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Getting Useful Gas and Stress Measurements Out of Exploration Drilling

I. Gray

Sigra Pty Ltd

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Ian Gray [1]

INTRODUCTION

This paper focuses on two areas, gas and stress. It discusses the measurement of relevant parameters for mine design and aims to assist operating mines keep abreast of changing conditions to avoid problems. An understanding of the factors which affect the reservoir capacity of a coal seam is essential as an aid to better mine planning.

DESCRIPTION OF A COAL SEAM RESERVOIR

Coal seams are frequently gas reservoirs and may pose significant problems for mining. It is important to establish the behaviour of this reservoir as part of the exploration process.

The gas in coal seams is stored in the seams by a process of sorption, which involves aspects of surface bonding and chemisorption. The gas stored in pore space is usually far less than that stored in the coal itself. The coal matrix changes dimension depending on the level of moisture and gas in the coal. This feature is of extreme importance.

Most coal seams exist initially in a state where all the pore space is filled with water, although exceptions where gas caps exist can be found. In these latter instances, fluid production may start with gas. In the more usual case, gas production will not occur until the water pressure has been lowered to less than the sorption pressure (akin to a bubble point in an oil reservoir).

Once the pressure in the cleats in the coal has been lowered, desorption of gas from the coal may occur. The process of gas movement in the coal solid is considered to be one of diffusion. This occurs from the solid to the fracture space where the pressure is lowered and bubbles form in the fractures.

The flow within the fractures in the coal follows Darcy's law of flow down a potential gradient (pressure and gravitational components). The presence of gas and water within the fractures leads to a two-phase flow regime, in which water impedes the movement of gas and vice versa. Coal seams frequently display several forms of fracturing. These can be divided into microfractures, cleats, major joints and faults. All are important in the behaviour of coal as a reservoir. Flow from coal is a process of diffusive flow into microfractures to the cleats and from cleats to any major joints or faults that may exist. The fractures all have direction and contribute to a directional permeability dependent on their orientation. The cleated coal may be considered to represent, in oilfield terms, the matrix permeability, whilst the major fractures represent fracture permeability.

The permeability of coal is generally directly related to the effective stress to which the coal is subjected. Effective stress is the total stress field (a tensor) minus the fluid pressure. Permeability is thus a tensor dependent on stress and fracture orientation.

The effect of stress on coal permeability may be described in non-directional terms by Equation 1 below:

$$k = k_i \, 10^{\left(\frac{s_i - s}{a}\right)} \tag{1}$$

[1] Principal, Sigra Pty Ltd

where k is the permeability at effective stress s,
k_i is the permeability at initial effective stress s_i,
a is the effective stress change required to produce a ten-fold reduction in permeability,
s_i is the initial effective stress, and
s is the effective stress.

In coals, a may range from a lower value of about 2 MPa up to high values. The higher the value of a, the less permeability is influenced by changing effective stress. The softer the coal, the lower a tends to be. If a is of similar or lower value than the expected drop in reservoir pressure, then stress related permeability changes may be expected to be extremely important.

As reservoir pressure drops, the effective stress within the coal can be expected to increase and with it an associated permeability reduction. This behaviour does occur, particularly in the short term. In the longer term, an opposing effect may occur due to shrinkage. If the coal shrinks as it gives up gas and then dries out, the coal carries less stress and transference of stress to the surrounding rocks occurs. The condition may occur where no stress exists between cleats, in which case the permeability may increase sharply.

The process of fluid movement in coal may be interrupted by a producing borehole or by an absence or blockage of any of the levels of fracturing. Gas production may be thought of as having several contributing steps.

If the diffusion coefficient is low or the spacing between fractures too great then, despite an apparently high permeability, the gas release may be limited by the diffusive escape of gas from the solid coal. Similarly, if the matrix permeability is too low then gas production will be impeded by this. The presence of major fractures may lead to permeability that is an order of magnitude different to that of the matrix. However, high fracture permeability is of little benefit if the matrix is blocked and diffusion is the only mechanism by which gas may reach the fractures.

Faults often act as boundaries between areas of different reservoir characteristics.

