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# In-situ stress measurements and stress change monitoring to monitor overburden caving behaviour and hydraulic fracture pre-conditioning

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ABSTRACT

A coal mine in New South Wales is longwall mining 300 m wide panels at a depth of 160–180 m directly below a 16–20 m thick conglomerate strata. As part of a strategy to use hydraulic fracturing to manage potential windblast and periodic caving hazards associated with these conglomerate strata, the in-situ stresses in the conglomerate were measured using ANZI strain cells and the overcoring method of stress relief. Changes in stress associated with abutment loading and placement of hydraulic fractures were also measured using ANZI strain cells installed from the surface and from underground. Overcore stress measurements have indicated that the vertical stress is the lowest principal stress so that hydraulic fractures placed ahead of mining form horizontally and so provide effective pre-conditioning to promote caving of the conglomerate strata. Monitoring of stress changes in the overburden strata during longwall retreat was undertaken at two different locations at the mine. The monitoring indicated stress changes were evident 150 m ahead of the longwall face and abutment loading reached a maximum increase of about 7.5 MPa. The stresses ahead of mining change gradually with distance to the approaching longwall and in a direction consistent with the horizontal in-situ stresses. There was no evidence in the stress change monitoring results to indicate significant cyclical forward abutment loading ahead of the face. The forward abutment load determined from the stress change monitoring is consistent with the weight of overburden strata overhanging the goaf indicated by subsidence monitoring.



## 1. Introduction

SCT Operations Pty Ltd. (SCT) have been conducting overcore stress measurements and stress change monitoring using the ANZI strain cell for over 25 years in a range of surface and underground mining environments. The ANZI overcore and strain change monitoring instruments are essentially similar in construction with one measuring the 3-dimensional strain changes when the in-situ stresses on the rock are fully relieved and the other measuring 3-dimensional strain changes associated with mining induced ground disturbance [1]. The work described in this paper applied overcoring and stress change monitoring to investigate the in-situ stress state and stress changes in the overburden strata as part of a strategy to characterise the overburden behaviour and modify its behaviour using hydraulic fracturing.

The coal seam currently being extracted is overlain by the 16–20 m thick Digby Conglomerate. The conglomerate was assessed prior to mining as being capable of hanging up for 60 m during longwall start-up and producing an initial caving event capable of producing a windblast. The conglomerate strata were also assessed as having potential to cause periodic weighting on the longwall face during regular mining. As part of a strategy to manage the windblast and periodic caving hazards, SCT and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) were commissioned to undertake investigations to support a program of hydraulic fracturing pre-conditioning of the conglomerate strata. Stress measurements and stress change monitoring were undertaken as part of this program.

Fig. 1 presents a mine plan showing the location of stress measurements and stress change monitoring sites. Two measurements conducted at the Longwall 101 start-up area measured the in-situ stress regime in the conglomerate prior to the commencement of longwall mining. The stress measurements were used to predict the orientation and breakdown pressures of the hydraulic fractures. The results indicated stress conditions had potential to be favourable for emplacing horizontal fractures suitable to pre-condition the conglomerate. A full-scale trial conducted at the start of Longwall 101 confirmed that the hydraulic fractures were forming horizontally [2].

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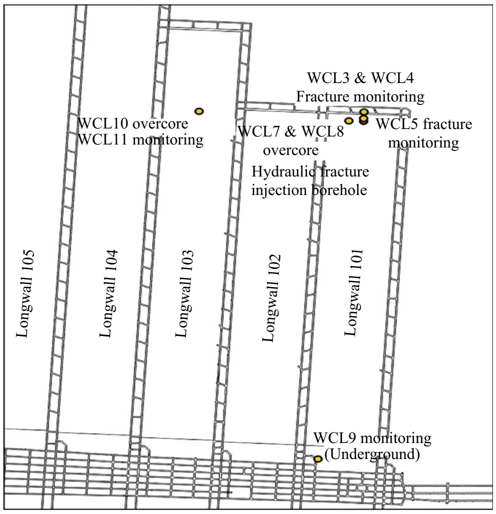



**Fig. 1.** Mine plan showing location of overcore stress measurement and stress change monitoring at mine site.

Several successive stress measurement and stress change monitoring campaigns were undertaken after the commencement of longwall operations to measure the changing stress regime in the conglomerate. Forward abutment loading and horizontal stress changes during final retreat of Longwall 101 were measured through periodic monitoring of a single ANZI strain change-monitoring cell installed into the coal barrier pillar behind the finish line.

An overcore stress measurement was conducted in the conglomerate over Longwall 103 after the extraction of the first two longwall panels. Stress change monitoring in the conglomerate at the same location provided a means to measure the cumulative stress change in the strata during longwall approach. The forward abutment loading and horizontal stress changes in the conglomerate were measured using this instrument.

## 2. ANZI strain cell

The ANZI strain cell comprises a soft, inflatable membrane supporting 18 electrical resistance strain gauges that can be pressure bonded directly to the rock surface of a borehole using epoxy cement. Several versions and configurations of the ANZI strain cell have been developed for different applications. Fig. 2 shows the 58 mm diameter strain cell and a smaller 48 mm version that is now commonly used for installations conducted in surface exploration holes through HQ drill rods using wireline technology to drill the pilot hole. The installation details and operation of the ANZI strain cell is described in Mills [1,3,4].

