WHY HORIZONTAL STRESS AND STRAIN IN UNDERGROUND MINES MATTERS

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Abstract

This paper presents a description of what causes stress in the ground, the effect on mining of stress and means to measure stress. Such measurement requires interpolation both within a borehole between point measurements and the development of a model of stress within the area influenced by mining. This model should be updated regularly as mining progresses and verified by more measurement.

Stress and with it rock properties have obvious implications for all underground structures. This extends from shaft and drive support to being sure that what should collapse does. A failure to take this approach may lead to block caves that do not cave or do so in unpredicted directions.

Several examples are presented from both coal and metalliferous mining, along with civil engineering tunnelling of real stress distributions and the effects that they have had.

Introduction

An understanding of the three-dimensional state of stress within the earth's crust (in situ stress) is fundamental in the engineering disciplines of mining, petroleum and civil engineering.

The concept of vertical stress as being equal to the weight of the overburden is accurate when the average vertical stress is considered. It can vary from place to place with local effects. In contrast, the magnitude of the horizontal in situ stress field generally cannot be predicted without measurements. While vertical in situ stress is fundamentally related to gravity, horizontal in situ stress is primarily tectonic in origin; that is, it relates to the earth's crust and the large-scale processes which take place within it.

The Earth's environmental segments include, in descending order, the atmosphere, hydrosphere, lithosphere, and asthenosphere. The lithosphere is the outermost shell of the earth. It occurs under all the earth's surface, be it continents or oceans. It is made up of a rocky, brittle crust and the top part of the mantle. The earth's crust is usually about 40 km thick under flat continents, but it ranges from 5 km under the oceans to 100 km under mountainous areas of continents. Below the lithosphere is the asthenosphere, a highly viscous, mechanically weak and ductile region in the upper mantle of the earth. A section through the lithosphere from Meschede (2015) is presented in Figure 1.

The lithosphere is broken up into in excess of 50 identified tectonic plates, the largest being the African, Antarctic, Australian, Eurasian, Indian, North American, South American and Pacific plates. These tectonic plates drift slowly on the surface of the asthenosphere, repeatedly clustering together, and then separating again. The plates that exist are shown (NASA, 2002) in Figure 2. Plate motion is driven by the convection of fluid magma at the interface between the lithosphere and the asthenosphere. Magma is the fully or partially molten rock mass of the earth's interior and is the source of all igneous rocks. As the tectonic plates forming the earth's surface move and interact with each other, tectonic processes such as earthquakes, volcanoes, mountain-building and seafloor spreading take place.

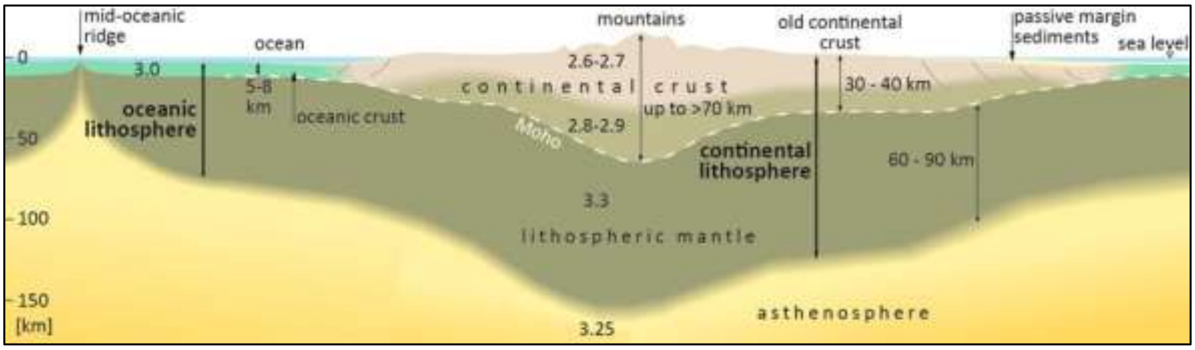

Figure 1. Variations in thickness of continental and oceanic lithosphere. Numbers refer to mean density (gm/cm^3). Moho refers to Mohorovičić discontinuity (Meschede, 2015)