DETERMINATION OF RESERVOIR PROPERTIES

Determining reservoir properties is extremely important to the viability of a mine. Normal mining exploration should include the correct procedures to ensure that the correct reservoir parameters are obtained. In addition to measuring gas content, an endeavour should be made to determine diffusion coefficients and permeabilities. The plural is used here deliberately, as coal usually exhibits at least two diffusion coefficients and permeabilities to match the varying fracture types.

Gas Content and Diffusion Coefficient

Coring is a good start to assessing the gas production characteristic of a coal seam gas reservoir. It enables a sample of the coal to be obtained and provides a hole in which to conduct reservoir tests. This hole may then be used as an entry to the reservoir for monitoring.

The coal core can be taken and placed in a desorption vessel so that the gas released can be measured in volume and type. The use of strain gauges to measure the change in dimension of the coal is recommended. If the coal core is of regular cylindrical form it is theoretically possible to arrive at diffusion coefficients. This is a result of fitting diffusion equations to the short and long term release of gas from the core. Unfortunately very few coal cores are neat cylinders, more typically they are fractured and of variable composition.

Despite this, the same equations that are used to describe the diffusion from a cylinder also fit the rates of desorption extremely well. The real issue is then of examining the core carefully and making an estimate of what sort of characteristic dimension applies to the coal lumps.

Gas is invariably lost on core recovery and it is usual to estimate the amount by measuring the cumulative gas release with time as soon as the core can be placed within a canister. A plot of the square root of time since removal of the core and cumulative gas release usually plots as a straight line as could be expected from the equations relating to short-term diffusion. This can be extrapolated back to zero time to arrive at a lost gas estimate. The slope of the curve may be directly related to the initial diffusion coefficient.

The fitting of the diffusion equation to the longer term desorption characteristic usually leads to a good fit, but invariably the associated diffusion coefficient is significantly lower than the one arrived at by examining the initial gas desorption characteristic.

The process of diffusion is therefore open to question. Why two diffusion coefficients? An explanation may be found in the fact that initially significant pressure of gas in the micro-cleats could be enlarging these and expediting the release of gas. Alternatively, there could simply be two or possibly more diffusion behaviours. If the long-term diffusion coefficient can be estimated, however roughly, then for that number to be of value, it must be associated with an open fracture spacing. From these two numbers the rate of diffusion can be calculated.

It is therefore extremely important to have some idea of the cleat spacing in the coal. Unless the cleats are extremely closely spaced, and their separation can be measured within core, the estimation of cleat spacing is unfortunately quite difficult.

Permeability Measurement

Measuring a coal reservoir's permeability is frequently challenging because of (i) stress-dependent permeability displayed by coal; (ii) shrinkage which affects stress; and (iii) two-phase effects. Additionally, the fracture permeability is frequently significantly greater than the matrix permeability. What, then, is the best way to proceed given these factors?

The first and most simple test for permeability is to get a piece of core and to look at it. If no fractures exist, and particularly if the coal has a waxy feel to it, then it is likely to be tight on the scale of core. If fractures are visible, but filled, then a similar comment applies. If the core contains cleats that are free of infill, then the prospects are much better for gas production. This does not necessarily mean that it will be permeable, because cleated coal can be very tight under high stress conditions. This applies particularly if the coal is soft.

The next stage of assessing the core for permeability is to pick it up and suck through it. This may seem amusing, but it is remarkably effective in allowing one to gain some feeling for the nature of the fractures and their ability to carry gas. An inability to suck air through the core at zero stress implies a much bigger problem for passing gas under stress.

On a more formal note, it is most important in assessing the permeability of coal to realise that any measurement must be put in the context of the state of development of the reservoir and that a permeability measurement made at a specific time may be quite different from one that exists later. It is equally important to be able to predict whether the coal seams' permeability will increase or decrease. Self-sealing coals do exist, as do instances of permeability enhancement of two orders of magnitude.

Given the complications associated with stress permeability relationships, it is generally not wise to introduce two-phase effects (flow of gas and water) during initial reservoir testing. Picking the stress related permeability effects is quite complex enough. The use of a drill stem test (DST), which may occasionally produce a minor amount of gas, followed by an injection fall-off test is advocated.