The overcoring method of stress relief involves removing the in-situ stresses acting in the ground by drilling over the strain cell to form a cylindrical annulus of rock into which the strain cell has been previously installed in a pilot hole. The strain cell measures the small deformations that occur in multiple directions as the stresses are removed by the overcoring process. By also measuring the mechanical properties of the rock, the magnitude and direction of the small deformations can be used to determine the complete 3-dimensional in-situ stress field. The confidence that may be placed in the final stress measurement result is indicated by the internal gauge correlation and expressed as the correlation coefficient. Six independent strain measurements are required to provide a 3-dimensional stress measurement result. With 18 gauges available, the statistical analysis has 12 degrees of freedom available to provide a strong indication of the confidence that can be placed in the instrument.

**Fig. 2.** Instrument assembly for the double 58 mm ANZI stress cell and the single 48 mm ANZI stress cell.

Strain change monitoring cells are essentially similar to overcoring strain cells except that, instead of measuring the change in stress when the in-situ stress is completely removed by overcoring, they measure the changes in stress that occur as a result of mining activity.

## 3. Overcore in-situ stress measurements

Overcore in-situ stress measurements were conducted at two locations at the subject mine from vertical boreholes drilled from the surface. The first measurements were undertaken at the hydraulic fracture trial site at Longwall 101 start-up prior to the commencement of longwall operations. The second site was located on the centreline of Longwall 103, 435 m from the start line. The measurements at Longwall 103 were conducted after the extraction of Longwall 101 and 102.

The point measurements discussed in this section have been normalised for variation in elastic modulus between measurement locations for direct comparison. The process of normalisation involves making allowance for the variations in horizontal in-situ stress that are observed in horizontally bedded rock with different elastic modulus. Fig. 3 presents a summary of the stress measurements results normalised to a rock with an elastic modulus of 16 GPa.

Two ANZI strain cells, WCL7 and WCL8, were overcored in the conglomerate at a depth of 145 m at Longwall 101. The two independent results show close agreement in both magnitude and orientation, and indicate essentially the same stress field. The major principal stress has a magnitude of 9.0 MPa and is effectively horizontal and oriented 15° grid north (GN). The intermediate principal stress has a magnitude of 5.5 MPa, dipping at about 20° and oriented at 285° GN. The minor principal stress is sub-vertical with a magnitude of 3.1 MPa.

A single ANZI strain cell, WCL10, was overcored in the conglomerate at a depth of 172 m over Longwall 103. The major principal stress indicated by WCL10 is horizontal with a magnitude of 14 MPa and oriented at 27° GN. The intermediate principal stress is sub-horizontal and has a magnitude of 5.1 MPa, dipping 24° at 117° GN. The minor principal stress is sub-vertical with a magnitude of 4.1 MPa.

Fig. 4 presents a plan of the stress measurement sites showing the overcore locations and the orientation and magnitudes of the measured horizontal stresses normalised to a rock with an elastic modulus of 16 GPa. A slight rotation in the horizontal stress field and a 5 MPa increase in the magnitude of the major stress at Longwall 103 is observed, possibly associated with some stress concentration around the corner of Longwall 102.

The dip of horizontal stress commonly parallels the dip of the strata in horizontally bedded rocks where units of varying stiffness overlie each other. The major principal stress is effectively horizontal at both measurement sites and roughly consistent with the dip

