Safety in Mines Research Advisory Committee

Final Project Report

Application of indirect stress measurement techniques (non strain gauge based technology) to quantify stress environments in mines

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Executive Summary

Reliable values of in situ stress are essential for the valid modelling of mine layouts. Available non-strain gauge methods are reviewed as potential practical techniques for South African mines. From this review it is concluded that the following methods could be attractive for use in this mining environment:

- Estimation of in situ stresses, using the existing in situ stress database and observations and interpretations of failure around openings, is a very important technique for developing an understanding of the in situ stress state. It is recommended that it should always be the first approach applied to obtain an indication of the in situ stress directions and magnitudes. It should also be used as a check on the results of other methods of in situ stress measurement. This method should however, not be used in isolation, but with other methods to build an understanding of the stress regime.
- Kaiser effect gauging, using the monitoring of acoustic emission to determine the Kaiser effect change point. Considerable development of this method has taken place in the past few years, and it is now being applied successfully to determine the in situ stresses in mines in Australia. It is applicable to both greenfield sites as well as existing mining operations. From orientated core from a single borehole, the full three dimensional in situ state of stress can be determined. All detailed work is carried out in the laboratory, so there is no interference with normal mining operations.
- Sleeve fracturing such as developed by Serata Geomechanics Inc appears to be well suited for routine measurement of in situ stress since 20 to 30 tests can be carried out in a day and the fracture can be induced in the borehole at any desired direction. There are drawbacks to the method for application in South African mines – a smooth borehole drilled to close tolerance is required, and at least three boreholes are required to determine the full three dimensional in situ state of stress. At present the maximum stress that can be measured is 40 MPa.
- Back analysis of in situ stresses using deformations measured around excavations as a result of changes in the geometry of that or adjacent excavations. This is not rated as a routine method of determining in situ stresses, but the approach is valuable since a large volume of rock is involved. Therefore, if the opportunity arises with suitable deformation measurements being available, the approach is ranked as a method that should be used. The in situ stress results, based on the deformation of a large volume of rock, will be valuable for comparison with the stresses obtained from other methods.

It is concluded that the most suitable “new” method of in situ stress measurement is the use of Kaiser effect gauging, with the Kaiser effect change point being determined by means of acoustic emission monitoring. It is recommended that some research and development of this method should be funded to gain the necessary familiarity and experience with its application to make it a routine method of in situ stress measurement in South Africa.

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1 Introduction

Knowledge of the in situ state of stress in a rock mass is essential for the proper planning and design of mine layouts to optimise stability and safety of mining operations. The in situ stresses are essential boundary conditions for all design and analysis.

The in situ state of stress in a rock mass can be determined by direct measurement, and there are numerous methods of measurement which are currently in use. Although some measurements of in situ stress were carried out prior to 1950, significant research into methods of in situ stress measurement began in the 1950's and has continued to the present time. In South Africa, research in the 1950's and early 1960's led to the development of borehole strain cells for the measurement of both two- and three-dimensional states of stress. This work was completed in the mid-1960's at which stage South Africa was a world leader in the area of in situ stress measurement. No significant further research in the field of in situ stress measurements was carried out in South Africa until the mid-1990's, in spite of the fact that mining had progressed to much greater depths, where stress conditions are even more critical. At this time there was renewed interest in stress measurements owing to the demand for better quality input data for mine design and evaluation purposes. As part of this new research activity, investigation and preliminary development of a new method of in situ stress measurement, considered to be practical for deep level gold mining conditions, was carried out (Stacey, 1998). Although prototype testing of the approach was carried out, it has not been developed to the extent that it can be used on a routine basis. The concept was subsequently extended and further developed for application in coal mines (Sellers and Coetzer, 2002).

As a result of recent perceptions regarding the effect of in situ stresses on strata behaviour in coal mines and the requirement of data for the development of new mines, there is renewed interest in alternative stress measurement methods, in particular in indirect techniques that do not make direct use of strain gauges. In this report a review of stress measurement techniques that fall into this category is carried out. The content of the report is the following:

- a consideration of the perceived requirements of a method of in situ stress measurement desirable for the mining industry;
- a brief review of the more common methods of in situ stress measurement. This is included to put the alternative techniques into the appropriate comparative context;
- identification and review of indirect methods which have been developed and about which published information is available;

- ranking of the methods in terms of reasoned applicability to South African mining conditions;
- conclusions and recommendations.

2 Perceived requirements for a method of in situ stress measurement in the mining industry

In the consideration of a reliable practical technique for in situ rock stress measurements in deep gold mines (Stacey, 1998), the following requirements were considered to be desirable for a routine method of in situ stress measurement in the mining industry:

- the technique must be undemanding on the requirement for services provided by the mine. It must have as little impact as possible on the mining production and exploration operations, and should preferably require no input of time from these personnel. If possible, it should require no attendance by any mine personnel during the measurement programme. Mine personnel should clearly be welcome to participate, should they wish to do so, but there should be no requirement for their involvement. In summary, the technique should, as far as possible, minimise the input required from the mine in terms of personnel and services;
- the technique should be simple with regard to all aspects - preparation, installation, instrumentation and economical in terms of time requirements;
- the technique should allow many measurements to be made in a short period of time. The preference should be to obtain a large number of lower accuracy measurements rather than one or a few apparently high accuracy results. This will allow the results to be treated statistically and therefore avoid localised effects;
- the technique should be applicable in shallow, low stress environments as well as deep, high stress situations. It should not be sensitive to high stress effects such as spalling and microcracking of the rock;
- the technique should be flexible. It should be possible to implement at very short notice, require a minimum of preparation, be possible to apply in excavations of limited size, and be non-restrictive in terms of location. It should also be able to be implemented on a stop-start basis, not requiring a long continuous period for a measurement programme - it should be able to accommodate the availability of measurement sites, transport and personnel;
- the technique should preferably not involve the calculation of stresses from measured strains using elastic theory (which would usually require the retrieval of rock cores and laboratory testing to determine the deformation properties of the rock or rock mass)

With the recent surge in the development of new platinum mines, a further desirable requirement can be added:

- the technique should be able to be used in greenfield situations, in which underground excavations (required by most common in situ stress measurement methods) are usually not available.

In this report, the desirable requirements identified above have been taken into account in reviewing and evaluating alternative methods of stress measurement.

3 A brief review of the more commonly used methods of in situ stress measurement

Significant early reviews of methods of in situ rock stress measurement were carried out by Leeman (1964a), Leeman (1964b), Obert (1967), and Leeman (1969a). The recent book by Amadei and Stephannson (1997) covers the subject in some detail. A bibliography and list of references have been combined in this report to provide a source of further background information and detail, should this be required by the reader.

Most of the methods of in situ stress measurement involve the observation of a change in deformation or stress resulting from a change in the geometry of an opening in the rock, and the subsequent calculation of the field stresses from those measured changes. Most of the methods are associated with boreholes as the "opening" in the rock mass.

Amongst the borehole-based methods of in situ stress measurement there are methods that measure borehole deformation, borehole strain, borehole surface strain, and stress change. Only the more common methods will be dealt with.

Methods that measure borehole deformation (for example the USBM borehole deformation meter) and strain are probably the most common types. Stresses are calculated from these deformations or strains using elastic theory. In all cases the closed form theoretical solution relating the elastic stresses and strains around the borehole or borehole end is known.

Application of these methods requires high quality diamond core drilling, with associated equipment, facilities and devices, often using large diameter (150 mm) bits, and a special device for centring of the pilot hole. Success with the method is also dependent on good quality rock such that intact overcores at least 300 mm long can be obtained. Since elastic theory is used for the calculation of the in situ stresses from the measured deformations, it is important that no failure of the rock occurs around the borehole which might lead to non-elastic behaviour. The elastic material parameters of the rock material also needs to be obtained from laboratory testing.

Strain relief on the borehole end due to overcoring is measured by strain gauges bonded directly onto the rock forming the end of the borehole in the CSIR Doorstopper method (Leeman, 1964c; Leeman, 1969b). This method yields the in situ secondary principal stresses in the plane of the borehole end. Measurements in three differently orientated boreholes are necessary to determine the complete state of stress in the rock.

Good quality diamond core drilling, with associated equipment, facilities and services, is necessary for the application of this method. The method is not as sensitive as the deformation meter to drilling quality and core quality since only a short length of core stub is necessary for a successful measurement. Additionally, the method can cope with higher stress levels since the stress concentration at the borehole end is less than that on the sides of the borehole.

The CSIR Triaxial Strain Cell and CSIRO HI Cell measure the strain relief on the wall of the borehole. They are the same in principle, the differences being in the structure of the cell and in the detail of their practical implementation (Leeman and Hayes, 1966; Leeman, 1969b; van Heerden, 1976; Worotnicki and Walton, 1976). The approach requires the same drilling facilities as the borehole deformation meter. In good rock conditions it is possible to use a smaller diameter overcore such as an NXCU or even an NXC size.

Amongst the many practical factors necessary, successful measurements are dependent on obtaining a sufficient length of intact overcore. It has been found that this is difficult to obtain under high stress conditions when discing of core may occur (Worotnicki 1993) or dog earing may be incipient or present on the walls of the borehole. Bonding between strain gauges, or an inclusion cell, and the rock is critical (Rocha and Silverio, 1969). It is likely that this type of problem would be present in high stress conditions in which rock failure may occur and where non-durable rock occurs.

A "variation" of this method on a large scale is bored raise rosette overcoring (Brady et al 1976, Chandler 1993). It requires a bored raise or tunnel, which is effectively a very large diameter borehole. The rosettes are of long gauge length, which can be 200 to 300 mm, and are located at three positions around the periphery of the circular excavation. In the original application (Brady et al, 1976) the rosettes consisted of sets of pins into the rock, with the distance between the pins being measured using a mechanical gauge. In the more recent application (Chandler, 1993), wire resistance strain gauges with a gauge length of 120 mm were bonded to the rock surface.

The Interfels Borehole Slotter creates strain relief by cutting a slot in the wall of the borehole (Bock and Foruria, 1983; Bock, 1986; Interfels, 1991) and measuring the strain relief adjacent to this slot. Measurements from three slots are required to enable the calculation of the secondary principal in situ stresses in a plane normal to the axis of the borehole. To obtain the complete state of stress in the rock, slotter measurements need to be carried out in boreholes drilled in three different orientations. The method is attractive from a practical point of view since many slots can be cut during a mining shift, and many slots can be cut in a single borehole.

The measurement of strain relief is by means of a mechanical contact strain gauge, and therefore the condition of the rock on the wall of the borehole is critical to a good result. Cracking or spalling, which might occur under high stress conditions, will have an adverse effect on the measurement and could invalidate the result.

Hydraulic fracturing, as a method of in situ stress measurement, is now well established. It appears that Scheidegger (1962) and Fairhurst (1964) were the first to suggest the method for in situ stress measurement, and early research in the field was carried out by Haimson (1968) and Von Schoenfeldt (1970). It is a stress measurement method that gives a direct output of stress without the need for calibration or calculation of stress from measured strain using appropriate stress-strain theory.

Fluid pressure is applied to a test section of a borehole isolated by borehole packers in a series of pressurisation cycles. The pressures which are required to generate, propagate, sustain, and reopen fractures in the test section are related to the in situ stress field. A significant amount of equipment is required to carry out a full scale hydrofracture test.

To be able to interpret the orientations of the in situ principal stresses, it is necessary that the borehole is drilled in the direction of one of the principal stresses. This is considered to be a disadvantage in mines in that the orientations of the principal stresses are usually not known, particularly if they have been disturbed by mining. Prior estimation of the expected stress field by means of the interpretation of observational methods discussed in Section 4.2, in such a case will be essential.

Variations on the standard hydraulic fracturing method are sleeve fracturing and the HTPF method (hydraulic tests on pre-existing fractures) described by Cornet (1986) and Cornet (1993b).

In situ stress measurement by hydraulic fracturing will be dealt with in more detail in Section 4.3.

The flat jack stress measurement technique is one of the oldest methods of stress measurement (Tincelin, 1952; Habib and Marchand, 1952). The method involves the cutting of a small slot into the surface of an excavation, with the deformation of the rock adjacent to the slot, as a result of the cutting of the slot, being monitored. This is normally done by monitoring the spacing between two pins fixed to the rock adjacent to the slot. After the slot has been cut a small flat jack is grouted into the slot and then pressurised, with the pin separation again being monitored. When the separation is the same as existed before the slot was cut, the magnitude of the pressure represents the in-situ stress magnitude in the excavation wall at that location normal to the plane of the slot. A variation on the method is the use of a cylindrical jack (Bowling, 1976).

For the method to be applied successfully, the rock quality on the surface of the excavation must be in very good, unfractured and unbroken condition. In mining conditions, particularly at deep level, this is considered to be a major disadvantage, and it is unlikely that flat jack tests will be successful under these conditions.

Back analysis is a technique, which has been developing for more than 20 years, and has been made feasible by the availability of computers and numerical stress analysis techniques. The principle of the method is that the in situ stresses and the deformation characteristics of the rock mass interact and thus, when an opening is created, the resulting deformation or stress changes can be used to back-calculate the stresses and deformation properties. A comprehensive description of the method is given by Akutagawa (1991). Compared with strain cell overcoring systems, a large volume of rock is involved, which is an advantage with regard to the representativeness of results.

