Mechanics of Rib Deformation—Observations and Monitoring in Australian Coal Mines

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ABSTRACT

The risk of fatalities from rib failure is still prevalent in the coal mining industry. This risk has prompted further research to be conducted on rib deformation in order to understand the mechanisms of rib failure, with the long-term objective being to improve rib support design. This paper presents the results of ACARP research project C25057, which investigated the mechanics and drivers of rib failure. The results of rib deformation monitoring at three different mines in Australia provides rib deformation characteristics for overburden depths ranging from 160 m to 530 m. Monitoring includes deformation during development drivage conditions and during the longwall retreat abutment stress environment. The rib deformation monitoring covered three different seams: the Goonyella Middle Seam, Ulan Seam, and Bulli Seam in the Bowen Basin, Western Coalfield, and Southern Coalfield, respectively. The observed mechanisms driving the rib deformation ranged from bedding shear failure along weak claystone bands to vertical shear fractures to kinematic failures driven by shear failure dilation. The variation in mechanisms of rib failure, together with the seemingly consistent method of rib support design, prompts the question: What exactly is the role of rib support?

INTRODUCTION

The current risk of rib fatalities in the coal mining industry has prompted further research into understanding the mechanisms of rib failure. Three Australian mines assisted further research by providing sites for rib deformation studies as part of the Australian Coal Association Research Program (ACARP) project C25057. The mines included in this study were Moranbah North Mine, Ulan West Mine, and Appin Mine. This paper provides key results of the rib deformation monitoring relevant to assessing the mechanisms of rib deformation.

The approach of monitoring rib deformation and rib support loads was used to measure and characterise the dynamic rib deformation present in both development and longwall retreat stress environments. The characterisation of rib deformation, together with rock failure modelling, was used to determine the mechanisms for failure within the rib and to assess the interaction of rib support with the failure process. The mechanisms of rock failure are considered an important factor in understanding the drivers for the failure. Consideration of the site-specific failure mechanisms can provide for a more tailored support design.

MECHANICS OF RIB FAILURE

In underground coal mining, the types of rib failure typically include kinematic failures, such as planar, wedge and toppling failures, or stress driven failures, such as shear failure and buckling. These failure types can occur in isolation or in combination with each other.

These failure types, however, are often the result of more complex rock failure mechanisms. For example, a wedge of rib may not only be driven by discontinuities, such as cleat and bedding, but may be a combination of

- Discontinuities including cleat and bedding
- Shear stress localised on a non-coal band within the rib acting to fail on the bedding of the non-coal contact and therefore reduce the strength of the bedding
- Vertical stress-driven shear fractures creating dilation within the rib to push out the wedge

There are a number of factors that directly influence the rib failure mechanisms and the ultimate rib stability. These key factors include

- Rib height
- Cleat and joint network
- Mining induced fractures
- Stress (vertical, tributary and abutment loads; 3D stress—σ_1, σ_2, σ_3)
- Coal strength
- Presence of weak contacts (e.g., bedding, claystone bands, mylonite)
- Roof and floor lithology and stiffness
- Reinforcement or skin confinement
- Roof and floor deformation (physically interacting with the rib)

There are also indirect factors that influence rib stability primarily due to their impact on stress distribution and stress driven deformation. Some of these indirect factors include

- Direction of mining
- Pillar geometry
- Seam depressurisation
- Roof and floor deformation (redistributing stress)

Understanding the drivers of failure mechanisms is highly beneficial in providing the best rib support design. This may also highlight the current limitations in rib support methodology to proactively support the correct failure mechanism for the ribs.

LITERATURE REVIEW

There is limited literature available on the field measurement and characterisation of the mechanics of rib deformation in Australian coal mines. The majority of public domain data is from industry research and is presented in Fabjanczyk, Tarrant, and Guy (1992), Gale and Fabjanczyk (1999), and Colwell (2006). A summary of the coalfields, coal seams, and mines with this published data is presented in Table 1. The data presented in this paper provides public domain rib deformation measurements for two seams not represented in this dataset: the Goonyella Middle Seam and the Ulan Seam. The Bulli Seam monitoring in this research represents increasing overburden depth, which is a common scenario that many mines increasingly face as shallow resources deplete.

FIELD MONITORING PROGRAM

A rib and roof monitoring array was implemented at all sites to define and measure the progression of deformation in response to the dynamic mining process on both development and longwall retreat. One longwall retreat site involved two sites, one mid pillar and the other at the approach to an intersection, to observe possible variation.

The instrumentation array in the ribs consisted of extensometers (measuring lateral strain), horizontal strain gauged shear strips (measuring vertical shear in the rib), and instrumented rib bolts. Roof deformation was also monitored using extensometers. The extensometer type varied between sites and consisted of sonic extensometers, Tell Tales, or GEL extensometers. Often two extensometers with four or five anchors were installed to monitor an 8-m-depth profile to increase the location detail. Different extensometer types were also installed for redundancy.

The development instrumentation was installed 3 to 5 m from the face and monitored during roadway advance. The longwall instrumentation array was installed ahead of the longwall abutment loading and monitored during the approaching and passing of the longwall. An example instrumentation array for the development and longwall sites is presented in Figure 1.

Table 1. Summary of Australian coal mines with rib measurement data.

Basin	Coalfield	Mine	Seam	Data Source
Sydney Basin	Southern Coalfield	Westcliff Colliery	Bulli Seam	Fabjanczyk, Tarrant, and Guy, 1992; Colwell, 2006
		South Bulli	Bulli Seam	Fabjanczyk, Tarrant, and Guy, 1992
	Western Coalfield	Springvale Colliery	Lithgow Seam	Gale and Fabjanczyk, 1999
		Angus Place Colliery	Lithgow Seam	Fabjanczyk, Tarrant, and Guy, 1992; Colwell, 2006
	Newcastle Coalfield	West Wallsend Colliery	West Borehole Seam	Colwell, 2006
		Wyee State Mine	Fassifern Seam	Fabjanczyk, Tarrant, and Guy, 1992
Bowen Basin	Bowen Basin	Oaky North Colliery	German Creek Seam	Colwell, 2006
		Oaky No. 1 Colliery	German Creek Seam	Colwell, 2006
		Kestrel Colliery	German Creek Seam	Colwell, 2006
		Crinum Mine	Lilyvale Seam (LV0) (German Creek equiv.)	Gale and Fabjanczyk, 1999; Colwell, 2006

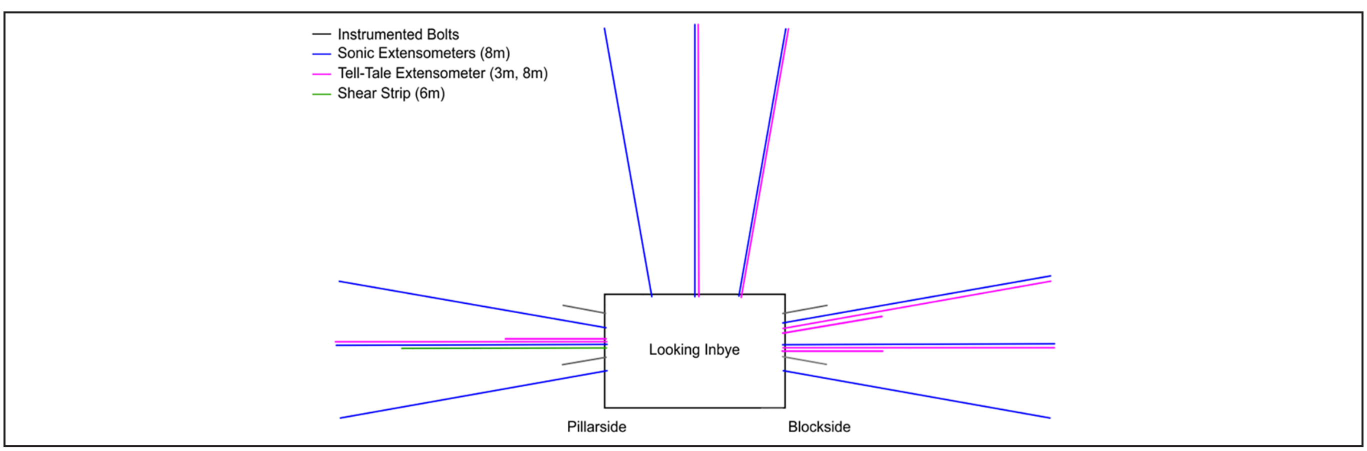

Figure 1. An example of the instrumentation layout used across the monitoring sites.