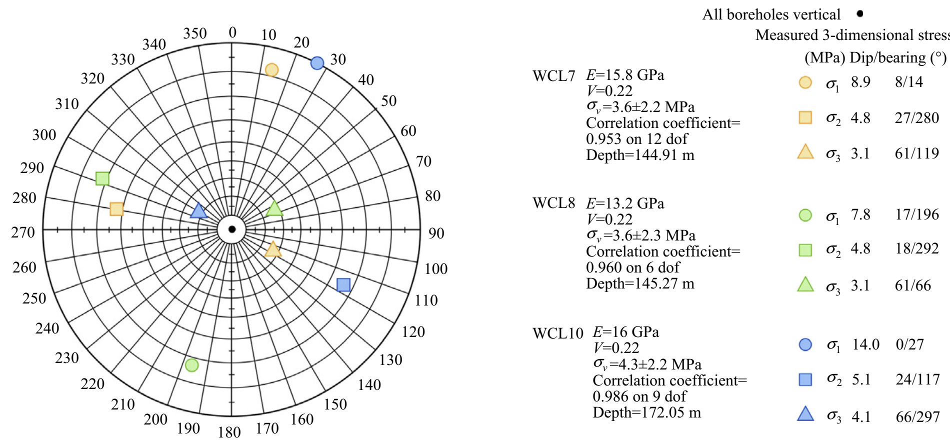



**Fig. 3.** Detailed stress measurement results from Longwall 101 and Longwall 103.

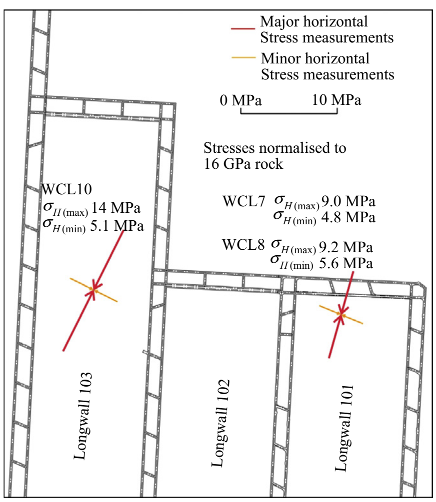



**Fig. 4.** Orientation and magnitude of horizontal stresses from overcoring at Narrabri Mine normalised to 16 GPa rock.

of the coal seam in that direction. The intermediate principal stress (minor horizontal stress) is dipping to the west in response to the westerly dip direction of the coal seam for the Longwall 101 measurements that were conducted pre-longwall mining. The minor horizontal stress at Longwall 103 dips to the east. This opposing dip may be partly associated with horizontal stress relief and general ground movement towards the combined Longwall 101–102 goaf.

The vertical stress indicated by both WCL7 and WCL8 is 3.6 ± 2.2 MPa, and the vertical stress indicated by WCL10 is 4.3 ± 2.2 MPa. Vertical stress is a function of overburden weight, with the indicated magnitudes of vertical stress equal to the nominal 3.1 MPa weight of overburden strata anticipated at 145 m depth at Longwall 101. This vertical stress magnitude has been confirmed by measurement of closure pressure in horizontal hydraulic fractures formed at this site. The vertical stress at Longwall 103 was measured as 4.3 ± 2.2 MPa at 175 m depth which is slightly higher than the 3.8 MPa value obtained by extrapolating the Longwall 101 value to this depth but within the 95% confidence limits of the vertical stress measured.

The stress measurement results indicate that hydraulic fractures created in the Digby Conglomerate are likely to form horizontally by opening against the lowest principal stress, which is vertical. The measurements indicated hydraufacilitate caving of the conglomerate strata.

During the first stage of full scale trials, five fractures were placed within the conglomerate sequence at a depth of 140–160 m. The orientation of fractures was monitored using a tiltmeter array and multiple offset fracture intersection occurred at monitoring boreholes drilled at various distances around a central injection borehole [2]. Analysis of the tiltmeter data recorded during the trials indicated fracture dips of 2–20°, providing assurance that the fractures were essentially horizontal. Temperature profiling and pressure monitoring in offset boreholes during the fracture trial detailed by Mills et al. further confirmed near horizontal intersections into nearby observation boreholes [4]. Fracture monitoring concluded that parallel horizontal fractures sequentially placed 1.25 m along a vertical borehole would maintain their initial spacing to a radial distance of 30 m or more [4].

## 4. Stress change monitoring of hydraulic fractures

Three ANZI strain change monitoring cells, WCL3, WCL4 and WCL5, were used to measure the stress changes during the hydraulic fracturing trial at Longwall 101 start-up. Two strain cells, WCL3 and WCL4, were installed in the Digby Conglomerate at depths of 143 and 147 m, respectively, from a borehole collared 50 m to the north of the injection borehole. A single strain cell, WCL5, was installed in the Napperby Formation into siltstone, immediately overlying the Digby Conglomerate at a depth of 129 m, from a borehole collared 15 m north of the injection borehole.

The stress changes induced by the propagation of a hydraulic fracture through a rock mass are complex and variable depending on the orientation of the fracture and location of the monitoring point. Previous stress monitoring of hydraulic fractures described by Mills and Jeffrey at Salvador Mine in Chile demonstrate that a stress cell located close to the plane of the approaching hydraulic fracture will commonly show an initial tensile stress change as the rock is stretched ahead of the fracture [5]. This is followed by a compressive change as the tip of the fracture passes near the instrument and the rock is compressed by the fluid pressure within the fracture. The magnitude of stress changes in the rock mass and the ability to infer the location of the fracture tip becomes less perceptible with increasing distance from the hydraulic fracture.

The stress monitoring results show a high degree of internal correlation with the correlation coefficient approaching 1.00 once the stresses begin to change. The ANZI stress monitoring cells were able to monitor low level stress changes (<0.1 MPa) within the rock mass with a high degree of confidence. A reduction in correlation indicated a resolution in the stress change measurements of about 0.05 MPa.

Low magnitude sub-vertical tensile stress changes of less than 1 MPa were observed in the conglomerate at WCL3 and WCL4 during the period of hydraulic fracturing. The peak stress change occurs late in the injection period or during shut-in and flow back because the monitoring cells were 50 m from the injection hole monitoring hydraulic fractures with an estimated average radius of 30 m. Sub-vertical stress changes were commonly tensile indicating close alignment of the fracture plane with the monitoring point from a fracture that is sub-horizontal. Tensile stress changes indicate the fracture tip did not reach the 50 m distance to the borehole in which the strain cells were located. Small horizontal stress changes in one or both of the horizontal stresses result from the Poisson's ratio effect of the change in vertical stress. The Poisson's ratio effect is discussed later in this paper.