The method makes use of the measured response of the rock mass, by means of installed instruments, as a result of an adjacent excavation or step in excavation. For example, this could be produced by the advance of a tunnel, the excavation of a chamber in stages, or the advance of a stope face. The measurements that could be used are displacements, strains or stresses, or a combination of them.

Sakurai and Shimizu (1986) describe a simplified form of in situ stress determination using back analysis. In this approach two assumptions are made - the value of Poisson's ratio is assumed not back calculated, and the vertical stress is calculated from the overburden. The modulus of elasticity and the in situ stresses are then back analysed making use of a boundary element numerical analysis formulation.

Zou and Kaiser (1990), Kaiser et al (1990) and Wiles and Kaiser (1994a, 1994b) deal specifically with the determination of in situ stress from excavation induced changes, using monitored data from installed instruments, mainly strain cells. Back analysis forms the basis of the overlapping borehole method of stress measurement proposed by Stacey (1997).

The method requires a situation in which facilities and time exist for the installation of suitable instruments, as well as the facility of careful additional excavation to create the deformation response. The appropriate numerical analysis technique and computer facilities are also required.

Many other methods for determination of in situ stresses have been proposed, developed theoretically, developed experimentally, and applied occasionally. These other methods include the following:

- observational approaches, including observation of core discing and borehole breakouts;
- the use of geophysical techniques;
- analysis of micro-cracking in destressed rock samples;
- measurement of anelastic strain recovery;
- use of a dilatometer or similar instrument to pressurise a borehole;
- Kaiser effect gauging by monitoring acoustic emissions;
- borehole deepening.

Most of these methods fall into the category of indirect techniques, not directly requiring strain gauges, which is the main area of investigation in this report. Some of them have been developed significantly in recent times and will therefore be dealt with in some detail below.

4 Non strain gauge based methods of in situ rock stress measurement

In this review, non strain gauge based methods are interpreted as those methods, which do not use strain gauges in situ for measurement of strains. Therefore, methods that use strain gauges for measurements in the laboratory on retrieved cores or other rock specimens are included in the review.

4.1 Estimation of in situ stresses

Estimation of in situ stresses is included as a “method” since it is a means of obtaining an initial estimate of likely stresses in an area prior to any physical measurements being carried out. It is also an important means of testing the validity of in situ stress measurements that may have been carried out in the area.

Many in situ stress measurements have been carried out in Southern Africa, and the World Stress Map (Anon, 1997; Zoback, 1992) provides further data. These data were recently compiled into a database as part of SIMRAC project GAP511 (Stacey and Wesseloo, 1998). In this project, available stress measurement data were rated in terms of their perceived quality and reliability. A summary of the information is shown in Figures 1 to 3. These figures give the orientations of the horizontal principal stresses, and the ratios of the major and minor horizontal stresses to the vertical stress, plotted as a function of depth.

It is common that the vertical or overburden stress σ_v is determined from the depth below surface, H and the average unit weight of the overburden, γ:

$$\sigma_v = \gamma \cdot H$$

or more specifically,

$$\sigma_v = \sum_i \gamma_i \cdot h_i$$

where γ is the unit weight of a stratigraphic layer and
h is the thickness of the layer and the summation is done for all overlaying layers

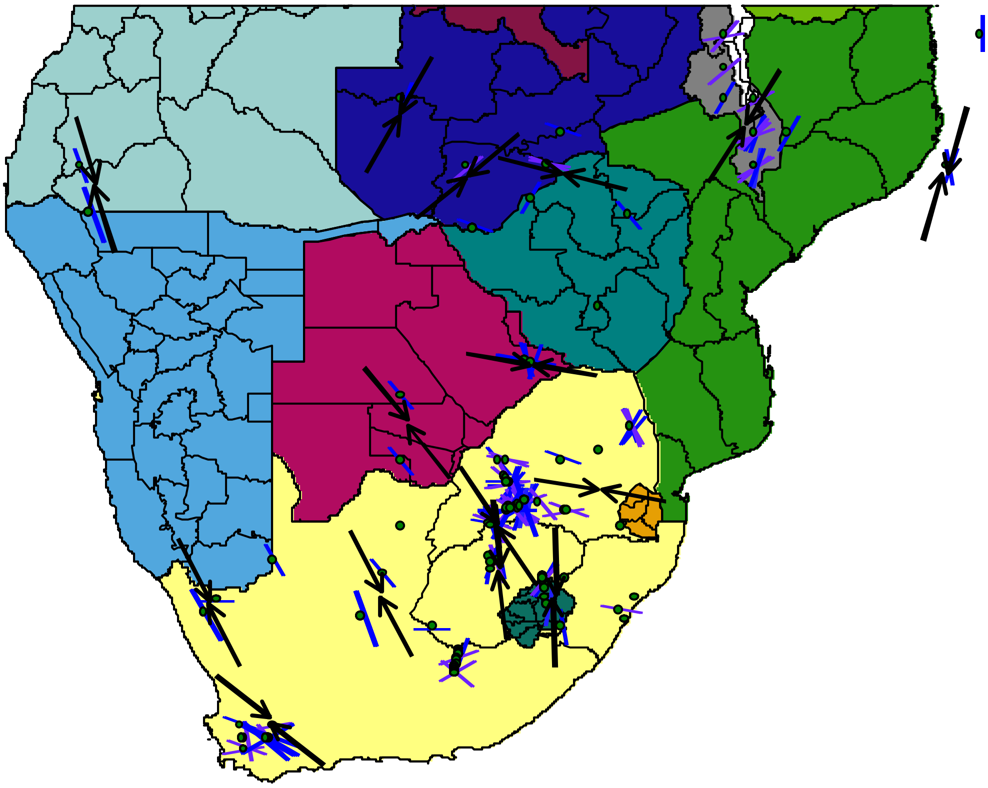


Figure 1 *Orientations of horizontal principal stress from in situ stress measurements and observations in Southern Africa (modified after Stacey and Wesseloo, 1998)*

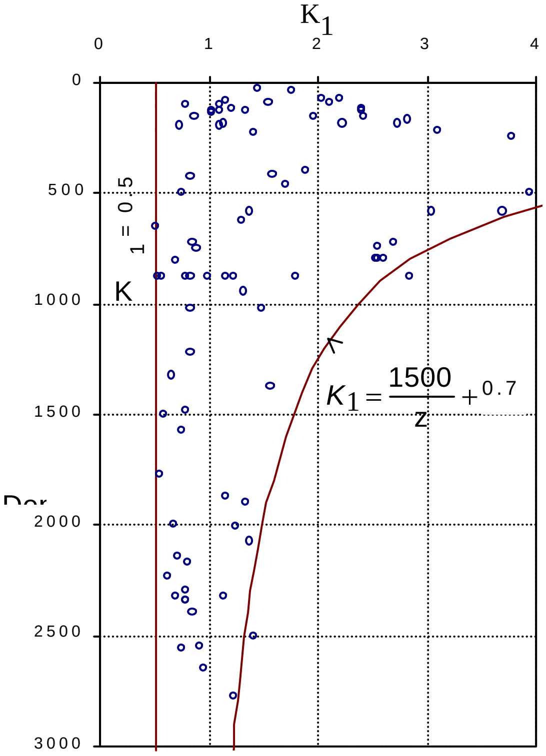


Figure 2 *Major horizontal to vertical stress ratio vs. depth (modified after Stacey and Wesseloo, 1998)*

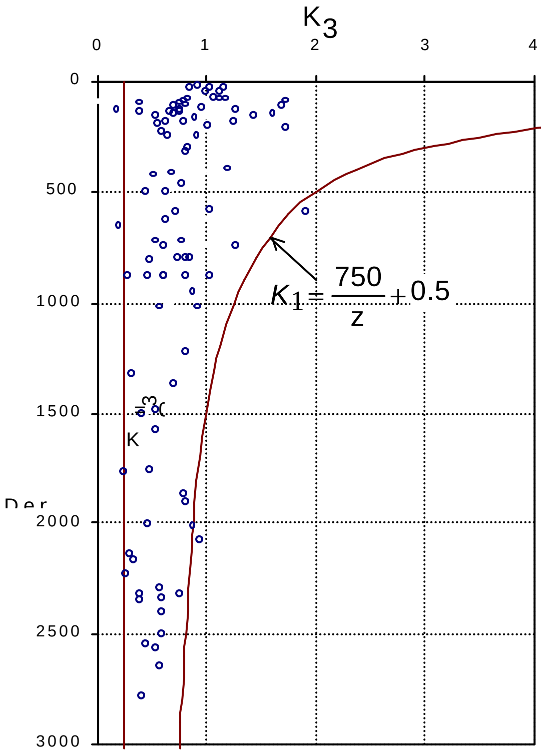


Figure 3 *Minor horizontal to vertical stress ratio vs. depth (modified after Stacey and Wesseloo, 1998)*

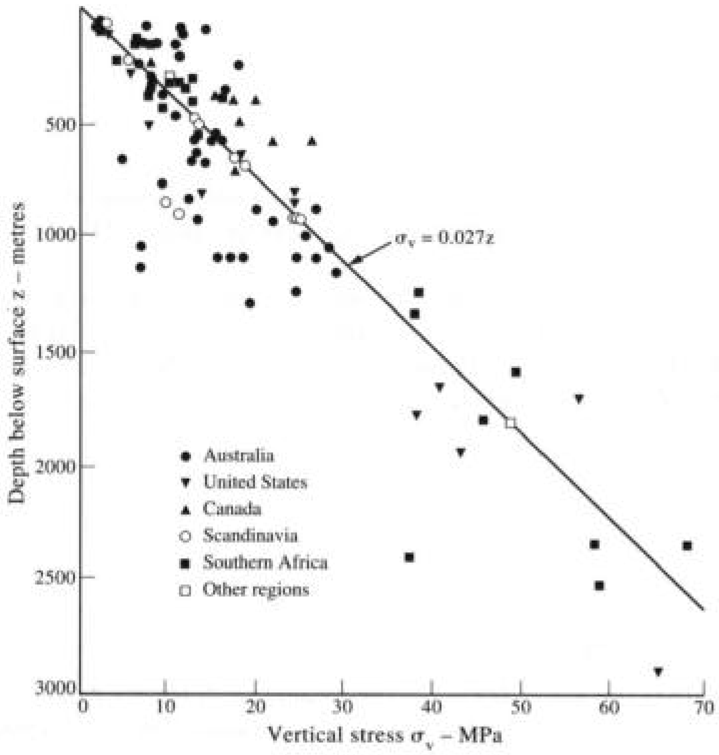


Figure 4 *Variability in vertical stresses, measured internationally (after Hoek and Brown, 1980)*

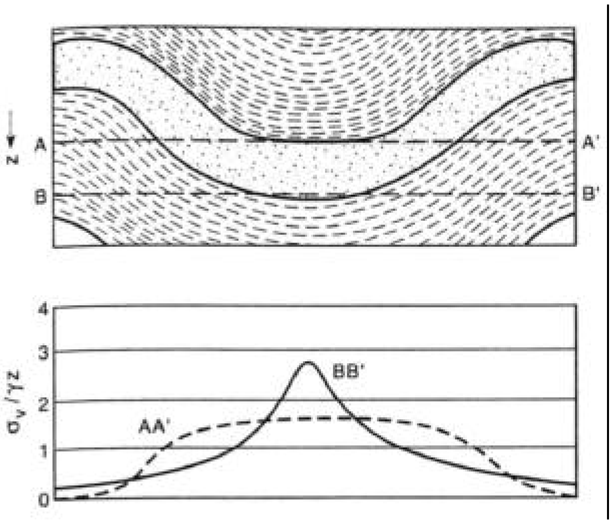


Figure 5 Example of effect of geological structure on vertical stress

If a measured in situ vertical stress does not agree with the overburden stress calculated in this manner, then the first assumption should be that the measurement is incorrect. It is possible, however, that the vertical stress will be affected by geological structures, by non-homogeneities in the rock mass, and by topographical variations. Figure 4 shows the degree of variation in measured vertical stresses in different parts of the world (Hoek and Brown, 1980).

Stress conditions often may change significantly across structures such as faults, dyke contacts and major joints. Stiffer geological materials tend to attract stress, so that stress in say a dyke may be higher than in a rock such as quartzite in close proximity. These effects may influence the vertical stress to some extent. Such an effect on the vertical stress is illustrated in Figure 5 (Goodman, 1989).

The effect of topography on vertical stresses depends on the height of the hill or valley in relation to its width. The alternative surface geometries in Figure 6 illustrate the effect of topography and could be used with regard to the estimation of vertical stresses. Figure 6 consist of a set of graphs showing the change in $\frac{s_v}{g \cdot z}$ with depth for different topographies.

Figures 2 and 3 can then be used to obtain a first estimate of in situ horizontal stress conditions, or to check on the validity of stress measurement results.

