Successful Application of Hydraulic Fracturing to Control Windblast Hazard at Moonee Colliery

K.W. Mills, Geotechnical Engineer, Strata Control Technology Pty Ltd
R.G. Jeffrey, Petroleum Geomechanics Group Leader, CSIRO Petroleum, Melbourne, Australia.
D.W. Jones, Chief Engineer, Coal Operations Australia Ltd, Newcastle, Australia

Proceedings of 19th Conference on Ground Control in Mining, Morgantown, August 2000

ABSTRACT

This paper describes the first successful use of hydraulic fracturing to induce caving events “on demand” in Australia. Moonee Colliery operate a longwall immediately below a thick conglomerate strata. This strata temporarily bridges across the extracted longwall panel to create a large area of standing goaf. When this standing goaf eventually collapses, the windblast generated presents a significant hazard to men working on and around the longwall face.

Hydraulic fracturing has been successfully introduced to take control of the timing of these caving events so as to eliminate the risk of windblast injury. The longwall face area is completely evacuated during the treatment. Water is pumped into an injection point located in the conglomerate strata above the standing goaf. A horizontal fracture is generated and grows outward from the injection point, separating the conglomerate strata below the fracture horizon. At some point the strata can no longer span and a goaf fall is initiated. After a treatment, mining can be recommenced with the windblast hazard eliminated.

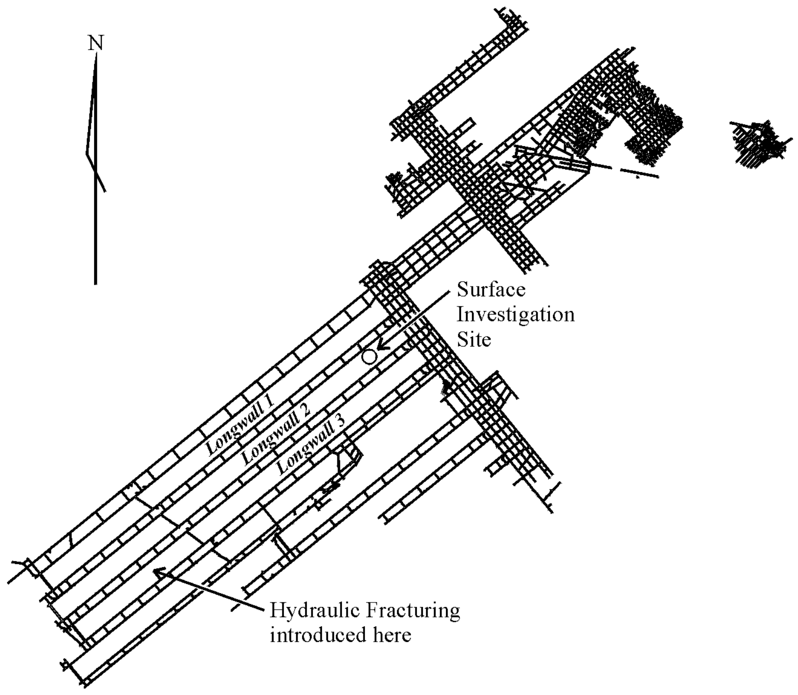

Figure 1 Site plan showing layout of Moonee Colliery

INTRODUCTION

Moonee Colliery is located in New South Wales, 30 km south of Newcastle. The colliery longwall mines the lower 3 to 3.5 m of the Great Northern Seam. A plan of the mine layout is shown in Figure 1. The longwall panels are 100 wide and separated from each other by 35 m wide chain pillars, sized primarily for subsidence control purposes. The depth of overburden ranges from 90m in the north to 170m in the south.

The immediate roof comprises 1.5 to 1.8 m of coal and claystone material that caves directly behind the longwall supports. The Teralba Conglomerate that overlies the Great Northern Seam is 30 to 35 m thick and is able to temporarily bridge across the longwall goaf. When the conglomerate eventually caves, it does so suddenly, more or less as a single mass over an area some 50 to 300 m long by 100 m wide. The windblast generated presents a significant hazard to men working on and around the longwall face.

Soon after longwall mining began, micro-seismic monitoring was introduced as a way to predict, from the signature and frequency of micro-seismic events, the onset of caving with sufficient warning to enable men on the face to seek a safe location prior to the windblast (Edwards 1998). While this technique was successful as a predictive tool and continues to be an integral part of the windblast management plan, it does not offer any form of control over the timing of caving events.