Fig. 5 shows the stress changes measured by WCL5 located in the Napperby Formation during the first hydraulic fracture in Borehole LW101A. The peak stress observed approximately 17 m above the hydraulic fracture was 0.52 MPa soon after the hydraulic fracture was placed in the conglomerate strata at a depth of 146.5 m. This stress had reduced slightly to 0.26 MPa some 1.5 h later at which time the fracture was shut-in and contained an excess pressure of 0.3 MPa.

As seen in Fig. 5, CSIRO monitoring indicates that the fracture was shut in at 2:32 p.m. and flowed back at 5:20 p.m. so pressurised fluid was contained in the fracture during the entire period of this plot. Fracture closure occurred at 4:08 pm.

Compressive sub-vertical stress change was measured by WCL5 approximately 10 m above the conglomerate and 15 m from the injection borehole in response to the hydraulic fractures passing through the conglomerate below. The small compressive horizontal stress changes are consistent with the Poisson's ratio effect from the increase in vertical stress. A reduction in vertical stress during the approach of the fracture tip was not observed in the strata above the conglomerate due to the vertical separation between stress cell and fracture tip below.

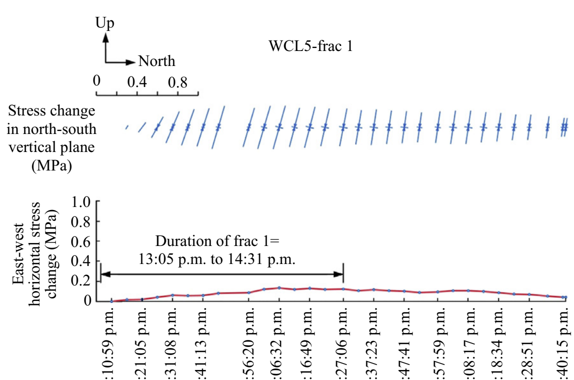



**Fig. 5.** Stress changes measured by WCL5 during hydraulic fracture 1 in Borehole LW101A.

Variability in the stress change responses measured during the emplacement of sequential hydraulic fractures is consistent with fracture asymmetry caused by the interaction of consecutive fractures [2]. Some fluid remains in the fracture and bleeds back into the well once the packers are moved ahead of the next treatment. These fractures induce a change in the stress field around them, and this changed stress influences the growth of the next fracture, potentially causing it to curve towards or away from the previous fractures and grow asymmetrically. Once a fracture grows asymmetrically, the next fracture is likely to grow so as to avoid the residual vertical stress created by the previous fracture. The centre of the subsequent fracture is thus offset relative to the centre of the previous fracture.

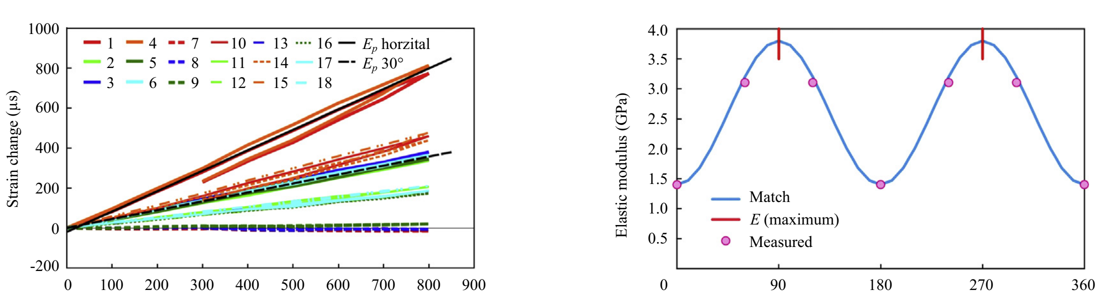
## 5. Stress change monitoring at Longwall 101 finish line

An ANZI strain cell, WCL9, was installed in the upper section of the coal seam from Longwall 101 Shute Road and located 5 m outbye of the finish line. The acquisition of strain data was undertaken manually, with download frequency increased during final retreat of Longwall 101 when the rate of stress change was greatest.

The in-situ pressure test shows a linear response from all gauges indicating good adhesion to the rock, rock properties that are elastic and that no microcracking has developed as a result of the applied pressure. Close correlation between opposing circumferential gauges (gauges 1 & 4, 2 & 5 and 3 & 6) indicate essentially homogenous behaviour. However, variability in the strain response around the borehole shown by the circumferential gauge pairs indicates the elastic modulus of the coal is highly sensitive to the magnitude of in-situ stress concentrated around the borehole, a phenomenon that is observed in other rock strata as well. Fig. 6 shows the elastic modulus ranges from 1.4 GPa at the top and bottom of the borehole to 3.1 GPa on the sides where stress concentration is highest. When a sine function is placed through the measured variation in elastic modulus around the borehole, the location of maximum elastic modulus is at 90° (borehole sides), indicating the major principal stress in the coal is the vertical component, since the borehole was drilled sub-horizontally (at an upward inclination of 28°).

Fig. 6a shows the variability in the circumferential gauge response, and Fig. 6b presents the variability in elastic modulus around the borehole indicating highest stress concentration on the sides of the borehole from a vertical major principal stress.

