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# Factors influencing caving

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## Abstract

*This paper examines the interaction of rock properties, rock stress and fluid pressure in initiating caving or strata collapse. The paper looks at the measurement of appropriate rock properties, rock stress and fluid pressure to determine how and when failure will occur. It also examines how fluid pressure operates within the rock mass – whether through the effects of poroelasticity or directly on fracture faces. It discusses the transition between these states within the rock mass. The emphasis of the paper is on measurement rather than on modelling and techniques to get the appropriate measurements are discussed. Field cases within laminated strata are covered.*

**Keywords:** *caving, stress, effective stress, fluid pressure, permeability, measurement*

## 1 Introduction

Both block caving and sublevel caving as well as longwall mining require the rock to collapse as part of the mining process. In the former case the caving process provides the broken ore which is mined, and failure of the cave to develop will lead to a lack of ore. In the latter two cases the ground above that being mined must collapse in a controlled manner. If this does not happen, then dangerous situations may eventuate related to sudden collapse of the ground with associated air blast and other problems. Of equal concern is the progression of caving in a direction where it was not meant to go, as this may lead to a loss of ore and a subsidence pattern that is quite unacceptable. It is therefore most important that a prediction is made of whether caving will occur and where it will progress to. If it does not appear that reliable caving will occur then it is necessary to consider whether the mining technique is suitable or whether some method of preconditioning is required.

Once rock breakage occurs it will fall into the void below under gravity. The stresses that cause the rock to break are those caused by body force (gravity), those caused by internal strain and those caused by external loading. The distribution of these is probably complex and will be changed by mining. In addition to the total stress, the action of fluids in changing effective stress needs to be considered. While the concept of effective stress has long been understood in soil mechanics, it is generally ignored in rock mechanics. This should not be the case, though the way in which it acts is more complex than that in soils.

Stresses are relieved perpendicular to an opening boundary and concentrated tangentially to it. The way in which they are concentrated is determined by the shape of the opening and the rock properties.

## 2 Stress in rock

The stresses and strains in rock are a function of gravitational effects, external load, thermal changes, diagenesis and their material properties including elastic, creep and post failure behaviours. Other than being reasonably certain of the average vertical stress being lithostatic, there can be little certainty about stress in the ground. The limits on stress are the strength of the rock. Where this is significantly faulted or jointed the cohesive component of strength is destroyed and the limits on stress are the frictional behaviour on these discontinuities. Where no significant discontinuities exist, or where those that do exist have become healed, then the action of cohesion may enable stresses to reach a much higher level.

Even where major faults exist there can be large differences in stress with time. A good example of this is the reverse fault that moved causing the Great Sendai Earthquake of March 2011. This led to the Tsunami which severely damaged the Fukushima nuclear reactor. The stress on this fault builds up over about a 300 year cycle as subduction takes place, whereupon an earthquake occurs and with it a major stress redistribution. Gray et al. (2013) describe the complex stress distribution in the sedimentary rocks of the Illawarra region of New South Wales. This is heavily influenced by movement on strike slip and reverse faults that has led the principal stresses rotating by 90 degrees over the mining area.

This paper also presents the concept of tectonic strain (Gray 2000). This is the lateral strain to which the rock mass must be subject to generate measured stresses. It is found that in most cases within sedimentary deposits on the eastern side of Australia, tectonic strains are generally fairly even though the stresses may vary sharply between lithologies of differing stiffness. Where this is not the case the reasons are typically faulting or an erosional surface within the stratigraphic sequence. Figure 1 shows a theoretical case where the major and minor tectonic strains vary monotonically but the stresses vary widely.

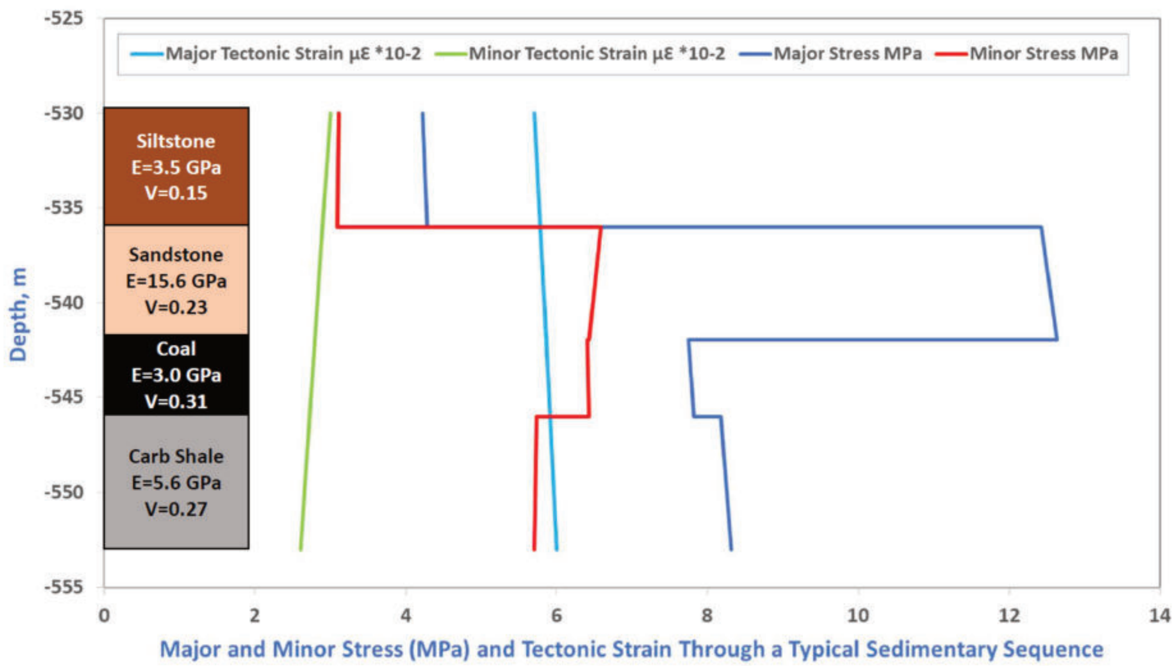



**Figure 1 Example of stresses in layered sedimentary strata with varying stiffness**

In more complex geologies such as those associated with igneous and metamorphic rocks, the stress distributions vary even more widely as the geometry is more complex and the rock will have been subject to cooling and possibly diagenesis. Generally, it can be said that the more complex the geology then the more complex the stress distribution within it. The concept of some far field stress value that is more or less constant is usually invalid and can be dangerous. Therefore, the concept that stress can be measured at some distance from a mine and return a sensible value for mine design is nonsense. Because the distribution of stresses can be so complex, it is highly desirable to measure stress where mining is going to take place, even if the virgin stress condition has already been changed by mining. Figure 2 shows an open pit with complex geology and plan to go underground. This is partially dependent on the stress in the rock mass. This clearly requires more than a few far field measurements.

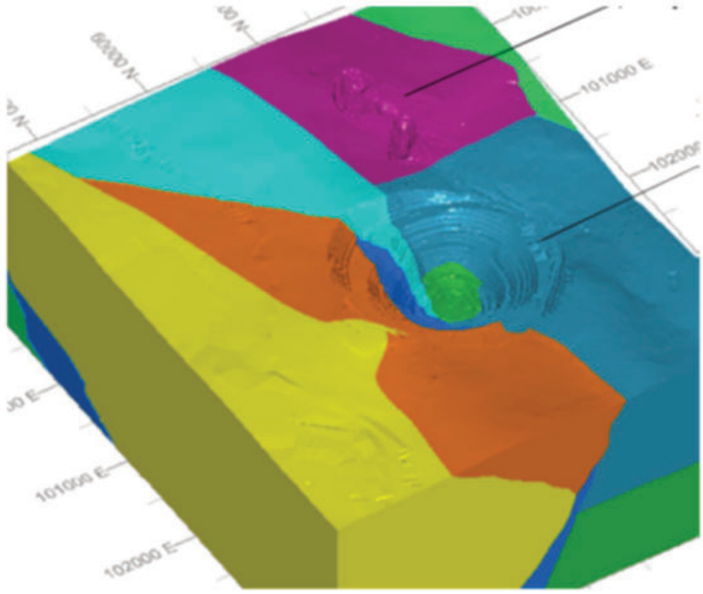



**Figure 2 Complex geology results in a complex stress regime**

# 3 Effective stress in rock

Effective stress may be described as the stress that causes a body to deform. In the case of mining that body is usually a rock mass. To describe this, let us conceptually take a block of rock and subject it to an external stress which causes it to deform. If we then internally pressurise the rock with fluid, it will regain some fraction of its original dimension. The fraction that it regains will depend on the poroelastic coefficient of the rock which lies between zero and unity. If the rock lacks porosity then that value of the poroelastic coefficient will be zero.

