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Real Stress Distributions in Sedimentary Strata

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Abstract

This paper examines the stress fields in two coal mines and in a coal seam gas field in Eastern Australia at depths of up to 600 m. These stresses have been measured using multiple overcore measurements (50 to 100 per site) undertaken from surface at each site and supported by the examination of borehole breakout trends. The paper also comments on the appropriateness of these and other stress measurement techniques.

The stress distributions have been found to range from situations where they can be modelled very well using simple tectonic strain theory to those which are far more complex. Those that can be readily understood are cases where the stresses are produced by a combination of lithostatic effects and constant tectonic strains through the rocks of varying stiffness in the sedimentary sequence.

More complex cases may be found where the tectonic strain theory generally applies but is modified locally by the effects of faults which invariably serve to relieve stress. A highly complex situation is presented in which the initial principal stress distribution was clearly NE-SW in orientation and this was changed through reverse and slip strike faulting so that in most cases the principal stress is now at perpendicular to that that previously existed. There are, however, locations, generally close to faults, where the principal stresses rotate through the sequence.

In addition to the stress measurements that have been made in virgin ground the results of stress measurements have been made over areas where the coal seam has been mined by longwall mining. While the stress field has been changed the level of stress in these rocks has been found to be remarkably consistent.

Key words: Stress, Strain, Coal, Goaf, Gob, Mining, Longwalls

1. Introduction

Once sediments are laid down in a marine or lacustrine situation they are subject to compaction and the stresses within the sediment should theoretically lie between the active and passive states of stress in a soil mass. These limits change with the internal friction angle of the soil mass associated with a reduction in void ratio brought about by overburden load leading to some degree of internal failure. The civil engineering geomechanics groups tend to refer to the ratio of horizontal to vertical stress through a factor *Ko* (Terzaghi and Peck, 1948) which can be related to the internal frictional angle of a soil. Indeed the simplistic assumption used to be made that any soil mass that showed a high *Ko* value had been subject to vertical unloading through erosion. In reality the consolidation is accentuated by the effects of earthquakes which impose enormous shear loads on the unconsolidated mass leading to further compaction and the generation of horizontal stresses that would be greater than would be expected due to overburden loads alone. The sediments eventually undergo a process of diagenesis. The rock mass created has properties that more resemble that of an elastic solid, albeit one in which some of the initial soil like stresses from the period before diagenesis may continue to exist.

The stresses in an elastic solid may be easily determined as being made up of the overburden load and the effects of strains imposed upon this elastic mass. The limitation on stresses within such a mass is that brought about by failure along fault and joint planes. In this paper we re-iterate the concept of tectonic strain (Gray, 2000), which is the strain component required to generate the measured stresses in the rock, and use it to compare the states of loading of sedimentary rocks of varying stiffness.

2. Methods and techniques of stress measurements

There are several methods that can provide information on stress within the strata. The most reliable of these are stress relief systems, particularly by overcoring followed by hydraulic fracturing and breakout interpretation.

The most common method for measuring stress in mining situations is overcoring. Overcoring has been undertaken for many decades (Leeman, 1968). It involves drilling a pilot hole at the end of a borehole, placing some device that measures strains or dimensions in the hole, and then drilling over the top of that hole to relieve the stress and thus cause a dimension change. This dimension change is measured and so is the rock modulus and Poisson's Ratio. By the use of mathematical formulae it is possible to calculate the magnitude and direction of the stresses existing in the rock. For the overcore system to work the rock should remain within its elastic range, and preferably the reasonably linear elastic range.

Hydraulic fracturing as a stress measuring method was first described by Haimson and Fairhurst (1967). This method can be used to determine the major and minimum horizontal stresses from a vertical hole but to do so also requires the rock behaves elastically. If the rock is inelastic or has sustained failure around the borehole, hydraulic fracturing may only be used to determine the minimum horizontal stress. Care must however be taken as the loading stress that a packer applies to the borehole wall can control the fracture initiation pressure.

The orientation of the major horizontal stresses may be deduced from a hole that has suffered breakout failure of the borehole wall. This failure may be found from an orientated acoustic scan of the borehole wall. It is possible to derive the major and minor stresses within the rock mass when hydraulic fracturing is used in combination with information on borehole breakout and there is also information on the compressive strength of the rock where breakout has occurred. The strength measurement of the rock should be gained from core and not a sonic log as the relation between the sonic log and the actual rock strength is generally too tenuous to be used reliably.