Fig. 7 shows the results of the strain monitoring for WCL9 conducted over a 71-day period during which time, the face retreated the final 166 m of Longwall 101. A consistent rate of retreat is maintained for the initial 18 days of monitoring and then slows




(a) Pressure test results

(b) Elastic modulus variation

**Fig. 6.** In-situ pressure test results for WCL9.

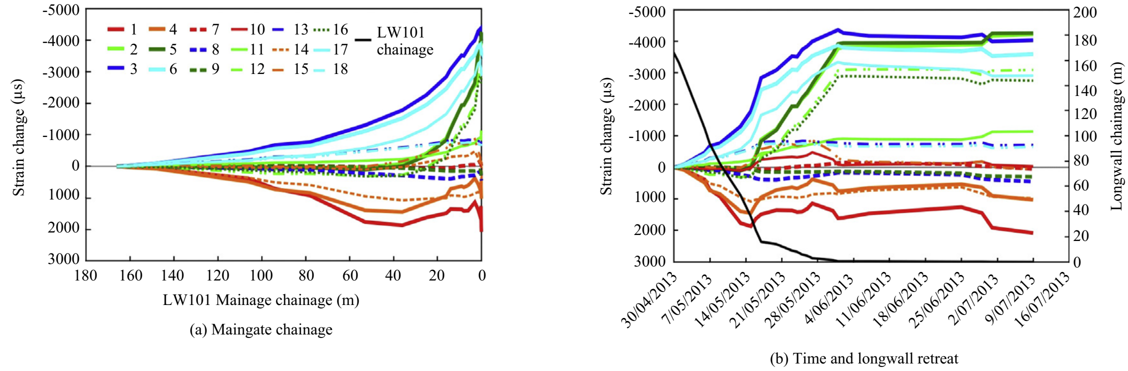



**Fig. 7.** Strain changes measured byWCL9.

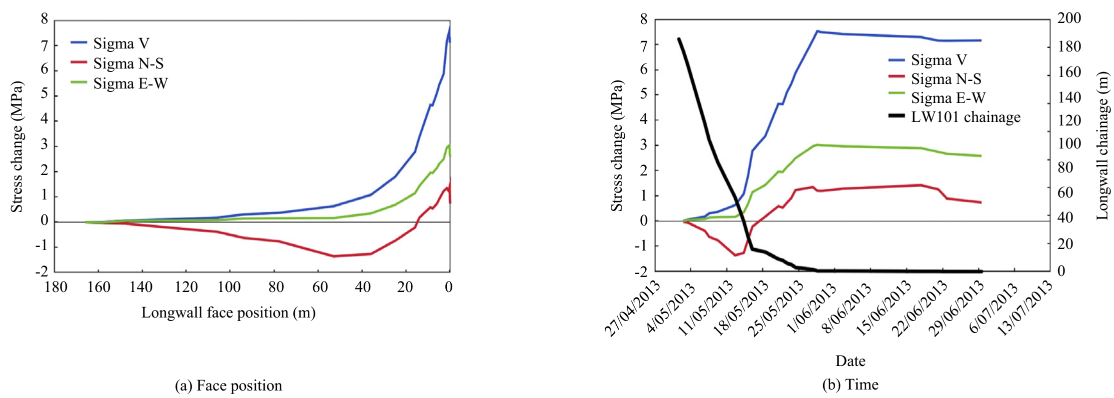



**Fig. 8.** Stress changes measured by WCL9 resolved to show the true vertical stress and horizontal stresses aligned N–S and E–W (consistent with the orientation of the Longwall pane l).

for the next 14 days as the face approaches the take-off roadway. The final 39 days of the monitoring period covers the progressive removal of shields off the face. An average correlation coefficient of 0.99 on 12° of freedom for the monitoring period is considered a result in which a high level of confidence may be placed as a point measurement of the in-situ stress changes. The monitoring shows high sensitivity strain changes between the rate of strain change and the rate of longwall retreat. The strains stabilise when there is a hiatus in mining, indicating the instrument is responding closely to the stress changes caused by mining.

The horizontal stress changes measured by WCL9 show minimal rotation from the pre-mining in-situ horizontal stress field, largely due to the close alignment of the Longwall 101 axis with the major principal stress (longwall panel and Sigma 1 oriented 4° GN and 15° GN respectively). Fig. 8 presents a plot of the stress changes measured by WCL9 resolved to show the true vertical stress and horizontal stresses aligned north–south and east–west, consistent with the orientation of the longwall panel. As expected, there is a gradual increase in vertical stress associated with the forward abutment and a relaxation of horizontal stress towards the approaching longwall, which accelerates during the final 30 m of retreat. For a rock with an elastic modulus of 3 GPa, the stresses on a plane aligned up the panel show that the major stress change is essentially vertical (dipping 81°) reaching a maximum 7.7 MPa at the completion of mining, with a small reduction to 7.4 MPa after the shields were removed. There is a 1.3 MPa horizontal stress increase by the end of mining aligned with the panel axis, before a reduction to 0.6 MPa after the shields were removed. There is an increase in horizontal stress oriented approximately parallel to the longwall face starting at about CH50 m, reaching 3.1 MPa by the end of mining, before reducing to 2.5 MPa after the shields were removed.