Hydraulic fracturing was introduced to take control of the timing of caving events. The longwall face area is completely evacuated during the period of the treatment and, although a windblast still occurs when the goaf falls, the risk of injury is eliminated.

The concept of generating a fall "on demand" using hydraulic fracturing is fundamentally different to the concept of pre-conditioning the strata ahead of mining to promote caving. When the strata is pre-conditioned by hydraulic infusion, hydraulic fracturing, or any other means, it may be induced to cave more readily but unless caving occurs continuously and immediately after the supports advance there is still no control of the timing of the caving events and a windblast hazard persists.

BACKGROUND TO HYDRAULIC FRACTURING

Hydraulic fracturing is widely used in the petroleum industry to stimulate oil and gas production from underground reservoirs. At Moonee, f water is injected into a short section of borehole at sufficient pressure to overcome the stresses around the borehole and the tensile strength of the rock. Once the fluid pressure rises high enough to overcome the forces holding the rock together, a fracture, initially only a fraction of a millimetre wide, is initiated in the rock. The fracturing fluid injected into the hole enters this fracture, pressurising and opening it. As injection continues, the fracture spreads laterally away from the hole and aligns itself, as it continues to grow, in a direction perpendicular to the lowest principal stress.

The fluid pressures and flow rates required to keep the fracture growing are typically well within the range of readily available pumping technology. The pressure is primarily a function of the minimum stress in the ground – higher pressure is required for higher minimum stress. The flow rate to keep the fracture growing is primarily a function of the strata permeability and the rate at which the fracture is required to grow – more permeable strata requires more flow to maintain a given rate of fracture growth.

The application of hydraulic fracture technology to actively promote caving within a specific timeframe is new to coal mining in Australia. Hydraulic infusion had been undertaken a decade earlier at Newstan Colliery (Holt 1989) on a trial basis to "soften" massive sandstone ahead of longwall mining but this was discontinued after the first trial. In the metalliferous mining industry, hydraulic fracturing had been used successfully to promote caving of ore at Northparkes gold and copper mine (van As and Jeffrey, 2000) but, at Northparkes, caving typically occurred some days or weeks after treatment.

Overseas experience of water infusion in China reported by Pan et al (1983) and in South Africa by Summers & Wevell (1985) appears successful for promoting caving but does not offer a way to take control of the timing of caving events. Konopko et al. (1997) report success in Poland and Haramy et al. (1995) in the US of using hydraulic fracturing to modify strata behaviour and encourage caving.

At Moonee, hydraulic fracturing is attractive as a method to control caving because the minimum stress in the conglomerate above the goaf follows a trajectory that is approximately the same shape as the stable geometry of the fallen goaf. By initiating the fracture at a point close to the top of the final stable arch profile, a fracture that is essentially circular in plan can be extended outward from the injection point to approximate the final arch.

The radially expanding fracture has the effect of artificially removing the tensile strength of the rock over a larger and larger area (typically greater than 25 to 30 m in radius) while at the same time applying a fluid pressure down on top of the uncaved strata. Jeffrey and Mills (2000) discuss the mechanics of hydraulic fracture growth at Moonee in more detail. As long as the fracture continues to grow, instability of the strata below the fracture horizon is inevitable. Once a critical point is reached, the lever arm generated by gravitational forces acting on the detached strata continues to propagate the fracture independently of the hydraulic fracture process.

The main limitation to the fracture continuing to grow is from loss of water into the formation or out to any form of free surface. Free surfaces, such as the open void of the mined goaf, the already fallen goaf, or natural joints of high permeability, have the potential to restrict the size of the fracture developed.

GEOTECHNICAL INVESTIGATIONS

A staged program of geotechnical investigations was undertaken in the period leading up to the first underground treatment. These investigations were integral to characterising the strata behaviour and implementing a successful treatment strategy.

Visual Observations

Visual observations and survey measurements of the goaf geometry provide an initial basis to assess the ground behaviour and the potential for using hydraulic fracturing.