The in-situ stress (IST) measurement technique developed by the author (Gray, 2000) is designed to provide the best possible combination of desirable features. In essence the tool is similar to the United States Bureau of Mines borehole deformation gauge (Merrill, 1967) in that it is a biaxial deformation device used to measure the change in diameter of a pilot hole. The advantages of the IST tool are that it is smaller, measures six diameters of the pilot hole and does not use a cable for communication. This means that the use of tool is not restricted by depth. It has been used in measurements to 1 km in depth and could be used to 2 km. The overcore system is primarily set up to be used as part of a Boart Longyear HQ wireline coring system.

The process is outlined in Figure 1. It involves pulling the core, then in place of the inner barrel a stump grinding bit is run and used to remove any upstanding core stump. This is withdrawn and a pilot hole drill is used to create a hole 500 mm long and 25.5 – 26.5 mm in diameter. The pilot hole drill is withdrawn on wireline and the tool lowered into the hole where it locks into place. The rods are pulled back so that the on board orientation tools can detect the location of the tool free from magnetic interference. The core barrel is then pumped into the rods and coring commences.

During the overcoring operation a record of diameter change is obtained and stored electronically. Once coring has been completed the core containing the tool is pulled and the diameter measurements and those taken from the accelerometers and magnetometers are downloaded. The core is tested for Young's modulus and Poisson's Ratio and the results are used with the deformation information to arrive at the biaxial stress field perpendicular to the borehole. Because the orientation of the tool is measured the direction of the principal stresses can be found.

The tool is a biaxial device and if testing is only conducted in a single borehole an assumption must be made as to the stress in the axial direction of the hole. As the tool is normally used in vertical drilling from surface the assumption is usually that the vertical stress is that of overburden weight. Where this has the most limitation is within zones where reverse faulting leads to areas of increased vertical stress and adjacent zones of reduced stress. Because of the biaxial nature of the measurement process it is not possible to deduce any shear components of stress that are not perpendicular to the borehole.

Despite these limitations the ability to perform a stress measurement at 800 m depth in about 3 hours and to be able to examine the overcore trace directly on retrieval of the tool along with the core provides a very significant advantage compared to other systems.

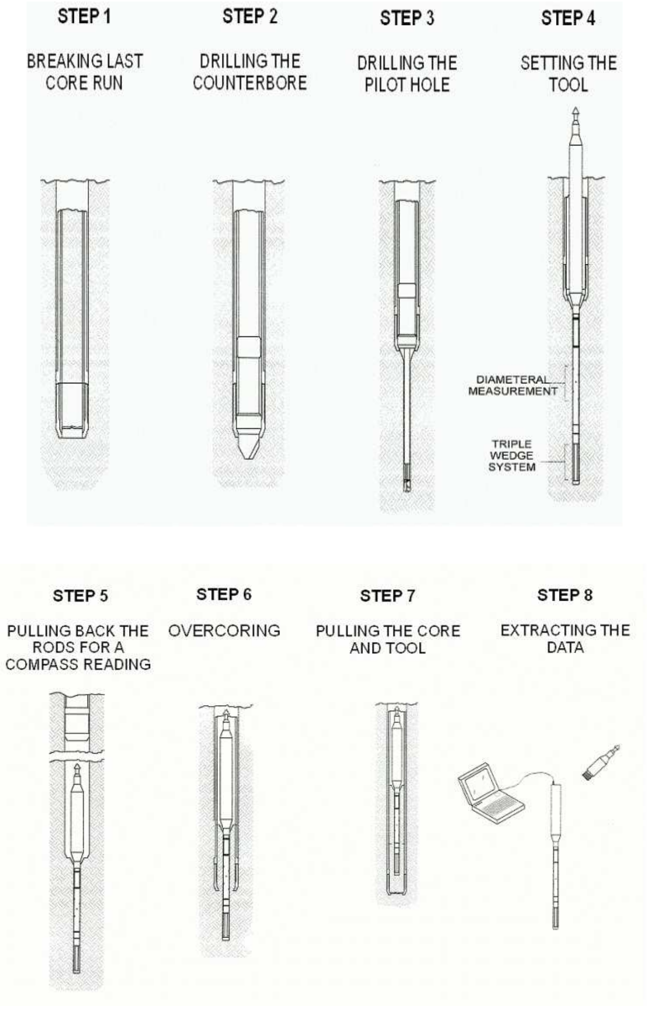

Figure 1. The IST overcoring process.

3. Definition of tectonic strain

The stresses vary through sedimentary sequences and are strongly influenced by local geological structures such as faults and folds. It is found that faults are invariably stress relief features. Stiffer strata tend to carry more stress than that of lower modulus and that through a sequence it is possible to get widely varying horizontal stress magnitudes.