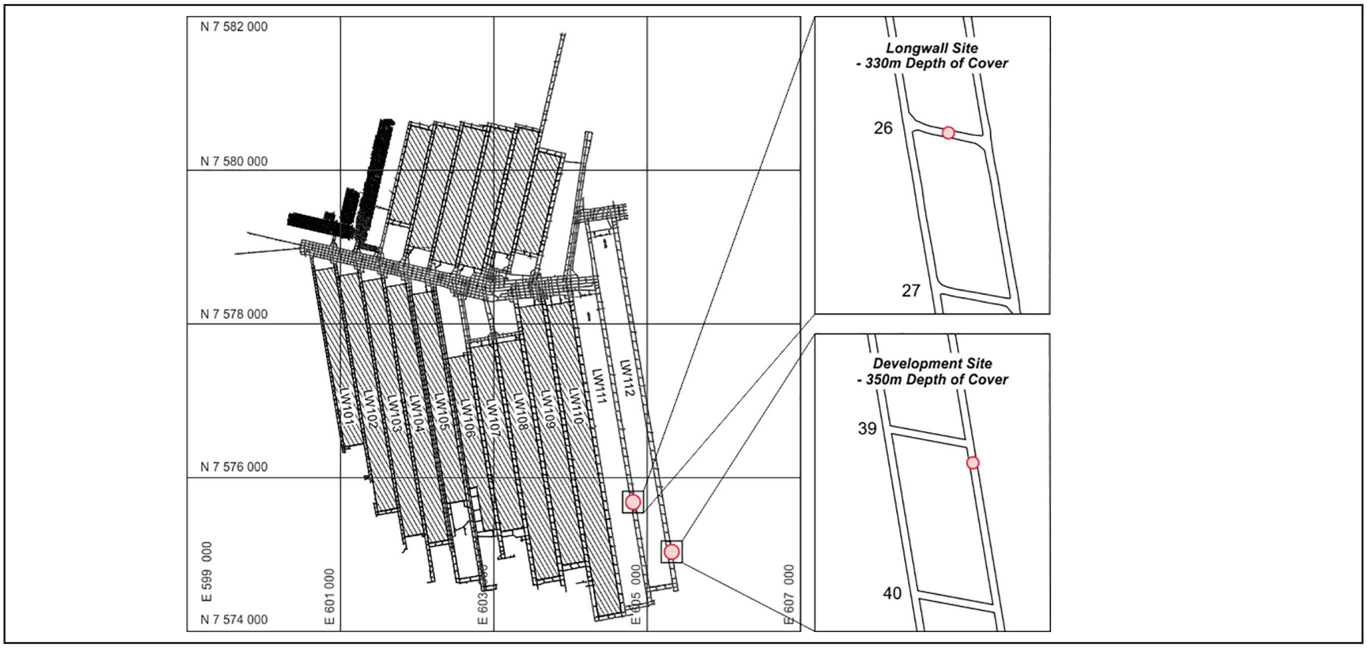

Figure 2. MNM mine plan and rib monitoring site locations (Heritage, 2018).

MORANBAH NORTH MINE

Moranbah North Mine (MNM) in located 16 km north of Moranbah in the Bowen Basin, Australia. MNM mines the Goonyella Middle Seam, a 5.5- to 6-m-thick seam with a mining horizon that leaves approximately 0.5 m of coal in the floor and 1.5 to 2 m of coal in the immediate roof. The coal roof makes for minimal stress and deformation in the roof. The MNM mine plan and location of monitoring sites are presented in Figure 2.

The rib deformation at MNM was monitored on development and retreat. Both monitoring sites under different stress environments of tributary and abutment loading scenarios indicated rib deformation driven by bedding shear activation of the Tonstein Band (a 10- to 20-cm claystone band located approximately 1 m above the floor).

Development Monitoring Site

Minimal deformation was observed at the development monitoring site. The instrumented bolts, shear strips, and sonic extensometers all showed deformation occurring to a maximum of 1.1 m into the rib, with magnitudes less than 15 mm, with deformation focussed in the lower part of the rib. This deformation profile was consistent during the first 30 m of continuous miner advance.

A subsequent survey was conducted on the development site approximately two weeks after the previous survey, when the continuous miner was more than 200 m past the monitoring site. This survey showed a step change in deformation. The middle and lower rib bolts showed an increase in load, with a higher load change in the lower rib bolts. The shear strip showed an increase in depth of softening and an overall change in direction of movement in the rib from upwards to downwards (relative to further into the pillar). Figure 3 and Figure 4 show the changes in rib bolt loads and vertical shear into the rib after 30 to 200 m of continuous miner advance.

Changes in rib behaviour significantly after the initial dynamic stress changes of development, are caused by further stress changes or time-related changes in rock properties. As the longwall was more than 1.5 km from the development monitoring site, it was inferred that the changes likely be due to water and clay activity in the Tonstein Band. Rib spall is often observed at and below the Tonstein Band at MNM significantly outbye of the initial drivage. The monitoring observations of delayed rib deformation could explain the rib spall experience at MNM.

Longwall Retreat Monitoring Site

The longwall monitoring site was located in a cut-through in the centre of the pillar. Although the abutment load gradually increased on the chain pillars, the deformation in the ribs occurred as a step change. The inbye and outbye ribs acted independently of each other due to the different average pillar loads in relation to the location of the longwall face.

The inbye rib was first to experience a step change in deformation behaviour. Before the step change, the inbye rib showed a depth of softening to 1.6 m, with a magnitude of displacement of 10 mm. The step change occurred when the longwall face was parallel with the monitoring site. At this time, the lower extensometer sheared off at the location of the Tonstein Band, while the depth of softening increased to 4 m, and the magnitude of rib displacement increased to 65 mm. A similar step change was observed in the outbye rib; however, all extensometers sheared off at a depth greater than the depth of softening prior to the step change.

The extensometer data for the longwall retreat site is presented in Figure 5, and the shear strip data is presented in Figure 6. Detail of the additional instrumentation can be found in Heritage (2018). The interpretation summary of the deformation about the roadway for the longwall retreat conditions is presented in Figure 7.