Figure 2 shows an example of the natural goaf geometry observed in a goaf fall at the start of Longwall 1. The goaf caves to form a broadly arch-shaped stable geometry 12 to 15 m high in the centre of the panel with an essentially open void above the fallen material. Numerous observations of both natural goaf falls and hydraulic fracture induced goaf falls indicate a generally similar arch shaped profile and height of caving. The material above the standing arch profile remains stable once the goaf has fallen.

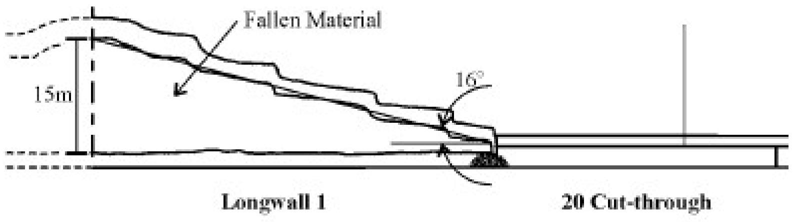

Figure 2 Goaf cross section observed from 20 Cut-through, Maingate 1.

The other observations relate to the size and frequency of natural falls.

In Longwall 1, there were approximately 40 individual falls. In the subsequent panels, prior to the introduction of hydraulic fracturing, the number of falls halved and the amount of standing goaf involved in each fall doubled. This observation suggests that horizontal stress and pore fluid pressure are factors in the caving process. In Longwall 1, the magnitude of both horizontal stress and pore fluid pressure is greater than in subsequent panels, so the frequency of natural falls is higher. In subsequent panels, the existence of the previous goaf provides a horizontal stress shadow that reduces the horizontal stress magnitude and a drainage path that reduces the pore fluid pressure.

In the first three longwall panels, the first goaf fall is approximately twice as long as the subsequent goaf falls. This observation suggests that standing goaf length, and by implication either time or gravitational forces are significant factors in the caving process.

In Situ Stress Measurements

The in situ stress was measured using two ANZI stresscells (Mills 1997) and the overcoring method of stress relief. The stress measurements indicate a relatively low horizontal stress environment. The major horizontal stress is approximately 8MPa acting at N30E, slightly anticlockwise of the axis of the longwall panels. The minor horizontal stress is 4MPa acting in a perpendicular direction, more or less across the panels. The vertical stress at the measurement site was 4MPa consistent with the overburden depth of 160m.

The in situ stress measurement provided an invaluable framework within which to interpret the failure mechanics of the conglomerate strata and the hydraulic breakdown pressures in boreholes oriented in various directions.

The measured stress field also confirmed that preconditioning of the conglomerate strata would be ineffective. A hydraulic fracture initiated in the conglomerate strata would align more or less along the longwall panels and would rotate from vertical to horizontal depending on the relative magnitudes of the two minor stresses. Fractures in these orientations would not necessarily be helpful in promoting caving and would not provide control over the timing of caving events.

Overburden Properties

The Teralba Conglomerate is mainly composed of pebbly conglomerate strata in a sandy matrix. Located within this essentially unbedded strata, there are irregular lenses of fine-grained sandstone typically 0.3 to 0.5 m thick. These are not laterally persistent and their thickness varies over distances as short as a few metres. There are no continuous horizontal partings within the conglomerate. The conglomerate is cross-cut by several sets of subvertical joints, but these do not appear to have a major influence on the timing of caving although they sometimes define the edges of a goaf fall.

A comprehensive set of mechanical property data was already available from tests on core recovered from several holes near the start of Longwall 1. Figure 3 summarises these strength test results and shows that the sandstone lenses are consistently stronger and have a higher elastic modulus than the conglomerate strata.