Figure 3 shows the concept of poroelasticity. On the left the cube has been loaded with a unit stress which has reduced it from the wireframe to the smaller block. On the right that block, still under external unit stress, has had injected into it fluid at unit pressure and recovers to some fraction of its original size. The fraction of recovery can be described by the poroelastic coefficients for the rock.

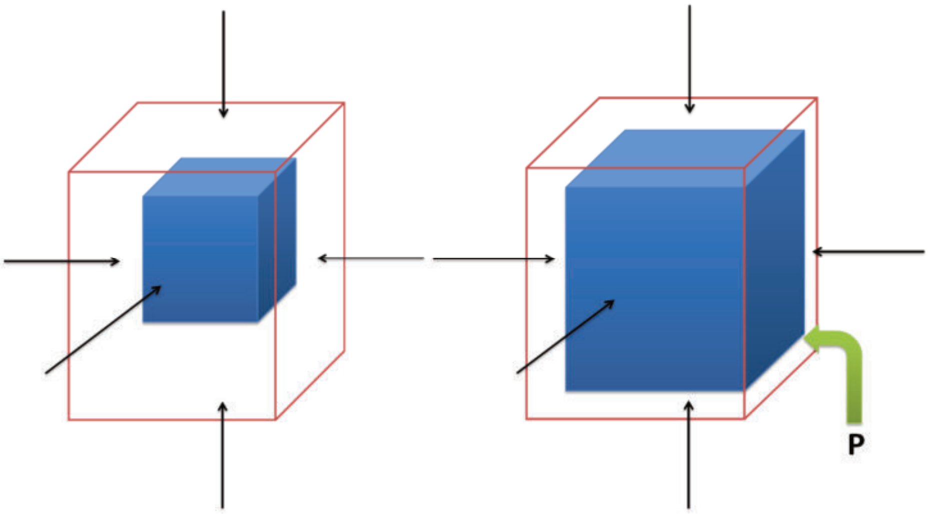



**Figure 3 The concept of poroelasticity**

It is a characteristic of some measurement techniques to quote high values for poroelasticity, even if dealing with granite, despite their very low porosity. The term Biot's or Biot–Willis (Biot & Willis 1957) coefficient is used, rather than poroelastic coefficient. Biot's coefficient is usually measured by volumetric process and is a scalar, whereas the term poroelastic coefficient is used here to describe a tensor where the direction matters. Measurement of poroelasticity using strain gauged sedimentary rock samples has shown more moderate values of the poroelastic coefficient (Gray et al. 2018b). Detailed work on coals has shown that the poroelastic coefficients in this material are quite anisotropic and dependent on the level of effective stress (Gray et al. 2018a). This anisotropy and stress dependency is a function of the small level fracturing within the coal. It would appear that these fractures can open and close with stress, so that at lower stresses normal to the fractures the poroelastic coefficient is higher. Stress variations in this material can change the poroelastic coefficient from 0.7 to near zero. While no testing has yet been conducted on harder rock containing microfractures much the same behaviour may be expected but at higher stresses.

In soils the effective stress is simply considered to be the total stress minus the pore fluid pressure (Terzaghi & Peck 1948). Thus, the value of the poroelastic coefficient used is unity though deformation is seldom considered. This assumption is supported by experiment on the failure behaviour of soils. If the assumption is made that the grains of a soil are in point contact with water in between them then this makes sense. It makes less sense in a clay with aligned plates but is still used and provides sensible answers.

Water pressure has generally been taken into consideration when analysing the stability of rock blocks near surface which contain open joints. Dealing with the effect of fluid pressure within rock at depth is less well defined. The petroleum industry will focus on poroelastic behaviour in terms of a porosity – compressibility product to describe fluid storage within the rock mass. They may periodically quote, but seldom use, Biot's coefficient, and will frequently ignore jointing. Consideration of how to handle the effects of fluid in a jointed rock mass at depth is lacking.

While unjointed rock may be expected to behave in a poroelastic manner if it contains joints its behaviour will be different, being more controlled by the action of fluid pressure within these. This behaviour also applies to fractures that develop with mining. These joints and fractures have surfaces which the fluid pressure acts normally upon. The effect of fluid in these is therefore directional.

It is generally useful to consider the effect of fluid pressure within joints in terms of stress rather than deformation, though the dilation of a joint under changing external stress and internal fluid pressure will change the overall dimension of the rock mass.

The effective stress on a plane through a rock mass will depend on the total stress minus the product of the open area of the joints that the plane intersects with and the fluid pressure that exists within these open zones. Thus, if the plane being considered is the same as that of a joint then the value of effective stress may be significantly lower than if the plane is separated from the joint or crosses it. From the viewpoint of analysis for potential failure on some surface, this planar concept is too limiting and the surface being considered must be allowed to be non-planar and to statistically include the near intersection of the joints with that plane. The analysis of joint location, orientation and openness matters. Thus, the measurement of jointing in core and through acoustic televiewer images, must be undertaken diligently. Determining what fraction of a joint is likely to act as though it is open requires careful logging of the core itself, paying particular attention to the jointing including the nature of infill. This is an aspect of rock mechanics that needs development. Another effect to be considered is the change in pressure of liquids within sealed fractures or pore space due to a change in external stress.

One of the consequences of the dilation and growth of fractures is that the effective stress is not simply the total stress minus some constant coefficient times the fluid pressure. Rather the coefficients are varying and the more destressing and fracture growth that occurs, then the higher that coefficient is likely to become. This effect is evident in excavation slopes, where these effects change the behaviour of the rock mass so that it becomes more susceptible to water induced failure. The same behaviour can be expected to apply to the rock mass above caves.

To consider a jointed case and how fluid acts within we examine the case of a series of en echelon fractures. These are marked in white in Figure 4. If we take a surface marked in red through these the intersection is small and alpha is approximately zero. If we take the blue surface, it only intersects one of the fractures and the value of alpha is approximately 0.25. If we consider the jagged surface marked in green which runs along the fractures but skips between them the value of alpha is approximately 0.8. From the viewpoint of effective stress and failure the surface being considered matters greatly. From an analytical viewpoint the stress only applies to a plane and therefore multiple planes need to be considered in the analysis.

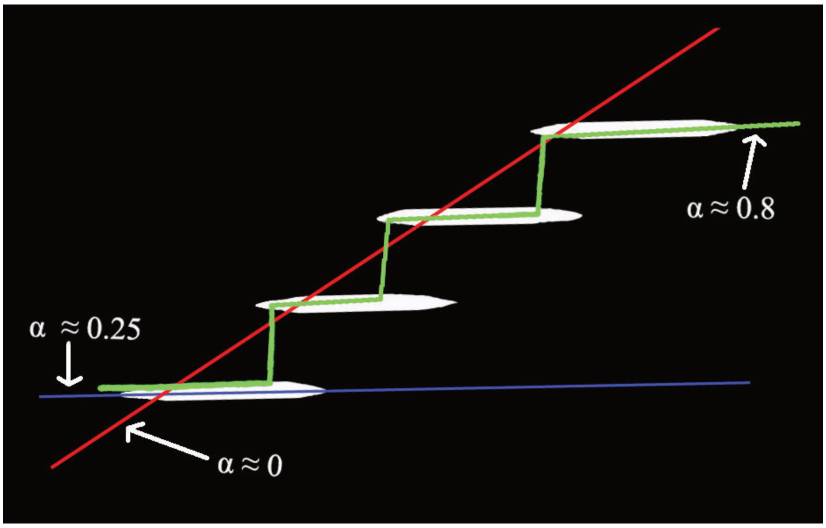



**Figure 4 En echelon fractures with varying surfaces of analysis**

Extending this concept of a progressive geometric change to the coefficient of effective stress, $\alpha$, we may consider the case of a slope shown in Figure 5. On the left the fractures in the slope are not fully connected and a worst case value of $\alpha$ may be 0.6. On the right side of Figure 5 the fractures have extended and linked up so that $\alpha$ approaches a value of 1.0.

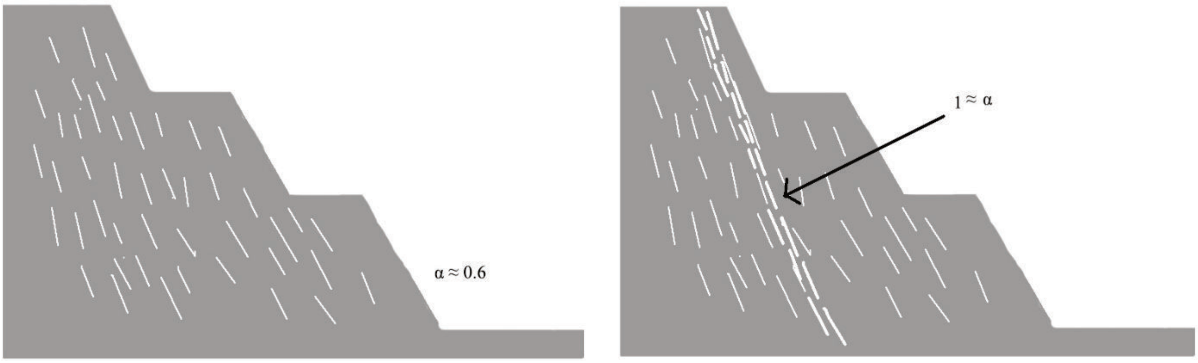



**Figure 5 Slope fracture growth with progressive failure**

# 4 The measurement of stress

## 4.1 Overview

Rock stress measurement must be divided into techniques that can be used in intact rock and those that are used in rock that has failed or will fail during the drilling of the borehole used to measure stress within it. All techniques have their limitations and most interpretations of rock stress require detailed analysis of the result itself and what it means in terms of the stress within the overall rock mass. The prime techniques that can be used are listed in Table 1 along with their applicability.

