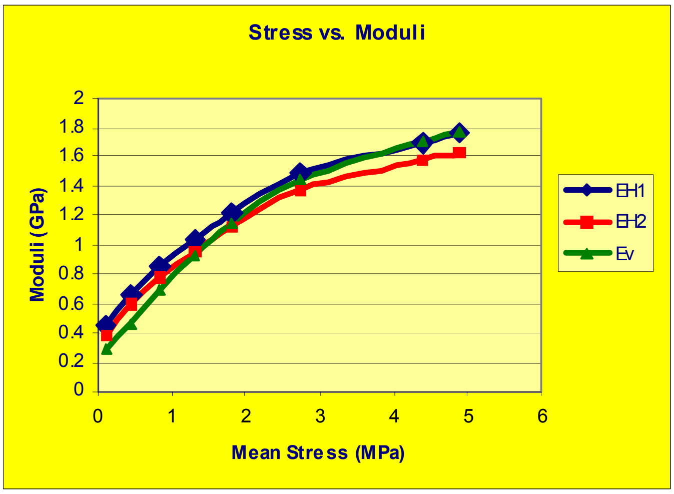


**Figure 6 - Stiffness versus effective mean stress behaviour of a coal sample under hydrostatic loading**

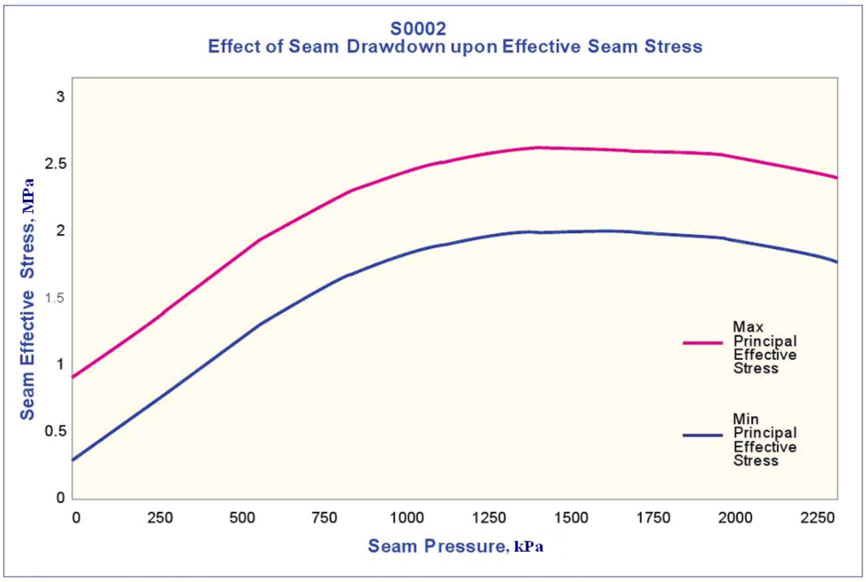


**Figure 7 - The stress path due to drainage of a Northern Bowen Basin coal**

The two horizontal effective stresses increase with a drop in reservoir pressure from 2050 kPa to 1250 kPa. Below this pressure the effects of shrinkage are significant and the effective stress decreases are marked. As the coal in question has a very low permeability the implications of this are important. It is likely that drainage will be very slow until the reservoir pressure is dropped to 1250 kPa whereupon the process of drainage will speed markedly. Getting the coal to this reservoir pressure may require closely spaced horizontal holes and the use of stimulation such as hydrofracture to enhance initial drainage.

It should be appreciated that the equations which are used to derive the results presented in Figure 7 are based upon uniform drainage over a wide area. The real position from a mining perspective is likely to be different as uniform drainage is unlikely.

## THE EFFECT OF VARYING EFFECTIVE STRESS ON PERMEABILITY

It can be readily shown in tests on coal core that the permeability of coal is directly related to the effective stress which exists. This type of relationship is shown in Figure 8. Equation 16 shows a log permeability-effective stress equation can be used to describe this relationship. The permeability of stiffer coals may be expected to be less affected by changing stresses though stiffer coals show much greater stress change associated with shrinkage behaviour.

$$\log k = \log k_o - \sigma' / b \quad (16)$$

In the most dramatic cases it appears that *b* may be as low as 3 MPa thus indicating a change of one order of magnitude in permeability with 3 MPa effective stress change.