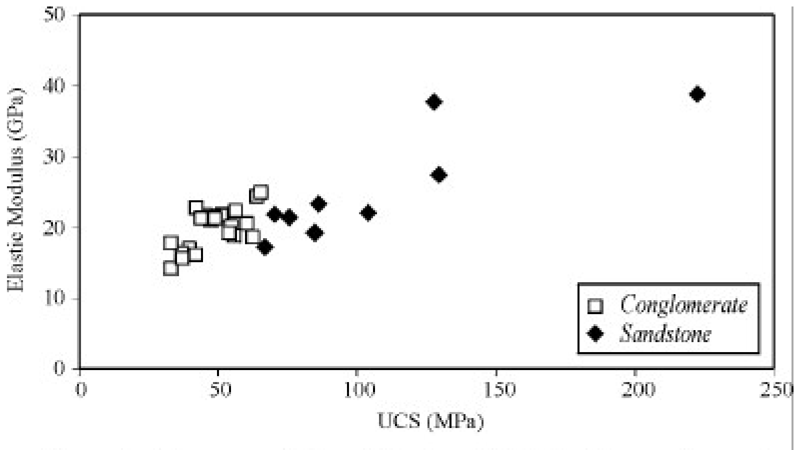

Figure 3 **Summary of strength test results for Teralba conglomerate.**

The conglomerate has an elastic modulus of 20 ± 5 GPa, a uniaxial laboratory strength 50 ± 10 MPa and a tensile strength of approximately 4 MPa. The sandstone has a higher, more variable elastic modulus ranging from 19 GPa to 39 GPa and a higher uniaxial laboratory strength averaging 80 MPa. Although the strength and stiffness properties of both materials are quite variable, there does not appear to be any consistent variation in stiffness or strength either up through the conglomerate strata or laterally along the panel.

Numerical Modelling

Two two-dimensional elastic models of the conglomerate strata above the goaf were generated using FLAC (Cundall & Board 1988) as a guide to the stress conditions before and after caving (Figure 4). These models were relatively simplistic with a following load applied to the top boundary of the conglomerate. The effect of a following load is recognised to overestimate the bending stresses in the conglomerate beam. Nevertheless, with this in mind, the stresses indicated by the model were found to give a useful guide to estimating the local stress environment at various stages of the investigation.

The modelling indicated that:

- Longwall mining significantly modifies the stresses in the conglomerate roof.
- The modified stressfield is more conducive, than the pre-existing stressfield, to generating an approximately horizontal hydraulic fracture provided the injection point is located high enough above the base of the conglomerate to avoid any tensile stress zone (5-7m).
- The modified stresses are not sufficient to immediately overload the roof strata.

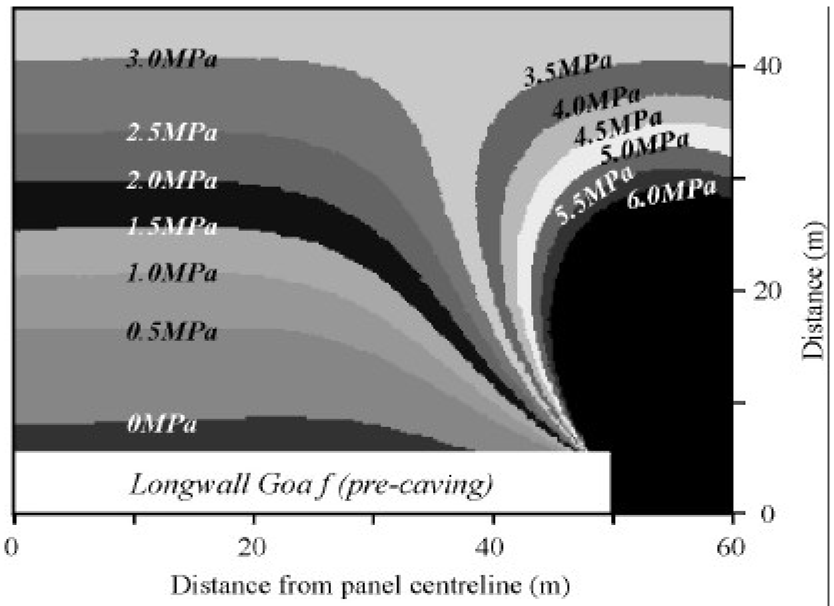

Figure 4(a) Vertical stress distribution indicated by numerical modelling prior to a goaf fall.