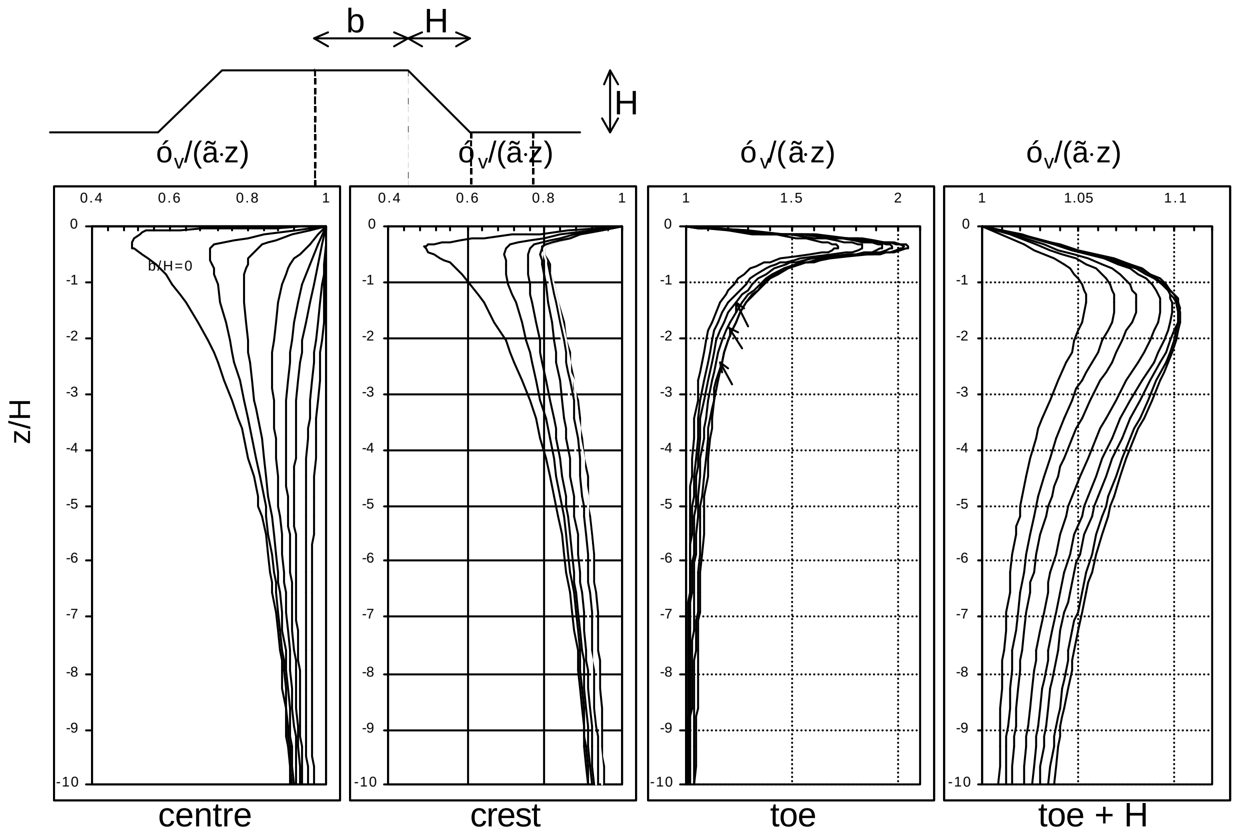


Figure 6a Effect of surface topographies on in situ stresses - hill

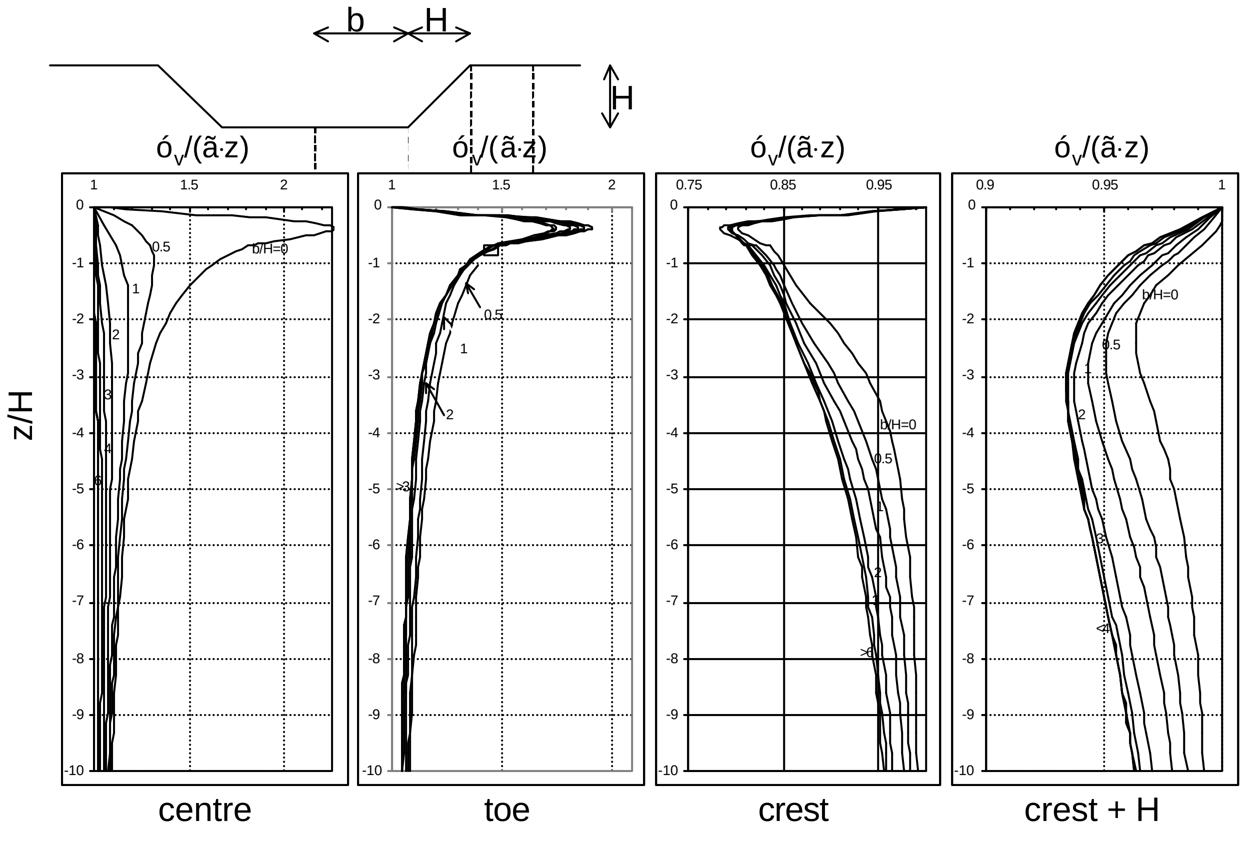


Figure 6b Effect of surface topographies on in situ stresses - valley

4.2 Observational methods of in situ stress determination or estimation

Observations of the behaviour of openings or holes made in stressed rock can provide very valuable indications of the magnitudes and, more particularly, the orientations of in situ stresses.

4.2.1 Borehole breakouts (dog earing)

“Borehole breakout” is the more widely used term for what is known in South African mining as “dog earing”. This phenomenon refers to the stress induced failure that occurs on the walls of a borehole resulting in spalling or sloughing of material from the borehole wall as shown in Figure 7. It is commonly observed in deep boreholes.

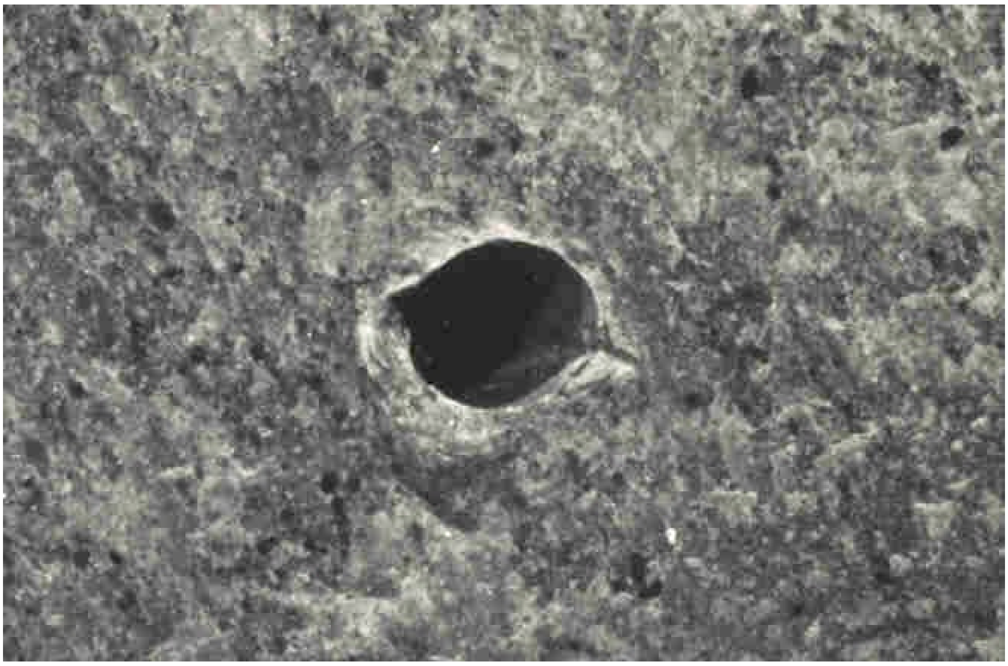


Figure 7 Example of stress induced sloughing of material from a borehole wall

The locations of the breakouts on diagonally opposite sides of the borehole are usually aligned with the orientations of the secondary principal stresses acting in the plane normal to the borehole axis. They can therefore often provide a reliable indication of the orientations of in situ stress fields, and were used extensively to determine the orientation of horizontal in situ stresses in the World Stress Map project (Zoback, 1992) and the North Sea (Cowgill et al, 1993).

Attempts have been made to use breakout data to estimate the magnitudes of in situ stresses (for example Zoback et al, 1985; Zoback et al 1986; Lee and Haimson, 1993; Haimson and Song, 1993). In these attempts, the width and depth of the breakout have been measured as a basis for estimating the stresses. Haimson and Herrick (1986) found that the depth and circumferential extent of the completed breakout were directly proportional to the state of stress normal to the borehole axis. Whilst this approach may have some potential for estimating indicative values of stress, and relative or comparative values of stress, it is unlikely that it will be successful in the adequate quantification of stress magnitudes in South African mines. This is due to the fact that breakout mechanisms will be different for different types of rock, and extents of breakout will vary depending on rock properties and in situ conditions (water, temperature, drilling, etc).

4.2.2 Core discing

Core discing appears to be closely associated with the formation of borehole breakouts. In brittle rocks it has been observed that discing and breakouts usually occur over the corresponding lengths of core and borehole. The thinner the discs the higher the stress level. However, the formation of discs depends significantly on the properties of the rock and the magnitude of the stress in the borehole axial direction (Stacey, 1982). In addition, the type and technique of drilling, including the drill thrust, can significantly affect the occurrence of discing (Kutter, 1991). It is therefore unlikely that observation and measurements of discing will be successful in quantifying the magnitudes of in situ stresses. Nevertheless, the shape and symmetry of the discs can give a good indication of in situ stress orientations (Dyke, 1989). If the discs are symmetrical about the core axis, as shown in Figure 8, then it is probable that the hole has been drilled approximately along the orientation of one of the principal stresses.

A measure of the inclination of a principal stress to the borehole axis can be gauged from the relative asymmetry of the disc. For unequal stresses normal to the core axis, the core circumference will peak and trough as shown in Figure 9. The direction defined by a line drawn between the peaks of the disc surfaces facing in the original drilling direction indicates the orientation of the minor secondary principal stress.

Figure 8 Core discs symmetrical with respect to the core axis

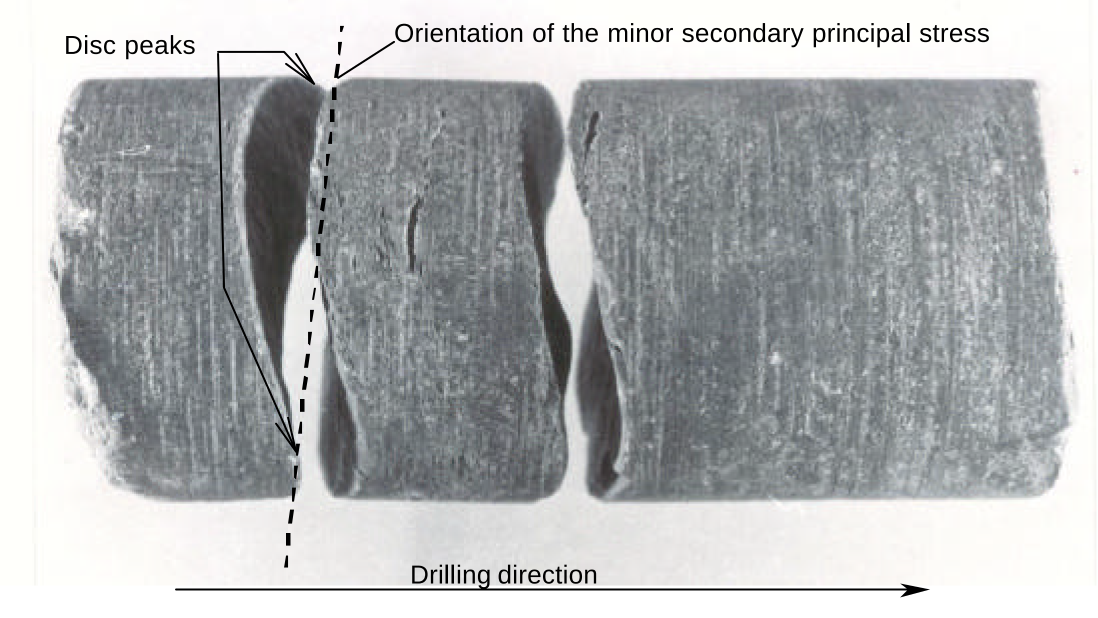


Figure 9 Core discs resulting with unequal stresses normal to the core axis

If the discs are rather uniform in thickness as shown in Figure 8, the two secondary principal stresses normal to the core axis will be approximately equal. Lack of symmetry of the discing, as shown in Figure 10, indicates that there is a shear stress acting across the borehole axis and that the axis is not in a principal stress direction.