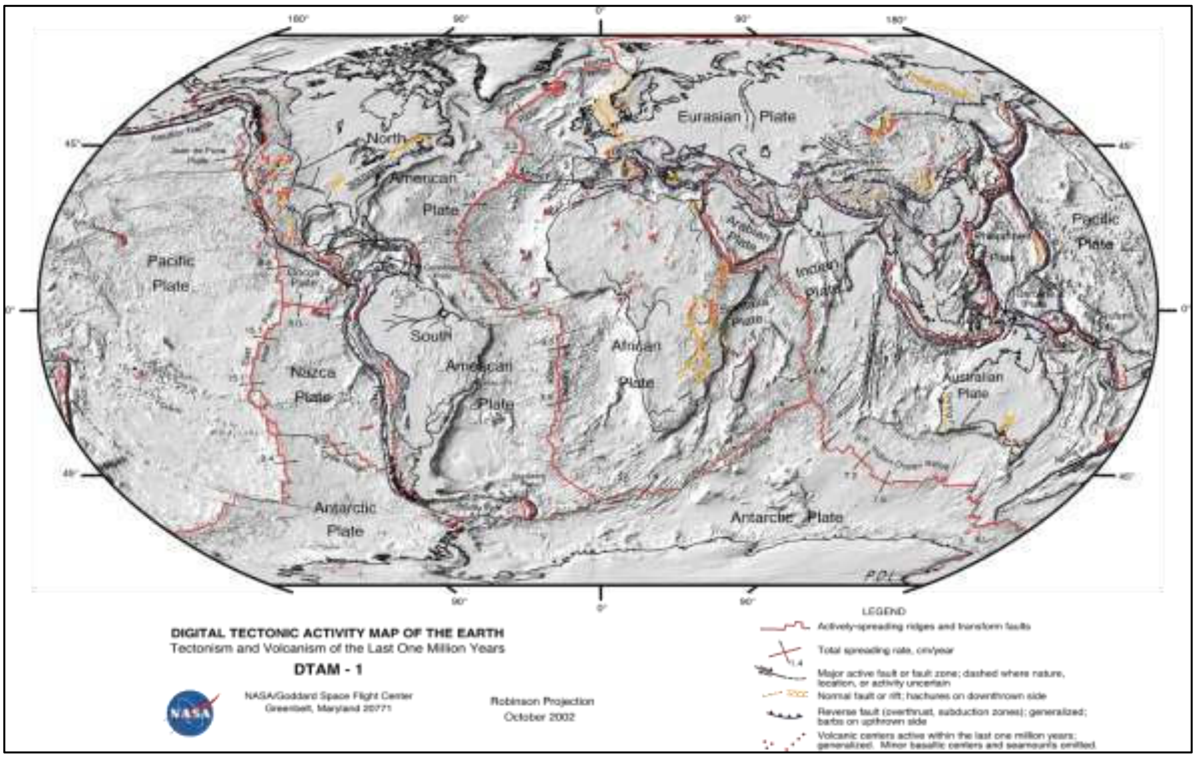

Figure 2. Digital tectonic activity map of the earth (NASA/Goddard Space Flight Center, 2002)

The rocks of the earth’s lithosphere are solid, rigid and brittle. They are also highly variable, including rocks of igneous, sedimentary and metamorphic origin.

Along with gravity, the stresses associated with tectonic activity control the average vertical and horizontal stress. However, there are many local departures from these average values. These are caused by the processes of diagenesis, faulting, folding and cooling. How these processes interact with rock of varying mechanical properties frequently leads to complex stress distributions. In simplified form, these are generally adequately split into vertical stress, major horizontal stress and minor horizontal stress. In some, but not most cases, there is significant departure from this definition based around a vertical principal stress axis.

The variation in stress distribution is dependent on both lithological and structural geological complexity. The more complex this is, the more variation in stress magnitude and distribution. There is no typical stress distribution. To determine stress, it first needs to be measured and interpreted in terms of the geology to provide a model for stresses through an area of interest.

Stresses and Mining

Mining encompasses a whole range of techniques to get rock out of the ground. All of these rely on controlling deformation of the ground and sometimes that of the surface above mining. In some cases, deformation must be minimised. Typical examples of this are the permanent shafts, drives or roadways in underground mines. It may also include the movement around stopes and that of open pit walls. In the latter case, the deformation needs to be minimised so that personnel safety and access to the pit is maintained.

In other cases, mining requires major deformation as part of the mining process. Examples of this are block and sub-level caving underground mining operations. In these, if the rock does not break and collapse though draw points then the mining system does not work. Another example that requires major deformation is in longwall mining for coal. Here the strata above the extracted coal must break up and form a goaf in a controlled fashion. Failure to do so leads to severe loads on the longwall powered supports, face collapse and the possibility of air blasts through sudden falls.

The breakage of rock is a function of the strength and its associated stress field. The latter is a function of the rock lithology modified by the presence of joints, or faults. Determining how rock will behave requires knowledge of the stress within the rock mass at various stages of mining and the strength of the rock mass.

Mine Drives, Roadways and Shafts

All of these are subject to the action of stress. If there is too little horizontal stress then there may be inadequate friction mobilised to support the rock surrounding the opening. If there is too much stress then the rock mass will break up. How it breaks up will be dependent on the rock properties and the stress magnitudes and directions. As with all underground openings, anisotropy within the rock and rock jointing will have a large influence on the nature of failure. The level of rock stress that exists will, along with the rock properties, determine the nature of rock support that will be needed maintain these openings. The question as to whether mine openings will require point anchored or fully grouted bolts, cable bolts or some frictional grip bolting system needs to be answered. Rock support design is dependent on the interaction of the support behaviour, stress and material properties of the rock.

Caving Techniques

Block and sub-level caving require the rock to break up and fall through draw points. If the rock mass is weak then gravitational forces may cause the rock to break up and fall. The design of such caving systems has evolved from concepts initially proposed by Laubscher (1994). When higher strength rock masses are encountered which will not readily collapse under gravitational force, there needs to be some basis for determining what will happen. In these cases, the rock stress may cause the rock to be supported by the mobilisation of friction by stress. Alternatively, the stress may lead to the breakup of the rock at the top of the cave. In cases where this will not happen the option of pre-conditioning using hydrofracture may be considered. The success of hydrofracture is totally dependent on the stress distribution within the area that requires treatment. The direction in which a hydrofracture propagates is controlled by the rock stress and jointing within the rock mass that alters the rock’s tensile strength. Knowing what to do depends on knowledge of the rock stress and strength.

Stoping

The stresses within a rock mass are disrupted and re-distributed by ore removal in the various types of stoping. The removal of rock means that the void created no longer carries stress. The stress and area product is a force that must be carried by the surrounding ground. The re-distribution of this force will change the stresses in the remaining rock mass. In some cases, the stress may be carried without exceeding the rock strength of the rock that is left. Alternatively, it may lead to failure. Depending on the rock properties and the stress redistribution, this failure may be gradual or it may occur suddenly and be associated with seismic activity. Where large areas of stressed rock have been extracted, the regional stability of the area may be adversely affected. A prime example of this is recent major failure that has occurred in the Kiruna iron ore mine in Sweden (LKAB, 2020). This mine uses the sub-level caving mining method. Here, a sudden sequence of failures have induced major seismic activity which constrained ore production for several months.

Another recent example of severe damage to mine infrastructure, including the loss of a main vertical shaft, occurred due to block caving at the Jingerquan nickel mine in China (Ding et. al. 2016). This has been attributed to a very high anisotropic horizontal stress environment. Horizontal displacements up to 0.47 m were recorded. The use of stope fill can reduce the effects of this but fill material is generally not stiff enough to absorb significant stress. The availability of this technique is also dependent on having suitable fill material available to put back into the stopes.