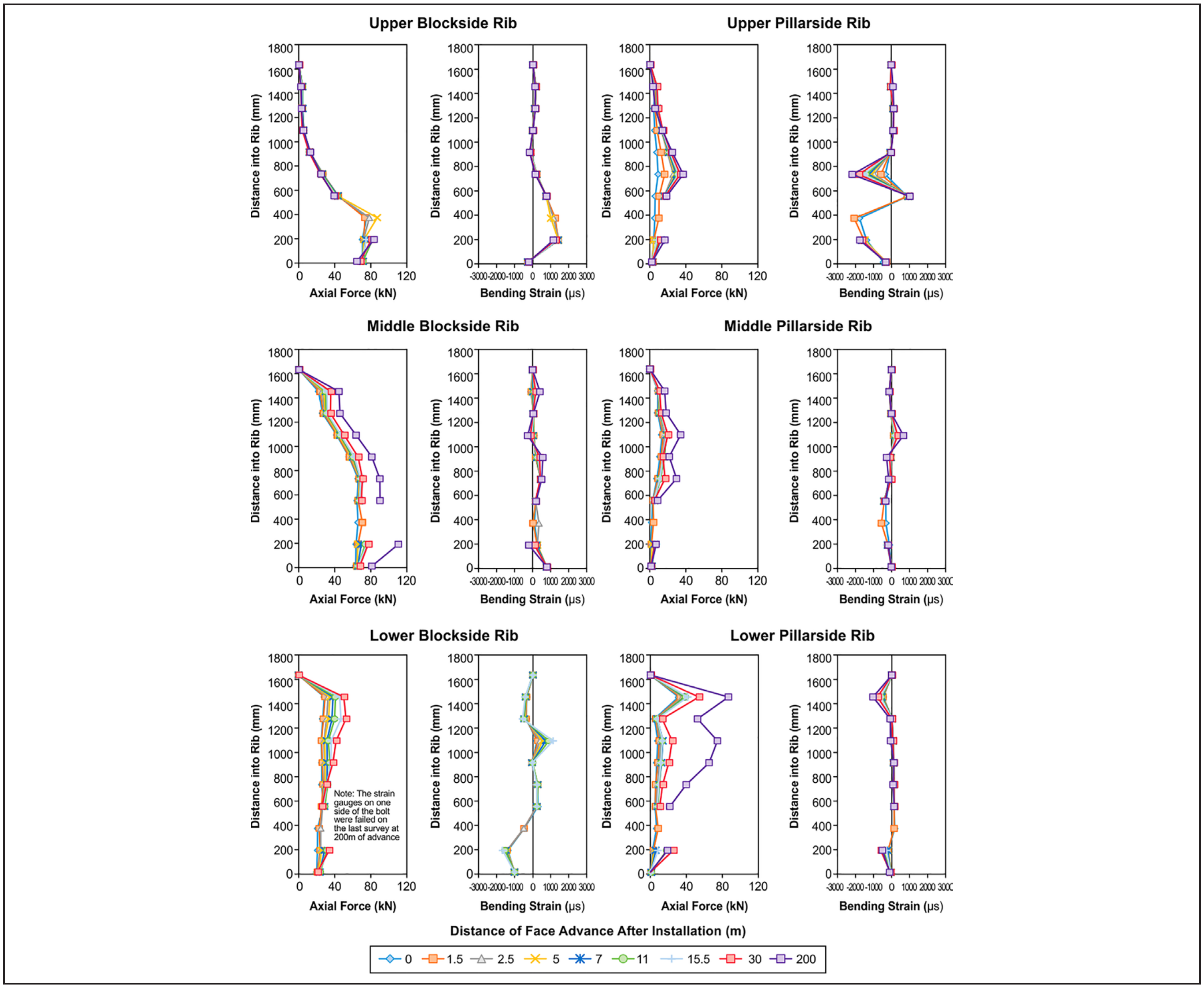

Figure 3. Bolt loads for the MNM development site (Heritage, 2018).

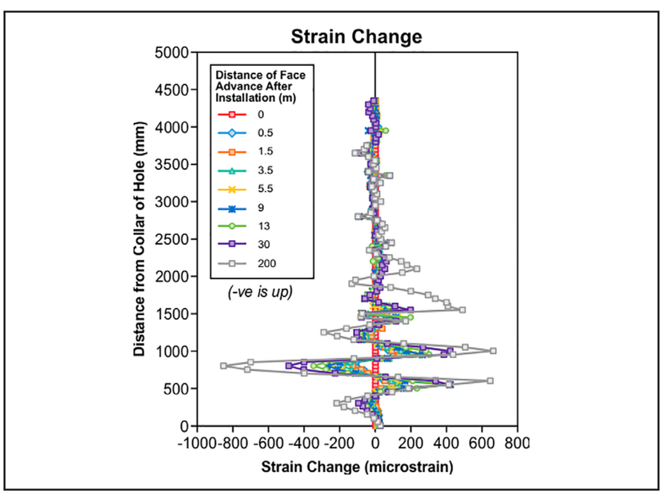

Figure 4. Shear strip data for the MNM development site (Heritage, 2018).

Mechanisms of Rib Deformation at MNM

The drivers of increased rib deformation at MNM is inferred to be the shear activation of the Tonstein Band. Whether that is water and clay activity on development or bedding shear failure due to shear stress in an abutment load scenario, the lower rib appears to deform significantly in relation to the stability of the Tonstein Band. The mechanism of rib deformation begins with bedding shear failure of the Tonstein Band, which reduces the ability for the rib to generate confinement. The reduction in confinement of the rib then reduces the overall strength of the rib. This reduction in strength causes failure to develop further into the rib.

ULAN WEST MINE

Ulan West Mine is located in the Western Coalfield of New South Wales, Australia, approximately 50 km northnortheast of Mudgee. Ulan West Mine extracts the Ulan Seam, an approximate 9-m-thick thermal coal seam. The seam consists of a number of claystone bands throughout. The overburden depth range for the monitoring sites at Ulan West is 160 to 200 m. The mine plan and site locations