Fig. 9 presents a plot of the stresses viewed in a vertical plane along the panel axis, showing the vertical stress dipping slightly in a downward direction towards the goaf and contrary to the common expectation of the front abutment angling towards the solid coal. The dip direction of the vertical stress indicates there has been shear movement in the upper strata in a direction towards the goaf. As the longwall has come to the end of the panel, the vertical stress has dominated and the stresses become aligned vertically in the plane of view. The stresses observed in a plane along the face viewed looking into the goaf, dip towards the goaf, consistent with the same behaviour across the panel. These observations are supported by the top right/bottom left deterioration in the ribs that have been observed in the chute road.

A small amount of stress change can be seen in the last week of monitoring that is consistent with the shields being removed. The most significant change is in the horizontal stress towards the longwall goaf where the removal of the shields adjacent to WCL9 has resulted in a reduction in confinement of about 0.6 MPa. After all the supports were removed, the stresses stabilise again. This result indicates that the shields have effectively been providing horizontal confinement to the face of about 0.6 MPa, but the loss of this confinement has evidently not been sufficient to cause the coal to become overloaded at the take-off location of Longwall 101 because the vertical stress has not changed significantly.

The 0.6 MPa horizontal stress change when the supports are removed confirms the role of the longwall shields in providing a significant level of horizontal confinement to the roof strata immediately above and ahead of the longwall face. If the roof strata were

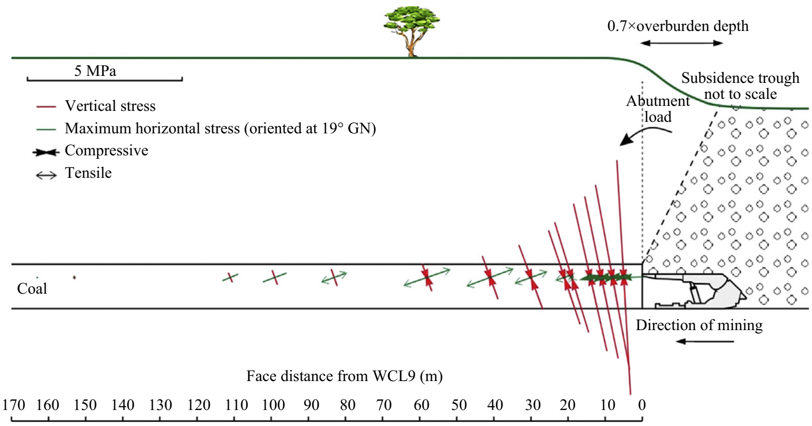



**Fig. 9.** Stress changes in coal indicated by WCL9 viewed in section on a plane along Longwall 101 panel axis, looking west.

close to failure, 0.6 MPa of confinement would add another 2–3 MPa of strength to the rock (assuming a typical triaxial stress factor of 4–5) which is a significant strength increase when the vertical stress is 10–11 MPa. The confinement provided by the shields also underlines the benefit of having the longwall supports all in a line and all acting together. If only half of the supports are able to be set to the roof effectively, the strength increase imparted to the rock strata is also halved and rock failure ahead of the face can occur more easily.

## 6. Stress change monitoring in conglomerate at Longwall 103

A single ANZI strain cell, WCL11, was installed in the Digby Conglomerate at 175 m depth in a borehole collared 435 m from the Longwall 103 installation face on the panel centreline. WCL11 was installed 2 m below the WCL10 overcore stress measurement location.

Fig. 10 shows the strain readings for WCL11 acquired using an automated data logger located at the borehole collar that recorded strains every 30 min throughout the 68-day monitoring period. The inflation line was decoupled from the back of the instrument at the end of the pressure test when the internal pressure of the stress cell was equal to the hydrostatic head in the borehole. The gradual compressive strain changes in the circumferential and 45° gauges that occur for the first 52 days of the monitoring period result from a slow reduction of the water level in the borehole and corresponding reduction in the internal hydraulic pressure of the stress cell.

As shown in Fig. 10, it is notable that WCL11 installed at approximately CH1960 assuming no deviation in borehole verticality. Fig. 10a shows that gradual compressive strain change are caused by decreasing internal pressure in the instrument from the lowering of the water level in the borehole.

Perceptible strain changes caused by mining commence when the face was located 150 m from the instrument. The period of active stress change continues for the next 16 days until the instrument was decommissioned before it was undermined, when the face was located approximately 10 m away. An average correlation coefficient of 0.99 on 12 degrees of freedom for the monitoring period is considered a result in which a high level of confidence may be placed as a point measurement of the in-situ stress changes.

The rate of longwall retreat is relatively constant during the period of active stress change. The stress cell shows a high level of sensitivity to ground movements where brief longwall stoppages are reflected in the strain data as periods of relative stability. There is acceleration in the rate of strain change beginning when the face is located 50 m from WCL11. When the strains are viewed with respect to longwall chainage, there is one step change that occurs when the face is located 30 m away during a longwall stoppage indicating some readjustment in stresses is occurring during this period.