Once again, knowledge of the stress distribution within the ground is, along with knowledge of rock properties, key to the design and management of stope mining.

Longwall Mining

Despite the fact that longwall mining induces vertical collapse, it is highly influenced by the action of horizontal stress. As with all other mining, the roadways require support to keep them up during mine and longwall panel development. Once mining takes place, the stress situation changes dramatically. The support offered by the coal seam is removed and, depending on the level of stress and the rock properties, a goaf may readily form due to the development of tensile or shear stress in the roof of the seam. In more massive roof conditions, these may not lead to goaf formation readily. Under such conditions, the roof may hold up and then fall with a resulting air blast. It may also fall in large blocks that impose very high loadings on the powered hydraulic supports and the face.

The way in which the goaf breaks up is determined by the stresses within the rock mass and the rock properties. In a sub critical situation, the goaf does not propagate to surface, rather leaving an arch of rock above it. Whether this rock then fails due to horizontal stress re-distribution needs to be determined. In supercritical cases, the goaf may form by multiple shear failures which dislocate contact between stratigraphic layers. In some cases, this occurs through to surface while in others it only occurs in the layers immediately above the extracted seam. Above this, the block ends do not dislocate by shear but remain in contact with the result that stress is transmitted through the rock mass above the goaf. This was shown to be the case by Gray, Wood and Shelukhina (2013) for the case of rocks above Grasstree mine in the Bowen Basin of Queensland, Australia.

Where the stress is disrupted by the formation of the goaf, very substantial lateral movements may take place. These leads to shear between bedding planes into the goaf. Hebblewhite (2001) reports the case where, due to longwall mining, lateral surface movements of 100 mm took place moving twin large concrete six-span, box girder bridges with piers up to 55 m in height uniformly laterally. The bridge itself was undamaged.

Payne (2019) reports the movement of roof strata in excess of 1.0 m into an opencut highwall following longwall mining at Broadmeadow mine, Queensland, Australia. One of the effects of such movement between the roof and floor rocks is that the tailgate pillars are subject to significant shear (Tarrant, 2005). Ross, Yu and Nyikos (2006) report the case where the mining of a longwall panel was accompanied by the shearing of a 10.4 m diameter concrete lined shaft by 19 mm at the West Elk mine in Colorado, USA. This mine was in a highly anisotropic horizontal stress environment (Agapito, Gilbride and Kootz, 2005).

Determining such effects prior to the event requires a knowledge of stress and material properties.

Real Stress Distributions

In 1978, Brown and Hoek published a plot of known stress distributions versus depth in the form of the ratio of the average horizontal stress versus the vertical stress. This is shown in Figure 3. The general trend is for lower ratios at depth compared to near surface where the stress ratio is shown to a value of 3.5.

While this plot is outdated, it is useful in showing a trend. However, due to variability it does not provide any basis for design. The stress in any rock may be considered to be limited to the shear, or less frequently the tensile strength of the rock, which may contain geological faults. Under circumstances where the vertical stress is a minimum, the horizontal stress is limited by movement that would lead to, or has led to, the development of a reverse fault. In the presence of a reverse fault without any cohesion, the major horizontal stress under active tectonic movement could lie between 4.6 times the vertical stress if the angle of friction is 40° on a fresh break and could reduce to 2.0 times if the angle of friction was 20° as in an active polished fault surface. The same ratios may apply to slip strike faults where one horizontal stress is the major stress while the other is the minor.

The complications with using any known faults to determine the stresses is the lack of an understanding of the properties of the fault surface. These may have variable friction angles and may develop cohesion during periods of inactivity. Cohesion will change the possible major to minor stress ratios.