Hydrofracture and hydrojacking may, in the right circumstances, both deliver a minimum stress result directly from fluid pressure measurement without any knowledge of the rock type being required for the analysis process. Analysis of hydrofracture to obtain the major stress orthogonal to the borehole does however require the rock to be linearly elastic. Overcoring requires both measurement of deformation and the rock's elastic behaviour, it can however yield a total local stress tensor under the right circumstances. Core ovality can yield a major – minor stress difference orthogonal to the hole, but analysis requires the rock's elastic properties to be known. The analysis of borehole breakout is based on elastic behaviour to failure around a borehole followed by compressive failure of the hole wall. This is a complex process and one that cannot be satisfactorily completed on the basis of breakout information alone. These four measurement techniques are reasonably direct, being based on pressure, deformation and rock property determination.

While the last three techniques are shown as providing a source of stress measurement under all three situations considered methods in the process by which they accomplish this are much less direct than the first four. They might be considered very indirect. The Kaiser effect is one where a material begins to emit small level seismic noise when it is loaded beyond its previous stress level. Deformation rate analysis (DRA) involves the measurement of the incremental change in strain per incremental change in stress between steps in a sawtooth cyclic loading cycle. Anelastic strain recovery refers to the technique of measuring the deformation of as soon as it reaches surface and relating this to the state of stress in the core via a viscous deformation model.

**Table 1 Some methods of rock stress determination**

| | No borehole wall failure | Borehole wall failure | Fractured rock mass |
|---|---|---|---|
| Hydrofracture | X | X | – |
| Hydrojacking | – | – | X |
| Overcoring | X | | |
| Borehole breakout | – | X | – |
| Core ovality | X | X | |
| Kaiser effect | X | X | X |
| Deformation rate analysis | X | X | X |
| Anelastic strain recovery | X | X | X |

If the drilling of the hole does not lead to any form of rock failure that can be detected by such a device as an acoustic televiewer then it is possible to make the deduction that the stresses in the rock at the borehole wall are less than the strength of the rock. This is useful in itself and particularly if an opening of similar geometry to the borehole, such as a shaft, is going to be developed in the direction of the borehole. Where an opening is to be developed in a different direction or is of a more complex shape then the information obtained from examining the borehole wall alone is insufficient for design purposes. In this case the most useful method is usually overcoring.

## 4.2 Hydrofracture

Hydrofracture is another method by which stress may be determined. It is essentially a biaxial stress measurement with significant limitations. Figure 6 shows hydrofracture in concept, along with one of the potential problems, in this case the possibility of the hydrofracture being captured by pre-existing joints.

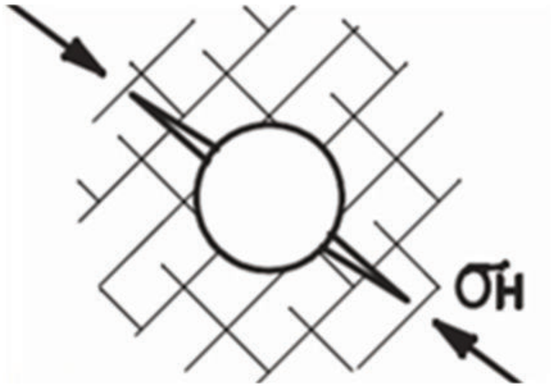



**Figure 6 Hydrofracture stress measurement**

In the form normally adopted hydrofracture involves sealing a section of borehole with inflatable packers and pressurising the zone in between until the rock fractures. Pumping is maintained for a period and then the test zone is shut in and the pressure permitted to decline. Careful analysis of the pressure decline enables the fracture closure pressure to be determined. The zone may then be repressured to re-open the fracture and the process repeated. Figure 7 shows a pressure trace within the test zone of a hydrofracture operation. Pumping starts and the pressure rises to break down pressure when the fracture propagates. Pumping is then stopped and the test zone is shut in. The fluid leaks off into the rock mass and is accompanied by a pressure decline. The shape of this decline changes when the sides of the fracture touch. This is known as the fracture closure pressure and, in the right conditions, corresponds to the minor stress.

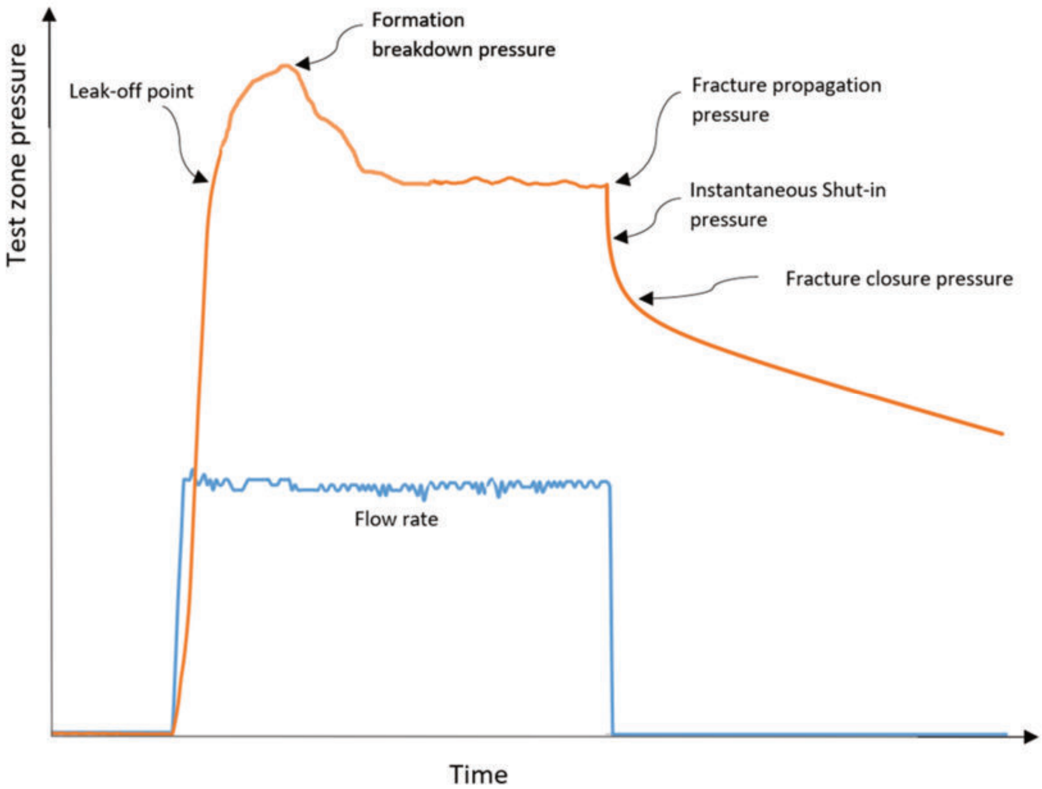



**Figure 7 Hydrofracture pressure response**

While ideally there is supposed to be a single closure pressure corresponding to the minimum stress in the rock, a rotating fracture or a fracture that is captured by multiple planes of weakness shows multiple closure pressures, making interpretation difficult.

The interpretation of the re-opening pressure to enable the calculation of the major stress requires that the fracture closes perfectly, that the minimum stress has been determined accurately from the closure pressure and that the rock behaves in a linear elastic manner. To these need to be added the condition that the axis of the borehole should be aligned perpendicular to the plane of minimum stress. Despite all of these significant limitations hydrofracture is sometimes the only option, especially where borehole breakout has occurred. Its use in conjunction with borehole breakout information enables an indication of major and minor stresses and is the method most frequently used by the oil and gas industry to gain information on stress in the sedimentary sequences that they encounter.

The hydrofracture process has some limitations. The first of these is that the packers must be at a higher pressure than the test zone fluid or leakage would occur past them. This has the consequence that packers may, and frequently do, initiate the fracture. Keeping the borehole wall scaling pressure of the packer just above test zone pressure is essential to minimise this potential problem. The second limitation is that there is no control over the direction of fracture propagation. The fluid pressure in the test zone will act on the wall of the hole and fracture initiation can be expected to be in a tensile mode approximately in the axis of the hole. It will however rotate to be perpendicular to the direction of minimum stress unless captured by pre-existing structures that require less pressure to open them than that required to overcome the tensile stress of the rock.