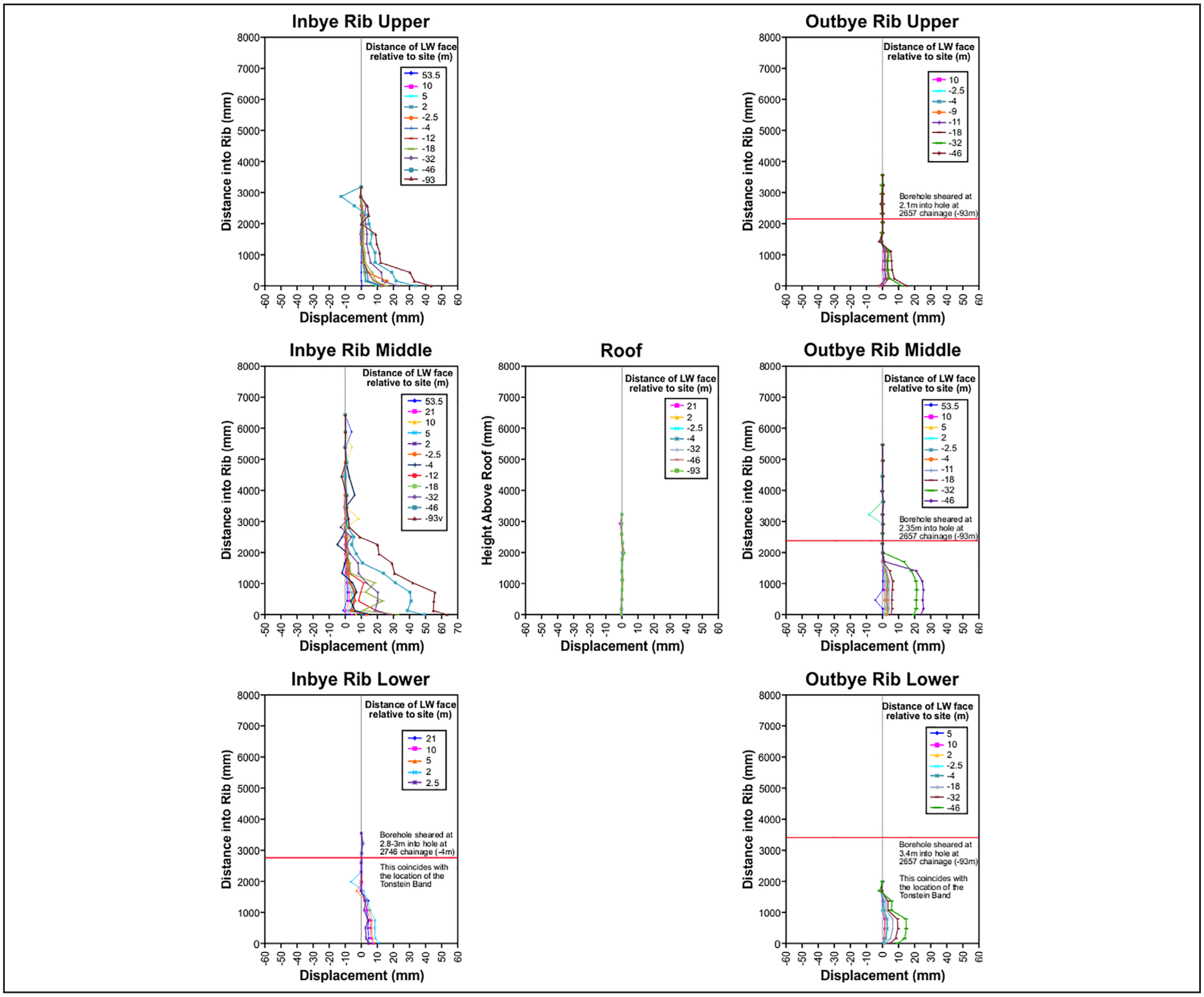

Figure 5. Extensometer data for the MNM longwall site (Heritage 2018).

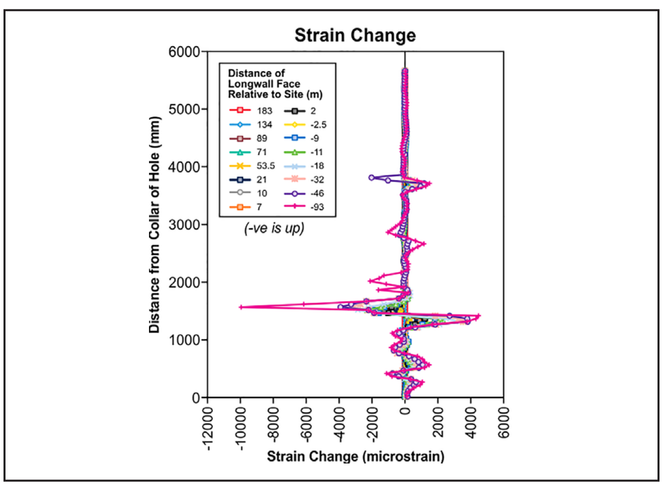

Figure 6. Shear strip data for the MNM longwall retreat site (Heritage, 2018).

for development and retreat scenarios are presented in Figure 8. The longwall site is located in the maingate belt road.

For a shallow mine, such as Ulan West Mine, deformation is not typically caused from a high-stress environment. The development site showed negligible deformation in both the roof and ribs and minor bolt loads. The longwall monitoring site showed the onset of rib displacement due to longwall retreat at approximately 55 to 90 m from the longwall face. (The range is due to the interval between surveys.) Roof deformation was negligible up to 5 m from the longwall face, where it then increased up to 5 mm to the face. The longwall site showed different deformation mechanisms on the block side and pillar side ribs.

The block side rib showed thin slabbing in the upper portion of the rib. This thin slabbing may be attributed to tensile failure of the skin. The extensometers in the block side rib showed greater displacements occurring in the upper rib compared with the mid-rib, with the majority of the displacement in the 0 to 0.5 m interval.

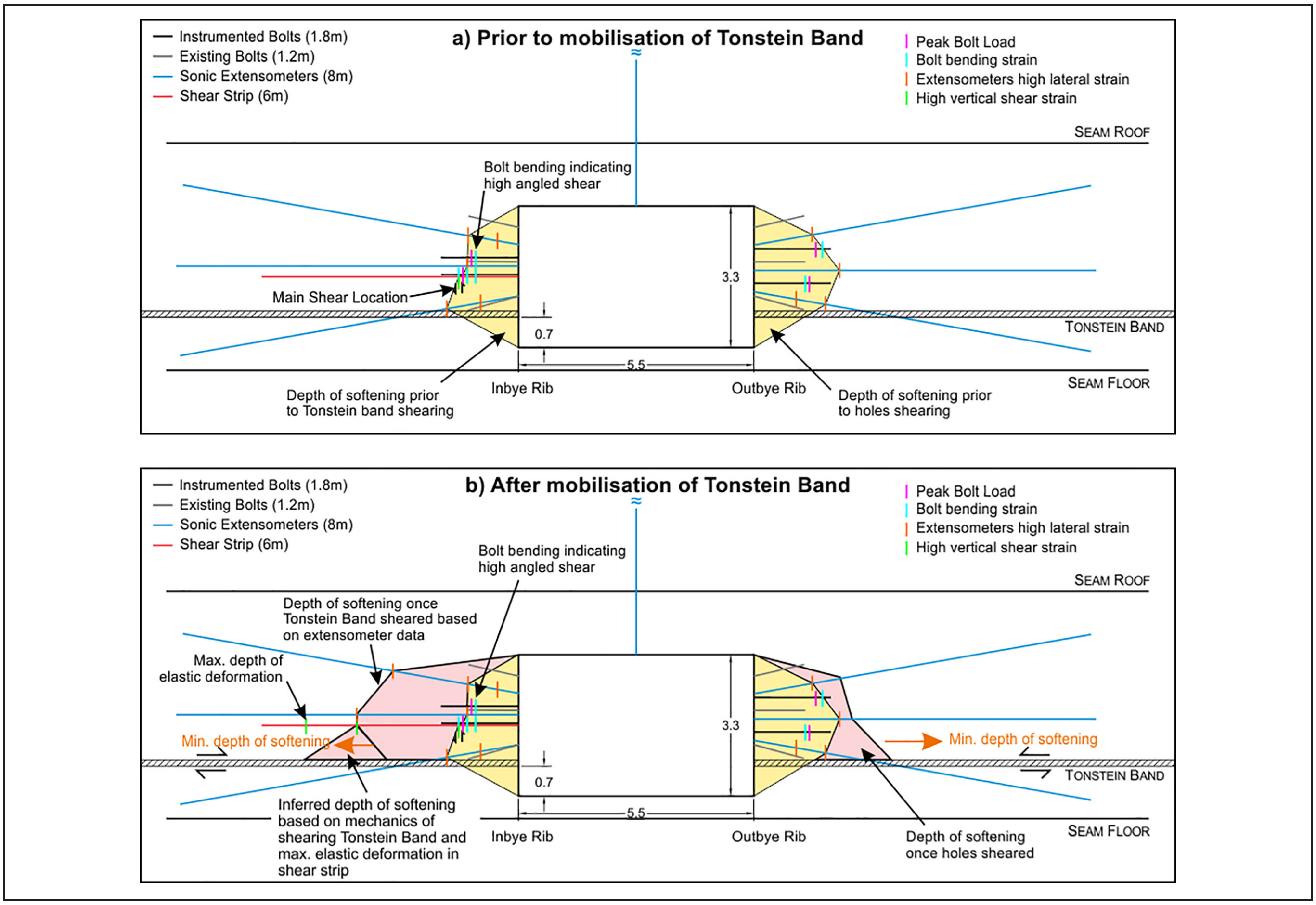

Figure 7. Interpretation of the MNM longwall retreat site deformation (Heritage, 2018).