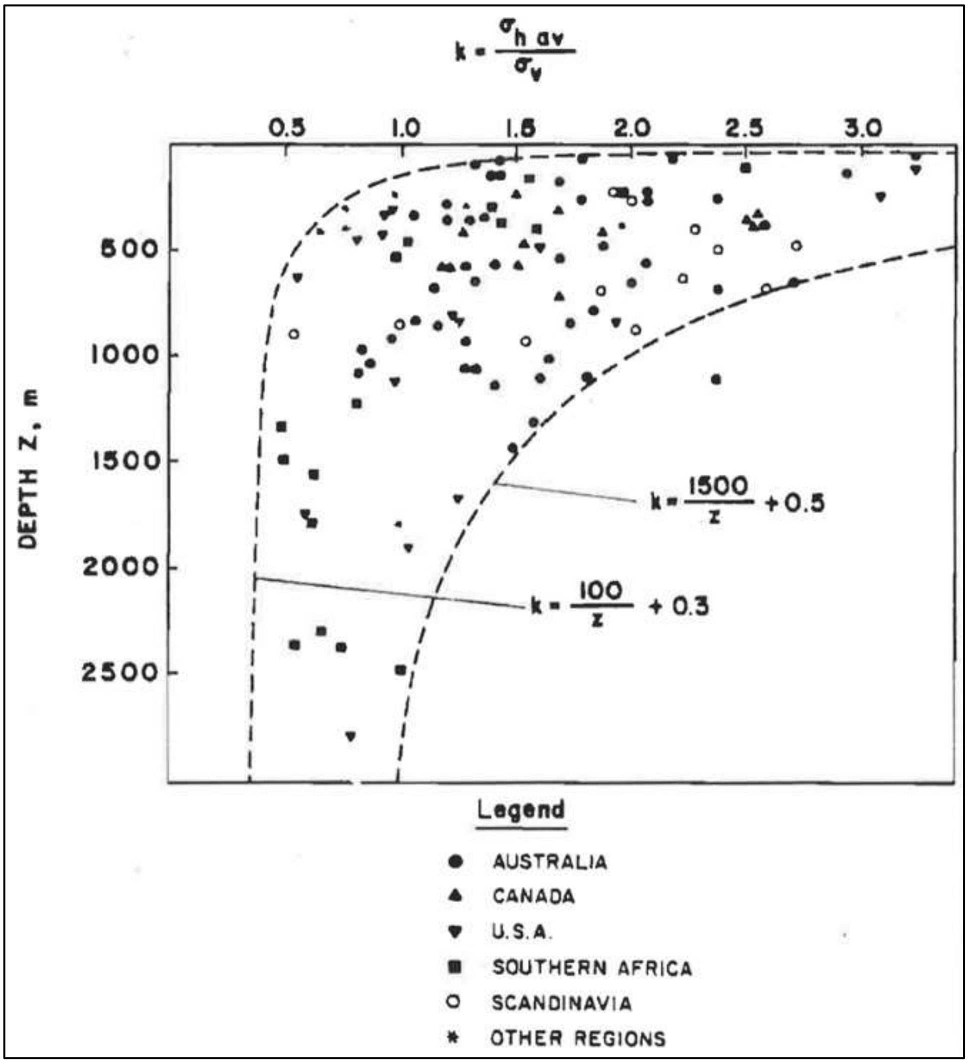

Figure 3. Variation on ratio of average horizontal to vertical stress ratio with depth (Brown and Hoek, 1978).

The existence of a fault does not mean that it is currently stressed to a state where it is about to slip. There are many cases where the stresses that have led to the faulting have totally changed. This may be because of changing tectonic movement, erosion or the actual change in stress on the fault associated with its last movement.

An extremely good example of this is the 2011 Tohuku earthquake which led to the tsunami that caused extensive damage to eastern areas of Japan including to the Fukushima nuclear reactor. Here, a reverse fault has been moving and slipping for a very long period of time with associated tsunamis. In this, the stress build up due to subduction adjacent to Japan leads to an earthquake with a rising sea floor that drives the tsunami. The horizontal stress is dissipated by the movement during the earthquake and the direction of major stress turns at right angles to what existed prior to the event, possibly even causing localised normal faulting. Over a period of about 300 years, the stress builds up again only to be followed by another major earthquake. Thus, we have a period of vastly changing stress magnitude and complete directional change.

Gray, Wood and Shelukhina (2013) have found a similar situation to the south of Tahmoor coal mine in the Sydney Basin, New South Wales, Australia. Here, some 100 overcore stress measurements were undertaken in the roof and floor of the Bulli seam. In addition, many kilometres of acoustic televiewer images were examined for borehole breakout. The resulting roof and floor tectonic strain distributions are shown in Figure 4. The reason for doing this work was due to the extreme strata control problems encountered in the mine.

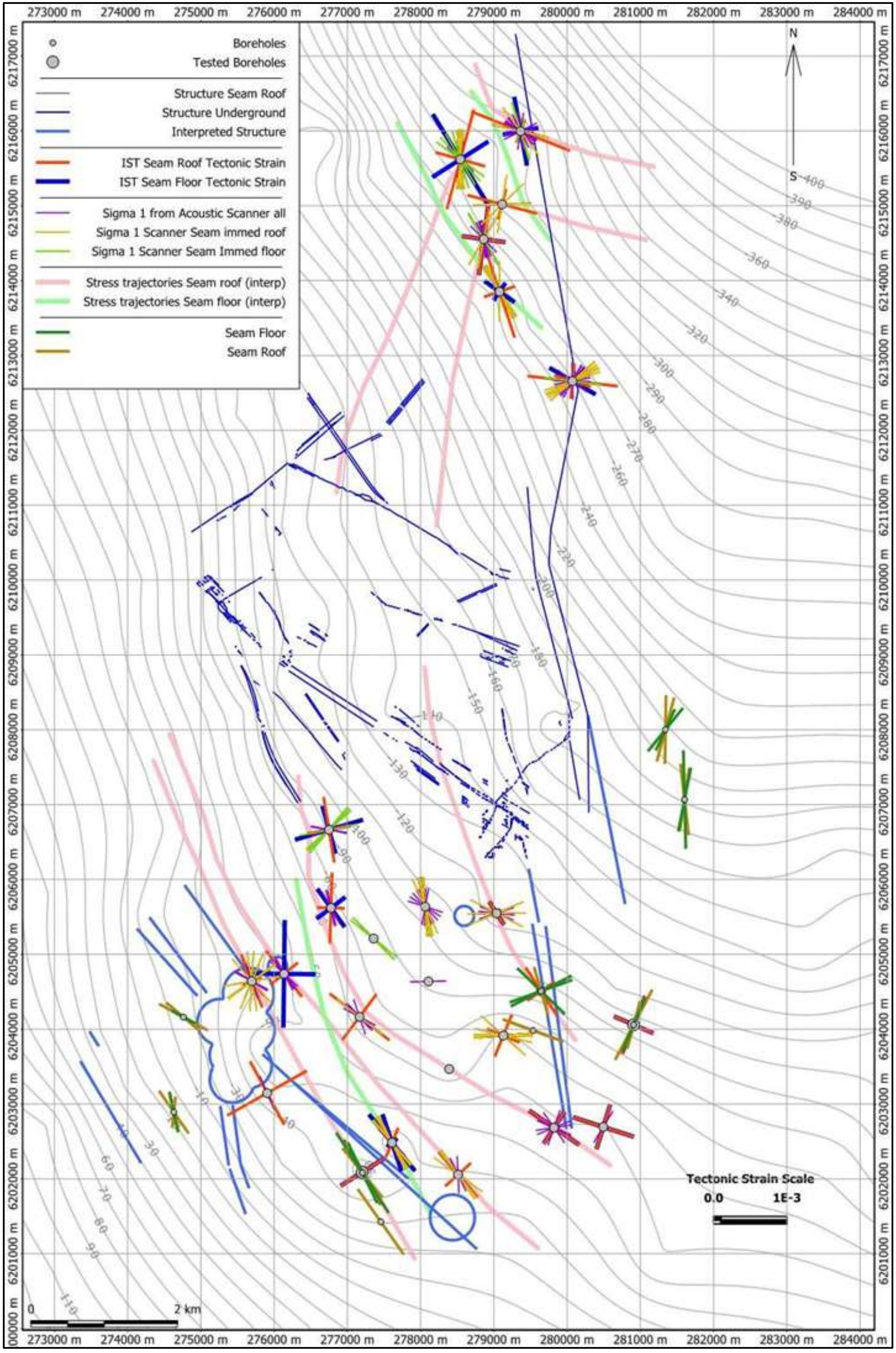

Figure 4. Stress information over the Southern NSW mine showing the results of IST overcores and borehole breakout superimposed on known structural information.