## 4.3 Hydrojacking

A variant of hydrofracture is hydrojacking. This is used to assess the stress in jointed rock. It involves straddling a joint with packers and pressurising it until the joint opens. After a flow period the test zone is shut in and the joint is allowed to close and the closure pressure determined in a similar manner to hydrofracture to provide information on the stress normal to the joint. Practically there are many limitations. The most usual being that it is not possible to isolate a single joint to be tested within the hole. Even if this is possible there is in most cases a high probability that the joint will connect to others so that during leak-off multiple closures occur. Figure 8 shows the before and after hydrojacking televiewer images of a section of borehole. These contain multiple fractures and at least one of these was opened during the injection process. The problem is that it is not possible to determine which ones.

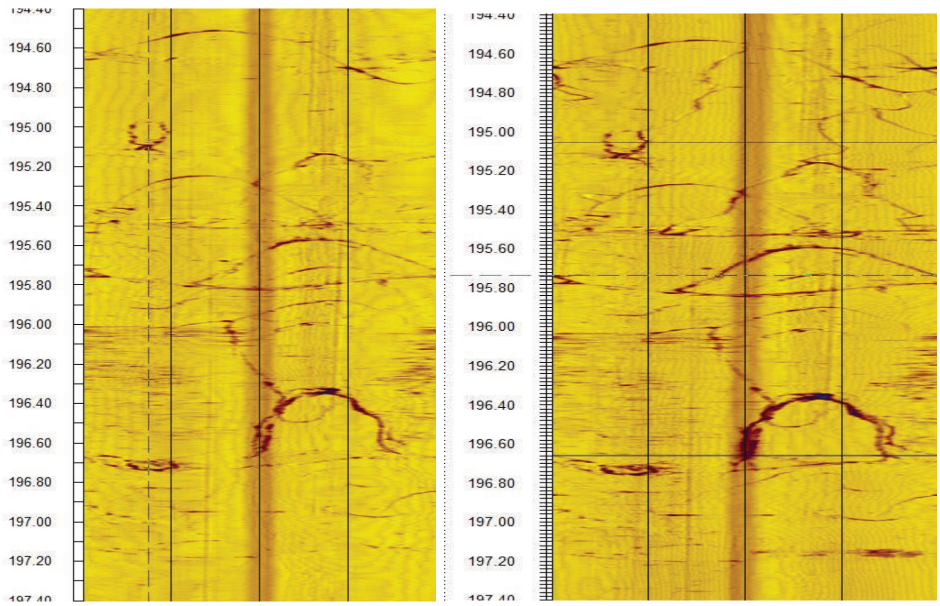



**Figure 8 Hydrojacking: (a) On the left is before; (b) On the right is after. Spot the difference?**

## 4.4 Overcoring

Overcoring is a process in which some form of smaller pilot hole or cone is drilled ahead of a core hole and a device to measure its diameter or the strain on the wall of the hole is installed. Coring then takes place over the top of this, thus relieving the stress in the pilot hole or cone. The change in strain or dimension of the pilot hole or cone is monitored during the overcore process. The analysis of stress is based upon this deformation and the elastic properties of the rock.

The USBM overcore device (Obert et al. 1962) enables the measurement of a change in pilot hole diameter during overcoring. Provided an assumption is made about the axial stress the two-dimensional stress field orthogonal to the borehole may be made. The next important development in this area was by Leeman (1969) who developed an end of hole device, known as a doorstopper, and more importantly a three-dimensional device. The latter was particularly useful as it provided a good degree of redundancy in measurements. Both of these devices used strain gauges which were adhered to rock. Neither enabled the measurement of strain during the overcoring process. This was achieved by the CSIRO HI Cell which could be monitored via cable during overcoring. However, this instrument lacks direct contact between the strain gauges and the rock and under high strains can suffer separation between its glued in place epoxy sleeve and the rock. This was addressed by Mills & Pender (1986) who used a device with strain gauges fixed to an expanding packer.

Figure 9 shows the process of overcoring using the Sigra IST2D tool as part of the wireline coring process. Step 1 shows the breaking off of the core which is then withdrawn. Step 2 shows a countersink being drilled. Step 3 shows the pilot hole being drilled. Step 4 shows the stress measurement tool locked into the pilot hole. Step 5 shows the core barrel being pulled back so that the magnetometers can work free of magnetic influence. Step 6 shows overcoring of the stress measurement tool – in this case with a wireline coring system. Step 7 shows the inner barrel, core and stress measurement tool being withdrawn. Step 8 shows the stress measurement tool being downloaded. The stress measurement is dependent on the deformation measurements and the rock's elastic behaviour.

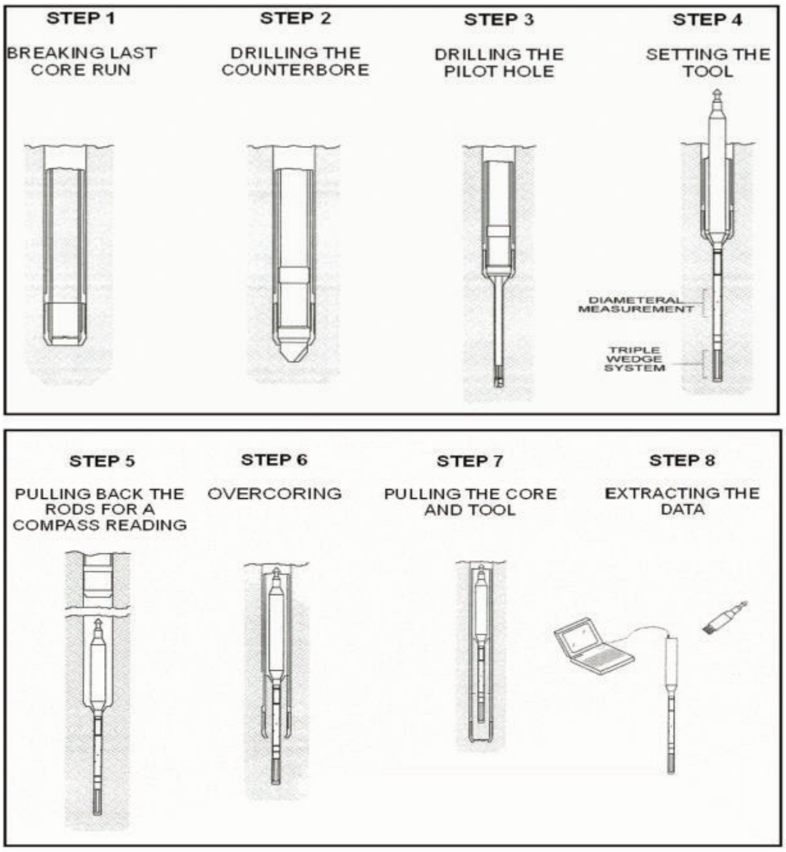



**Figure 9 Sigra IST2D two-dimensional overcore system**

Where the overcore cell measures the diameter of the pilot hole, such as the USBM device or the Sigra IST2D cell the measurement is one of the stress field orthogonal to the borehole. It does however require an assumption of the stress in the direction of the hole. In many cases where a vertical hole is being drilled in relatively uniform topography and geology, this assumption can be quite reasonably and reliably made to be that of overburden load. Where the hole is being drilled at an angle, or the geology is complex, such that it is not possible to make any assumption about the stress in the axis of the hole or where a true three-dimensional stress field is required then cells with multiple strain gauges that glue onto the pilot hole or cone are required. The Sigra IST3D system is one of the latter. The choice of whether to use a two-dimensional tool or a glue-in three-dimensional tool may be one of timing, as the strain gauge glue used in the latter takes time to set.

Figure 10 shows an overcore using the Sigra IST3D glue-in overcore cell in an overcore which has been conducted as part of Boart Longyear wireline coring system. This is a form of soft inclusion cone cell.