To interpret this, the process of reducing the stresses to tectonic strains is useful. The tectonic strain is the strain which the strata must be subject to so as to generate the stresses that exist within it. The tectonic strain is derived from measuring the stress, subtracting from it the horizontal component of self weight generated stress to arrive at the tectonic stresses. The strains required to generate these are then calculated. The equations for deriving tectonic strain in one direction are presented below. The equation for the orthogonal tectonic strain is similar.

$$\sigma_{h/sw} = \sigma'_{v}\left(\frac{v}{1-v}\right) \tag{1}$$

$$\sigma_{tec/1} = \sigma_1 - \sigma_{h/sw} \tag{2}$$

$$\varepsilon_{tec/1} = \frac{\sigma_{tec/1} - v\,\sigma_{tec/2}}{E} \tag{3}$$

Where E is the Young's Modulus
v is Poisson's ratio
$\sigma_{h/sw}$ is the horizontal stress generated by self weight with zero lateral strain
$\sigma_{tec/1}$ is the stress due to tectonic strains in direction 1
σ'_v is the effective vertical stress due to self weight
$\varepsilon_{tec/1}$ is the tectonic strain in direction 1

While this approach uses simple elastic calculations it is remarkable how frequently the tectonic strains are fairly even while the stresses vary significantly. It is the rule on which to base interpretation while deviations from it must be treated as the exception. A sound value of the tectonic strains gives a basis for the calculation of all the stresses through the sequence. Using the tectonic strain values and the Young's modulus and Poisson's ratio of the other rocks it is possible to calculate the stresses that exist in these (Figure 2).

Exceptions to the rule occur at unconformities and where complex faulting and folding exists. Each of these has to be dealt with on a case by case basis and a large mine lease may require tens of overcore stress measurements and hundreds of borehole breakout analysis. If the latter are combined with hydrofracture it is possible to determine the magnitude in addition to direction of the principal stresses. This information needs to be interpreted in conjunction with all structural information that is available and such as may come from seismic reflection surveys.

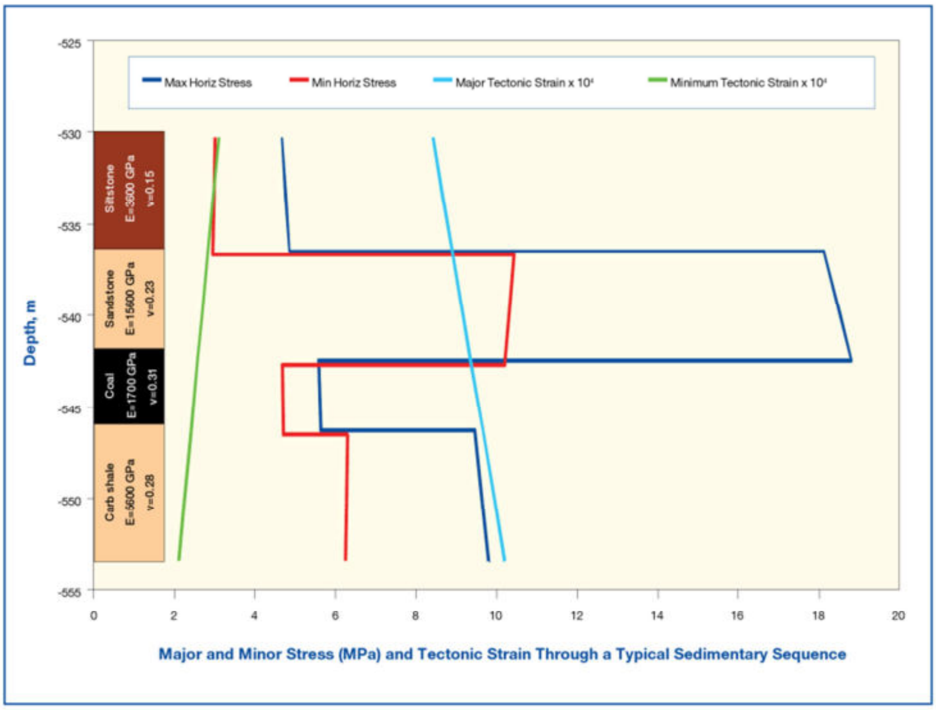

Figure 2.Theoretical example of major and minor stress distribution in strata of gradually changing tectonic strains.

Within the context of the coal measure strata found along the eastern side of Australia it has been found to be useful to describe the various tectonic strains according to Table 1.