A procedure sometimes used is to core a seam and to pull back the core rods to above the seam. This is followed by running a twin packer DST tool through the drill string and displace water out of the string using compressed air. Packers are then set , one below and one in the string, to release compressed air. The bottom valve can then be opened by lowering the string and inducing flow into the rods. The gross flow rate of gas and water is measurable on a surface gas flowmeter. The volume of water in-flowing may be measured by means of a head increase in the rods above the DST tool. The bottom valve is then closed and pressure builds up and is measured by a bottom hole pressure transducer. During the build-up period, the rods are filled with water. An injection test at a constant rate is then performed and the hole is then shut in while pressure approaches equilibrium.

The exact mechanism of the test may be varied if DST tool in which the packers are inflated off the rig pump is used. Essentially the test remains the same. A trace of bottom hole pressure from a DST and injection fall-off test is presented in Figure 1. The tool used is shown in Figures 2a and 2b.

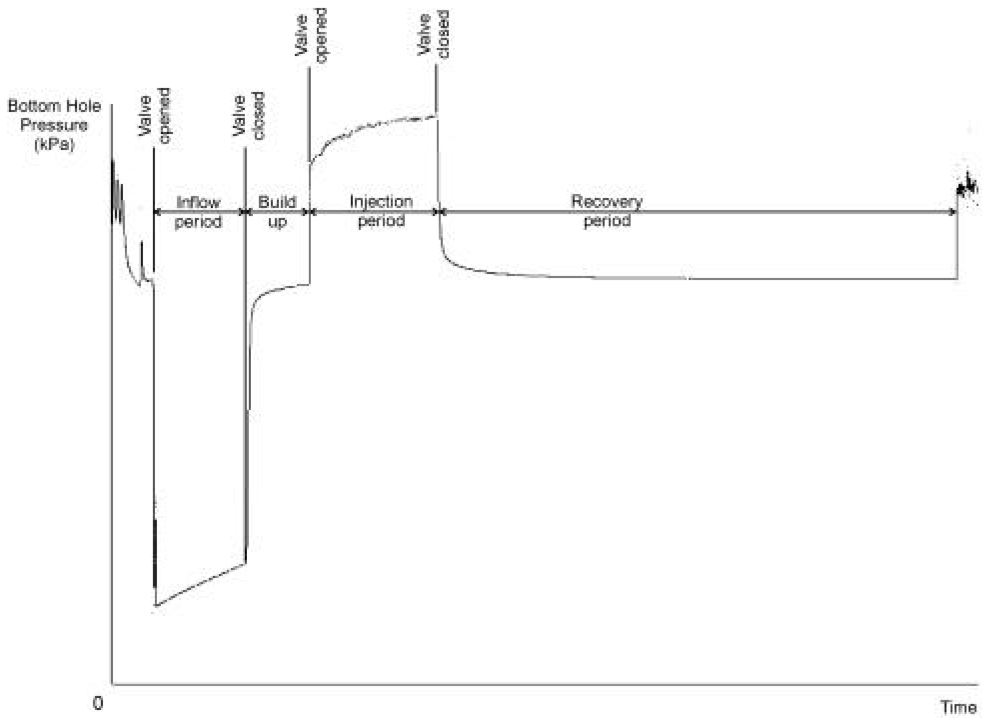

Fig 1 - DST and injection fall-off trace.

Fig 2a - A DST tool being lifted on a wire-line.

Fig 2b - Stress measurement tool about to be lowered into HQ drill rods.

The DST flow period may last from several hours to a few minutes, depending on formation characteristics. The same applies to the recovery period. The DST test gives an indication of the injection flow to follow. The injection test is usually conducted at a single rate, though in some instances it is useful to vary this to see what the short-term local response is to rate changes.

The analysis of DST or injection fall-off tests in coal may be simple or complex, depending on the seam. If the coal seam is permeable, the permeability not particularly stress-dependent or the sorption pressure low, then a normal Horner-type analysis is usually sufficient for both the build-up and fall-off behaviours. If, however, the seam deviates from these characteristics, then the assessment of seam parameters becomes significantly more complex. The analysis essentially becomes one where a simulator is required that incorporates all the complex characteristics of coal seam reservoir behaviour.