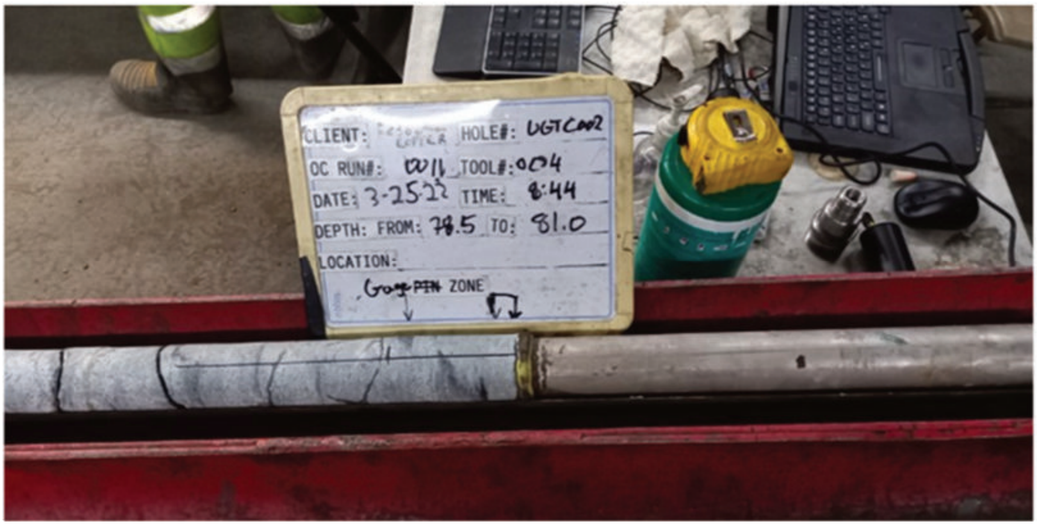



**Figure 10 Sigra three-dimensional IST3D glue-in overcore tool set into core**

It is possible to analyse overcores that have been conducted in rocks that are non-linearly elastic or anisotropic provided they are reasonably homogeneous and do not behave in a plastic manner. Table 2 shows the types of analyses that are required for the various levels of elastic behaviour. Where finite element models are required the workload in analysing the test increases significantly. Whether this work is justified will depend on the situation. What is always justified though is proper testing to determine the rock properties. Simple uniaxial tests are not usually adequate and neither is biaxial reloading in the field. Rock properties are best determined by loading either the overcore itself or a similar piece of rock in a triaxial cell using multiple combinations of axial and confining stress to determine the rock's elastic properties (Gray et al. 2018a).

**Table 2 Overcore analysis method**

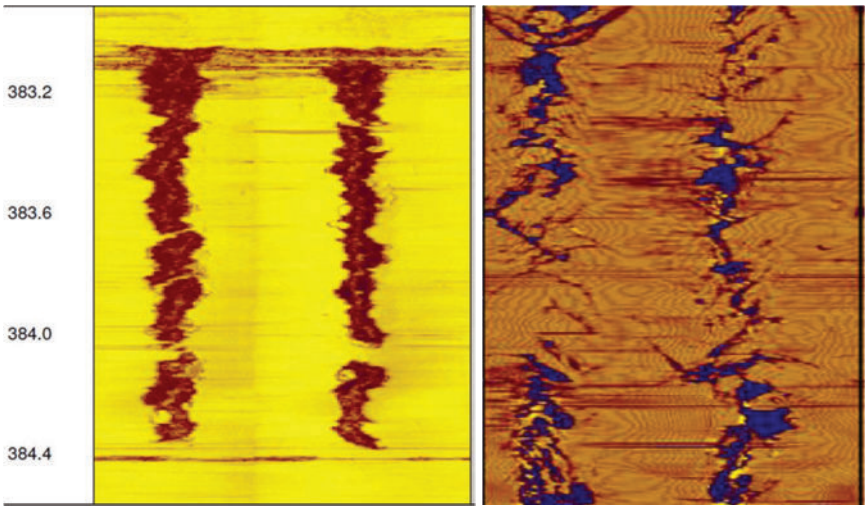
| Rock properties | Isotropic | Axisymmetric anisotropic | Non-axisymmetric anisotropic | In-homogeneous |
|---|---|---|---|---|
| Linearly elastic | Analytical | Analytical | Finite element | Approximate analytical |
| Non-linear | Finite element | Finite element | Finite element | Practically impossible |

## 4.5 Borehole breakout

Borehole breakout involves examining an acoustic televiewer image for compressive failure of the borehole wall. This is an indication that the stress at the borehole wall is greater than the strength of the rock perpendicular to the hole axis. While this can be used to give a direction of the major stress it does not enable the major and minor stresses to be determined. This is because the only reliable information available is a measurement of the width of the breakout crush zone and this is inadequate to solve for the major and the minor stress perpendicular to the hole axis. The other complication is that the compressive strength of the rock perpendicular to the hole wall is seldom known. If the minor stress is known from some other measurement, such as hydrofracture, or the difference between the major and minor stresses is known from core ovality measurement then a solution for the major stress may be approximated if the rock properties are adequately known.

Figure 11 shows two acoustic televiewer images. The one on the left is in siltstone while the one on the right is in metasiltstone. The breakout width in the siltstone can be approximated while that in the metasediment cannot. The former may therefore be used in the determination of stress values while the latter may not.

In some cases boreholes suffer tensile failure. These are caused by a combination of rock stresses, the poroelastic effects of fluid pressure within the rock mass and the drilling mud pressure within the borehole. These are in effect hydrofractures that occur during drilling. They are indicators of stress direction and may be used to provide a boundary on rock stress estimation.




(a) (b)

**Figure 11 Showing an acoustic televiewer image of breakout in a (a) siltstone and (b) a metasiltstone**

## 4.6 Core ovality

A recent development, is the use of core ovality as a measurement. This works because the core expands elastically as it is cut. Provided the core bit is not too long and parallel internally, so that regrinding of the core occurs it is an elastic measurement method. Proper core bit design with an internal expanding taper can be used to avoid this problem.

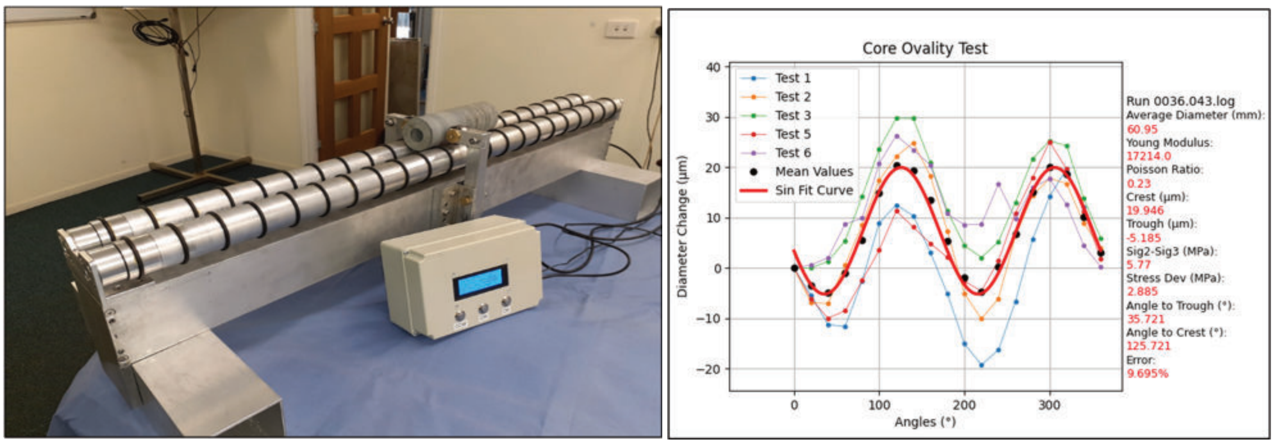
Core ovality is referred to as diametrical core deformation analysis (DCDA) in the seismology and geothermal power sectors. Following the publication of theory in Japan by Funato & Ito (2013), who named it DCDA, the concept was then applied in a seismological study relating to earthquake stress measurement in a 2,000 m borehole along the Japan Median Tectonic Line active fault zone where it was compared with established borehole breakout and hydraulic fracturing methods (Onishi et al. 2016). In South Korea, DCDA was compared with other methods in a 4,200 m deep hole in granodiorite as part of a geothermal power project. Kim et al. (2020) reported that DCDA stress measurements were validated by the traditional methods but at a reduced cost.

By 2021, trials of DCDA began to occur outside of East Asia. In Switzerland, Zieglear & Valley (2021) report on a 4,900 m deep hole where drill cores in monzogranitic and monzonitic rocks were recovered for a geothermal power project. In the Brazilian Iron Quadrangle, de Andrade Penido et al. (2021) compared DRA with DCDA and hydraulic fracturing (HF) methods at depths of up to 400 m with inconclusive results. While DCDA and HF compared favourably, DRA did not. This was explained by DCDA and HF using elastic methods, while DRA used inelastic methods. It should be noted that DCDA is a non-destructive test and DRA is destructive.

Yabe et al. (2022) report on parallel DRA and DCDA testing at the Mponeng gold mine in South Africa. Mponeng is the deepest underground mine in the world with workings up to 4,000 m. In 2007, a major Mw 2.2 earthquake occurred triggered by mining activities. Microseismic records identified the location of the earthquake at 3,300 m depth in the location of a major gabbro dyke. A borehole was drilled from an underground chamber located near this level. The core consisted of the gabbro dyke (UCS 180 MPa) and associated quartzite footwall (300 MPa) and quartzite hanging wall (350 MPa). Good correlation between DRA and DCDA measurements were reported.