Table 1. Description of Tectonic Strains

Tectonic strain description	Range
Very low	$< 0.1x10^{-3}$
Low	$0.1x10^{-3} – 0.3x10^{-3}$
Moderate	$0.3x10^{-3} – 0.6x10^{-3}$
High	$0.6x10^{-3} – 1.0x10^{-3}$
Very high	$> 1.0x10^{-3}$

4. Stresses in Coal Measure Rocks

4.1 Example of Even Tectonic Strain across Boundary of Quite Different Stiffness Strata

Table 2 shows an example where one overcore was made directly following another in a coal bearing sedimentary sequence in a the Surat Basin of Southern Queensland, Australia. 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 metres lower in a very strong medium grained sandstone with a modulus that was 24 times greater. Despite this difference the calculated major tectonic strains were almost identical while the minor tectonic strains were similar.

Table 2. Stresses and tectonic strains in Juandah Coal Measures in the Surat Basin.

Depth	Young's Modulus (MPa)	Poisson's Ratio	Principal Stresses		Tectonic Strains	
			Major	Minor	Major	Minor
507.49	1315	0.09	1.13	0.79	$0.314x10^{-3}$	$0.0366x10^{-3}$
508.89	31646	0.17	11.72	5.01	$0.302x10^{-3}$	$0.0532x10^{-3}$

This is a striking example of the evenness of tectonic strain across sediments of greatly varying stiffness.

4.2 Southern NSW mine

The mine is located approximately 70 kilometres South West of Sydney in the Southern Highlands region in Sydney basin. Approximately 100 stress measurements using the IST technique were conducted to the north and south of the current mine in prospective new mining areas. In addition acoustic scanner logs were examined for indications of borehole breakout.

The geological location is just to the west of the Nepean fault as shown in Figure 3, which shows the structure of the Sydney basin. The associated nearby structures are the Nepean Monocline which curves around from WNW to NNW with the Camden Syncline to the west. The Nepean Fault has an orientation which is virtually N-S in orientation.

Most of the IST measurements in the Northern mining area and South exploration areas have been undertaken in the near roof or floor of the Bulli Seam which is planned to be mined. Reliance was placed on acoustic scans to determine the orientation of the major stress away from this seam. In some places IST overcores were achieved in areas that subsequently suffered breakout after overcoring. In virtually all of these cases the breakout confirmed the direction of principal stress measured by the IST measurements. In addition the levels of horizontal stress indicated that breakout would occur. Indeed in some cases minor levels of breakout did occur within the pilot hole leading to erratic readings on one of the pin sets of the IST tool. Such phenomena are easy to pick from those of an otherwise clean overcore trace and the result from the pin set can then be discarded.

Attempts were made to deduce the stress magnitude from the breakout information taken from the acoustic logs. To do this would have required either a measurement of the minor principal stress by hydrofracture or a reasonably constant ratio between the major and minor stresses as well as a good knowledge of the uniaxial compressive strength of the rock. As no hydrofracture had been undertaken, the ratio of major to minor stress as measured by the IST overcoring varied and its direction frequently rotated, the first two criteria were not met. In addition a reliable relation between the geophysical sonic log and the uniaxial compressive strength could not be established.