Not all assessments of permeability need be so complex that they require a simulator to find a solution. Some characteristics may be found by basic calculation. One of the first comparisons to look at is the inflow rate during a DST test and the injection rate. It is important if the flow rates are significantly different for similar variations from reservoir pressure. If the DST inflow rate is significantly higher than the injection rate then in all probability well-bore damage (plugging of the fractures surrounding the borehole) has occurred. This will be revealed in the nature of the pressure change after well closure, with instant pressure changes indicating well-bore damage.

When a DST inflow rate is significantly lower than the injection rate there is a good indication that stress-related permeability effects are important. The reduction in fluid pressure around the well-bore during a DST test leads to increased effective stress and in a coal with stress-dependent permeability, a reduction in permeability. As the pressure drop extends from the well-bore, this effect spreads and cannot be lumped into well-bore effects represented by a single numerical value representing skin. The opposite effect occurs on injection with effective stress being reduced progressively from the well-bore outwards.

Curvilinear Horner build-up or draw-down plots are one of the characteristics of stress related permeability effects. Unfortunately, there are other causes of curved plots such as well-bore storage caused by packer movement and fractures. Numerical solutions for these effects can be found by the use of a simulator in which the primary unknowns are the in-situ permeability at reservoir pressure and the value of a (the effective stress change required to produce a ten-fold reduction in permeability).

Many well tests show more than one linear portion. This may be due to a matrix permeability that is different from the fracture permeability. Extending a test interval will help to confirm the real reservoir permeability. Alternatively, an interference test may be considered. Interference tests involve pressure monitoring remote from what is usually an injection well. Their advantages are three fold:

1. Because they are remote they do not suffer from near well-bore effects associated with skin or local effective stress changes around the well-bore;
2. If more than three observation points are used they permit the measurement of directional permeability; and
3. In a single-phase situation they permit the estimation of reservoir storage parameters.

On the down side interference tests are usually expensive to conduct.

A happy alternative that can more normally be accommodated is to fit exploration core holes with pressure transducers and to use these to monitor the reservoir during drainage. Such transducers are far more effective than compliance cores for gas content because they provide a continuous record of pressure (and hence gas content) rather than a single expensive sample.

Stress Measurement

An economic initial approach to finding directional permeability is to measure stress. Normally the direction of maximum permeability is perpendicular to the direction of minimum principal stress. So too, frequently, is the direction of the principal cleat. Thus, if the magnitude and orientation of the stress field can be determined, then the likely directions of principal permeability can also be determined.

Coal is frequently a cleated, weak material that makes the determination of stress impossible by overcoring, and virtually impossible by either hydrofracture or borehole breakout techniques. The rocks above and below the coal seam are, however, much more amenable to having stress measurements carried out on them. If no borehole breakage in these rocks occurs, then overcoring is undoubtedly preferable to hydrofracture techniques where the value of stress is sought. Where only direction is sought, multiple hydrofracture measurements may yield an adequate measurement of stress direction. Where borehole wall failure has occurred, scanners may be used to determine the orientation of the breakout.

The measurements used to determine stress by either hydrofracture or by assessment of borehole breakout are subject to more interpretation error than measurements accomplished by the overcore process. In addition, the mathematics to interpret the measurements is significantly less precise than those used to derive stress levels from overcore measurements. Stress is a tensor and the use of scalar measurements (pressure) to determine components of the tensor has limitations.

Converting rock stresses to coal stresses may be undertaken theoretically based on knowledge of the Young's modulus and Poisson's ratio of the coal. The limitations to this approach are the difficulty in measuring these parameters on many coals and the question of how creep and shrinkage have affected coal stress. An estimate of the magnitude of principal stresses in a coal seam is, however, useful for estimating directional permeability.

Monitoring the coal seam reservoir during drainage is extremely important. This monitoring should consist of three elements. The first two involve the measurement of gas flow and water flow from boreholes. Knowledge of one without the other is incomplete. Monitoring of water production is the key to knowing whether the reservoir is being effectively drained of water so that gas can be produced. Many potentially good reservoirs are simply drowned by an inability to keep out water that may come from the edges of the production field or from surrounding strata directly or via faults. The measurement of gas production is obviously important from a mining viewpoint. It is also a direct indicator of problem areas - a borehole not producing gas is a liability. The measurement of gas water ratio is also a good indicator of the reservoir state.