Figure 12 shows the Sigra system of core ovality equipment on the left while on the right are shown five traces of core diameter measurement difference with an average sinusoid fitted to these.

The diameter of the core is measured precisely at a number of locations. A sinusoidal curve can be fitted to this information and the major and minor diameters determined by a least squares process. These can be used along with the Young's modulus and Poisson's ratio to arrive at a difference between the major and minor stress orthogonal to the axis of the core. The process of measuring the core diameters is now automated and may be conducted every metre of core. This near continuous measurement allows the determination of where the stress regime changes, and it can be used as an indicator of where a more precise stress measurement may be made. It may also be used in combination with the minimum stress from hydrofracture closure to determine the major stress, or more usefully with information on borehole breakout, to determine major and minor stresses orthogonal to the borehole. The system has given very similar values of rocks stress difference to that obtained using the Sigra IST2D overcore tool in both a semi metamorphosed mudstone and in fine grained sandstone.




(a) (b)

**Figure 12 (a) Core ovality test equipment; (b) Traces in $\mu m$ from core testing**

## 4.7 The very indirect techniques

Yamamoto (2009) describes both the Kaiser effect and DRA. The DRA essentially examines the deviation of the deformation of the rock from elastic behaviour related to the progression of microfracturing when the previously existing stress is exceeded. The method requires extremely high resolution strain measurement. Yamamoto (2009) reports that the resolution of strain gauging should be better than 0.1 microstrain for rocks of more than 50 GPa stiffness. Hsieh & Dight (2016) refer to an accuracy of measurement of a few microstrain and comment on the difficulty of achieving this.

Reports of good matching between DRA and hydrofracture stress measurement exist but so do those where the system has not matched other systems.

The Kaiser effect is one where acoustic emission is detected from rock core on reloading. These emissions are supposed to increase when the reloading exceeds the pre-existing stress levels. Questions as to whether this effect continues some time after the core is recovered remain (Yamamoto 2009).

In practice the reloading of fragments of core for either DRA or the Kaiser effect is generally achieved under conditions of uniaxial loading. This raises the fundamental question as to how these can work reliably when the rock is under triaxial load conditions in situ. The progression of microfractures as an indication of stress must surely depend on the triaxial stress state within the rock. The use of either of these methods in highly non-linearly elastic rocks, let alone those that display plasticity must also be in question.

The anelastic strain measurement process is one where strain gauges are adhered to the surface of core as soon as it is recovered and the strain changes are then monitored (Zhang et al. 2022). This process must be undertaken under controlled conditions of temperature and moisture preferably matching those from in situ. Achieving this is not a simple process. The analysis of the strain changes requires some model of creep behaviour within the rock mass. The validity and applicability of such models is always in question and highly dependent on the rock type.

# 5 Fluid pressure and flow

## 5.1 Long-term pressure monitoring: piezometers

As fluid pressure in the ground is one of the key elements of effective stress, it is important to know what it is during a mining operation as it will affect the failure of the rock mass. This needs to start with knowing the fluid pressure prior to mining. If the rock has some permeability then it is possible to install more or less conventional piezometers. Though it should be noted that the conventional installation in deep holes is to cement grout the pressure transducers into the borehole.

This process of cement grouting pressure transducers in place is fraught with problems as it relies on having a permeable enough cement grout to enable a connection from the transducer to the borehole wall but one that does not provide intra-connection within the hole. In reality this is difficult to achieve. Part of the reason for this is that the cement particles form a nearly impermeable layer on the borehole wall penetrating into fractures thus sealing them. This can change the behaviour of the installation to one where there is a very poor connection to the rock mass and a somewhat better intra-connection within the borehole. The consequence of this is that the pressures within the hole are likely to be close to hydrostatic or, if they reflect the fluid pressure in the rock, do so with a very large pressure lag with time.

Gray & Neels (2015) describe a better installation method for piezometers in which a very low permeability cement grout is used and in which the grout is displaced by water injection at the location of each pressure transducer. This enables hydraulic connection between the rock and the pressure transducer. It is also a testable technique as water can be injected further and the pressure decline in the test zone, and any in hole connection issues, can be monitored.

Cement grouted piezometers are not ideal in very low permeability crystalline rock where fluid pressure only has meaning within the fractures that exist within it. Locating a pressure transducer precisely at a fracture at 1,000 or 2,000 m depth is difficult. Complications also exist with establishing a connection to the fracture which might be tight and hydraulically isolated. In the latter case the pressure within the fracture probably does not matter because it will affect a small area and will reduce dramatically on any dilation of the fracture. What does matter is where a fracture group with some area on which fluid may act are pressurised from some source. This means that some level of pressure is maintained as dilation occurs and fractures develop.

Pressure in fractured zones may be better monitored by the use of packers that isolate them and contain pressure transducers. Swell packers that expand in water are advantageously used for this purpose.

## 5.2 Permeability pressure and storage

The approach to measuring fluid pressure in fractured rock can be to measure the pressure during the exploration drilling stage or to leave some form of pressure monitoring in holes. In the case of exploration drilling the approach should be to measure permeability and pressure at the same time. A method which does this has been adapted from the oil and gas industry, and is particularly useful in this case. This is called the drill stem test (Dake 1979), generally shortened to DST. It has been adapted to be used as part of wireline drilling practice for use with Boart Longyear HQ or HQ-3 wireline coring and could no doubt be adapted to other wireline coring systems.

In one form the wireline drill stem test system involves running a straddle packer system through the drill string to seal around a test zone beyond the drill bit. This drilling fluid is displaced in the drill string with air from a compressor and the packers are set. The compressed air is then released and some time is allowed for the pressure in the test zone to stabilise. If the pressure in the test zone is significantly higher than that in the drill string the main valve is opened by raising the drill string and inflow occurs. This is permitted to continue for a time period or until the inflow volume into the drill string is sufficient and then the main valve is closed. The pressure build-up is then monitored.

This process is described by reference to Figure 13.

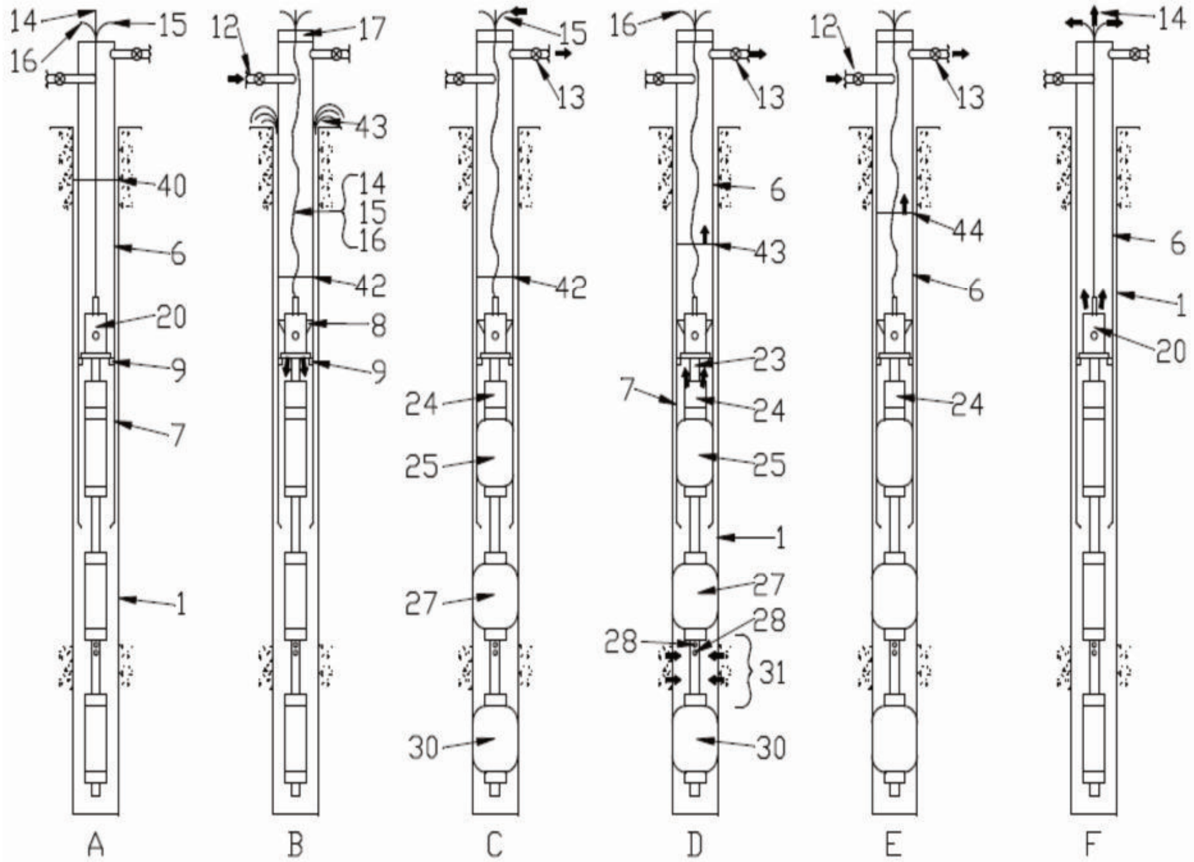



**Figure 13 Sigra through the bit drill stem test system**

Figure 13A shows the tool sitting on the landing ring (9) of the core barrel. A valve packer is located at (7) and below the drill bit are two other packers which straddle the test zone. In B the latches (8) are locked in and the drilling fluid is depressed by compressed air and flows out the top of the hole. In C the packers are set and the compressed air is released. The test zone pressure is then allowed to come to equilibrium. In D the drill string is raised opening the valve so that fluid flows from the rock into the drill string. In E the valve is closed by lowering the drill string which enables pressure to build up. In F the packers are deflated by pulling on the wireline to operate a dump valve. The system may then be withdrawn from the drill string by wireline.