Figure 10 Non-symmetrical core discing, indicating that the core axis is not a principal stress direction

4.2.3 Observations of failures in excavations

Excavations can be considered as large boreholes, and observations of the behaviours of the walls of the excavations in response to the in situ stresses can provide very valuable indications of the in situ stress field. Dog earing in bored excavations can be equally pronounced as in boreholes. Figure 11 shows a classic dog ear in the sidewall of a 5 m diameter tunnel. This shows that the major secondary principal stress normal to the tunnel axis (i.e. the maximum stress in the plane perpendicular to the tunnel axis) is vertical at this location.

Similarly, the dog earing in the tunnel in Figure 12 shows that the major secondary principal stress is inclined at about 12^o to the horizontal.

Figure 11 Dog earing in a 5m diameter tunnel

Figure 12 Inclined dog earing in a tunnel illustrating an inclined in situ stress direction (photograph provided by Dr C D Martin)

In coal mining the use of stress mapping for the determination of horizontal stress directions has been described by Mucho and Mark (1994). This approach is summarised in the following paragraphs. Since it is simple, it involves no direct costs and is considered to have value with regard to the provision of reliable in situ stress data.

Mucho and Mark (1994) identify the following set of principles with regard to horizontal stress:

a) the more closely the direction of drivage is aligned parallel to the major horizontal principal stress direction, the less the ground damage;
b) ground damaged by horizontal stress, including caved or goaf areas, will stress relieve or "shadow" adjacent ground, reducing or eliminating damage within this area;
c) when damage is immediate, occurring with mining or at least within a few hours of mining, the first opening to encounter the stress field will suffer the most damage;
d) openings or retreat face lines create stress concentrations that can be the locations of damage;
e) the direction of failure is in the direction of the minor horizontal principal stress;
f) where openings facilitate them, major failure features such as cutters and bottom (floor) heave will usually align themselves perpendicular to the major horizontal principal stress. Roof potting and shear failures will always exhibit this trend.

In the stress mapping approach, the following observations are made carefully:

- failure locations, orientations, geometry, type of failure, sequence of mining;
- shear planes, striations, rock flour, "freshness" of shear failures;
- offsets in blind bolt holes, tension cracks in the roof;
- roof potting, and relative lengths of major and minor axes in oval roof potting.

Mucho and Mark (1994) state that potting also gives an indication of the magnitude of the local stress field. It is considered that this may be approximately true in local areas, particularly if some form of calibration has been carried out. However, from an absolute point of view, the degree of potting is unlikely to be a satisfactory indicator of stress magnitude. This is due to the fact that any form of stress failure depends on the quality and brittleness of the rock and rock mass. Massive brittle (but strong) rock may fail at much lower stress levels than a less massive, less brittle rock mass. It has been observed that such failure can occur when the in situ stress level is as low as 10% of the UCS of the rock material (Stacey and Wesseloo, 1999).

An example of a generalised stress map with stress features and stress damage ratings is shown in Figure 13.

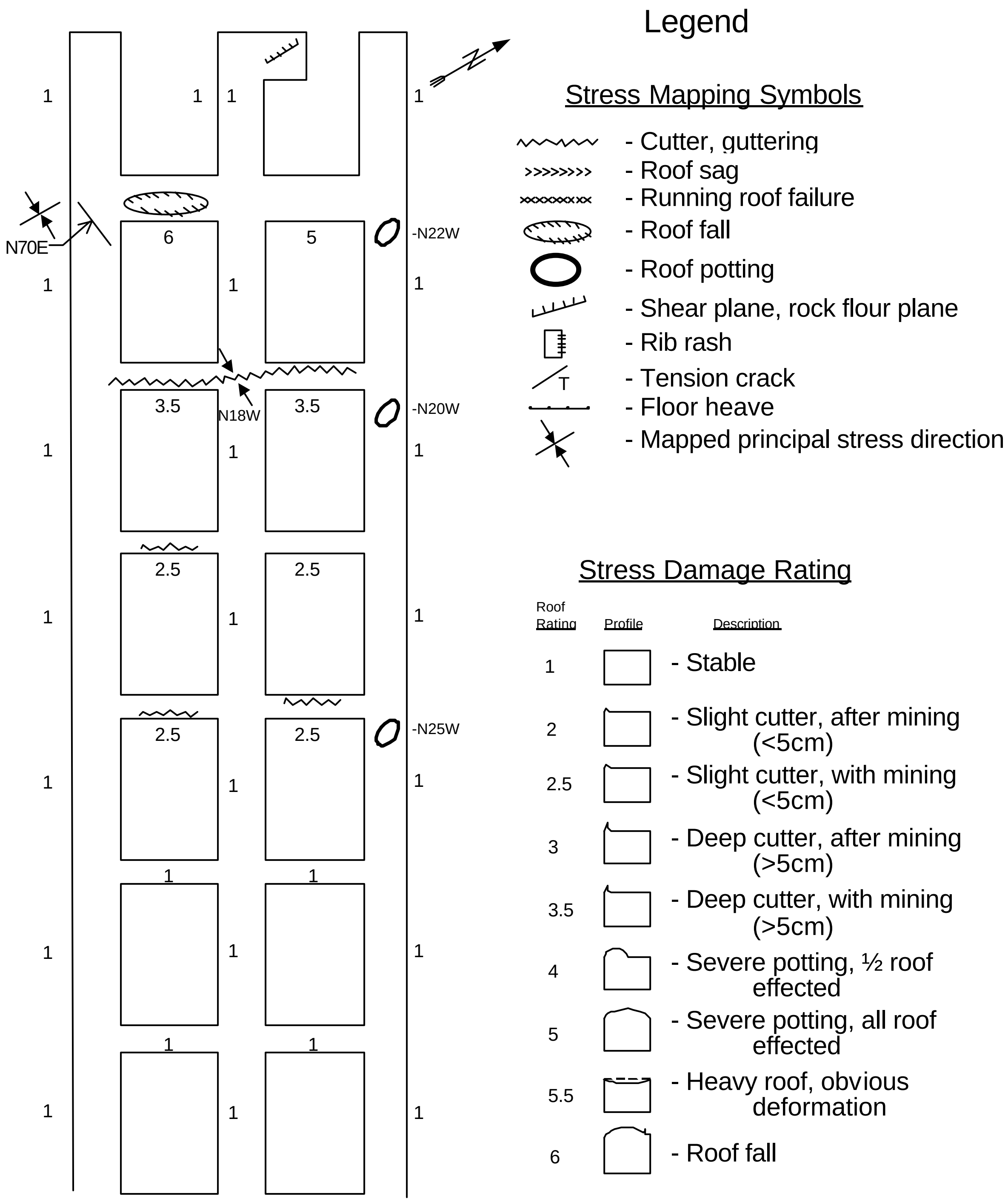


***Figure 13** Example of stress mapping*

4.3 Hydraulic fracturing methods

Hydraulic fracturing is now a well established method for determining in situ stress magnitudes. It has been widely used in the oil well industry. Although hydraulic fracturing had been used previously for other purposes such as borehole stimulation for increasing the yield of water supply or dewatering boreholes, Scheidegger (1962) and Fairhurst (1964) were the first to suggest its use for the determination of in situ stresses. Haimson (1968; 1977; 1983; 1993), Cornet (1993a), Rummel (Rummel, 1987; Rummel et al, 1983) and Zoback (Zoback et al, 1977; Zoback et al, 1980; Zoback et al,1986) played a major role in developing and promoting the use of the hydraulic fracturing technique. The method involves the pressurization of a length of borehole and the measurement of the pressure required to fracture the rock or reopen existing fractures. Three approaches will be dealt with in the following sections: conventional hydraulic fracturing in open boreholes, hydraulic tests on pre-existing fractures (HTPF), and sleeve fracturing.

4.3.1 Hydraulic fracturing

Conventional hydraulic fracturing involves the pressurizing of a short length of borehole, isolated using hydraulic packers on either side of it, until the hydraulic pressure causes the rock to fracture. The characteristics of the pressure induced breakdown and the subsequent reopening of the fracture under repressurisation are monitored carefully. The orientation of the induced fracture is measured using a borehole television camera or a special impression packer to obtain a physical record of the surface of the borehole. From all these data the orientations of the secondary principal stresses normal to the axis of the borehole can be interpreted. Vertical boreholes are usually used and it is assumed that the in situ principal stresses are vertical and horizontal.

The application of the method is illustrated diagrammatically in Figure 14.

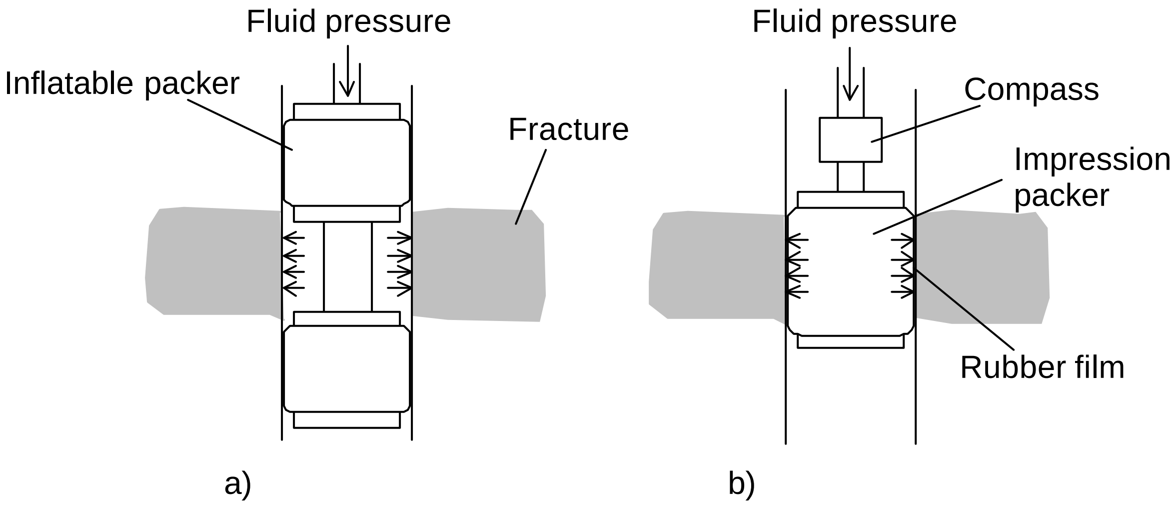


Figure 14 Hydraulic fracture application

The method requires special equipment, and associated services and personnel, to carry out a measurement. The borehole must be diamond drilled or at least have a smooth bore. Since packers are inserted in the borehole to seal off the test sections, the straightness and wall quality of the borehole are important. A system for hydraulic fracturing stress measurements in deep boreholes is illustrated in Figure 15. Although this represents the full sophistication of the method, it is illustrative of the sort of requirements that would be necessary for quality measurements at greenfields sites. A simpler set-up would be applicable for in mine tests.

After hydrofracturing, the borehole has to be inspected using a television camera, or a special impression of its surface taken using an impression packer, to determine the orientation of the induced fracture.