Finally, the measurement of reservoir pressure is of great value in assessing what is happening in a coal seam methane reservoir. The measurement of reservoir pressure can provide an indication as to whether the water pressure has dropped below sorption pressure and thus whether gas is free to move. Pressure also provides, through the sorption isotherm, a basis for measurement of gas in place and therefore is a key to any material balance calculation for a reservoir under production. It is considers that the only sensible use of reservoir simulators in monitoring reservoir behaviour is to force the simulator with known flows and to match pressures. Pressure measurement is essential to this.

Rock stress measurement is an important component of mine design. Much has been written on the need to orient mine layouts to minimise the effects of high stress. Just as important, though, are the effects of low stress. If the mine roof is jointed and stresses are low then inadequate horizontal stress may lead to roof collapse because inadequate friction is generated along the joints. The measurement of stress can therefore be as important in low stress environments as it is in high stress conditions. Another benefit of accurate stress measurement is in the location of structures. Stress values usually reflect the types of structures that may exist. For example, normal faults are frequently reflected by the existence of low horizontal stress across the faults. Changes in direction and magnitude of stress are normally associated with faulting.

Accurate, verifiable, stress measurement can be undertaken using overcoring. Sigra can undertake this from the surface as part of exploration drilling using the HQ coring system. This process is shown as steps 1 to 8 in Figure 3. The raw traces taken during the overcore are shown in Figure 4 and the processed stress interpretation is shown in Figure 5. The quality of individual traces is readily assessable from data such as that shown in Figure 4. The stress solution shown in Figure 5 is in terms of mean effective stress and deviatoric stress. The quality of the fit of the experimental data to the theoretical best solution is presented as an RMS error expressed as a percentage.