This system may be used for injection as well as production. This can be in the form of a falling head within the drill string followed by shut in as well as by pumped injection. The tool also exists in a closed chamber form where production is into a vacuum chamber. This suits low permeability operation where the quantity of fluid likely to be produced is low. Other variants exist which attach to the end of the drill string.

Figure 14 shows the pressure plots of a long drill stem test. Here the pink trace represents the packer inflation pressure. The red trace shows the in pipe pressure above the valve and the blue trace shows the test zone pressure.

Before the time mark A the hole had been pressurised to displace water, the packers have been inflated and the compressed air has been released. The test zone had then been permitted to approach equilibrium pressure. At time A the valve is opened and the pressure in the test zone drops to that in the drill pipe. Very little inflow occurs. The valve is then closed and the result is a very rapid pressure rise to the test zone pressure. The process is repeated at time B when the valve is opened for another inflow period.

The low inflow in this case is not a function of a low permeability but is rather one that is due to poor connection between the test zone of the borehole and the fractures or pores within the rock mass. This can be seen by the rapid rise in pressure when the valve is closed.

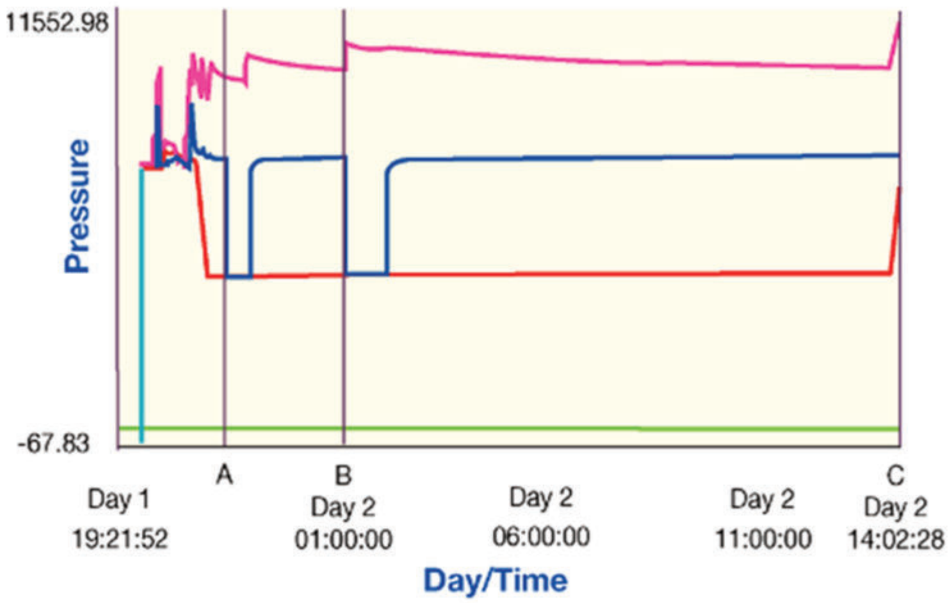



**Figure 14 Drill stem test pressure traces (kPa)**

Using the inflow volume and the characteristic shape of the pressure build-up curve it is possible to determine the permeability of the test zone and, if some assumptions are made, the mean effective radius of investigation and the well bore losses. It also enables the measurement of pressure in the test zone. If the pressure has dropped from the original stabilised pressure before inflow, then it is possible to deduce that the fractures are bounded and will not be refilled. If the same pressure is achieved before and after the test then it indicates that the fractures are connected to a source. This type of analysis can be used to indicate more about the nature of the fractures. Such analysis is common in the petroleum industry.

While it may appear to be simply another form of packer test, the DST or its analogue involving injection delivers far more information. The packer test as originally devised by Lugeon involved the injection of water into section of borehole under a pressure of 10 atmospheres and the measurement of a supposedly stabilised inflow rate. The value of 1 Lugeon corresponds to an inflow of 1 litre per metre per minute. This test is seriously deficient and should never be used for any form of serious measurement of groundwater. Its deficiencies include a lack of measurement of fluid pressure in the rock mass and the failure to separate the near well bore loss terms from those related to pressure drop away from the rock mass. The key to useful measurement is the recognition that pressure responses to injection or production from a borehole are transient and that successful methods involve isolating the transient response component. In the DST this is accomplished by having a flow period followed by a period of shut in where the pressure within the well is not influence by pressure drop through the well bore.

The measurement and ongoing monitoring of fluid pressure is important as it enables a determination of the pressure component of effective stress. While a potential head difference may exist between locations it does not mean that fluid is flowing. Rather it means that fluid may flow if there is permeability. To know what fluid is being conveyed means that permeability must be measured properly. While the drill stem test is extremely useful it still has the limitation that it does not permit the determination of anisotropy or storage behaviour This can only be achieved by pressure monitoring in adjacent locations to a well that is flowed. Gray (2017) covers the use of pulse testing from one hole to another to determine both anisotropy and inhomogeneity of permeability of the rock mass as well as storage behaviour.

# 6 Rock structure

The structure within the rock mass is frequently the most important factor in determining whether rock will cave. Unhealed joints lack cohesion and allow fluid pressure to act within them. They change their dimension progressively with failure and dilate, changing the effective area available for fluid to act upon and reduce the effective stress and hence shear strength. They can also be conduits for the inflow of water to the system.

The determination of the contribution and changes to effective stress of joints is in its infancy. It requires the extraction of core and its proper logging for the frequency, orientation and infill of the joints. A judgement has to be made as to whether fluid may act within the joint in its original state. Then another judgement has to be made as to whether the joint will open up with sufficient fluid pressure and how this opening may progressively occur.

The frequency of jointing needs to be determined and this invariably requires boreholes that are drilled at different angles so that all jointing is likely to be intersected. The spacing of joints actually drilled needs to be corrected to true spacings by dividing by the sine of the angle between the borehole and the normal to the joint plane. The real problem in analysis is in determining the persistence of the joints in area rather than simply length. Because of the physical limitations in drilling, this is an area that can probably only be dealt with by developments in geophysics.

# 7 An example from coal mining

While the emphasis on caving tends to be focused on block cave operations there is quite a lot to be learnt from longwall coal mining. It is just as important in longwall mining to have caving occur as in block caving. The reason for wanting caving to occur is different but the problems if it does not do so are just as serious. They include windblast (airblast) and extreme loadings on the face or pillars which may induce rockbursts.

Figure 15 shows a longwall where the first fall has occurred and where the immediate roof is falling behind the shields. To the left is the last break while to the right of this the rock mass is acting as a cantilever which is fixed over the coal seam. The possibilities for failure of the cantilever are a vertical tensile separation of the horizontal strata; a tensile failure of the top of the cantilever across the bedding; a horizontal compressive (shear) failure at the base of the cantilever; an upwards shear through the strata and a shear failure along the bedding planes which will carry a conjugate (complementary) shear stress to that acting through the strata due to the weight of the cantilever. If the cantilever breaks off as a massive block then it will impose an enormous dynamic load upon the shields. The subsequent static load may be significant also.