In Figure 4, the line lengths of these rosettes are uniform as the magnitude of the stress is not known. The Sigra IST stress measurement information is plotted on the basis of:

- average tectonic strain above and below the Bulli seam, or
- where no logical average can be arrived at, the individual values of tectonic strain are plotted.

The length of the longest side of the cross is:

- in proportion to the major tectonic strain, and
- in the same direction as the major stress/tectonic strain.

The shorter length represents the minor tectonic strain.

In the Northern mining area, there are quite dramatic changes of tectonic strain within the strata.
In the eastern side, the major tectonic strain above the Bulli seam is high and in an essentially E-W direction. Slightly to the west, the direction of major tectonic strain turns to the North and even NNE. The tectonic strain below the Bulli seam is in the north-west quadrant throughout the Northern exploration holes. Its magnitude is generally lower to the east and becomes greater and more northerly to the North and West. A substantial thrust structure is expected in this area that has led to a stress transfer from the above the Bulli seam in the east to below the seam in the west. In the South area, the tectonic strains above and below the Bulli seam appear to be of different magnitude and orientation. This area is close to a fault system associated with compressional buckling. To the east of this fault system, the tectonic strains would appear to be somewhat less indicating some level of stress relief above the Bulli seam.
Fewer stress measurements have been made below the seam. In the north and east of the South area, the tectonic strains seem to be of reduced magnitude compared to those in the east.
The direction of the principal tectonic strain sweeps around from N-W in the south to NNW to the north. It is suspected that this change in orientation that appears to continue right up into the North area where the direction becomes NNE follows that of the Nepean Monocline and Fault.
In the North area, the major principal tectonic strains abruptly change direction.
The reason for conducting the detailed study of stress in the new area to the south of the existing Tahmoor mine was the extreme roof control problems experienced in the older parts of the mine.
The reader may have noted that reference here is made to tectonic strain. Tectonic strain is defined here as the strain required to generate the existing stress within a rock mass. To arrive at the tectonic strain, the effects of self weight horizontal strain in a zero lateral strain environment are subtracted from the measured stress and then the tectonic strains that would be required to create the remaining stress are calculated. The use of tectonic strains has the advantage that it evens out stress variability brought about by differing stiffness rocks. Tectonic strain is explained mathematically in the Appendix.
In many cases, particularly those involving sedimentary strata, the tectonic strain approach to understanding stress has been found to be particularly useful, showing consistency where stresses varied widely. Exceptions are where faulting or disconformities exist.

In the case of the Moura area in Central Queensland, Australia some 68 overcore stress measurements spread over 10 boreholes were made at depths up to 900 m as part of an exploration programme for a multi-seam coal mine. Here the stresses were found to vary widely but when examined in terms of tectonic strain a remarkably level of uniformity was found. This can be seen in Figure 5.

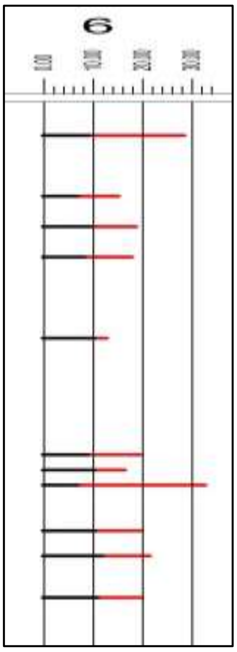

Figure 5. Major stress (MPa x 10) in red and major tectonic strain in microstrain in black from Moura over 400 m to 900 m depth

Table 1 shows an example where one overcore stress measurement was made directly following another in a coal bearing sedimentary sequence in the Surat Basin of Southern Queensland, Australia.

Depth	Young's Modulus (MPa)	Poisson's Ratio	Principal Stresses (MPa)		Tectonic Strains	
			Major	Minor	Major	Minor
507.49	1,315	0.09	1.13	0.79	$0.314\text{x}10^{-3}$	$0.0366\text{x}10^{-3}$
508.89	31,646	0.17	11.72	5.01	$0.302\text{x}10^{-3}$	$0.0532\text{x}10^{-3}$

Table 1. Stresses and tectonic strains in Juandah Coal Measures in the Surat Basin, Queensland, Australia (Gray et al, 2013)

Here, the upper test was conducted in a weak medium grained sandstone with a very low modulus, while the lower test was conducted 1.4 m below in a very strong medium grained sandstone with a modulus that was 24 times greater. Despite this difference, calculated major tectonic strains were almost identical, while the minor tectonic strains were similar. This is a striking example of the evenness of tectonic strain across sediments of greatly varying stiffness.

Within the context of the sedimentary strata found along the eastern side of Australia, it has been found to be useful to describe the various tectonic strains according to Table 2.