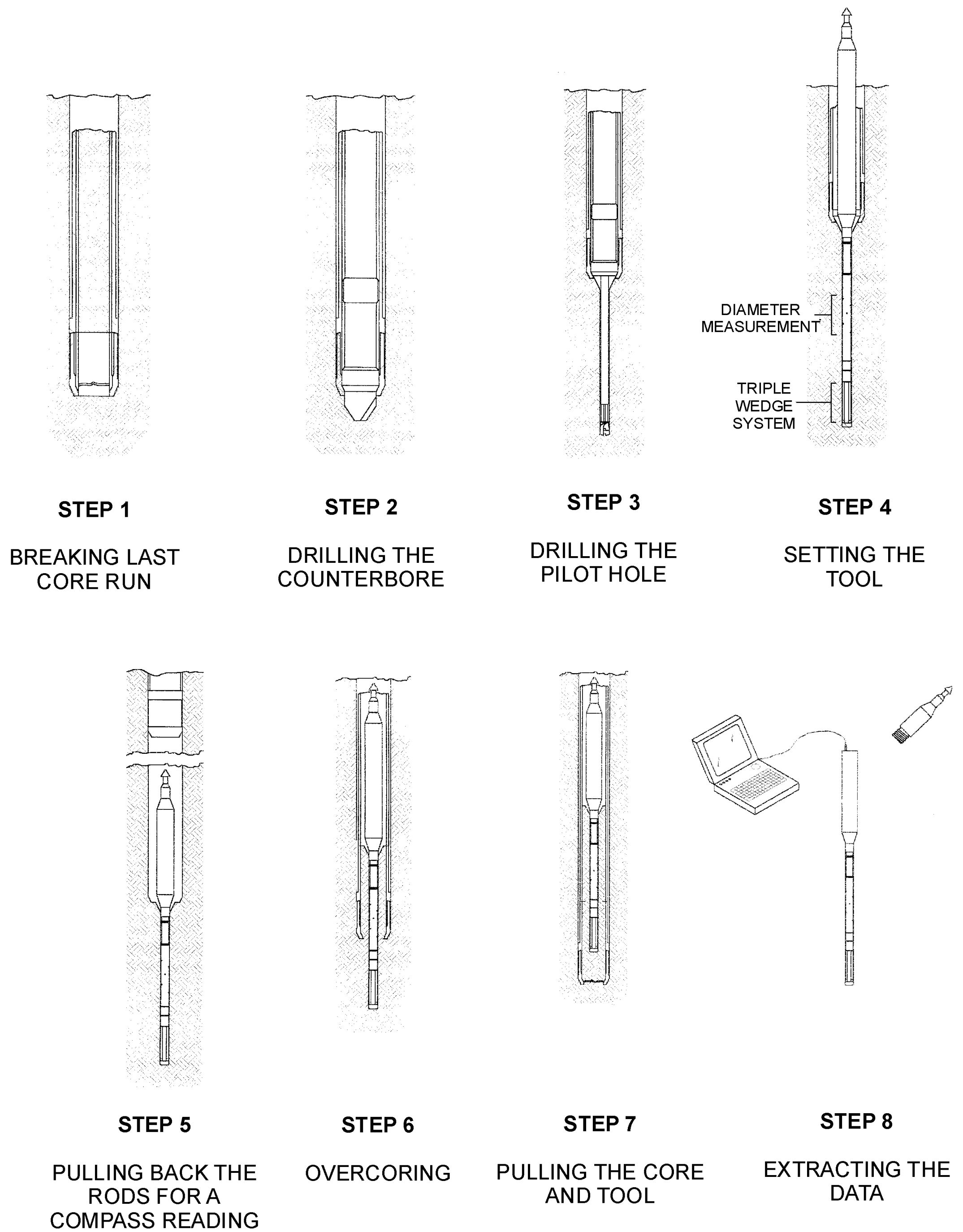

Fig 3 - Overcore steps 1 to 8

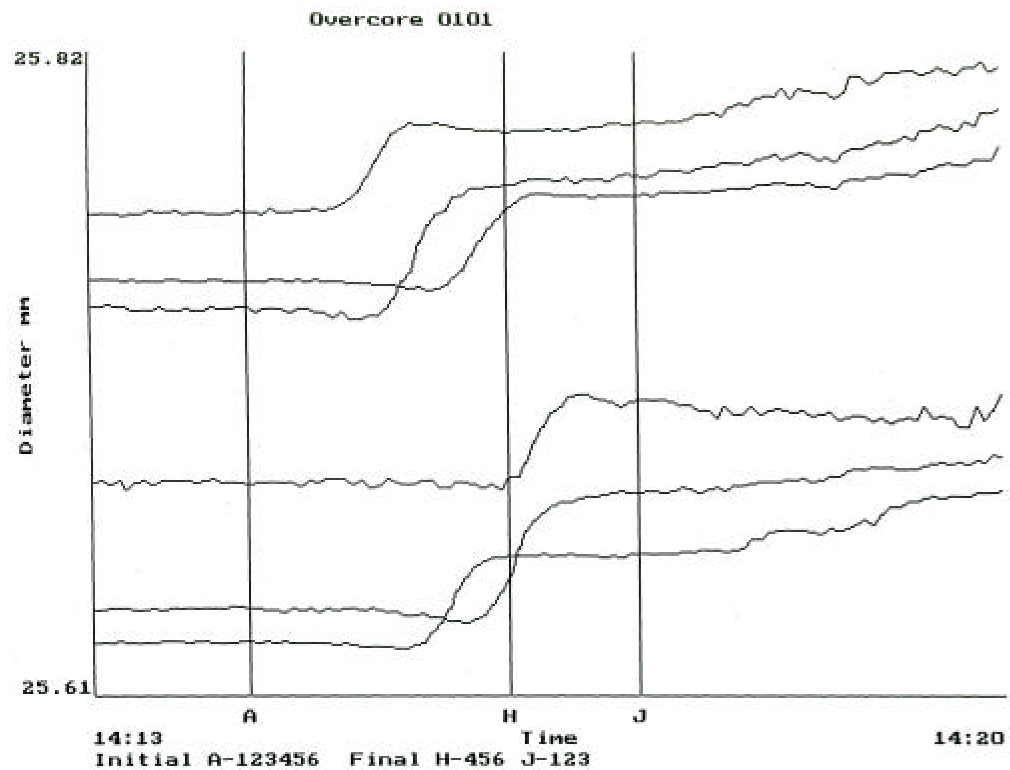

Fig 4 - Raw overcore diameter change traces.