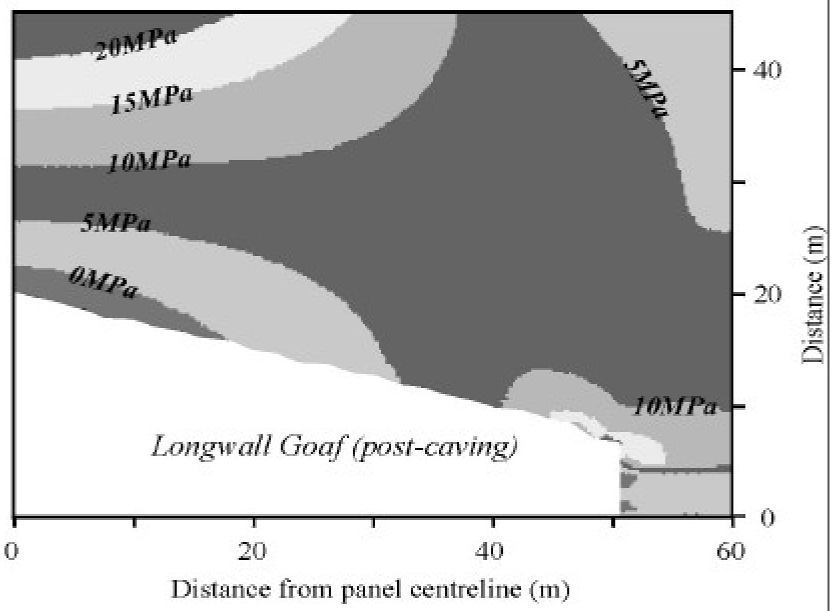

Figure 4(b) Horizontal stress distribution indicated by numerical modelling after the goaf has caved.

It was found that the stressfield indicated by the modelling was useful for interpreting the experience of breakdown pressures in both the vertical holes drilled in the initial investigation and in the horizontal injection hole used to generate the first goaf fall. Subsequent, more detailed modelling is reported in Jeffrey & Mills (2000).

Surface Investigation of Hydraulic Fracturing Parameters

A surface investigation was undertaken to determine the hydraulic fracture parameters (permeability and fracture growth rate) and to confirm that a horizontal fracture could be generated in a stress environment similar to that expected above the goaf. The surface investigation was conducted at a convenient surface location 30m from the outbye end of Longwall 2 on the panel centreline. The site offered stress conditions similar to those expected in the goaf, and had the advantage that, by working from the surface, CSIRO's high pressure pumping equipment and computer monitoring system did not need to be modified to meet intrinsic safety conditions for underground use.

The investigation was conducted using a central injection hole and three surrounding monitoring holes each approximately 110 m deep. The monitoring holes were drilled at distances of 5 m, 10 m and 13 m radially from the central injection point to intersect the top of the fallen goaf. These holes provided further confirmation that the caved zone extends to about 15m above the coal seam and an open void 2.5-2.8m high exists on top of the fallen material.

The monitoring holes were plugged at the top of the goaf and piezometers were installed to detect the arrival of the hydraulic fracture during the injection trial.

The investigation was successful in demonstrating that a horizontal fracture could be generated parallel to a free surface within 5m of that surface. The fracture initiated at a bottom hole pressure of about 5.0 MPa and propagated at a pressure of 1.4 MPa. The propagation pressure was lower than initially expected, but consistent with the stress field indicated by numerical modelling.

The fracture grew to a radius of 13 m in approximately 7 minutes at an injection rate of approximately 200 litres per minute. Based on the pressure records, the fracture appears to have grown to a radius of more than 25m by the end of the test.

Permeability tests confirmed that the natural jointing was significantly more permeable than the surrounding strata. The permeability of the conglomerate was measured in the central hole to be 0.35 millidarcy at 98m depth, but permeability in the conglomerate is expected to vary over a range from 0.01 to 5 millidarcy depending on secondary mineralisation and the existence of natural or stress-induced fractures.

Revision of the hydraulic fracture propagation model following the surface work indicated a likely injection time for the underground trials of between 50 minutes and 2 hours using water as the injection fluid. Modelling work indicated that a shorter time and greater efficiency in terms of fracture propagation rate could be achieved by the use of organic polymer gel as an injection fluid.

FIRST UNDERGROUND TREATMENT

The first underground hydraulic fracturing treatment was conducted on 30th June 1999. With approximately 55m of goaf standing, some 70,000 tonnes of conglomerate strata was induced to fall after pumping water for approximately 2 hours. The treatment was most significant in that it clearly demonstrated that hydraulic fracturing could be used to control the timing of caving events.

The success of this first treatment was particularly significant given the economic circumstances at the mine at that time (Hayes 2000). The general feeling of jubilation that was experienced when the goaf came in was quite extraordinary and will not be soon forgotten by those involved.