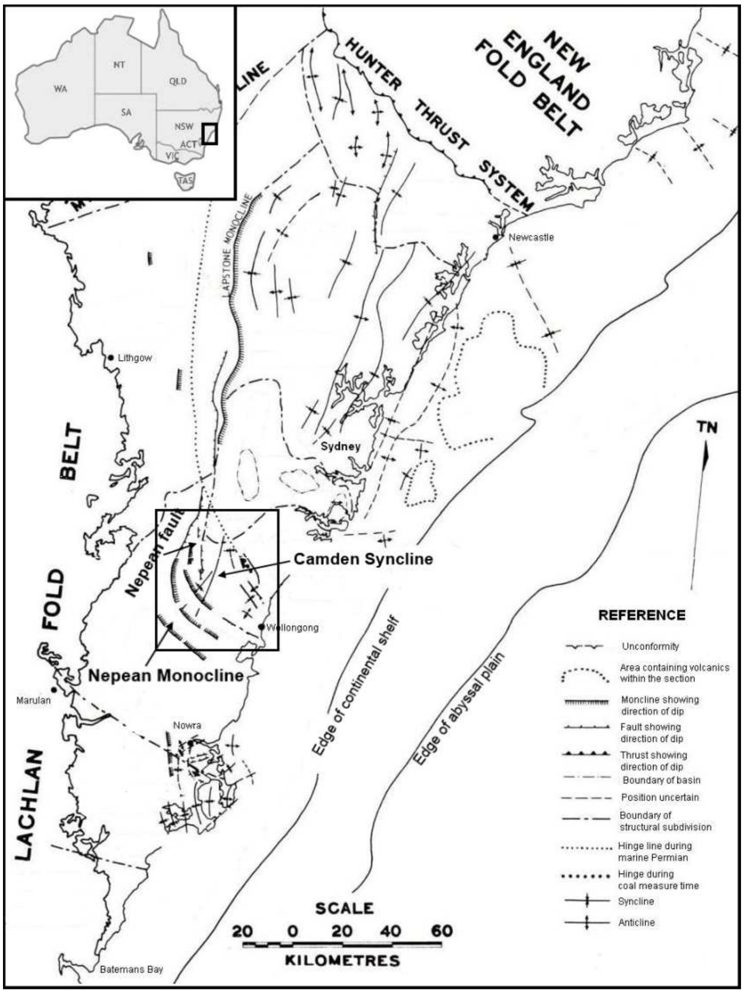

Figure 3.Structural geology of Sydney Basin southern New South Wales. Showing location of the mine. From Branagan 1976.

The frequent rotation of the stress direction with progressively deeper testing did not make sense until a full examination of all data was complete. The information on structure and the direction and magnitude of stress and tectonic strain is contained in Figure 4. The interpreted geological structure is also shown in the figure. The interpreted direction of major horizontal stress from borehole breakout is shown as rosettes of information. The line lengths of these rosettes are uniform as the magnitude of the stress is not known.

The IST 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. In the South the major fault zones appear to have very complex stress regimes with changing magnitude and direction. These seem to be associated with the faulting in the area which includes reverse and slip strike faults and in some cases normal faulting.

While the pattern is complex the overall theme is one where the original major horizontal stresses have led to faulting which has relieved these so that the direction of the major stress changes, sometimes by 90°.