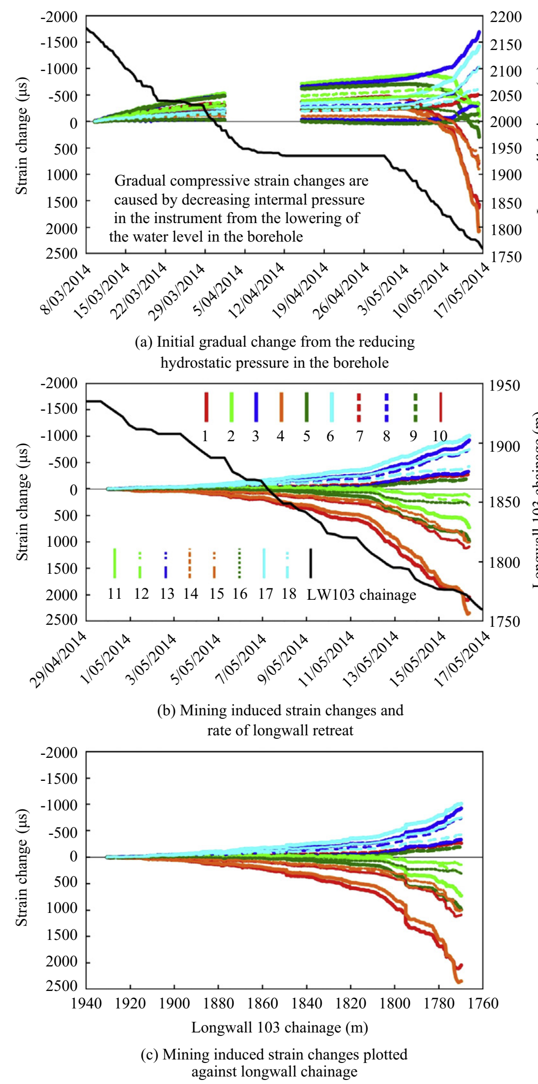



**Fig. 10.** Strain changes measured by WCL11.

The stress changes measured in the conglomerate by WCL11 were analysed using an elastic modulus of 15 GPa and a Poisson's ratio of 0.2. The mechanical properties of the rock were based on the laboratory core test for WCL11 and biaxial test results from WCL10. Fig. 11 presents a plot of the stress changes in plan view looking up the longwall panel showing the orientation of the horizontal stress field remained unchanged during longwall retreat. The final set of readings indicates a 12 MPa reduction in horizontal stress towards the goaf. The stress relief is oriented at 22° GN and consistent with the major principal stress direction of 27° GN indicated by WCL10. There is a 1.4 MPa increase in vertical stress and a 2.5 MPa increase in compressive stress across the longwall face. The intermediate and minor principal stress changes show ongoing rotation on the same plane during the monitoring period, with both dipping approximately 45° by the final readings.

It is notable that the stress magnitudes have been scaled to represent the horizontal stress change that would be expected in a rock with an elastic modulus of 16 GPa.

The total stress change in the conglomerate at Longwall 103 during longwall retreat can be investigated through the addition of stress change results from WCL11 and the pre-mining in-situ stress measurement results by WCL10. Combining the stresses is made possible because the measurements were conducted at approximately the same location in a rock with similar mechanical properties. Fig. 12 shows a plot of the cumulative stress changes in the conglomerate. There is almost full relief of the major principal stress and consistent with relief into the goaf, and an increase in compression for both the intermediate and minor principal stresses. The magnitude of the stress changes for the intermediate and minor principal stresses are sensitive to the Poisson's ratio effect from the much higher stress change in the major principal stress. The Poisson's ratio effect from the relief of the maximum principal stress lowers the indicated magnitudes of compressive stress increase for the other two stress components (Poisson's ratio effect is discussed in the following section).

The 2 MPa total increase in vertical stress at Longwall 103 is significantly less than the 7.4 MPa comparative stress increase measured at Longwall 101. Discrepancy relating to borehole verticality and the actual distance between WCL11 and the longwall

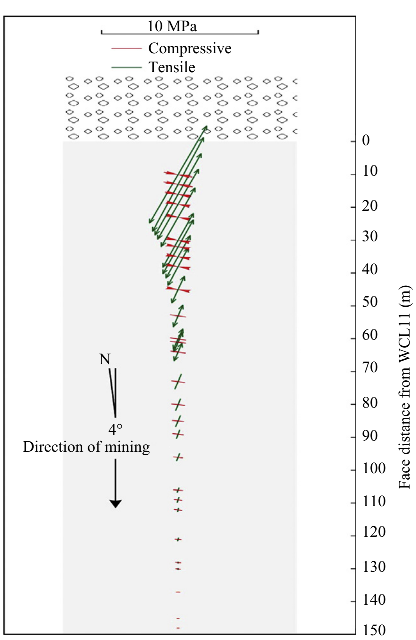



**Fig. 11.** Plan view of horizontal stress changes indicated by WCL11 during retreat of Longwall 103.

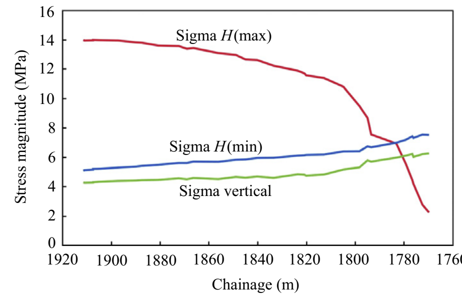



**Fig. 12.** Cumulative stress changes measured by WCL11 at Longwall 103 using the in-situ overcore stress measurement results indicated by WCL10 as a pre-mining baseline.

face may account for some of the disparity given that most of the total forward abutment loading at Longwall 101 occurred during the final few meters of approach. However, the lower than expected vertical stress at Longwall 103 is due, in part, to the Poisson's ratio effect from the near full reduction in the major principal stress (discussed in the following section).