This type of relationship is supported by core testing (Somerton, *et al.*, 1975; Gray, 1987). Field evidence exists through history matching, albeit with complications associated with the effects of shrinkage of coal and two phase flow effects. It is also supported by the results of permeability tests conducted at various depths in of a number of seams including the Goonyella Middle Seam.

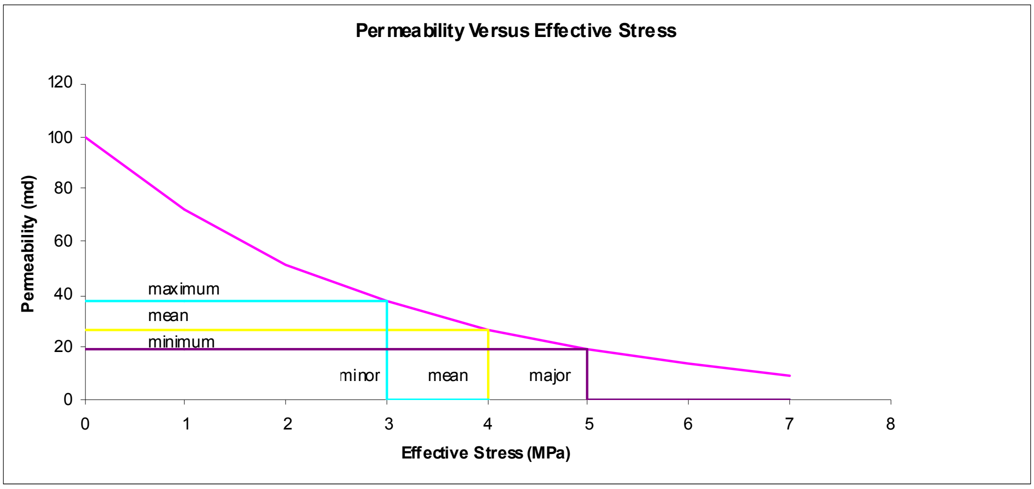


**Figure 8 - A prediction of permeability change with effective stress**

The significance of changing effective cleat width may be appreciated by the theoretically derived Equation 17 (Snow, 1968) for permeability based on cleat width and spacing. Permeability increases as the cube of effective cleat width and is directly proportional to the inverse mean cleat spacing.

$$k = \left( \frac{w^3}{12S} \right) \quad (17)$$

If permeability is measured then it is possible to arrive at an effective cleat width provided that measurements of cleat spacing have also been made. This then provides a basis for predicting how permeability may change when cleats open due the effective horizontal stress dropping below zero.

## A PRACTICAL EXAMPLE

Figure 11 approximates the situation as was thought to exist on the basis of field testing at Leichhardt Colliery in the Central Bowen Basin Queensland. It shows where the permeability began at 0.1 md with a 4.2 MPa seam pressure. Initial water drainage takes place to 3.8 MPa when the sorption pressure is reached and gas is emitted from the coal.

In this pressure range the permeability declines due to an increase in effective stress. This trend would continue (blue line) except that in the real case shrinkage occurred (red line) causing a reduction in effective stress and an increase in permeability to 1 md at 2.7 MPa gas pressure. At this pressure zero effective stress exists across the cleats. As gas pressure declines further the permeability increases dramatically to 500 md at 0.5 MPa pressure. This case is extreme but demonstrates the importance of shrinkage.

## CONCLUSIONS

This paper describes the process of determining the effective stress path of a coal by determining the initial stress level through the process of fluid removal, incorporating the effects of shrinkage. Permeability of the coal is strongly affected by the effective stress and therefore if this increases then permeability decreases and vice versa. Determining the likely stress path is a key to knowing whether permeability will increase or decrease with drainage. This is particularly important for those with coals in the low permeability range.