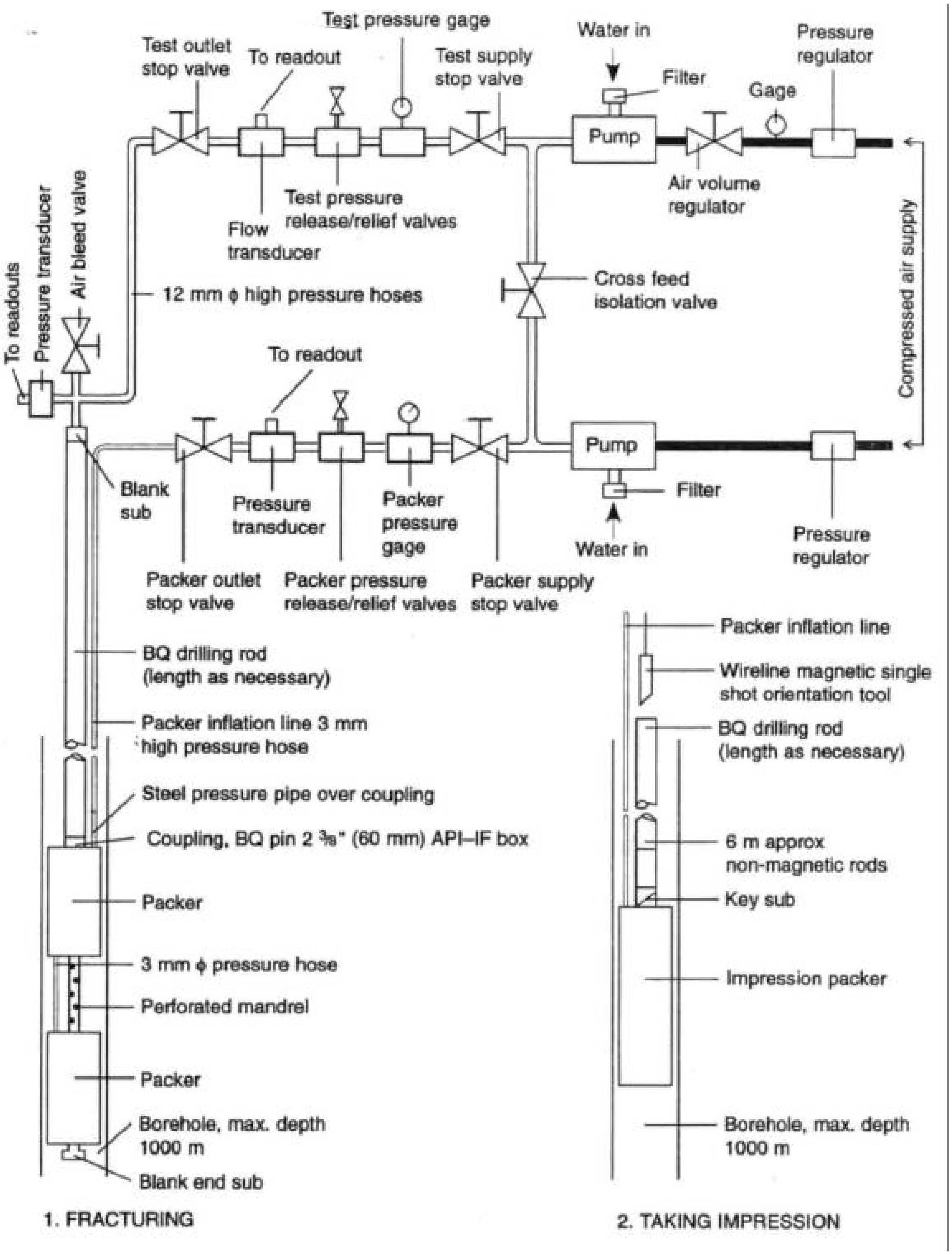


Figure 15 System for hydraulic fracturing stress measurements (after Tunbridge et al, 1989)

Figure 16 shows an idealised recording of a pressure versus time result for a hydraulic fracturing test.

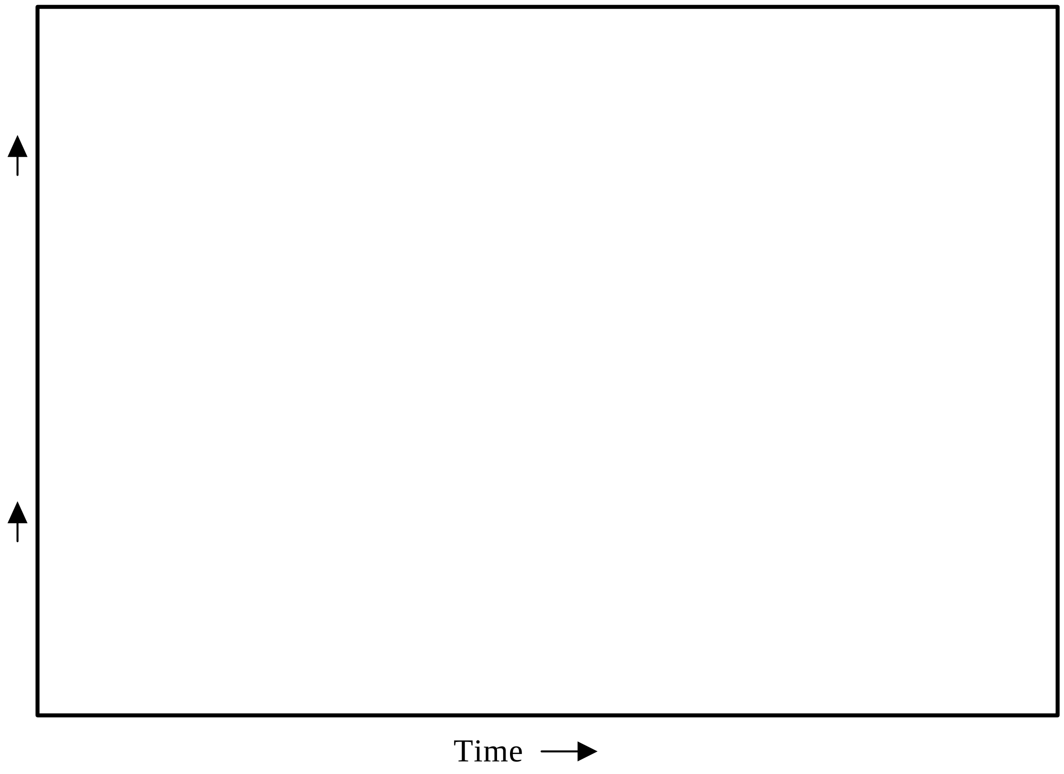


Figure 16 Pressure vs. time record for hydraulic fracturing (after Enever et al, 1992)

In non-porous rocks, which are most likely to be encountered in mining in South Africa, the minimum principal stress is given by the shut-in pressure. If a borehole is drilled in the vertical direction, and it is assumed that this is a principal stress direction, and that the minimum principal stress is horizontal, the major horizontal principal stress S_H can be determined from the following equation:

$$P_c = T + 3 \cdot S_h - S_H$$

Where T is the tensile strength of the rock
S_h is the minor horizontal principal stress
P_c is the fracture initiation pressure (Figure 16)

Interpretation of hydrofracture records can require expert input if the shut-in pressure is not distinct. Interpretation of test results is not a straightforward activity, and the experience of the interpreter has some effect on the in situ stress values ultimately determined. Different interpreters may derive somewhat different results from the same set of field data. In porous rocks in particular, interpretation of hydraulic fracturing tests may be very difficult and, owing to the pore pressure, definition of the major principal stress may be doubtful. In sedimentary rocks, beds with a thickness of at least 2 to 3m are necessary for satisfactory testing to be carried out.

Hydraulic fracturing stress measurements have been carried out at depths in the 6km to 9km range (Amadei and Stephannson, 1997) and therefore the method is, in theory, suitable for the high stress conditions encountered in deep level South African mines. At such high pressures, valves, tubing and packers must be of special design to be able to perform as required. In boreholes in which spalling or breakouts are occurring, there may be a risk of not being able to insert (or recover) the packers, and it may also not be possible to seal off the borehole satisfactorily. Borehole breakouts due to high stress levels may also interfere with the location of the fracture on the borehole wall, and this may lead to inaccuracy in determining stress directions.

It is clear from the above that the application of the hydraulic fracturing method in South African mines is theoretically possible, but would be expensive, and demanding on services. Perhaps the most severe restriction, however, is the requirement that the borehole be drilled in the direction of one of the principal stresses. In mining situations this is usually not known and is one of the in situ stress parameters to be determined.

4.3.2 Hydraulic tests on pre-existing fractures (HTPF)

The HTPF method is a variation on conventional hydraulic fracturing. It consists of reopening an existing fracture that had previously been identified in the borehole and isolated with packers. The orientation of the fractures also needs to be measured. The pressure that just balances the normal stress acting across the fracture is measured. By identifying at least six non-parallel pre-existing fractures and carrying out hydraulic tests on such fractures, six components of in situ stress can be determined, and hence the three dimensional in situ state of stress can be interpreted. The HTPF method is the only hydraulic method where the borehole does not have to be assumed to be drilled in a principal stress direction. It requires no assumptions regarding the in situ stress conditions or the rock mass deformation and strength properties. It is also not necessary to determine the tensile strength of the rock. The concept of the method is illustrated in Figure 17.

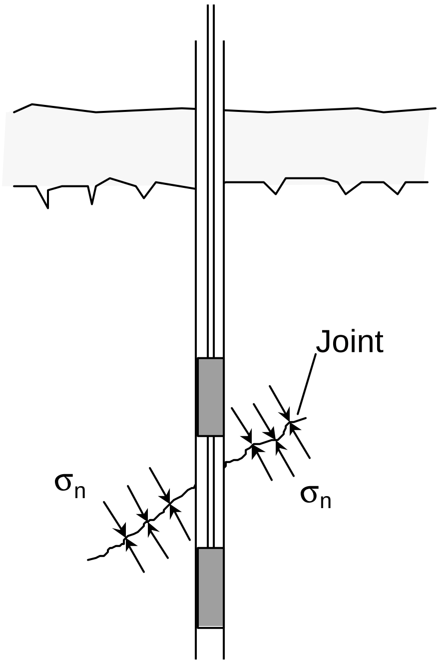


Figure 17 Concept of HTPF method

Although there are many positives regarding the method, there are also negatives: fractures (joints) must be well defined and uniform; there must be a sufficient number of joints, but not too many; many tests are required and the stress field must be uniform in the area of these tests. The method has been found to work well in homogeneous rock masses, but is not satisfactory in stratified and heterogeneous rock masses (Burlet et al, 1989).

Application of the HTPF method requires a similar equipment set-up as for conventional hydraulic fracturing.

4.3.3 Sleeve fracturing

Sleeve fracturing is similar to conventional fracturing except that the fluid is contained within a rubber sleeve. Therefore, the fluid expands the sleeve, which in turn applies pressure to the walls of the borehole causing a fracture to be induced in the rock. It appears that Stephannson (1983) was the first to apply this method, although it is known that the concept was suggested in South Africa in the early 1970's by Leiding (1970).

The conventional application of sleeve fracturing is almost identical to that of hydraulic fracturing. The sleeve is pressurized until a fracture is induced, with the pressure being monitored over time.

The pressure required for reopening of the fracture and the tensile strength of the rock can be used to calculate the horizontal in situ stresses (assuming that the vertical borehole is drilled in a principal stress direction). It is necessary to obtain an impression of the fracture formed to determine the directions of the horizontal in situ stresses.

A more sophisticated sleeve fracturing method, that has been developed and tested significantly, is that due to Serata et al (1992). In this approach, after the first fracture has been induced in a cycle of loading, fracturing and unloading, the pressure is increased until a second fracture is induced. This second fracture system usually occurs at right angles to the first fracture. During the testing, the deformations of the borehole walls are measured by four diametral transducers as illustrated diagrammatically in Figure 18.

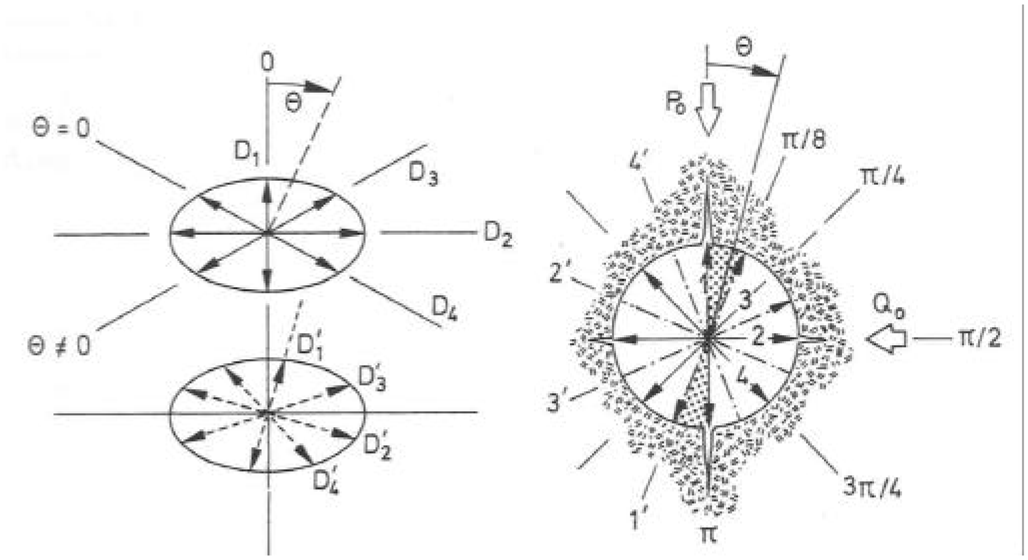


Figure 18 Deformation measurement in sleeve double fracturing system (Serata et al, 1992)

From the plots of pressure vs. diametral deformations, the two reopening pressures corresponding with the two fractures can be determined. Typical plots for reopening of the fractures are shown in Figure 19.