Tectonic strain description	Range
Very low	$< 0.1\text{x}10^{-3}$
Low	$0.1\text{x}10^{-3} – 0.3\text{x}10^{-3}$
Moderate	$0.3\text{x}10^{-3} – 0.6\text{x}10^{-3}$
High	$0.6\text{x}10^{-3} – 1.0\text{x}10^{-3}$
Very high	$> 1.0\text{x}10^{-3}$

Table 2. *Categories of tectonic strains in Eastern Australia (Gray et al, 2013)*

The effects of differing stiffness rocks on stress is not confined to sedimentary strata. The New Afton gold-silver-copper mine is an underground block cave mine located within the footprint of the worked out Afton open cut mine, British Columbia, Canada. New Afton Mine is a gold and copper deposit hosted by intermediate to mafic volcanic rocks of the Triassic Nicola Formation. Regional-scale fault zones serve as the principal controls for the emplacement of batholithic rocks and related porphyry-style mineralization (New Gold, Inc., 2019). Haveman et al (2020) report a test hole, UAC-07, was collared approximately 706 m below ground surface, and drilled to a depth of 451 m, being 1,157 m below surface, with 17 stress measurements evenly distributed to the total depth. Seventeen stress measurements were made using the Sigra IST overcore process. The results of these are shown in Figure 6. As can be seen, the stress is highly variable, changing with the rock's Young's modulus.

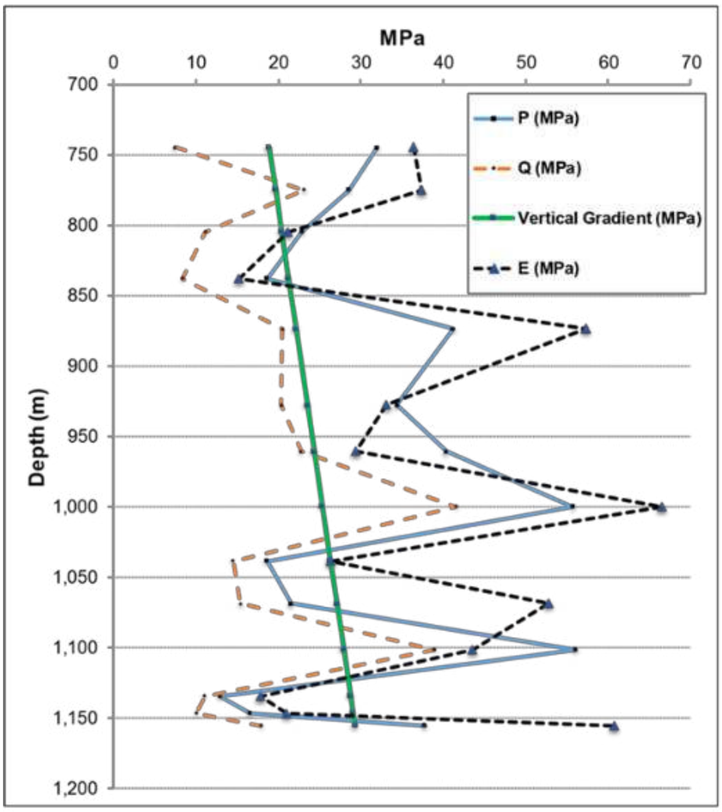

Figure 6. Major (P) and minor stresses (Q) with Young's modulus of the rock (E) from New Afton mine exploration (Haveman et al, 2020)

Some site investigation for a tunnelling project was undertaken in mountainous areas of south eastern Australia. Here multiple stress measurements were made in several boreholes up to 1,050 m depth. These are shown in Figure 7.

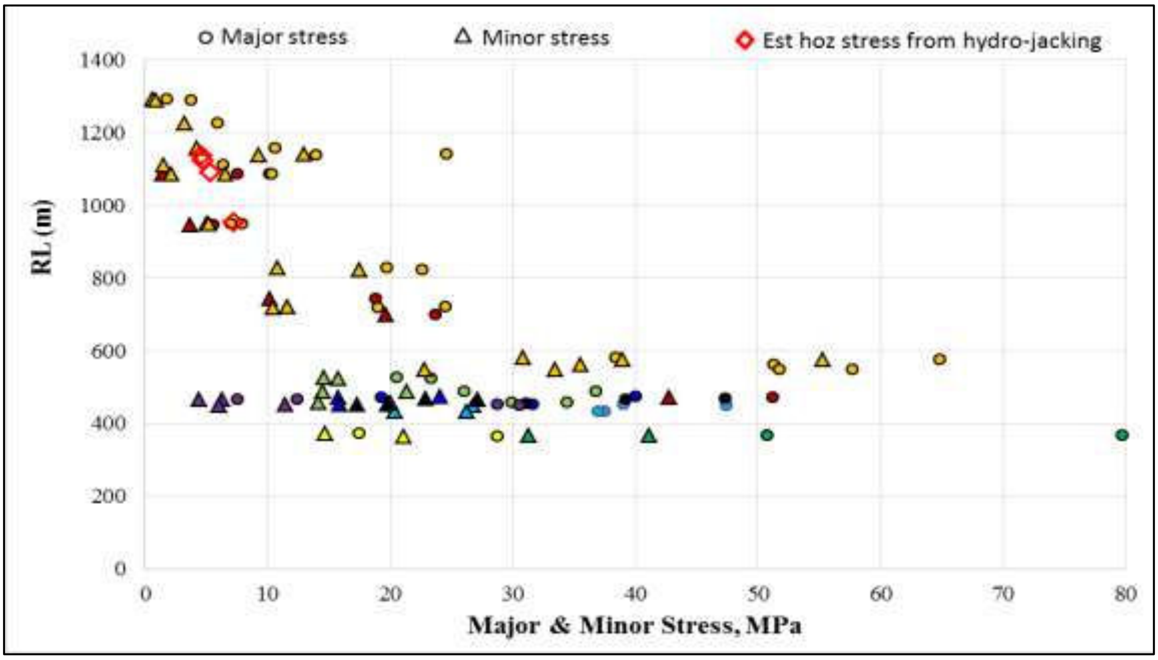

Figure 7. Stresses from project in SE Australia

As can be seen in Figure 7, the stresses increase with depth to about the 600 m level when the range changes suddenly with depth to become highly variable. This variation is the result of several large faults that have caused stress concentration and relief. These were confirmed by examining the acoustic televiewer images of the metasediments that showed sudden directional change in bedding. What is not shown is the widely varying directional change associated with the stresses below 600 m. The magnitudes of the higher stresses encountered are cause for concern in underground construction.