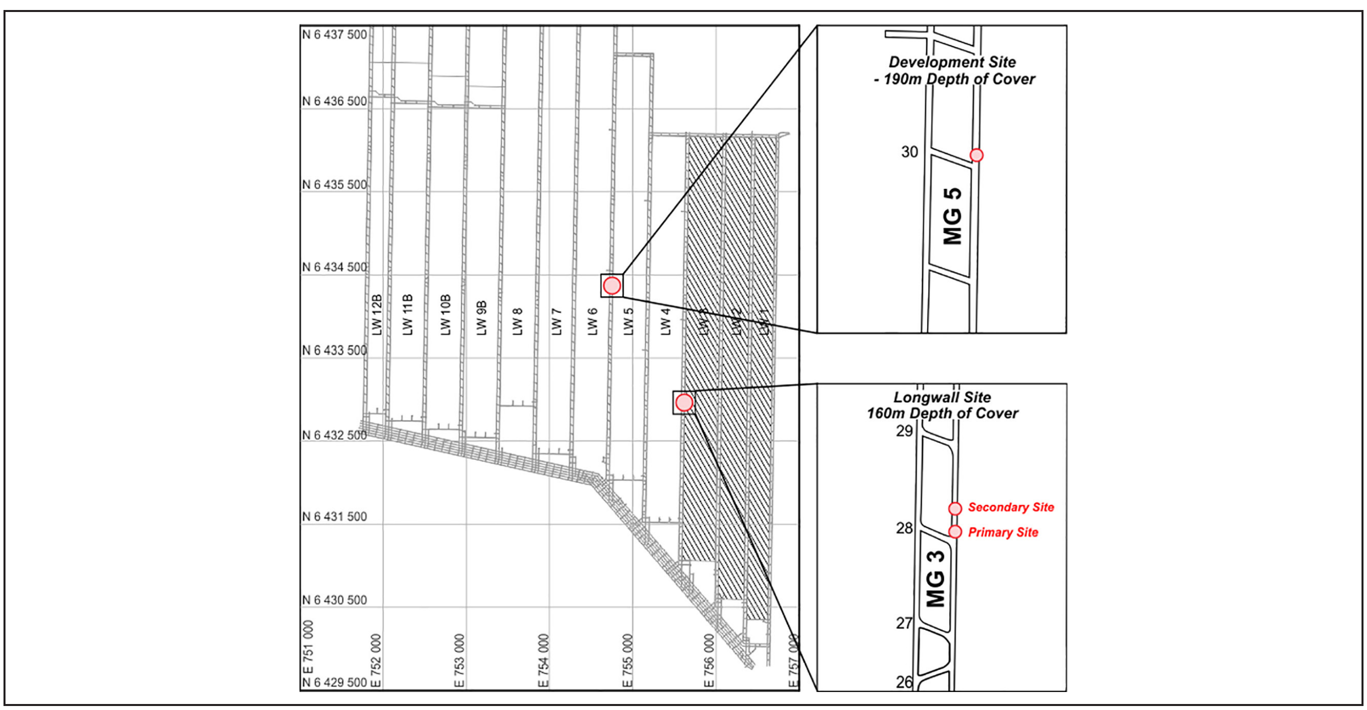

Figure 8. Ulan West Mine plan and rib monitoring site locations.

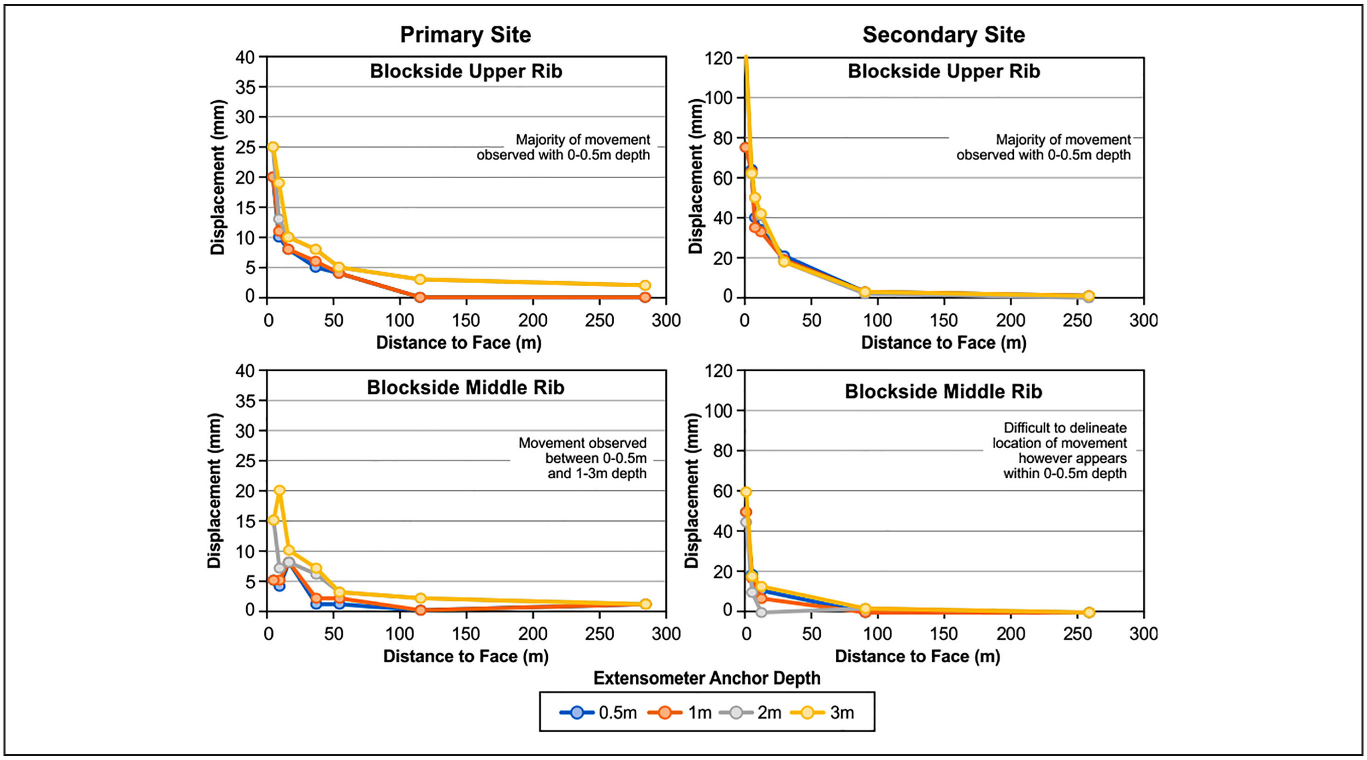

Figure 9. Rib extensometer data in relation to face distance for the longwall block side rib at Ulan West Mine.

Figure 9 shows a summary of the block side rib extensometer data in relation to the longwall position.