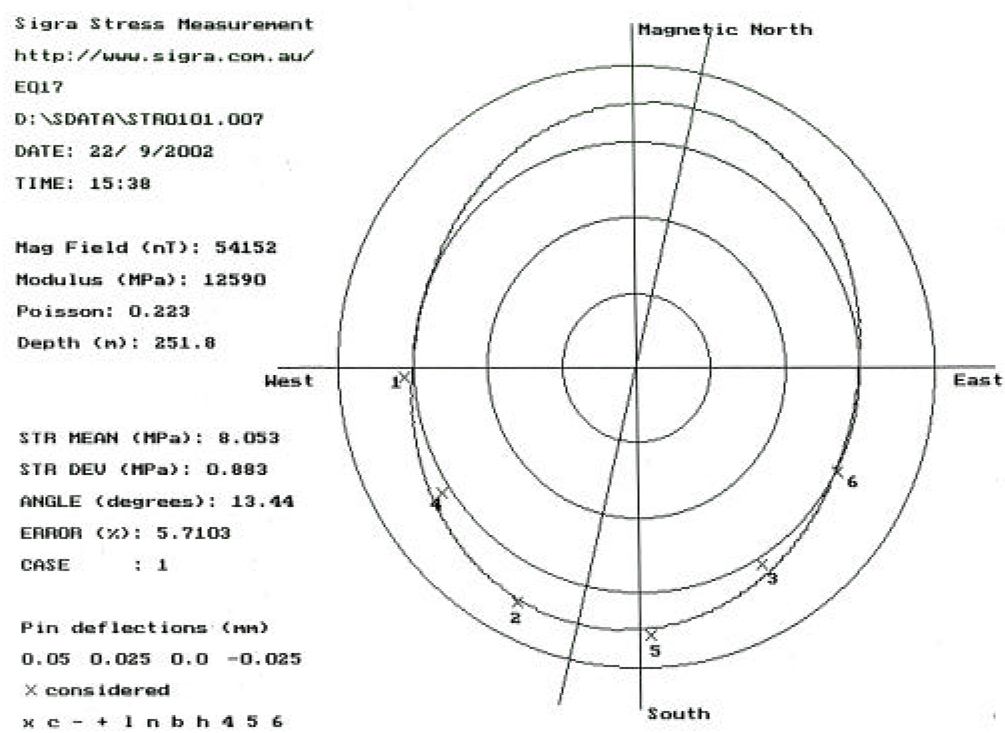

Fig 5 - Graphical presentation of overcore solution

Experience shows that the state of horizontal strain through coal measured through rocks tends to be far more uniform or uniformly varying than the stresses. The stresses tend to reflect the stiffness of the rocks. For this reason, it is preferable to measure stress then subtract the horizontal component due to self-weight, assuming a state of zero horizontal strain. Values of stress that reflect some other strain imposed on the rock mass can then be found and are referred to as tectonic strain. This calculated tectonic strain is a more useful indicator of the stress regime in the ground than are stress values alone. If depth, the Young's modulus and Poisson's ratio of the rock are all known then the stress for the rock can be calculated readily given the tectonic strain values.

The rock stress alone is not in itself of vital importance, what is important is the ratio of stress to strength of the rock. It needs to be remembered that both stress and strength vary with direction and that mining will change the stress direction. Frequently sedimentary strata are much weaker in shear along and tensile strength across the bedding planes. Failures frequently occur along these planes.

To assist mining operations understand their changing stresses, Sigra has now undertaken several stress change measurements in boreholes drilled from the surface. These have involved grouting triaxial and axial stress change cells in boreholes along with fluid pressure transducers. The use of post-initial set expansion agents to the grout permits such devices to be pre-loaded into the borehole so that unloading states [1] can be detected. The measurement of virgin stress and stress change then permits the calculation of stress during the mining cycle. This can be invaluable in assessing difficult to understand roof support problems.

The incorporation of fluid pressure transducers into such instrumentation arrays is important, as rock failure is a function of effective stress. Effective stress is the total stress minus the fluid pressure and hence fluid pressure may be a very important factor in failure. Fluid pressure increases due to strata compression have been detected up to 80 m ahead of a longwall.

CONCLUSION

The accurate measurement of coal seam reservoir and stress parameters is invaluable to mine design and successful operation. This paper details the methods developed by Sigra Pty Ltd for this purpose. The techniques described are based upon wire-line coring at HQ size, as is commonly practised in Australian coal exploration drilling.

[1] Unloading state- If stress reduces the state is one of unloading