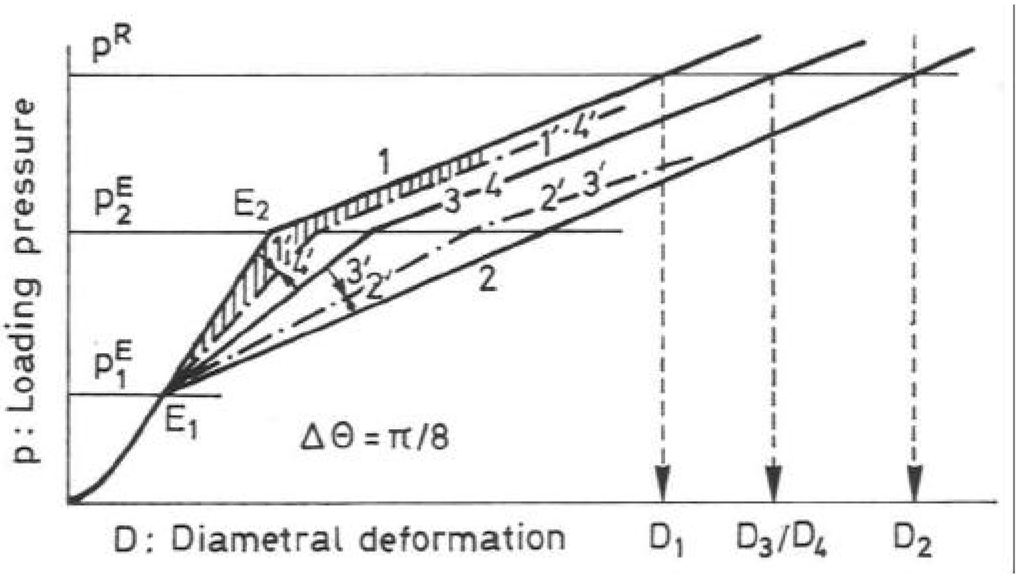


Figure 19 **Pressure vs. diametral deformation plots for sleeve double fracture testing (Serata et al, 1992)**

To calculate the in situ stresses, it is assumed that, at the time of reopening of each fracture, the tangential stress at the borehole wall is zero at the fracture location. The following equations are then applicable for a vertical borehole:

$$3S_h - S_H - P_1^E = 0$$
$$3S_H - S_h - P_2^E = 0$$

Solving for S_H and S_h gives:

$$S_H = (P_1^E + 3P_2^E)/8$$
$$S_h = (P_2^E + 3P_1^E)/8$$

Where S_H is the major horizontal in situ stress

S_h is the minor horizontal in situ stress

P_1^E is the reopening pressure for the first fracture

P_2^E is the reopening pressure for the second fracture

The orientations of the fractures, and hence of the in situ stresses, can be determined from the relative deformations measured by the four diametral transducers as shown in Figure 18. The orientation of the deformation ellipse defines the directions of the two principal stresses. In this method it is therefore not necessary to obtain an impression of the surface of the borehole wall to determine the location of the fractures. The method itself provides both the in situ stress directions and magnitudes.

Serata et al (1992) indicate that it is difficult to obtain sharp and consistent fracture initiation breakdown points, that is, it is difficult to define these breakdown points on the pressure deformation curves. There does not appear to be further published material on this method, and therefore it is possible that the problem of breakdown point definition has not yet been overcome satisfactorily.

In the most recent development of the sleeve fracturing system by Serata Geomechanics Inc (2001), a single fracture system is used. Two special steel friction half cylinders are used to create a single fracture at any desired orientation in the borehole, as shown diagrammatically in Figure 20.

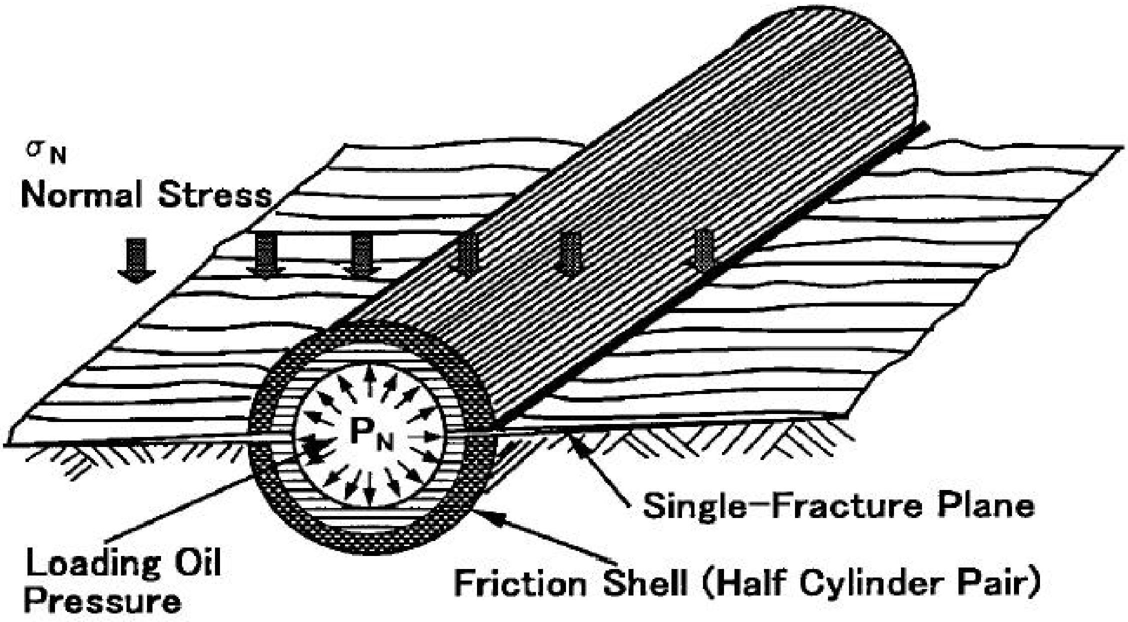


Figure 20 ***Single fracture stress measurement system (Serata Geomechanics Inc, 2001)***

When the fracture planes are reopened, the in situ stress normal to the fracture plane is determined from the curve of the pressure vs. the diametral deformation, as shown in Figure 21.

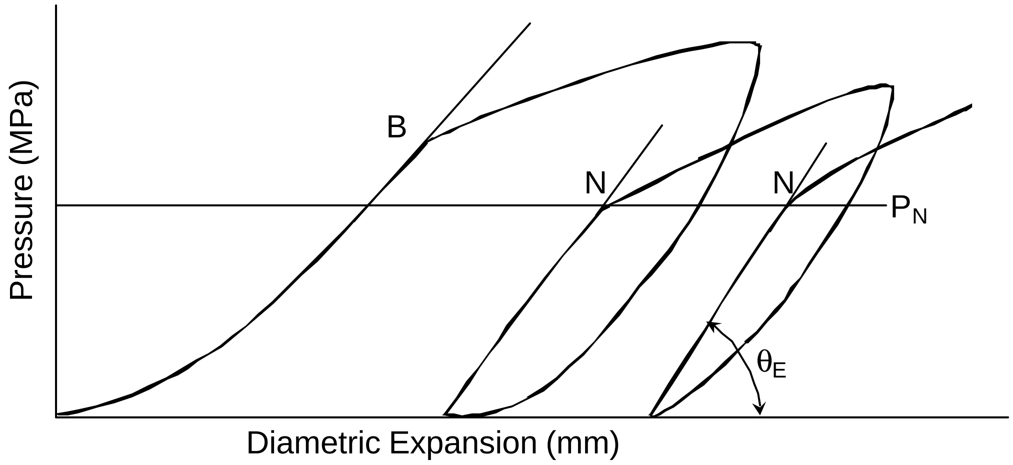


Figure 21 Pressure-deformation curves for single fracture system

The in situ stress normal to the fracture $ó_N$ is determined from the reopening pressure P_N and the rock stiffness, determined from the pressure-deformation curve:

$$ó_N = n \cdot P_N$$

Where $n = a(\tan è_E)^b$

$è_E$ is defined on the pressure-deformation curve in Figure 21

a and *b* are design factors for the instrument

Since the single fracture can be created at any desired angle, the method can be used to determine the three dimensional state of stress, making use of at least three boreholes with different orientations. The deformation modulus of the rock in each test direction is determined automatically as part of the test. It is claimed that 20 to 30 single fracture measurements can be made per day.

The application of Serata Geomechanics Inc (2001) method in its current format requires a smooth borehole (diamond drilled or reamed). This implies that quality drilling equipment with the capacity to drill these holes would be required. The further implication of these requirements is that the application of this method of in situ stress measurement would require the provision of such drilling equipment as well as the provision of compressed air and water services. The instrument will not work satisfactorily in a hole that is not smooth and circular. This implies that if any spalling/dog earing has occurred in the borehole, it will not be suitable for use with this system.

As with the conventional hydraulic fracturing system, the magnitude of in situ stresses that can be measured is dictated by the pressure capacity of the equipment. The maximum stress that can be measured by the Serata Geomechanics Inc system (2001) is 40 MPa (Serata Geomechanics, 2001). This is not a high magnitude in the context of deep level gold mining, and hence the method will require further development for application in such high stress conditions. Although the system appears to be attractive for use in lower stress mining environments, it is a concern that it appears to be “proprietary” – apart from the publications of Serata, there do not appear to be any independent publications or reports that would provide independent confirmation of satisfaction with the method. From the mining point of view, a detraction is the requirement for special boreholes.

4.4 Interpretation of stress “memory” in the rock

Rock, in situ, tends to develop a “memory” of the stress field under which it has been confined (for example, Kurita and Fujii, 1979; Charlez et al, 1986). A sample of this rock removed from this confining environment will react to its unloading and subsequent reloading, and the strains measured have been found to be representative of the original confining stress field. Acoustic emissions that occur on reloading of the rock are also representative of the original stresses and can be used to determine the in situ stress field.

Various methods that deal with stress history will be dealt with in this section. These methods are potentially very attractive with respect to determination of in situ stresses in South African mines. They make use of rock cores obtained remotely, with subsequent sample preparation and strain or other measurements being made under controlled conditions in the laboratory. Such methods therefore have potential application to both greenfields sites and to well established mining operations, and have the potential of being very cost effective.

4.4.1 Anelastic strain recovery methods

In the anelastic strain recovery (ASR) method, an oriented core sample is instrumented to monitor the strain changes with time, as the core relaxes or recovers from its former state of stress. Strains are measured in the laboratory on orientated cores or cubical samples. Interpretation of in situ stress directions can be made directly from the strain measurements. However, the determination of stress magnitudes is much more difficult, and requires a constitutive viscoelastic model for strain relaxation.

The method has been used successfully for determining in situ stress directions and ratios (Teufel, 1982). Results for stress directions have also shown good agreement with those of other methods such as hydraulic fracturing and observation of borehole breakouts (Warpinski and Teufel, 1989; Perreau et al, 1989). Matsuki and Sakaguchi (1995) used the technique and applied the theory developed by Matsuki (1991) and Matsuki and Takeuchi (1993). They found that the results were in poor agreement with those from an overcoring method.

There are numerous factors that can affect ASR methods (Amadei and Stephannson, 1997). The main factors are:

- Temperature variations that can result in thermal strains;
- Changes in moisture content and pore pressures in the rock sample;
- Non-homogeneous recovery of deformations;
- Anisotropy of the rock;
- Interaction between the rock and the drilling mud or water, including degrading of the rock;
- Residual strains;
- Core recovery time;
- Errors in core orientation.

Based on these sources of error, the fact that a viscoelastic constitutive model for strain relaxation must be assumed for the determination of stress magnitudes, and the rather limited use that has been made of the ASR method, it is unlikely that it will be a satisfactory method at this stage for application in South African mines.

4.4.2 Differential strain curve analysis

The differential strain curve analysis (DSCA) method involves cutting a cubical sample out of an oriented drill core, attaching strain gauges to its surface and then applying hydrostatic loading to the sample. The method is based on the following assumptions:

- When a rock sample is taken from a location subjected to a significant in situ stress field, the rock material will microcrack in proportion to the pre-existing effective state of stress;
- The directions of the original stress field determine the alignment of the cracks;
- In any direction there is a volumetric relationship between the cracks and the in situ stress magnitude in that direction;

- Under the hydrostatic loading, the contraction strain which takes place in a particular direction in the rock sample are analogous to the original strain in that direction.

The strain gauges measure the response of the cubical sample. If a minimum of 6 gauges, measuring 6 independent strains, is used, then the three principal strains due to crack closure can be determined. These strains are then related to the in situ stresses. Usually 9 or 12 strain gauges would be attached to the cubical sample. Orientations for 12 gauges are shown in Figure 22. Also shown in Figure 22 is the type of confining pressure vs. longitudinal strain curve that would be obtained for each gauge direction.

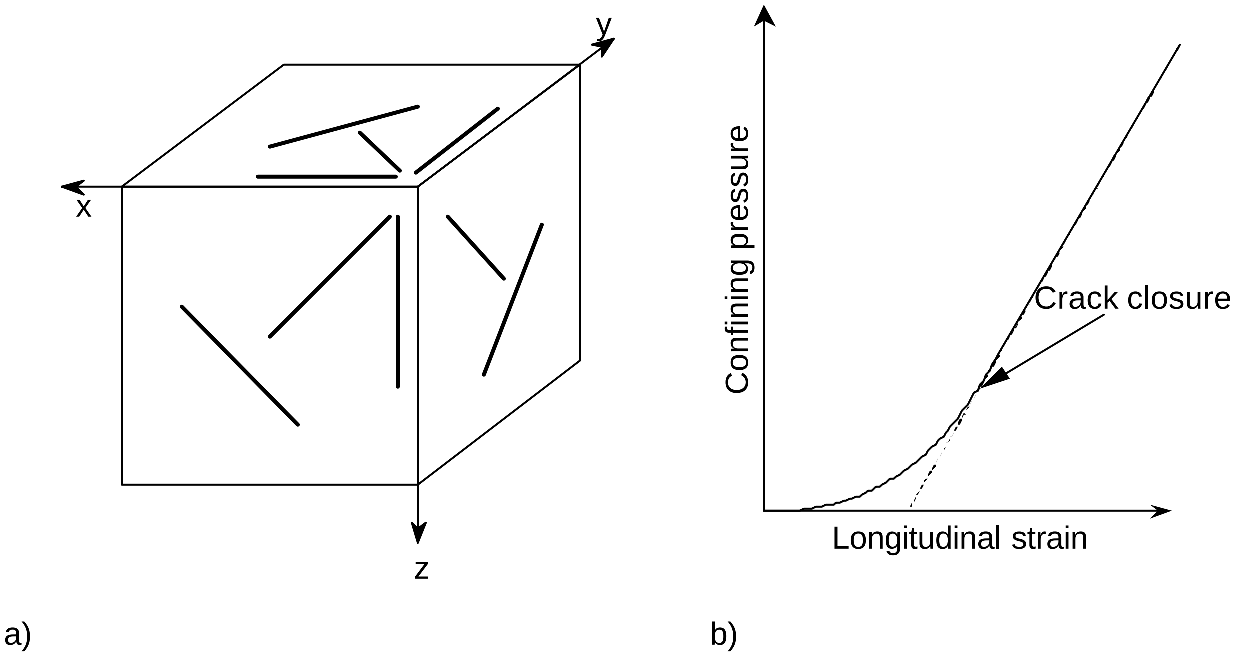


Figure 22 Strain gauge orientations and typical pressure vs. strain relationship for DSCA

The DSCA is a development of the differential strain analysis, a laboratory technique to characterise the porosity of micro cracks in rock samples at various pressures. This technique was modified by Strickland and Ren (1980) to enable it to be used to predict in situ stresses, and they used it for this purpose. Ren and Roegiers (1983) developed the method further and concluded that it was a cost effective technique that did not require any assumption regarding the orientation of the in situ stress field with respect to the borehole orientation.