The pillar side rib showed a significantly different mechanism of rib deformation to the block side. Slabbing of the lower rib was observed within 15 to 20 m of the longwall face. Slabs formed between two coal joint faces and a fracture plane that formed at the back of the slab. The upper bound of the slab was typically a bright coal band. The pillar side slabs formed with only 2 to 3 mm of rib displacement observed on the rib extensometers. Figure 10 shows the extensometer data for the pillar side lower extensometer in the rib horizon where the slabs form. The pillar side slabs occurred approximately every 5 m, coinciding with the locations of coal joint discontinuities forming boundaries of a slab. Other observations during longwall retreat were the distinct sounds of shear fractures propagating in the pillar side rib during longwall retreat.

Further investigation into the kinematic failure producing slabbing on the pillar side rib highlighted the fractures at the back of the slab were fresh mining-induced fractures with compressive vertical displacement. The back of the slab consisted of multiple fractures with high-angle fracture planes. These fractures were observed to occur at a minimum depth into the rib of 0.3 to 0.5 m into the rib. Both the high angle of the fractures and the compressive vertical displacement indicate that these fractures were formed by shear failure: both confined and back-of-the-envelope shear failure (shear failure where the minimum stress is tensile). A complex combination of failure modes were observed and included combinations of shear failure, back-of-the-envelope shear failure, and additional local tensile failures resulting from shear failure dilation.

Photos of the pillar side slabs bounded by coal joint discontinuities and shear fractures at the black of the slabs are presented in Figure 11. The photos also highlight the horizontal tensile failure of the skin where slabbing does not occur between coal joints. This tensile failure may first appear to be buckling; however, the observed shear fractures and dilation within the rib indicate that these are tensile fractures driven by the dilation further into the rib.

The slabbing observed on the pillar side rib is inferred to be driven by the abutment load forming shear fractures approximately 0.3 to 0.5 m into the rib. The shear fractures then dilate as they compress. This dilation pushes out the slab only where weak discontinuities are present, in this case, between two conjugate coal joints.

APPIN MINE

Appin Mine is in the Southern Coalfield of New South Wales, Australia, approximately 30 km northwest of Wollongong. Appin Mine extracts the Bulli Seam, an approximate 3-m-thick coking coal seam. The roof typically consists of sandstone or interbedded siltstone and an interbedded mudstone, siltstone, and sandstone floor. At the location of the site, a typical 3-m-high roadway was driven, before the floor was brushed, leaving approximately 0.7 m of stone in the floor. The rib, therefore, consisted of approximately 3 m of coal and 0.7 m of stone at the base of the rib. The mine plan and site location are presented in Figure 13. The monitoring site location was in the maingate belt road of LW707B at an overburden depth of approximately 530 m.

The rib condition at the monitoring site was in typically good condition. The block side showed some spall that occurred on drivage and was supported by the primary rib support. The total

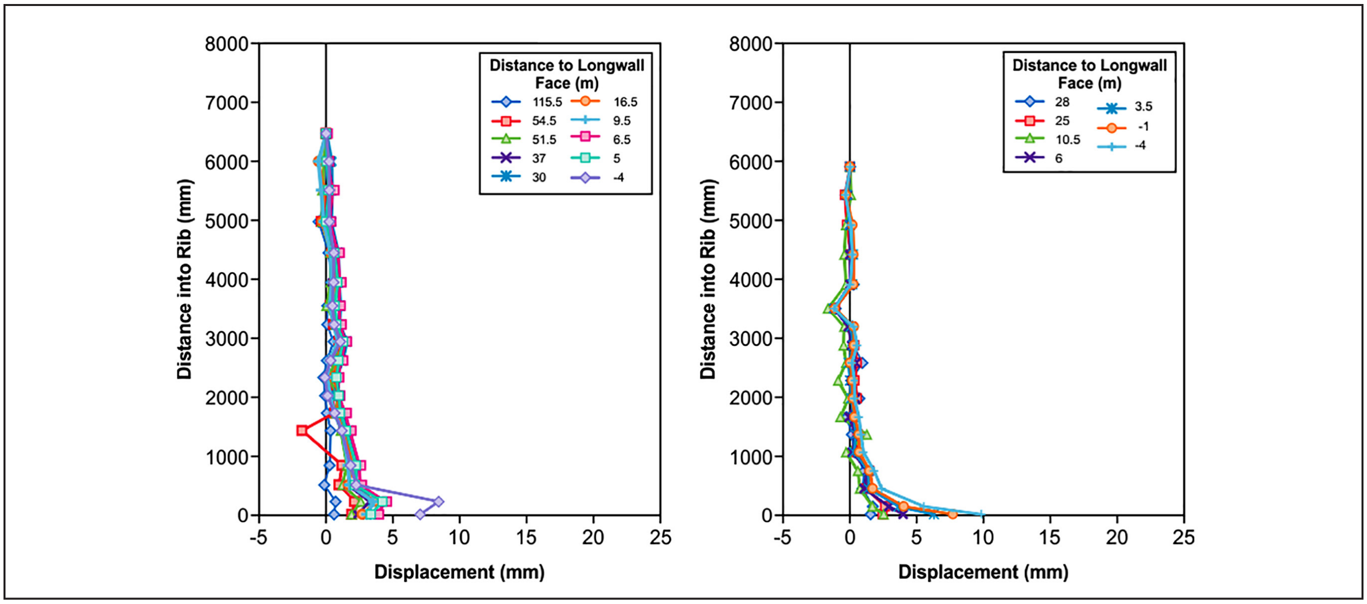

Figure 10. Rib extensometer data for the Ulan West Mine longwall site showing the pillar side lower rib deformation.