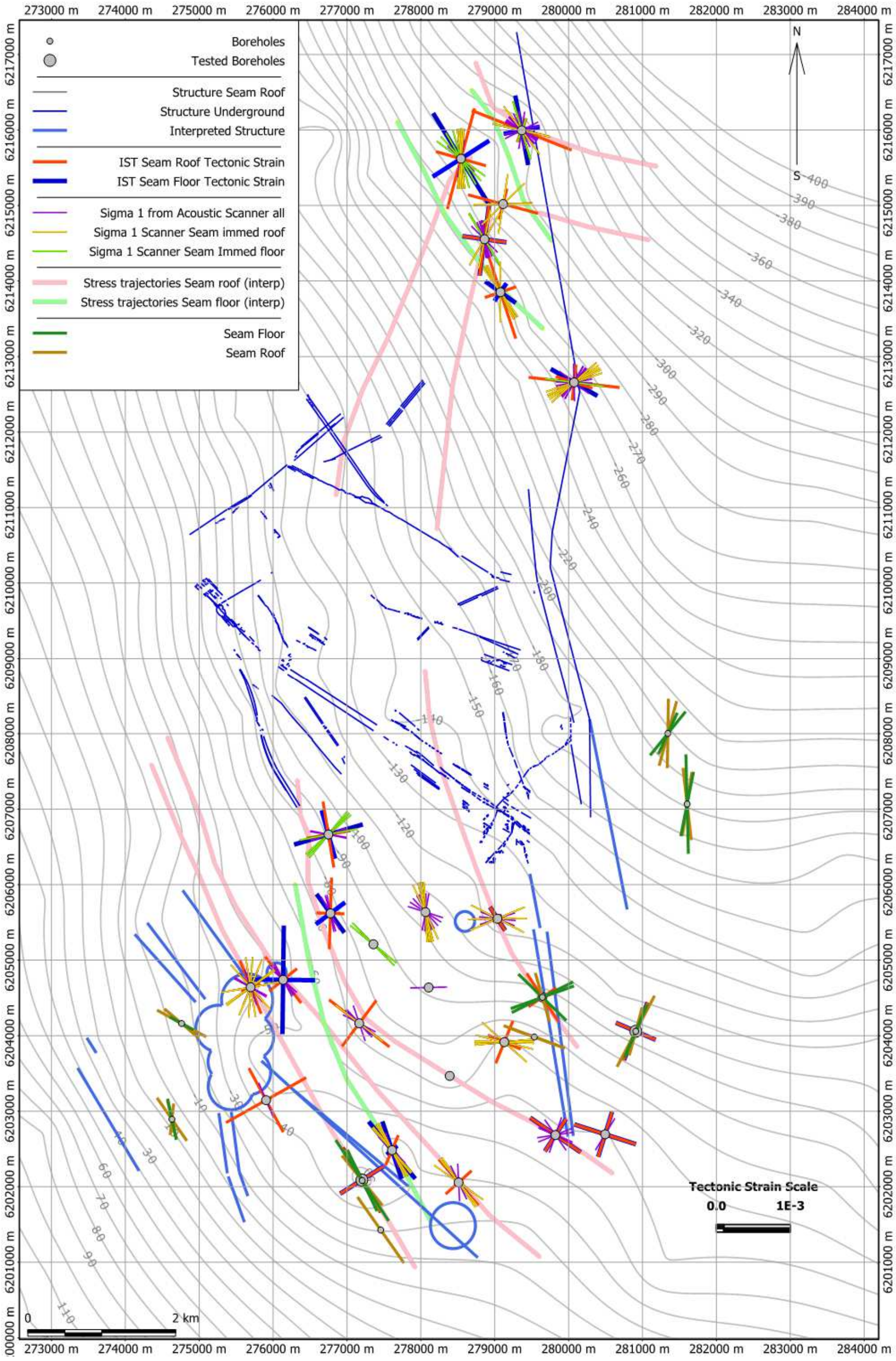

Figure 4. Stress information over the Southern NSW mine showing the results of IST overcores and borehole breakout superimposed on known structural information.

4.3 Grasstree Mine – Virgin Stress and Stresses Above a Goaf

Grasstree coal mine is located as shown in Figure 5. It is in the Bowen Basin Coalfield of Central Queensland some 25 kilometres south-west of Middlemount and 240 kilometres south-west of Mackay. An example of the sedimentary sequence in the area of Grasstree mine is shown in Figure 6.

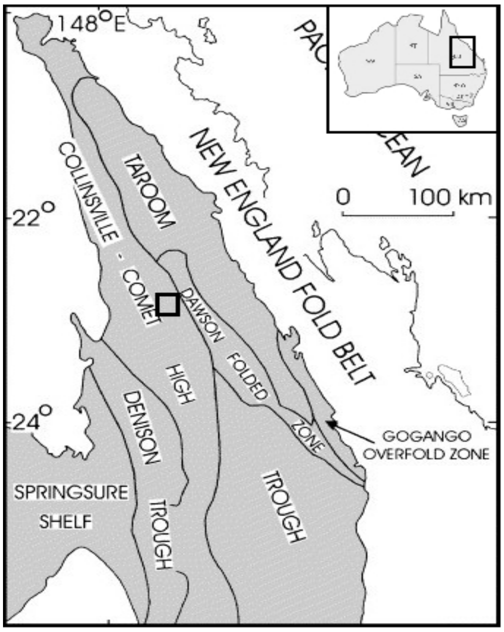

Figure 5. Location of Grasstree mine on a basic geological map of Queensland.