Rock Stress Measurement

The investment in the time and cost of rock stress measurement is frequently significant. Care needs to be taken to determine what is required and to maximise the amount of information that can acquired. Rock stress information may be needed to determine elastic deformation around an opening, the interaction between a plastic and elastic zone, or to be sure that major failure will take place as in a longwall goaf, block cave, or sub-level cave.

Overcoring

Overcoring is a technique that involves relieving the stress on surface, or at the bottom of a borehole, and measuring deformation or strain before and after stress relief. The deformation is related to stress using measurements of the rock's mechanical properties and the geometry of the test. The measurement of these rock properties is therefore just as important in arriving at stress values as the overcore operation itself.

In its most common form, overcoring takes place at the bottom of a core hole. A pilot hole is drilled at the end of the core hole and a cell is inserted into it. This may be a device that measures the diameter of the pilot hole or one that measures the strain on the pilot hole wall. In modern systems, this information is stored on board the cell rather than being transmitted out via a cable. This means that overcoring can be undertaken at significant distance from the hole collar. The cell may measure the diameter of the pilot hole or it may measure the surface strain on the pilot hole wall.

All overcore tests rely on the rock behaving in an elastic manner. This does not require the rock to be linearly elastic or isotropic, though the more complex the rock mechanical behaviour the more complex the overcore analysis. If the pilot hole wall breaks then the test process becomes invalid. The types of analysis used for overcoring have the form shown in Table 3, depending on the rock properties.

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

Table 3. Overcore analysis procedure

Hydrofracture

Hydrofracture is in concept simple, though less so to interpret. It usually involves pumping fluid into a test zone, normally between two packers within a borehole in un-fractured rock. The pressure rises until the tensile stress exceeds the rock strength at the borehole wall whereupon a fracture opens and propagates. In un-fractured homogeneous rock, the fracture can only start in the axis of the hole. If the borehole axis is not in the plane of the minimum principal stress the fracture will rotate to be perpendicular to it. When the fracture has extended, pumping is stopped and the fracture is allowed to close through fluid leak off into the rock mass. After closure, the pressure will still decline, and this decline may be used to determine the permeability of the rock mass. The straddled zone in the hole may then be pressurised again to re-open the fracture.

Hydrojacking

Hydrojacking is similar to hydrofracture except that a deliberate choice is made to open pre-existing joints within the rock mass. If a single joint set exists then these may be straddled by packers and opened in a similar manner to that used for hydrofracture. The fracture closure pressure deduced from the period after pumping ceases is an indication of the stress across the fracture plane.

Borehole Breakout

The process of drilling a hole creates a free face within the rock mass only confined by fluid pressure. It also causes a tangential stress concentration on the borehole wall. If the tangential stress at the borehole wall exceeds the tangential unconfined rock strength then the rock will fail in compression. In an even stress field, this may cause total failure around the hole wall. More usually, the stress field around the borehole is not even, and if the stress is high enough, it will cause a localised line of spalling along the length of the hole wall. This spalling is readily detected by the use of an acoustic televiewer. The width of the spall zone may be detected with some accuracy in fine to medium grained sedimentary material and less so in coarser sedimentary or igneous or metamorphic materials, which tend to break in a more jagged manner.

Borehole breakout provides information on the direction of the major stress and the ratio of the stress at the borehole wall to the tangential rock strength. If the hole does not show breakout, it provides no information.

Core Ovality

When core drilling takes place, the core is relieved of lateral stress and deforms. The difference between the major and minor diameters of the core may be used to provide information on the stress difference transverse to the core. This measurement works wherever intact core can be obtained. It requires a drill bit that does not re-grind the core to a uniform diameter and a precision measuring system.

Combining Stress Measurements

The problem with individual stress measurements is that they mean little in isolation. What is needed is a picture of stress distribution through the rock mass to be mined. This is best achieved by multiple measurements. However, there is a practical and budgetary limit to just how many individual measurements may be made. What is needed is some form of measurement that permits interpolation. In the case of a rock which does not show breakout on drilling the overcoring technique combined with core ovality measurement between overcores is the most promising. Indeed, core ovality changes may be used as an indicator of when to undertake another overcore.

Where exploratory boreholes do suffer from breakout, this serves as an indication of the ratio of the stress to rock strength ratio perpendicular to the hole axis. It also gives a measurement of the direction of the major principal stress. If hydrofracture is undertaken in the hole it will yield information on the minimum stress. If the width of breakout is measured and the rock strength perpendicular to the hole is known, this can be used with the hydrofracture results to approximately work out the magnitude of the major stress. The complication here is knowing the strength of the rock perpendicular to the borehole. Getting this requires taking sub cores orthogonal to the core and testing them for uniaxial compressive strength. This is a fiddly process which may not succeed, particularly in weak rock. Alternatively, and more commonly, the strength of the rock is approximated from sonic velocities arrived at by a geophysical logging. This has serious shortcomings too, as correlations of sonic wave velocity in the direction of the borehole may bear little relation to the uniaxial compressive strength of the rock transverse to the hole. Suffice to say that if a borehole has major breakout then it is an indicator of failure to come.

Conclusions

Rock stress distributions are complex. Different stiffness rocks will produce different stresses when strained by tectonic action, temperature change, diagenesis, metamorphism, faulting, folding or any of the multiple other changes that the rock mass is subject to. Because of all these effects, the distribution of rock stress becomes more variable with complex geology.