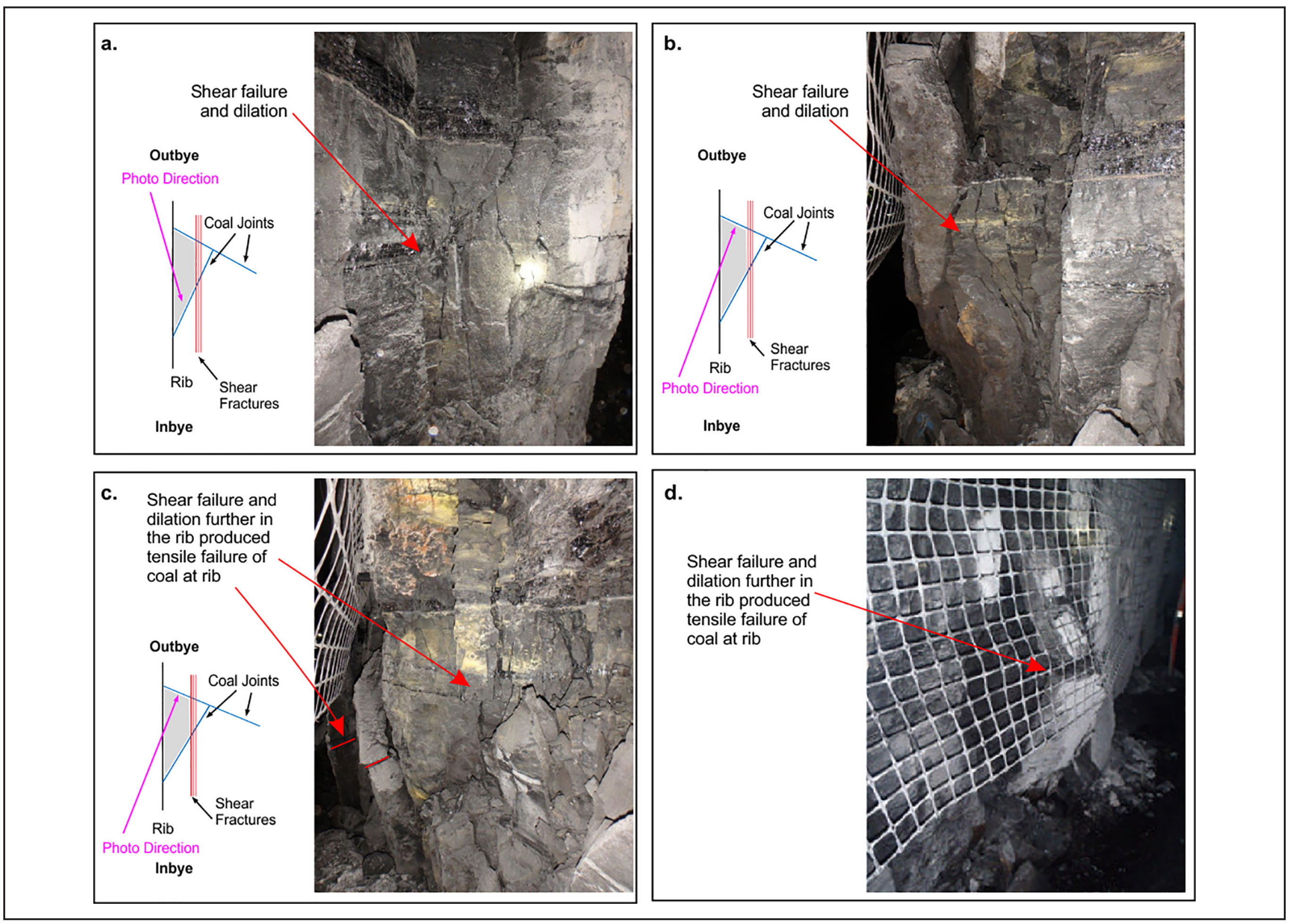

Figure 11. Ulan West Mine longwall site photographs showing shear failure at the back of slabs a) Example slab 1—photograph looking inbye b) Example slab 1—photograph looking outbye c) Example slab 2—photograph looking outbye d) Photograph of surface tensile cracks when a slab has not formed.

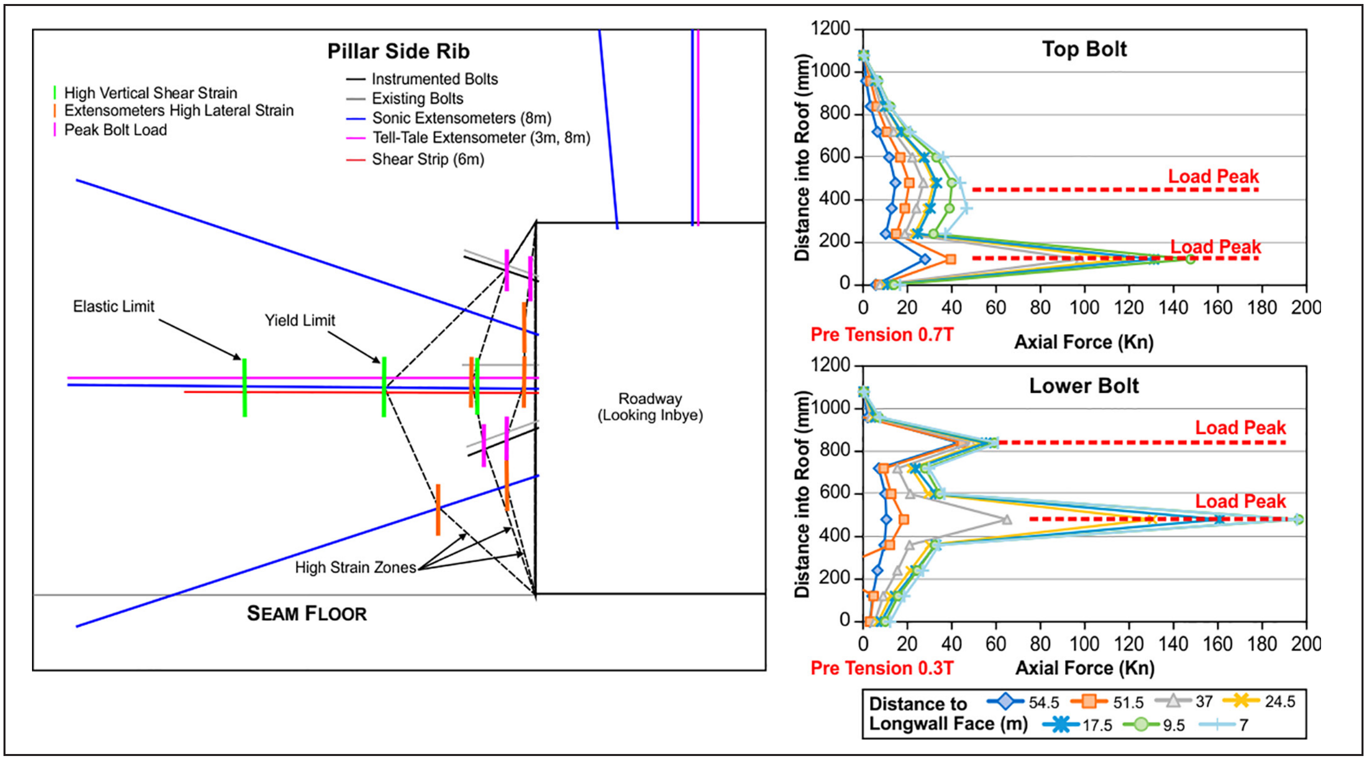

Figure 12. Ulan West Mine longwall site monitoring data showing zones of peak strain observed from extensometers, instrumented bolts and shear strip.

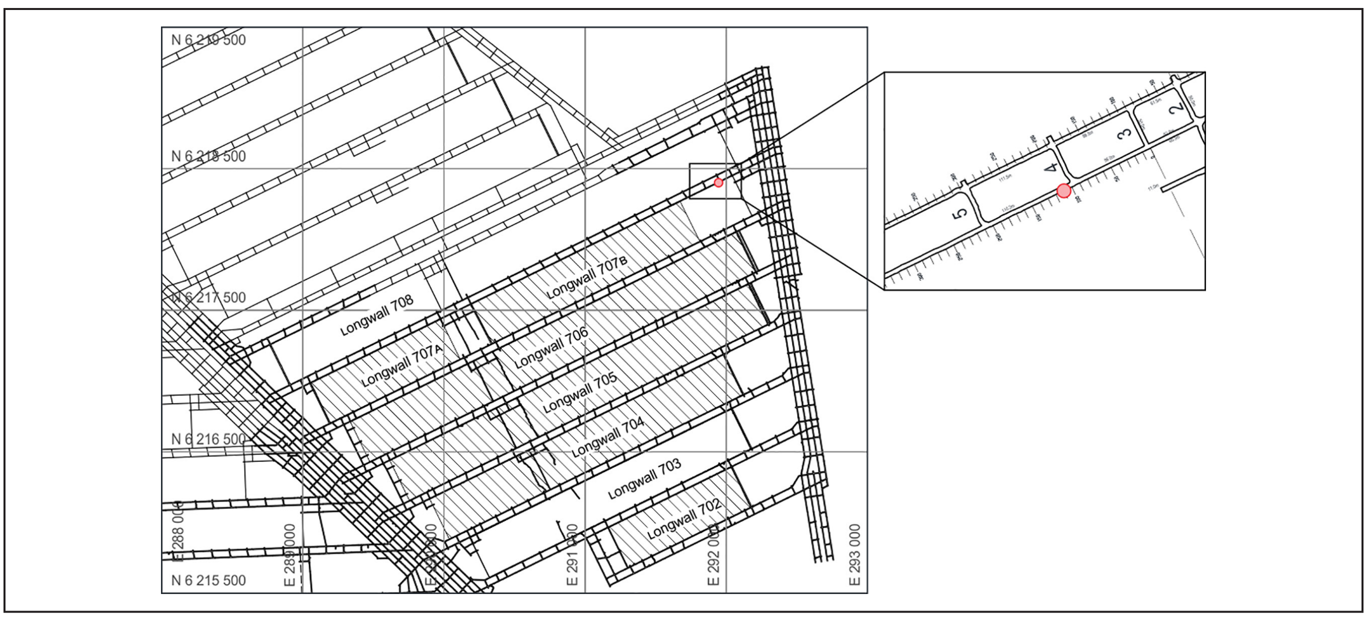

Figure 13. Appin Mine plan and rib monitoring site location.