DSCA in situ stress measurements carried out by Dey and Brown (1986) gave reasonable magnitudes and directions. Perreau et al (1989) found good agreement between horizontal stress orientations obtained from DSCA and other methods. Matsuki and Sakaguchi (1995) did not have success in determining the absolute in situ state of stress using DSCA. Figure 23 shows a set of results obtained by Oikawa et al (1993). The scatter in these results would be unacceptable for use in the South African mining environment.

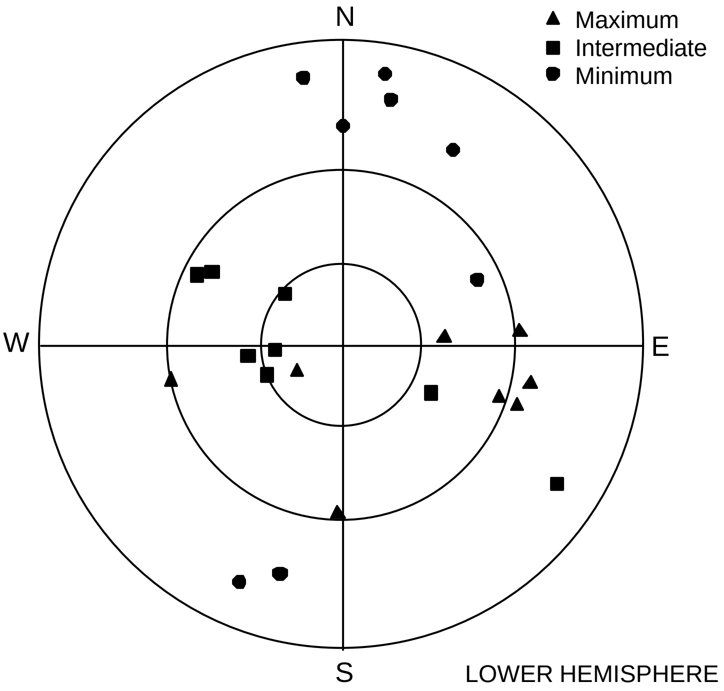


Figure 23 Example of in situ stress directions determined using DSCA (after Oikawa et al, 1993)

Although the method appears to have potential, it does not appear to have been used significantly for in situ stress determination. According to Ren and Roegiers (1983), the quality and reliability of DSCA results depend strongly on experience. Based on this and its limited use, it is unlikely that DSCA is a method that would be suitable at this stage for routine use in South African mines.

4.4.3 Kaiser effect method

Kaiser (1953) observed that when the stress on a polycrystallised metal was relaxed and then reapplied, there was a significant increase in the rate of acoustic emission when the previous maximum stress level was exceeded. This phenomenon has become known as the Kaiser effect. Goodman (1963) observed a similar effect in rocks. It appears that Kanagawa et al (1976) were the first to make use of the phenomenon to estimate in situ stresses, and Hayashi et al (1979) were also early users. A considerable amount of further development of the method has taken place. Hughson and Crawford (1986) demonstrated experimentally that, from a sample of rock extracted from a stressed environment, it was possible to determine the magnitude of the maximum stress to which the rock had been subjected, as well as how much more stress it could withstand before becoming unstable.

The Kaiser effect method involves the drilling of small secondary, orientated cores from the original core removed from the stressed environment. The original core must be orientated so the directions of secondary coring are known in relation to this original core orientation. The secondary cores are prepared with the required end flatness and parallelism, and then subjected to uniaxial compressive stress whilst the acoustic emissions from the rock are monitored using sensors attached to the core. On a plot of the applied stress vs. the acoustic emissions, the Kaiser effect change point is at the position on the curve where the slope of the plot noticeably increases. As the Kaiser effect changes in acoustic emission rate, the stress corresponds with the previous maximum stress to which the rock had been subjected. If a sufficient number of secondary cores are tested, the full three dimensional in situ state of stress may be determined. Hughson and Crawford (1986) noted that:

- The Kaiser effect does not occur abruptly at a precisely definable point, but within a transitional zone;
- The position and abruptness of this zone varies for different types of rock materials, and with the magnitude of the previous stress relative to the strength of the rock (Hughson and Crawford refer to the Stability Limited Stress of the material);
- The transition zone becomes large and indistinct if the maximum stress exposure time was brief.

The stress “memory” reduces over time, and hence it is necessary to carry out the tests within a relatively short time after removal of the original core. The length of the “memory” appears to depend on the type of rock (Hughson and Crawford, 1986). Kurita and Fujii (1979) conclude that no significant recovery of the Kaiser effect occurs within one month of removal from the stressed environment. Friedel and Thill (1990) found that the effect was retained for a period of up to at least 5 months. Other researchers have noted very much shorter retention periods, for example, several hours (Goodman, 1963), one to five days (Yoshikawa and Mogi (1981), three days (Boyce, 1981). These limitations are contradicted by the results of Seto et al (1998), who obtained satisfactory results for in situ stress determinations on cores that had been removed almost two years previously. Their results agreed to within 10% of values determined by other methods and by estimation of overburden stress.

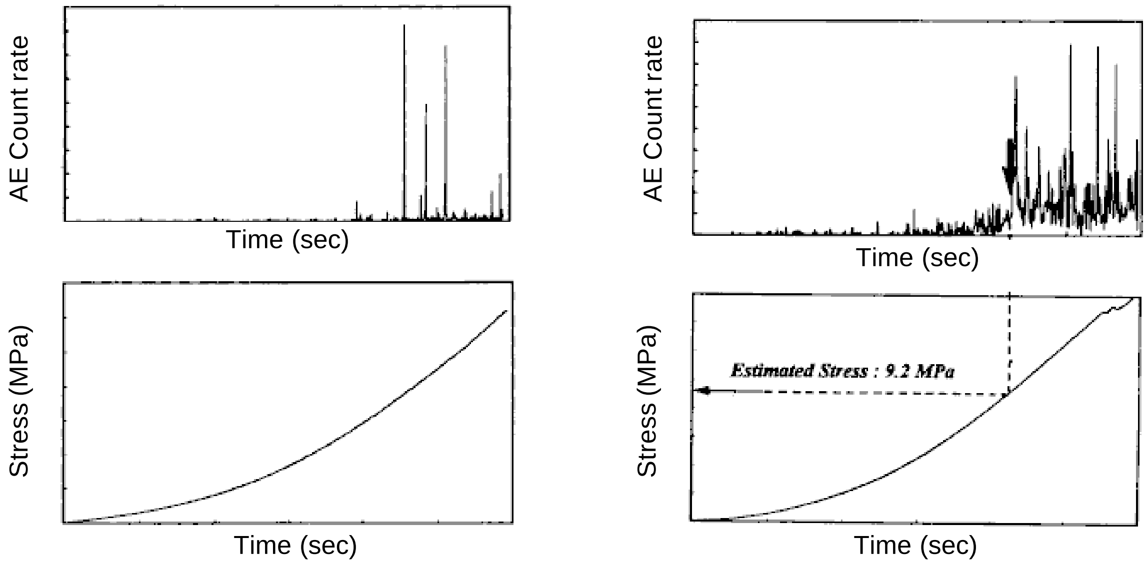
Hughson and Crawford (1987) and Holcomb (1993) indicate that the position of the Kaiser effect change is dependent on the confining stress, that is, it depends on the three dimensional state of stress. Holcomb argues, therefore, that the stress determined for the Kaiser effect change point using uniaxial loading will be in error and that the original state of stress cannot be uniquely determined. This is perhaps logical since the strain state depends on the three dimensional state of stress.

Momayez and Hassani (1992) refer to a technique called the “maximum curvature method” that determines the exact location of the Kaiser effect point by calculating the curvature at every point along the stress-acoustic emission curve. The maximum value for the curvature corresponds with the point where the change in the slope of the stress-acoustic emission occurs.

Hughson and Crawford (1988) indicate also that the Kaiser effect does not necessarily occur precisely at the previous maximum stress level – it overestimates the maxima that are low relative to the strength of the rock and underestimates the maxima that are high. They refer to a Felicity factor, which is the ratio of the Kaiser effect stress to the previous maximum stress.

Recent use of the Kaiser effect method for in situ stress determination in mines in Australia (Seto et al, 1998; Villaescusa et al, 2000; Seto et al, 2000; Villaescusa, 2001) demonstrate that none of these apparent limitations are significant. There appear to have been no problems with the determination of the Kaiser effect change point (it does not appear that they make use of the maximum curvature method), with the effect of confining stress, and there is also no mention of the application of a Felicity factor. In the testing, in situ stress results were determined with acceptable accuracy, and compared well with results obtained from other in situ stress measurement methods.

As an example of the application of the method, Figure 24 shows a plot of the applied uniaxial stress against the acoustic emission behaviour for a rock core, removed two years previously from a depth of 356m.



a) First Loading

b) Second Loading

Figure 24 Determination of the Kaiser effect change point and corresponding original stress (after Seto et al, 1998)

A comparison of stress at this site determined using different methods is given in the table below.

In situ stress determination method	**Stress magnitude (MPa)**
Overburden stress estimation	8.5
Kaiser effect method	9.2
Hydraulic fracturing method	8.9

Figure 25 illustrates results obtained from Kaiser effect and deformation rate analysis measurements (AE and DRA) compared with measurement results obtained by overcoring of hollow inclusion cells.

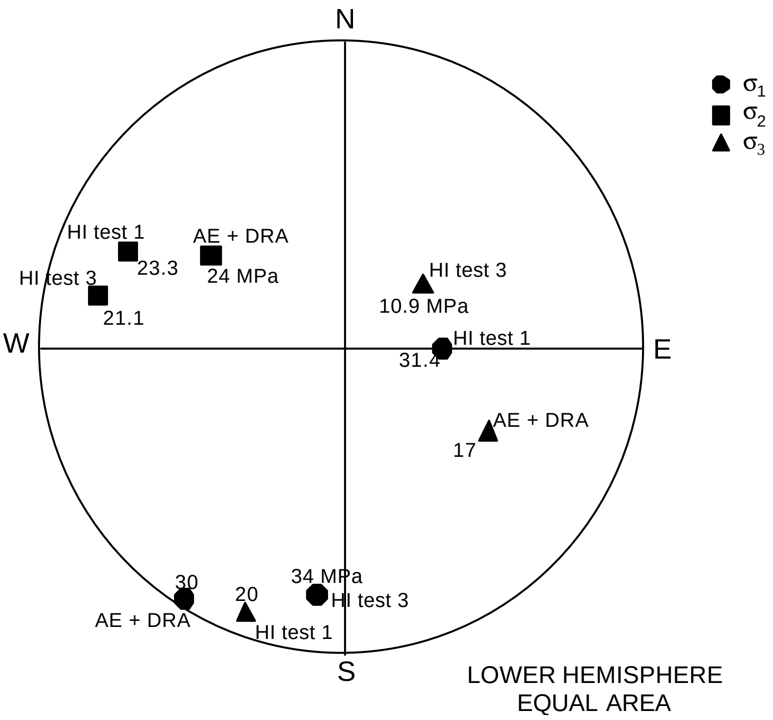


Figure 25 A comparison of in situ stress magnitudes and directions (after Villaescusa et al, 2000)

The use of the Kaiser effect method for determination of in situ stresses in South African mines appears to be very attractive for the following reasons:

- It gives a direct measure of stress. It is not dependent on the measurement of strain and the subsequent calculation of stress from strain, which requires the assumption of a relationship between stress and strain for the rock as well as measurement of the deformation properties of the rock. All of these factors can introduce errors.
- The full three dimensional in situ state of stress may be determined.
- Use can be made of original core obtained for other purposes, such as exploration, making the method cost effective.
- Core obtained remotely can be used, and therefore the method is applicable to greenfield sites, before any excavations have been made, as well as to operating mines.
- Since small secondary cores are used for the tests, many tests can be carried out using a limited length of original borehole core. Again this makes the method cost effective, with a large number of results being able to be obtained at relatively low cost. The more the number of cores tested, the greater the confidence in the results obtained.
- The necessary accurate and sensitive sample preparation and testing activities are carried out in the laboratory. This therefore obviates field based testing errors that are common in

the often harsh mining environment. Interference with production mining operations is also reduced or eliminated.