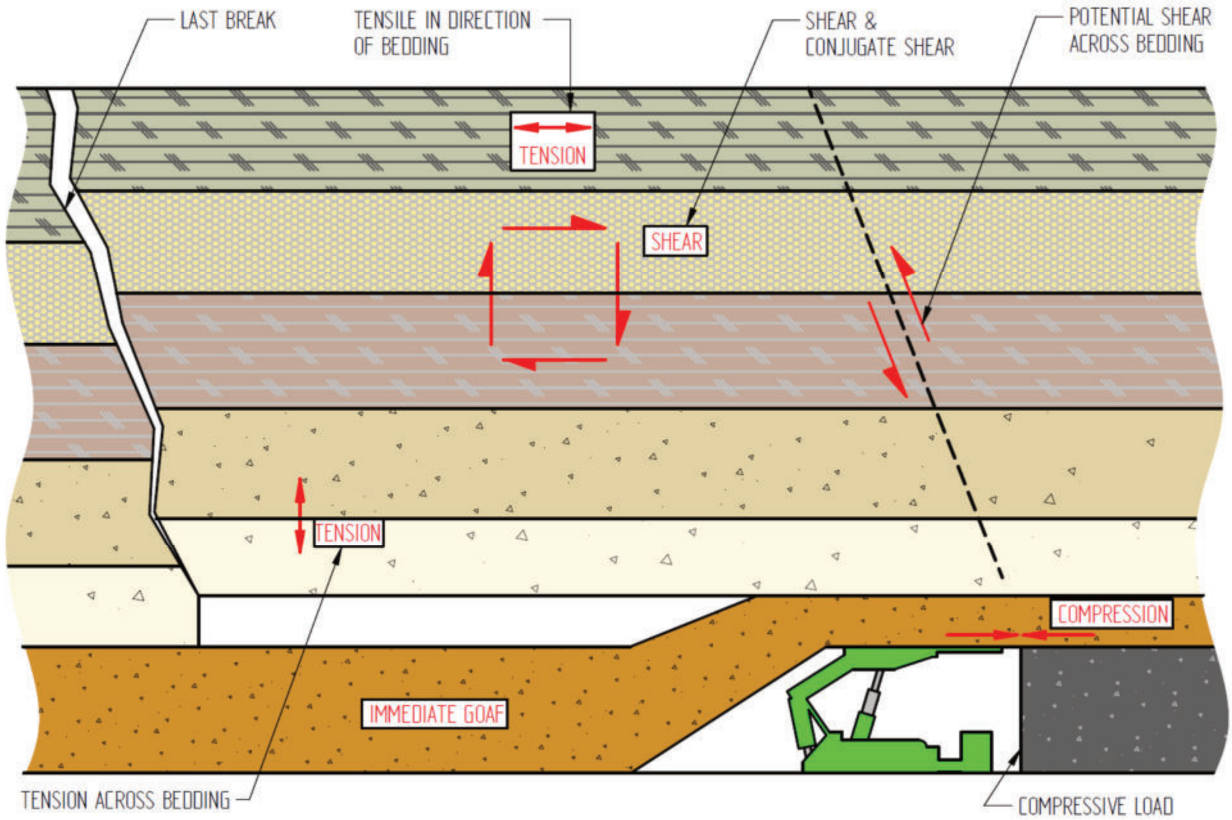



**Figure 15 Longwall with important stresses**

Anisotropy of the rock mass is important in sedimentary rock. Siltstones and fine grained sandstones with mica on the bedding planes may have a tensile strength across the bedding of 0.1 MPa and a tensile strength along bedding of 7 MPa. The cohesion component in shear across bedding may be 7 MPa but reduce to 0.5 MPa in shear along the bedding. This level of anisotropy means that failure in all modes must be considered and cannot be left to some numerical model that does not comprehensively deal with all these possibilities. Most continuum models cannot handle such variations in material strength, let alone the variations in the nonlinear, anisotropic behaviour before failure. Computer aided calculation of plate and stacked plate behaviour is more useful than a continuum model.

If this analysis leads to the determination that the goaf (cave) will not initially form or that the blocks need to be reduced in size to avoid windblast or loading problems then something needs to be done about it. The something is a form of preconditioning. The question is what will work? What is required is that the plates of rock that may fail are thinned so that the bending strength of the rock mass is dramatically reduced. This will enable the rock mass behind the shields to simply fold down in manageable blocks.

An obvious way to consider thinning the plates is to use hydrofracture from surface holes as a form of preconditioning of the rock mass prior to mining. If, however, the minor stress acts on a near vertical plane then this will not work as the fractures will form in the wrong way. In the unlikely circumstance that this wrong way is parallel to the face then the hydrofracturing will have to be extremely close to avoid large blocks dropping off onto the supports. More realistically the hydrofractures will cross the face and achieve little except some by causing difficult local conditions for the shields.

This stress situation rules out the use of hydrofracture as a preconditioning option. It still exists as an option in the zone which has been vertically destressed by the removal of the coal seam. Such techniques are used but from underground, usually by drilling between the shields, inserting packers and hydrofracturing. Alternatively, it is achieved by drilling from the gate roads across the block to a suitable horizon and hydrofracturing that. Working by this just in time approach may however end up being a bit too late.

If the stress situation does not suit hydrofracturing some value may be gained by simply drilling holes in critical areas as these will concentrate stress and may initiate fracture. If failure is in a tensile mode then raising the tensile stress by a stress concentration factor of two or three associated with a borehole may be all that is required to initiate failure. This may mean drilling up through the top of the massive strata plate where stresses under mining become tensile. This approach was used to initiate goaf failure along the gate road side of a longwall at Matla in South Africa.

The next preconditioning option is to use blasting which effectively enlarges the holes size so that more of the ground is weakened than by boreholes alone. This bigger dimension to the preconditioning hole increases the average stress. In addition, stress concentrations exist at the fracture tips. While used in China, such blasting practise has its risks associated with gas ignition in a coal mining environment.

One option that is not used is that of keeping holes filled with water at pressure so that with the start of fracturing the water operates within these. In its simplest form it may simply be a series of boreholes drilled from surface which are kept water filled and promote the formation of fractures as they start to develop. In the coal mining situation exploration holes are normally cement grouted so that are not intercepted by development roadways with the consequence that they dump several cubic metres of muddy water on the unsuspecting operator. Within the longwall block this would be less of a problem as the holes would discharge through fractures ahead of the face or into the goaf. Having 400 m of water head in a hole is fairly significant assistance to fracture propagation around that hole.

# 8 Conclusion

This paper has discussed two of the key factors that control breakage of rock in a cave. They are rock stress and the effects of fluid pressure on effective stress. The other critical factor is rock strength, though the latter is covered more by Gray (2020).

Methods of determining rock stress and the appropriateness of their use are presented. These may be summarised into those techniques which suit rock which has not failed, and will not fail around a borehole, and those cases where the rock is either fractured or will fracture around a borehole. The latter cases are of less concern from the viewpoint of inducing caving but pose more problems for development.

A balance needs to be struck between those measurements that deliver a more precise measurement, but are expensive, and those measurements that enable the rock stress to be less precisely estimated over a greater length of borehole. The more precise measurements are overcoring, providing the rock properties are elastic and reasonably linear, and hydrofracture, though this has limitations in the determination of the minor stress and still more complications in the estimation of the major stress. The less precise measurements which may give more coverage are borehole breakout, which is only applicable if this actually occurs, and core ovality measurement. The combination of core ovality with breakout or with hydrofracture provides the possibility of the determination of the major and minor stresses orthogonal to the borehole. A new tool to measure core ovality in the field is presented along with the concept that significant change in core ovality is a good indicator for the use of a more precise stress measurement system.

There are a range of less direct stress measurement systems all of which come with the risk of their inapplicability to the particular rock type being investigated.

The concepts of effective stress as it applies to a rock mass covering anisotropic, homogeneous poroelasticity, as might apply in a sedimentary rock mass are covered and compared with the concepts of how fluid pressure may act to change effective stress in a jointed rock mass. This entails both fluid pressure and the open area fraction of the joint set which is likely to increase as the rock mass dilates and fails. This means that effective stress is not simply a function of fluid pressure and total stress but rather the changing state of the rock mass. Determining how fluid will act in a complex jointed rock mass prior to and during failure is still an area requiring significant research.

Because of the importance of fluid pressure in rock as part of the effective stress equation the use of varying types of piezometer need to be considered. These include grouted in pressure sensors and the use of packer and pressure sensor combinations. The latter suit fractured crystalline rock masses. Grouted in sensors may suffer from a lack of connection to the rock mass and an alternative approach which ensures connectivity is presented. This involves fracturing the grout around the pressure sensor filter.

For fluid to be transported through a rock mass, permeability must exist and it should therefore be measured. The suggested system to do this most efficiently is a variant of the drill stem test adapted from the petroleum sector and used as part of wireline exploration coring. This enables zonal testing in a borehole and the measurement of fluid pressure and permeability without the complications of near well bore permeability variations which render many test techniques to be invalid. It also enables the determination of the radius of investigation of the test to be estimated.

Where it is determined that the rock mass is unlikely to fail of its own accord the basic principles of preconditioning are discussed. Which of these can be implemented is dependent on the level of stress within the rock mass and the directions of principal stress. The options are simply drilling holes to induce stress concentrations, adding explosive to these to enlarge their effect or the use of hydrofracture. The effectiveness of the latter is really dependent on the stresses at the time of its use as these will determine where the fractures propagate.

The case of a longwall goaf formation has been used because it is illustrative of the complications associated with ensuring caving takes place. It is made interesting by the extremely anisotropic nature of many laminated strata with hugely different shear and failure strengths across and along bedding. However, the same principals apply to a cave in hard rock, it is just that the rock strength and structure is likely to be very different.

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