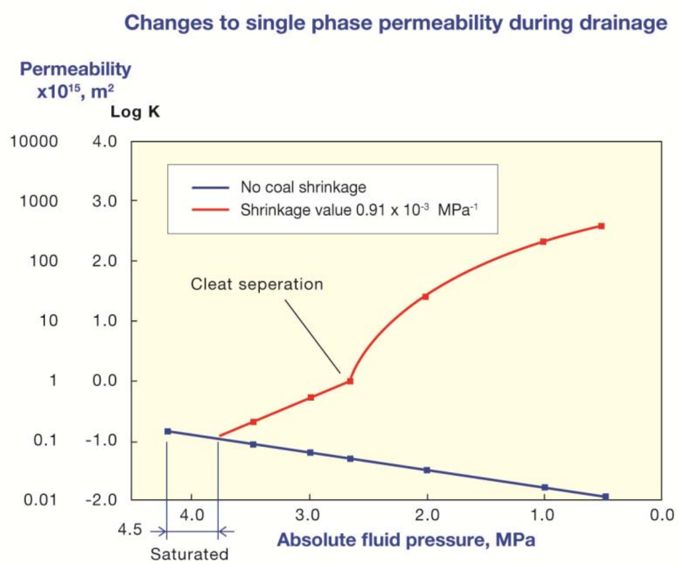


**Figure 11 - Changes to permeability due to effective stress and shrinkage (from Gray, 1987)**

Stress measurement by overcoring in strata adjacent to the coal seam provides information on the initial stress regime. The initial stress conditions can be transferred to adjacent strata of different elastic properties by using the concept of tectonic strain.

Where the coal has low permeability and the effective horizontal stresses do not decrease, but may indeed increase with dropping fluid pressure, then there is sometimes no potential to drain the seam using conventional drilling methods, even if these are assisted by stimulation such as hydrofracture of the in-seam drainage holes. From a mining perspective the only option is to remove material to drop the stress level. This is sometimes achieved by mining an adjacent seam which can be drained and worked thus de-stressing the problem seam.

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## NOMENCLATURE

$b$ is the stress – perm coefficient, $Pa^{-1}$.
$E$ is Young's modulus, Pa.
$g$ is gravitational acceleration, $m/s^2$.
$k$ is the permeability, $m^2$.
$k_o$ is the permeability at zero effective stress, $m^2$.
$l$ is the length in the direction of flow, m.
$P$ is the pressure , Pa.
$\Delta P$ is the change in fluid pressure, Pa.
$S$ is the mean cleat spacing, m.
$v$ is the apparent flow velocity, m/s.
$z$ is the elevation, m.
$w$ is the effective cleat width, m.
$\beta$ is the fraction representing the proportion of continuous fracture area (approximately unity).
$\Delta\varepsilon_{sh/1}$ is the strain change due to shrinkage in direction 1 in the horizontal plane. Note a positive value implies shrinkage.
$\Delta\varepsilon_{sh2}$ is the strain change due to shrinkage in direction 2 in the horizontal plane. Note a positive value implies shrinkage.
$\mu$ is the absolute viscosity, kg $m^{-1}s^{-1}$.
$v$ is Poisson's ratio, kg $m^{-3}$.
$\rho$ is the density of the fluid (mass/$length^3$).
$\sigma'$ is the effective stress normal to the cleats, Pa.
$\sigma_T$ is the total normal stress across a fracture, Pa.
$\Delta\sigma_{h/sw}$ is the change in effective horizontal self weight stress, Pa.
$\Delta\sigma_v$ is the change in effective vertical stress, Pa.
$\Delta\sigma'_{h/1}$ is the effective stress change in direction 1 in the horizontal plane, Pa.
$\Delta\sigma'_{h/2}$ is the effective stress change in direction 2 in the horizontal plane, Pa.
$\sigma_{sh/1}$ is the stress change due to shrinkage in direction 1 in the horizontal plane, Pa.
$\sigma_{sh/2}$ is the stress change due to shrinkage in direction 2 in the horizontal plane, Pa.