At this stage it is not known what effect fracturing of core, induced during the drilling process, will have on the application of the method. Applications to date in a mining environment have been at relatively shallow depth, and therefore generally at stress levels well below the strength of the rock. It is therefore possible that application in the deep level gold mines may be problematic. However, stress magnitudes of close to 100 MPa have been determined in mine pillars in Australia (Villaescusa, 2001), and this indicates optimism for the use of the method at high stress levels.

The success of the AE method for in situ stress determination in mines has recently been confirmed at more than 10 mine sites in Australia, involving numerous measurements (Potvin, 2002). These results represent measurements in both igneous and sedimentary rock types.

4.4.4 Deformation rate analysis

The deformation rate analysis method (DRA) also makes use of the “memory” effect. However, instead of the acoustic emission being monitored, the strain in the cores is measured by means of strain gauges bonded to the core as the uniaxial stress on the core is increased. The concept of the method is that there is a change in the stress-strain relationship of the rock when the point or previous maximum stress is encountered. The original stress can be determined from the change in gradient of the stress-strain curve under cyclic uniaxial compression tests. As indicated by Seto et al (1998) and Villaescusa et al (2000), the gradient changes are determined from cyclic loading tests, with the strain difference values between two cycles being measured as a function of the applied stress:

$$Äå_j = å_j(ó) - å_i(ó); j>i$$

Where $å_j$ is the strain measured in the j^{th} loading cycle, and

$ó$ is the applied stress corresponding with that strain.

This strain difference function represents mainly the inelastic strain difference between the two cycles. The reversible or elastic components of strain are cancelled by the operation in the above equation. Using the strain difference function, the point of gradient change of the applied stress-strain curve can be detected and hence the value of the original normal stress in the direction of the core axis determined.

Since the core sample preparation and loading activities involved in the DRA method are the same as those required for the Kaiser effect method, it is logical to apply both methods at the same time to determine the in situ state of stress. The simultaneous use of the two methods on the same core lends greater confidence to the in situ stress results obtained.

Villaescusa et al (2000) combined the results from Kaiser effect and DRA methods as shown in Figure 25.

The advantages identified above for the application of the Kaiser effect method in South African mines are equally applicable for the DRA method.

4.5 Geophysical methods

There is a relationship between the passage of seismic waves in a rock mass and the in situ state of stress in the rock mass (Swolfs and Handin, 1976; Isobe et al, 1976). The use of this to estimate the directions and magnitudes of in situ stresses does not appear to have been pursued, however.

Interpretation of earthquake data to obtain fault plane solutions, which give the directions of the horizontal in situ stresses, has been widely used. It is the basis of much of the data contained in the World Stress Map (Zoback, 1992; Anon, 1997). The method is a valuable source of in situ stress information, but does not allow determinations of in situ stress at particular locations, nor does it provide stress magnitudes. Hence, it is not generally applicable to South African mining conditions.

4.6 Back analysis of excavation deformations

When an excavation is made, or an excavation enlarged, in a rock mass, displacements around the excavation occur in response to the action of the in situ stresses. The relationship between the displacements and the stresses can be represented by a simple equation:

$$\{u\} = [F]\{ó\}$$

where $\{u\}$ is a matrix of displacements
$\{ó\}$ is a matrix of the in situ stresses

$[F]$ is the flexibility matrix, which is a function of the deformation properties of the rock and the geometry and dimensions of the excavation

If the displacements can be measured, then the in situ stresses can be calculated (back analysed) by rearranging the equation:

$$\{ó\} = ([F]^T[F])^{-1}[F]^T\{u_m\}$$

where $\{u_m\}$ is the matrix of measured displacements.

For solution of the equation, it is necessary to make use of a numerical stress analysis technique such as the boundary element or finite element methods. The back analysis method has been dealt with in detail by Akutagawa (1991). Although Sakurai and Akutagawa (1994) have extended the methodology to account for non-elastic rock behaviour, from a practical point of view the calculation of in situ stresses requires linearly elastic rock deformation behaviour. If a sufficient number of independent deformation measurements is available, the full three dimensional in situ state of stress may be determined. The assumption of linearly elastic behaviour is likely to be restrictive in many cases and in particular at deep level where the rock surrounding an opening is likely to be fractured and in a state of failure.

In the use of a back analysis technique, the larger the excavation involved, the larger the volume of rock that will be affected. The benefits of such an approach compared with other methods of in situ stress measurement have been outlined by Wiles and Kaiser (1994a). Examples of the use of the back analysis method have been published by, for example, Kaiser et al, 1990; Sakurai, 1988; Sakurai and Shimizu, 1986.

In mining operations, openings are often created in close proximity such that the excavation of the second opening will cause deformations of the first opening. Also, as tunnels are advanced, the perimeter of the tunnel close behind the face deforms as a result of the excavation (Wiles and Kaiser, 1994a and 1994b). These excavation induced deformations can be measured and related to the in situ stresses acting in the rock mass.

The application of the method is limited to the availability of sites at which excavation enlargements are being made (unless enlargements are made specifically for the purposes of in situ stress measurement) or adjacent openings are being excavated. This could have a large interference factor on mining operations. The dependence on openings being created means that the method is not applicable to greenfields sites. In addition, sophisticated instrumentation is usually required, with associated special borehole drilling, and this implies significant cost as well as further interference. The reliability and survivability of instrumentation in South African mines is known to be a serious problem, particularly if it is required to be effective over a significant period of time.

For the above reasons, back analysis is not an attractive method for general application in South African mining. However, it is considered to be a valuable method that can be applied on an ad hoc basis whenever a suitable opportunity arises.

5 Ranking of non strain gauge based methods of in situ stress measurement

Based on the review of alternative methods of in situ stress measurement above, those methods that are considered to have significant potential application to South African mining are dealt with in the perceived order of significance in the following sections.

5.1 Estimation of in situ stresses

Estimation of in situ stresses is given the highest ranking, since it is considered that it should always be the first approach applied to obtain an indication of the in situ stress directions and magnitudes. The following activities are suggested in the recommended order of application:

- reference to the Southern African database of in situ stress information. This will provide an indication of likely stress directions and horizontal to vertical stress ratios in the area. It should be assumed that the vertical stress is due to the overburden pressure;
- observation and interpretation of core discing, if any, in borehole core. This may give some indication of stress directions and possibly stress magnitudes;
- if geophysical type logging of boreholes has been carried out, calliper logs of the borehole may show up breakouts (dog ears), which will provide a very positive indication of stress directions;
- if underground excavations are available for inspection, observation of stress induced fracturing will give valuable indications of stress orientations and relative stress magnitudes. Routine application of the stress mapping technique, and subsequent interpretation of these mapping data, are recommended.

Estimation of in situ stresses is ranked highest of the methods for the following reasons:

- it involves no direct costs, simply an investment in time;
- it requires the rock engineering and geological personnel, who would be responsible for the estimations, to think carefully about the mining situation when interpreting the available information. This will have safety related benefits;
- it requires these personnel to inspect and investigate aspects that they would possibly not do otherwise, and again this will have safety related benefits;
- perhaps most importantly, these personnel on the mine will “own” their own design and analysis data, and it will be their responsibility rather than the responsibility of some “remote” organisation to provide them with the data.

Estimation and observation should be carried out even if the in situ stress is to be measured by other methods. It is important to realize that although this method is very powerful in developing an understanding of the stress state in the mining area, it is based on subjective interpretation and judgment, making it a very dangerous method if used in isolation. This method should therefore be used routinely, to develop an understanding of the stress state but should be complemented by data obtained from other methods.

5.2 Kaiser effect gauging using acoustic emission

The Kaiser effect technique to determine in situ stresses in South African mining situations is ranked second in order of significance for the following reasons:

- it is applicable to both local and remote situations, and therefore applicable to both existing mining operations and greenfield sites;
- it is applicable to both shallow and deep mining operations. The method has been used to determine stresses at depths of about 200 m and at a magnitude of 100 MPa;
- it can make use of borehole core retrieved for other purposes such as exploration. Testing can be carried out on non-ore core, so that there is no interference with exploration activities. A requirement is that the core is orientated, and this represents no problem since it is a standard operation in diamond drilling;
- it is possible to make use of “old” core (possibly one to two years, depending on rock type) provided that the orientation of the core is known. This should be easily feasible in sedimentary deposits in which the dip of the stratification defines the orientation;
- no measurements are made on site, hence there is no interference with mining production operations, nor requirement for special services;

- all accurate sample preparation and testing activities are carried out in a laboratory under controlled conditions, therefore limiting any experimental errors;
- sample preparation and testing make use of conventional equipment;
- since small secondary core samples are used, it is possible to carry out a large number of tests on a small amount of borehole core in a short period of time. The implication is that the cost of in situ stress measurements using this method is relatively low;
- the method gives a direct measure of stress, unlike most of the methods of in situ stress measurement in current use that measure strain changes;
- the method yields the full three dimensional in situ state of stress from tests on core from a single borehole. It is not necessary to have boreholes specially drilled in several directions.

A few years ago, when a review of in situ stress measurement methods was carried out (Stacey, 1995), this method was not considered seriously. Its practical effectiveness had not been demonstrated at that time. This situation has changed recently, however, as a result of the following:

- the method has recently been successfully applied to determine stresses in coal mines in Australia;
- a research project has been in progress in Australia for several years in which the method is being applied at numerous mines;
- results obtained recently in mining applications have been encouraging, providing significant confidence in the method.

The fact that the method is already being applied successfully in mining situations implies that it has now possibly establishing itself as an accepted method of routine in situ stress measurement.

The measurement of the Kaiser effect change point using acoustic emission appears to be the most satisfactory approach and it is this approach that is recommended. However, it is little extra effort to measure the strains in the sample at the same time, and therefore the concurrent use of the deformation rate analysis method to provide additional confidence in the determination of the Kaiser effect change point should be considered.

Some research and development will be necessary to learn the techniques and gain sufficient experience to establish the method as a routine method for in situ stress measurement in South Africa.

5.3 Sleeve fracturing

Conventional hydraulic fracturing is a well established method of in situ stress measurement, particularly in the oil well industry. It has an advantage that it yields directly the magnitude of the minor principal stress in a plane normal to the borehole axis. However, it has several disadvantages, the most significant of which are considered to be:

- the requirement that the borehole is drilled in a principal stress direction;
- clear determination of the major principal stress in the plane normal to the borehole axis is affected by the pore pressure in the rock.

Owing to these drawbacks it is not considered suitable for routine stress measurements in mines. Hydraulic testing of pre-existing fractures (HTPF) overcomes these problems. However, HTPF requires a large number of tests and therefore is also not considered suitable for routine application in mines.

Sleeve fracturing as developed by Serata Geomechanics Inc, however, appears to be much more suited to routine applications, for the following reasons:

- 20 to 30 tests can be carried out in a day;
- the fracture can be induced in the borehole at any desired direction. There is no requirement therefore to determine the fracture orientation using an impression packer;
- from the method the value of in situ stress normal to the direction of the induced fracture can be calculated easily from the test results.

The method is not given a higher ranking for the following reasons:

- smooth boreholes with a diameter of reasonably close tolerance are required. Tests cannot be carried out where the walls of the borehole are irregular, such as where spalling and breakouts occur;
- tests in three boreholes drilled at different orientations are required to determine the full three dimensional in situ state of stress;
- test equipment is specialised and appears to be proprietary, implying that stress measurements made with the method would probably be costly;
- the requirement for special smooth boreholes implies that special services would be required and that there would probably be interference with production operations;

- the method is not applicable to greenfield sites, and is limited at present to the measurement of a maximum in situ stress of 40 MPa.

5.4 Back analysis of measured deformations

The back analysis of in situ stresses using deformations measured around excavations as a result of changes in the geometry of that or adjacent excavations is not rated as a routine method of determining in situ stresses. However, the approach is valuable since a large volume of rock is involved. Therefore, if the opportunity arises with suitable deformation measurements being available, the approach is ranked as a method that should be used. The in situ stress results, based on the deformation of a large volume of rock, will be valuable for comparison with the stresses obtained from other methods.

6 Conclusions and recommendations

It is concluded that the most suitable “new” method of in situ stress measurement is the use of Kaiser effect gauging, with the Kaiser effect change point being determined by means of acoustic emission monitoring. It is recommended that some research and development of the method should be funded to gain the necessary familiarity and experience with its application to make it a routine method of in situ stress measurement in South Africa.

Stress estimation using the existing in situ stress database and observations of rock behaviour around openings should be practised in addition to any measurement of stresses. Routine stress mapping by rock engineering and geological personnel will provide additional on-going valuable information, and will be of benefit to safety. It is recommended that the development of a stress mapping and interpretation system for South African mines should also be funded. Such a system will provide the industry with a standardised method for mapping and interpreting the fracture behaviour of the rock mass in relation to the in situ stress field, and will aid communication on the subject.

Back analysis of stresses is valuable in that it involves a large volume of rock, and should be carried out as and when suitable deformation monitoring data are available.

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Appendix

Project Proposal