Approximately 40,500 litres of water was injected mainly at the mine supply pressure of 1.8 MPa. Only limited monitoring instrumentation was available during this initial treatment so it is difficult to be definitive on magnitudes. It appears that the fracture grew to about 30 m radius in 15 to 20 minutes of pumping. From that point on, fracture growth seems to have slowed down either because a natural joint was intersected or because the conglomerate beam below the fracture deflected sufficiently to absorb the additional flow.

Micro-seismic monitoring indicated an increasing flurry of activity prior to the fall that gave advanced warning of the event. A secondary fall occurred some 38 minutes later and was also preceded by a flurry of micro-seismic activity.

The actual pumping time required for the first treatment was within the expected range but at the upper end, suggesting that water may have been lost into pre-existing joints.

SECOND UNDERGROUND TREATMENT

A second hydraulic fracture treatment was carried out on July 15th, 1999. Figure 5 shows a summary plot of the pressure and convergence data recorded during this treatment.

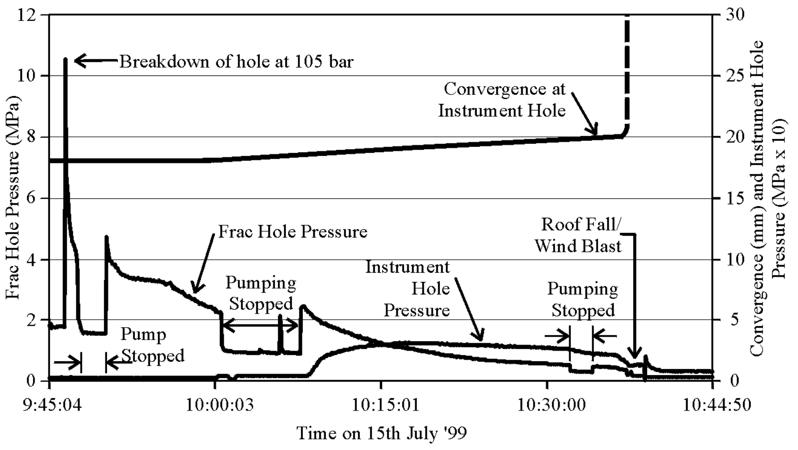

Figure 5 Pressure, flow and convergence records for second underground treatment.

The injection point detail was modified in this second treatment because of the high cost and time taken to drill a hole from the maingate. The injection hole was drilled vertically upward from the centre of the face to about 12m and connected to a high pressure hose trailed out into the goaf as the face advanced. Some 100,000 tonnes of rock (77m of standing goaf) was induced to cave after approximately 51 minutes of pumping 15,000 litres of water.

The injection points for the second treatment were installed after the longwall face advanced about 35 m beyond the previous fall. Two vertical holes were drilled into the conglomerate roof from the face. The first hole located in the centre of the face was designated as the injection hole. The second hole located 15 m along the face toward the tailgate was used as a backup injection hole and doubled as an instrumented monitoring hole. A second horizontal hole previously drilled from the gateroad was also instrumented with a pressure transducer to act as a sensing hole.

Both injection holes had a 25mm diameter injection pipe grouted into them with a short open space left at the top. Pressure monitoring tubes were run to the top of each hole to sense fluid pressure at the injection point. These tubes were connected to pressure transducers to allow monitoring of the pressure in the boreholes during the injection.

Roof to floor convergence monitoring instruments were also installed at the collar of each hole to measure the convergence between the roof and floor strata behind the face as the face advanced and during the fracture treatment. Once grouting was complete, mining resumed and the hoses and instrumentation cables were fed into the goaf as the chocks were advanced.

After about 30-35m of further advance, the injection lines were connected to the injection pump and the pressure transducers were connected to the data logging system.

A hydraulic fracture was initiated at a fluid pressure of 10.5 MPa. This breakdown pressure is consistent with the horizontal stresses acting around a vertical borehole and the tensile strength of the conglomerate strata. Once breakdown occurred, the pressure dropped rapidly at first and then more slowly as pumping continued. The pump was stopped on three occasions and on each occasion the flow rate driven by mine supply pressure increased. The goaf fell after 51 minutes of pumping.

The second treatment was more thoroughly instrumented. While clearly demonstrating the effectiveness of hydraulic fracturing as a means to induce goaf falls, it also provided useful information on the hydraulic fracturing process and general strata behaviour.