The stress changes indicated by WCL11 are gradual and do not show the step changes that could be expected from the steady build-up of stress and sudden relief from periodic weighting/caving events. The single small step change observed when the face was located 30 m from WCL11 relates to ongoing stress changes during a longwall stoppage and is not indicative of sudden stress relief caused by a caving event. The stress changes indicated by WCL11 are more consistent with regular and smaller caving cycles. There is no evidence of any significant cyclical forward abutment loading ahead of the face consistent with the absence of significant periodic weighting events observed underground during the approach to WCL11.

## 7. Forward abutment loading

The stress changes measured ahead of mining provide a method to estimate the total forward abutment loading as the area under the vertical stress profile. This loading can then be compared to the weight of overburden strata transferred onto the solid coal that is indicated by interpreting the results of subsidence monitoring data. However, the Poisson's ratio effect associated with horizontal stress relief needs to be taken into account.

When changes in stress occur in one direction, there are consequential changes in the stresses in the other two directions as governed by Hooke's law and referred to as the Poisson's ratio effect. The stress concentration or stress relief measured in a horizontal direction can cause increased or reduced vertical stress (in proportion to Poisson's ratio) provided the changes in horizontal stress occur over an area that is too small for full vertical loading from the weight of overburden strata to be re-established, such as in areas of high stress gradient around the forward abutment.

Fig. 13 shows a comparison of this abutment loading component and total vertical stress measured by WCL11. Forward abutment loading of 4.8 MPa is indicated by WCL11 when the face is located approximately 10 m from the instrument. By comparison, the vertical stress indicated by WCL9 remains largely uninfluenced by the Poisson's ratio effect because the magnitude of the measured horizontal stress changes are low, consistent with the coal's low elastic modulus, which results in it attracting/relieving less horizontal stress than the stiffer strata above and below. The abutment loading profiles for both WCL9 and WCL11 are similar when compared directly. The final forward abutment load at the face was not measured by either instrument; however, most of the total anticipated loading is likely to have been captured by WCL9.

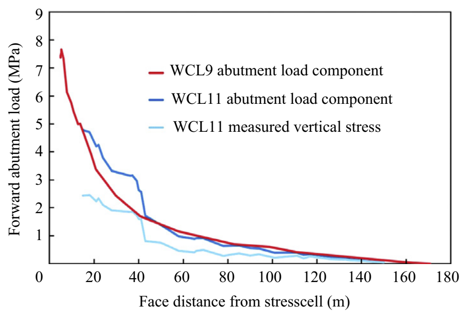



**Fig. 13.** Forward abutment loads indicated by WCL9 and WCL11.

The total vertical stress indicated by WCL11 including the Poisson's ratio component from horizontal stress relief is also shown (Fig. 13).

The total forward abutment loading can be estimated from integrating the area under the vertical abutment loading curve indicated by stress monitoring. The estimation indicates the forward abutment loading on the longwall face is approximately 230 MN/m assuming a maximum face loading of 7.5 MPa.

The vertical abutment loading must also be consistent with the weight of overburden strata that overhangs the goaf. This weight is able to be inferred from the overburden depth and the distance from a solid goaf edge to reach full subsidence [6]. The distance that the overburden is able to redistribute its own weight back onto solid abutments and chain pillars is able to be inferred from the distance from the solid edge of a longwall panel to the point where full subsidence is first established. Subsidence monitoring data from the mine indicate the maximum distance that the overburden is able to redistribute its own weight is approximately 0.7 times the overburden depth. The weight of overburden redistributed onto the face indicated by subsidence monitoring at the mine is estimated to be 217 MN/m at 170 m, consistent with the 230 MN/m loading indicated by stress monitoring.

## 8. Conclusions

The in-situ stress field in the conglomerate roof strata at the subject coal mine was measured before longwall operations commenced. These measurements indicate stress field likely to be suitable for hydraulic fractures placed in the conglomerate strata to form with a horizontal orientation, a result later verified through monitoring of full scale hydraulic fractures. Stress monitoring in offset boreholes formed part of the monitoring and indicated compressive stress were generated above the hydraulic fracture within the fracture radius and asymmetric growth of subsequent fractures was likely in response to the changed stress field.

Stress change monitoring in the conglomerate during longwall retreat shows almost full stress relief towards the goaf in the direction of the major principal stress. Stress change monitoring in the coal at the finish line indicated forward abutment stresses of up to 7.7 MPa and highlighted the role of the shields in providing confinement to the strata.

Allowing for the Poisson's ratio effect associated with horizontal stress relief, the forward abutment loading indicated at the two stress monitoring sites was essentially the same and consistent with the abutment loading calculated from the weight of overburden strata overhanging the goaf edge indicated by subsidence monitoring data. Subsidence monitoring data is much more readily available than stress change monitoring data and these measurements indicate that subsidence monitoring data can be used to estimate abutment loading for pillar design and other purposes.

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