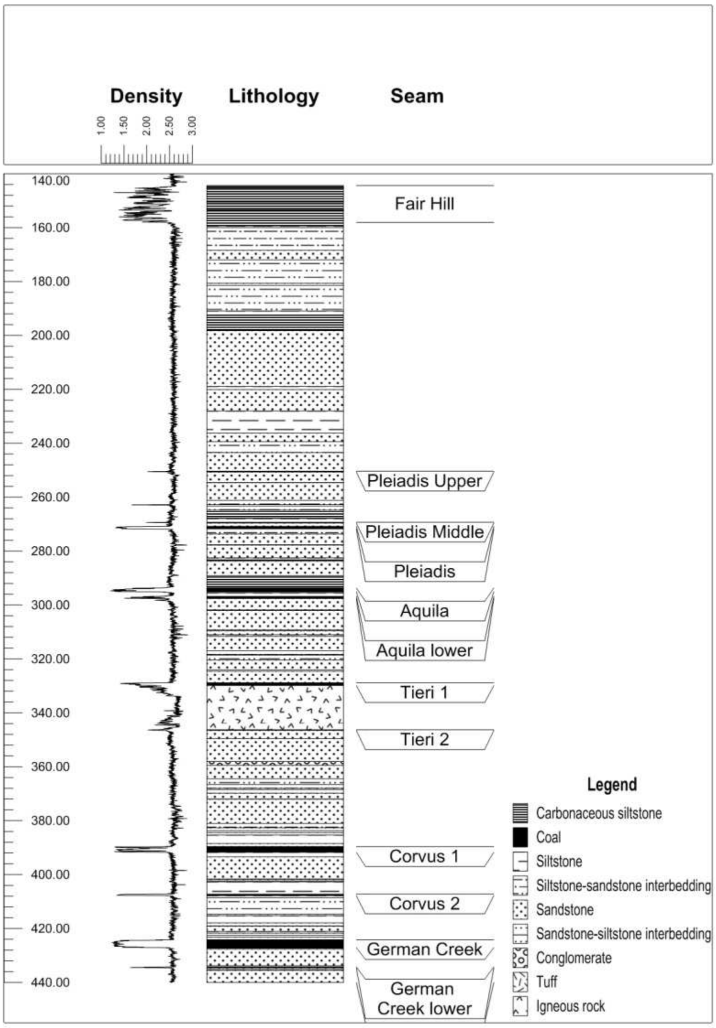

Figure 6. A descriptive log of the German Creek sequence with a geophysical density log.

The mine currently works the German Creek seam which is approximately 2.8 m thick and forms part of the German Creek coal measures. Above this seam is a sequence of coal seams with quite strong sedimentary rocks in between them. The Aquila seam is some 130 m above the German Creek seam in the sequence. Many stress measurements have been made over the general area which is a major provider of coking coal from several mines.

In 2012 stress measurements were made using IST overcore technique around the Aquila and German Creek seams in boreholes over the proposed Northern Grasstree longwall panels prior to any mining. It was also conducted in the South around the Aquila seam in holes over the longwall panels where the German Creek seam had been mined. The results of these stress measurements have been interpreted in terms of tectonic strain. Figure 7 shows the location of boreholes where overcore measurements were made.