Roof to floor convergence was measured during face retreat and then during the treatment. Approximately 15 mm of convergence was measured during 30 m of longwall retreat at a point 35m from the tailgate edge of the panel. Assuming that the roof and floor movements are approximately equal in magnitude, downward movement of the roof alone is estimated to be the range 10 to 30 mm in the centre of the panel 50 m back into the goaf.

During the treatment, 2 mm of downward movement was observed until immediately before the fall when roof to floor convergence accelerated.

A pressure rise, consistent with the arrival of the hydraulic fracture, was recorded at the instrument hole 15m away from the injection point after 11 minutes of pumping water at 340 litres per minute.

DISCUSSION AND CONCLUSIONS

Since the second treatment, hydraulic fracturing from vertical holes drilled from the longwall face has become a routine part of the operation at Moonee with treatments conducted about once every 10 days.

The application of hydraulic fracturing at Moonee Colliery has provided the mine with a method of controlling the timing of caving events in the conglomerate strata. With this control has come the ability to eliminate the risk of windblast injury for men working on or around the longwall face.

The geotechnical investigation undertaken to characterise the strata conditions and understand the basic caving mechanics underpinned the successful introduction of hydraulic fracture to Moonee Colliery.

Hydraulic fracturing is a tool that has application in many mining situations. A hydraulic fracture can be created over a large distance with relatively little effort. The orientation of the fracture is controlled by the stress field at the time of fracture generation, so there are opportunities to take advantage of stress fields modified by mining if the pre-existing stress field is not suitable for the desired outcome.

This project has demonstrated that the main ingredient to successfully implementing a hydraulic fracture treatment strategy is a good understanding of the stress environment and the strata behaviour.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of the management, staff and workforce at Coal Operations Australia Ltd and Moonee Colliery. Their enthusiastic cooperation at all levels was instrumental to the success of this project.

REFERENCES

van As, A. and Jeffrey, R.G. “Caving Induced by Hydraulic Fracturing at Northparkes Mines.” Proc. The Fourth North American Rock Mechanics Symposium. 31 July – 3 August, 2000. Rotterdam: A.A. Balkema.

Cundall, P. & Board, M., “A microcomputer program for modelling large-strain plasticity problems” Proceedings of Symposium on Numerical Methods in Geomechanics, 1998 pp2101-2108

Edwards, J.L.. “Seismic Monitoring for Windblast Prediction” Seminar on Mine Seismicity and Rockburst Management in Underground Mines. Australian Centre of Geomechanics, 3-4 Sept 1998 Section 14, pp 1-4.

Haramy. K.Y., Maleki, H., & Swanson, D.. “Stress detection and destressing techniques to control coal mine bumps”. Proc. Mechanics and Mitigation of Violent Failure in Coal and Hard Rock Mines, 1995. Special Pub. 95-01, USBM. pp 201-215

Hayes, P. “Moonee Colliery: renewing the economic viability of a mine using micro-seismic and hydraulic fracturing techniques in massive roof conditions” Proceedings of the 19th Conference on Ground Control in Mining 2000.

Holt, G.E.. “Water infusion and hydraulic fracturing to control massive roof caving” Report on NERDDC project 1081, 1989 1-140.

Jeffrey, R.G. & Mills, K.W. “Hydraulic fracturing applied to inducing longwall coal mine goaf falls”. Proc. Fourth North American Rock Mechanics Symposium, 31 July 3 August, 2000. Rotterdam: A.A. Balkema.

Konopko, W., Kabiesz, J., Merta, G., Makowka, J., Szubert, S., & Zehnal, J. “Directional hydraulic fracturing and the possibilities of its utilization” Prace Naukowe 1997 GIG 824:1-33.

Mills K.W. “In situ stress measurement using the ANZI stress cell” Proceedings of the International Symposium on Rock Stress, 1997 eds K. Sugawarra & Y Obara Kumamoto pp149-154.

Pan, Q., Xin, Y., Wang, S., & Niu, X.. “The application of the research on rock properties and micro-structure to coal mining engineering” Proc. 5th Congress of the ISRM, Melbourne1 0-15 April, 1983. 1:41-44. Rotterdam: A.A. Balkema.

Summers, J.W. & Wevell, E. “A study to determine the feasibility of high pressure water infusion for weakening the roof”. Proc. 2nd AAC Mining Symposium 1985 pp 197-205.