These stresses matter as they affect how rocks will behave on mining. It is important to know whether caving will happen or will need preconditioning to make it take place. If hydrofracture is being considered as the preconditioning option, then the stresses need to be known as hydrofracture will only propagate perpendicularly to the direction of minimum stress, unless it is captured by existing joints. It is just as important to know whether major permanent structures such as shafts are going to be adversely affected by the effects of rock movement due to stress changes brought about by mining. Unfortunately, the days when geotechnical engineers thought of rock stress in terms of a unique far field stress for a site have not yet quite gone. Numerical modellers tend to like to use the concept of a unique far field stress because it simplifies their models. This approach is not appropriate. Even if the far field stress is measured, it may bear little relation to the stresses within the mining area. It is necessary to measure these too and to be able to interpolate between measurements. The interpolation within a borehole may come from such techniques as borehole breakout or core ovality measurement. However, even with these most mines should develop a model of stress as it exists. In the most simple form, it requires gravitational loading and the application of tectonic strains. Faults and any abandoned workings will invariably complicate such a model. However, failing to take this approach will lead to unseen complications in later mining.

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APPENDIX – Stress and tectonic strain

It has been found useful in stress analysis to examine the stress situation at a site in terms of tectonic strain. This is explained below.

The average total vertical stress is over a wide area a summation of the product of density of all the superincumbent stratigraphic units with each stratigraphic unit's thickness multiplied by gravity as shown in equation 1.

$$\sigma_v = g \sum_z^0 \rho_i \Delta x_i \tag{1}$$

Where σ_v is the total vertical stress
g is the gravitational acceleration
ρ_i is the density of the *i*th stratigraphic unit
Δx_i is the thickness of the *i*th stratigraphic unit in the vertical direction
z is the depth from surface

The effective vertical stress is given in equation 2.

$$\sigma'_v = \sigma_v - \alpha_v p \tag{2}$$

Where σ'_v is the vertical effective stress
α_v is the poroelastic coefficient influencing the vertical stress
p is the fluid pressure

The total horizontal stress due to self weight in a laterally confined situation with zero lateral strain is given in equation 3 and the effective horizontal stress due to self weight in a similar case is given in equation 4.

$$\sigma_{hsw} = \sigma'_v \left(\frac{v}{1-v}\right) + \alpha_h p \tag{3}$$

$$\sigma'_{hsw} = \sigma'_v \left(\frac{v}{1-v}\right) \tag{4}$$

Where σ_{hsw} is the total horizontal stress due to self weight
σ'_{hsw} is the effective horizontal stress due to self weight
v is Poisson's Ratio for strain in the horizontal plane brought about by stress in the vertical direction
α_h is Biot's coefficient influencing stress in the horizontal plane
p is the fluid pressure

The relationships between the mean effective stress (σ'_m), the deviatoric stress (σ_D) and the major (σ'_1) and minor (σ'_2) principal effective stresses are given in equations 5 and 6.

$$\sigma'_1 = \sigma'_m + \sigma_D \tag{5}$$

$$\sigma'_2 = \sigma'_m - \sigma_D \tag{6}$$

Where σ'_1 is the major principal effective stress in a horizontal plane
σ'_2 is the major principal effective stress in a horizontal plane
σ'_m is the mean effective stress
σ_D is the deviatoric stress (which is not affected by fluid pressure)

If we now use a simplified elastic model which does not account for creep behaviour then we can subtract the effective horizontal stress due to self weight from the principal effective stresses to arrive at what we will term here to be tectonics stresses. These are shown in equations 7 and 8.

$$\sigma'_{t1} = \sigma'_{1} - \sigma'_{hsw} \qquad (7)$$

$$\sigma'_{t2} = \sigma'_{2} - \sigma'_{hsw} \qquad (8)$$

Where σ'_{t1} is the major tectonic horizontal stress
σ'_{t2} is the minor tectonic horizontal stress

It is desirable regionally to consider the strain caused by tectonic movements rather than focusing on stress fields. Stresses vary with the modulus of the rock. The stiffer the rock, the more stress it carries for a given strain. Using the values of tectonic stress calculated from equations 7 and 8 the components of tectonic strain in a plane stress environment (free surface) can be calculated as in equations 9 and 10.

$$\varepsilon_{t1} = \frac{\sigma'_{t1} - v\sigma'_{t2}}{E} \qquad (9)$$

$$\varepsilon_{t2} = \frac{\sigma'_{t2} - v\sigma'_{t1}}{E} \qquad (10)$$

Where ε_{t1} is the major tectonic strain
ε_{t2} is the minor tectonic strain

The tectonic strains may be thought of as the horizontal strains that are required to change the horizontal stresses in the ground from those which would exist due to gravity alone in a zero lateral strain environment. They need not be due to gross tectonic movement. Rather they may be due to local faulting or folding. Indeed a component of the tectonic stresses may come from soil like behaviour of sediments with normal or over-consolidation of these prior to lithification. Some dimensional change can be expected in such lithification and any further diagenesis of the rock and appear as a component of the tectonic strains. The effects of temperature on inducing strains may also be bundled into the tectonic strains.

Nevertheless in the event that fairly even tectonic strains are found to exist in several measurements in a rock mass we may use these to interpolate stresses between measurements.

To examine the average tectonic strain for a group of stress measurements the procedure is to rotate the principal strains into direct N-S & E-W strain and shear strain components and to find the mean of these. The principal tectonic strains and their direction may be calculated from these three mean strains. If tectonic strains are relatively uniform between adjacent stress measurements they may be used to calculate stresses in rock of varying Young's Modulus and Poisson's Ratio. The process is the reverse of that used to derive the tectonic strain.

The effective stresses due to tectonic strain may be calculated using equations 11 and 12.

$$\sigma'_{t1} = \frac{E}{1-v^2}(\varepsilon_{t1} + v\varepsilon_{t2}) \qquad (11)$$

$$\sigma'_{t2} = \frac{E}{1-v^2}(\varepsilon_{t2} + v\varepsilon_{t1}) \qquad (12)$$

The principal effective stresses may be calculated by adding the effective horizontal stress due to self-weight (from equation 4) to the above values of the major and minor tectonic stresses.