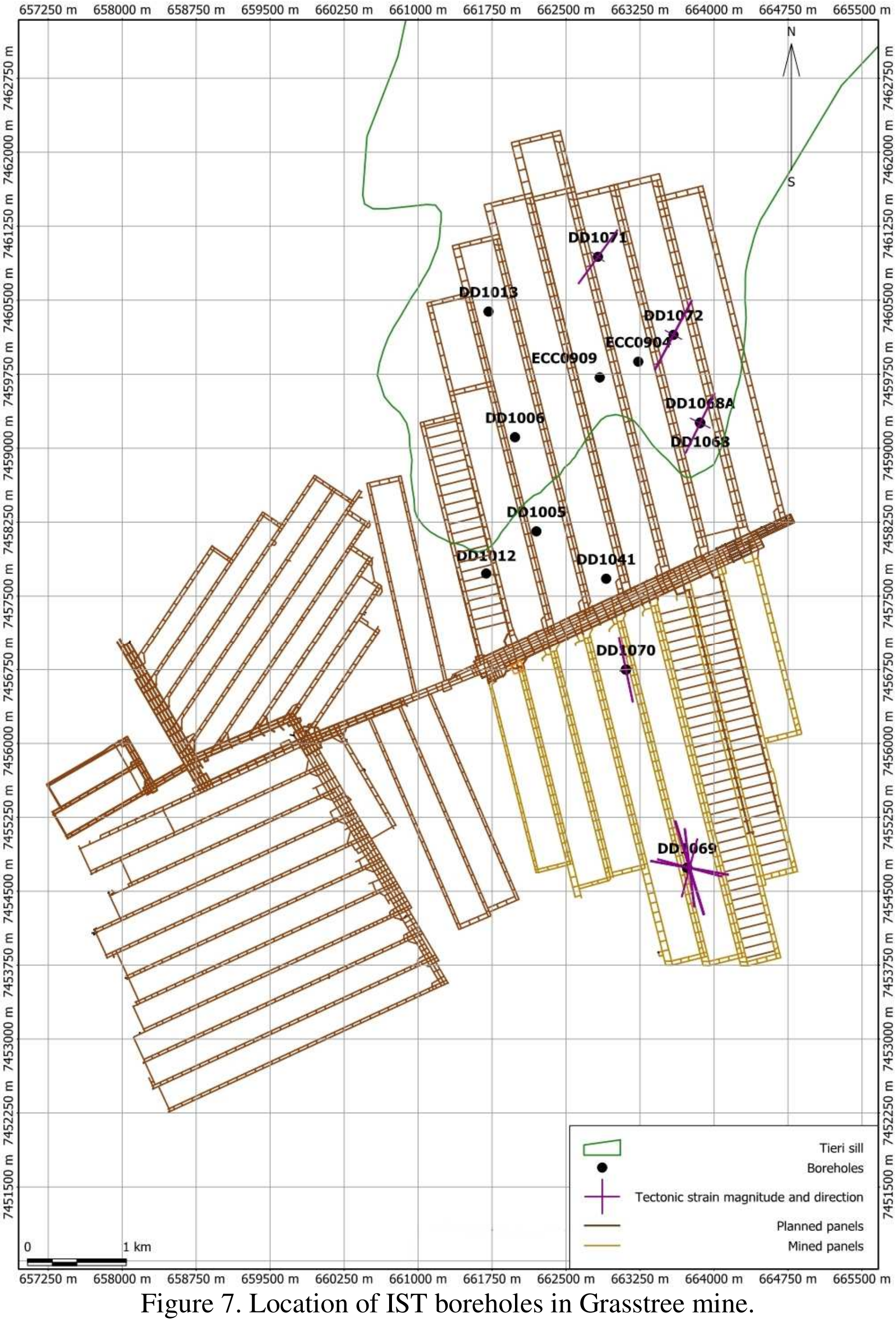

Figure 7. Location of IST boreholes in Grasstree mine.

The tectonic strains measured have been averaged over several measurements around the Aquila and German Creek seams over the northern groups of as yet unmined longwall panels. In the cases of DD1071 and DD1072 the strains were quite even through the sequence. The strains were a little less even around DD1068 but a reasonable average has been obtained. As can be seen these three holes show very similar direction and magnitude of tectonic strain.

The major tectonic strains are not in the moderate range but given the stiffness of the rock samples which lie in the range of 11 to 45GPa they can lead to the generation of high horizontal stresses which greatly exceed the component of lateral stress generated by self weight.

In addition to the stresses in unmined areas the stresses measured around the Aquila seam at about 170 m depth over the German Creek goaf of the mined panels to the south of the main headings are of particular interest. In the case of DD1070 the stresses have aligned with great consistency with the longwall panel and with very little lateral stress. In the case of DD1069 there is more variation in the apparent tectonic strains and the apparent tectonic strains across the panel are greater. This may be because the hole is placed above the German Creek seam pillars while DD1070 is located over the mined panel. In the case of both holes the apparent major tectonic strain is the same as pre-mining but it has been rotated in the direction of the panel.

A previous set of stress measurements conducted around the Aquila seam over the goaf of the German Creek workings at a much shallower depth of about 70 m showed that the stresses had been reduced to low values of more random nature but still with a reasonably consistent orientation.

5. Conclusions

The paper presents the findings of three cases of stress measurement in coal measures interpreted in terms of tectonic strain.

The first case shows how even the tectonic strains can be across a boundary of highly different stiffness.

The second case at Southern NSW mine shows just how complex the distribution of tectonic strains and stresses can be in an area where there is significant structural disturbance. In this case the stresses and calculated tectonic strains change and rotate. Where measurements are taken in the vicinity of known faults these changes can be quite sudden. The conclusion is that in some cases the major regional horizontal principal stress has led to reverse and slip-strike faulting which has locally relieved this stress making what was the minor horizontal stress become the major component. There is also some indication that some of the reverse faults travel up into and along the coal seams. This is a phenomenon that has been also observed in the German Creek seam.

The third case describes stress measurement over the area of Grasstree mine. Here three boreholes some 600 m apart showed very similar tectonic strains in the sequence over 130 m between the Aquila and German Creek seams.

The fourth case, also in the area of Grasstree mine, involved measurement of the stresses around the Aquila seam some 130 m above the extracted German Creek longwall panels. Here it was found that the calculated, and at this stage apparent, tectonic strains over the mined panel at a depth of 170 m realigned with the panel below and retained their magnitude. Those over the pillar also retained their magnitude however with a little more variable orientation.

We have concluded that generally the tectonic strain model can be used to describe the state of strain and hence stress through sedimentary strata. Measurements over tens of sites and thousands of IST overcore stress measurements have shown that the tectonic strain model applies in approximately 70% of cases. It is best to start with an interpretation based on the concept of tectonic strain and to then modify that for the more complex cases.

While the biaxial IST overcore system lacks information on stresses that exist out of its plane of measurement, that is perpendicular to the borehole, this is not a huge impediment to its use in vertical holes in comparatively flat lying sedimentary sequences where the vertical stress is well known. The speed with which the system may obtain measurements compared to glue in fully triaxial overcore systems and the ability to be able to critically review the overcore traces as soon as the tool gets to surface make it a very cost effective and attractive means to measure stress. It can be used in situations where failure due to the broken nature of the rock, such as in the testing reported over the goaf of longwall panels, reduces the probability of success because the failed test may be rapidly repeated.

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