primary and secondary support installed in the ribs included four cuttable bolts per meter on the block side and three steel 1.8 m bolts per meter plus two 2 m cables per two meters on the pillar side. The monitoring instrumentation was installed when the longwall face was 350 m from the instrumentation site.

Observations of the rib conditions during longwall extraction were minor bulge in the upper portion of the rib; minor fretting was observed at the top, and very minor spall occurred at the base of the ribs. The rib bulge was approximately 200 mm at 15 m from the face and increased up to 400 mm near the face. This rib bulge occurred between the top two rib bolts on the pillar side and

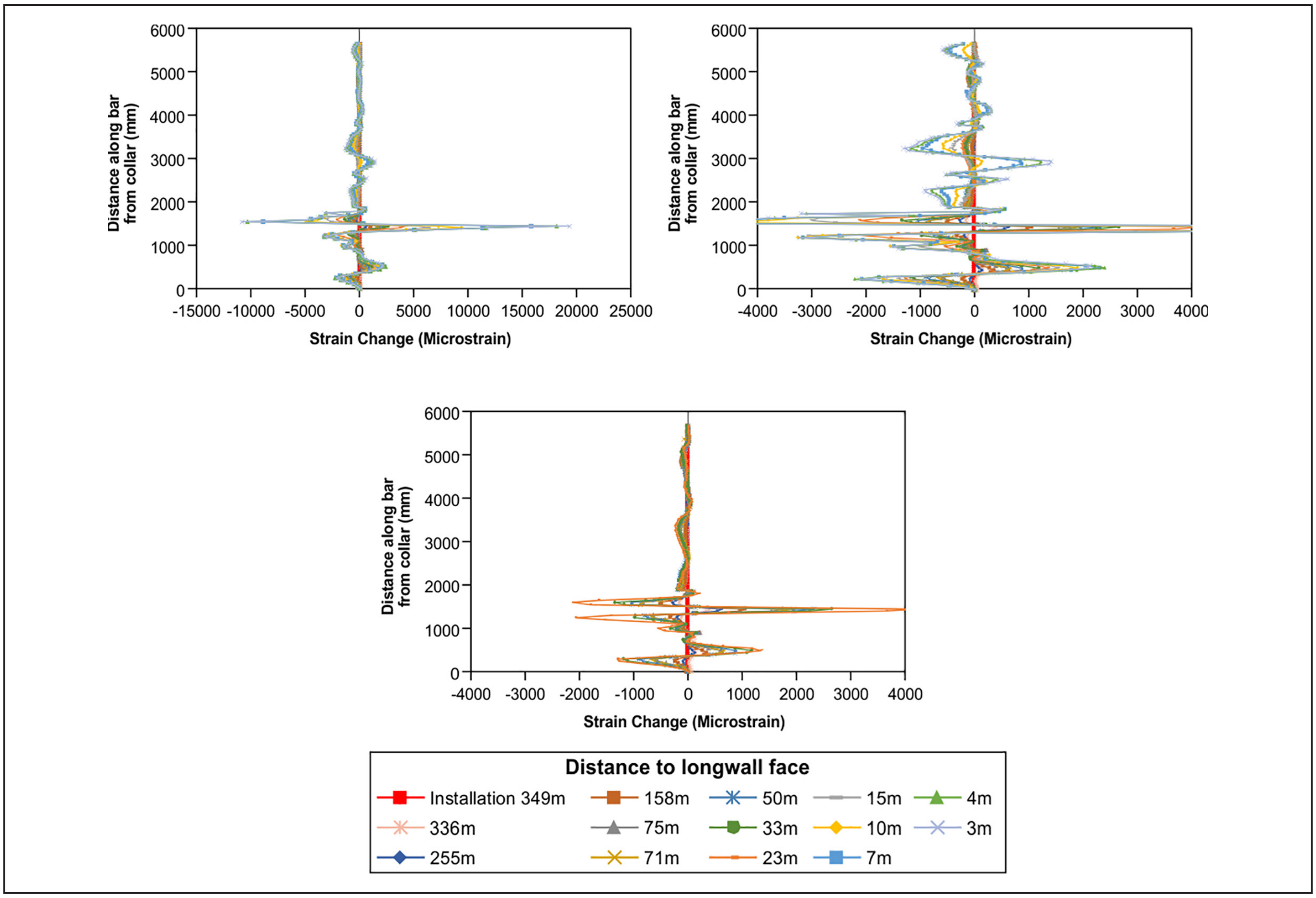

Figure 14. Shear strip data for the Appin Mine longwall retreat site.

between the middle two rib bolts on the block side. The bolts did not appear to move considerably with the bulge, indicating this bulge to be relatively shallow.

The mechanism for deformation within the ribs was observed to be shear failure occurring to at least 6 m into the ribs. The key stages of the rib deformation observed form the monitoring include

- A zone of high strain prior to longwall extraction to 1.8 m into the rib
- Deformation on existing failure planes to 6 m into the rib after installation of instrumentation (longwall distance of 150 to 350 m from the site).
- Multiple new failure planes between 2 m and 6 m into the rib once the longwall was 15 m from the instrumentation site

The shear strip data from the pillar side rib is presented in Figure 14 and shows the above described stages of vertical shear deformation within the rib. The top left figure in Figure 14 shows the vertical shear strain for all the monitoring data, relative to the end of the shear strip at 6 m into the rib. This figure shows vertical shear locations occurring along the entire 6 m length of the shear strip. The top right figure is a smaller scale to observe the smaller shear displacements along the shear strip. The bottom figure shows the shear strain for the longwall up to 20 m from the instrumentation site. Comparison of the two detailed figures shows that new shear fractures appear between 2 and 6 m from the rib, when the longwall is at 15 m from the site.

The extensometer data about the roadway supports the high-strain zone to 1.8 m into the midrib. The midrib extensometer data is presented in Figure 15 and shows an increase in rib deformation at approximately 20 to 30 m from the longwall face. Smaller lateral displacements are observed beyond a 20 to 30 m face distance, which supports the early movement on existing failure planes observed on the shear strip.

Figure 16 illustrates the interpretation of the high-strain zone in the near rib in addition to the extent of deformation observed to the limit of monitoring. The shear strip limit was 6 m into the rib, with strain observed at the end of the shear strip, while the extensometers (GEL extensometers and Rock-Its) observed small displacements between the 6 and 8 m anchors. This infers that the extent of deformation extends to a minimum of 6 to 7 m into the rib.

Further investigation into the shear displacements of the shear strip show the displacements of shears within the rib are typically a result of upwards rib movement relative to further into the rib, followed by the formation of a shear plane with the rib side block shearing downwards. This shear strip data indicates that

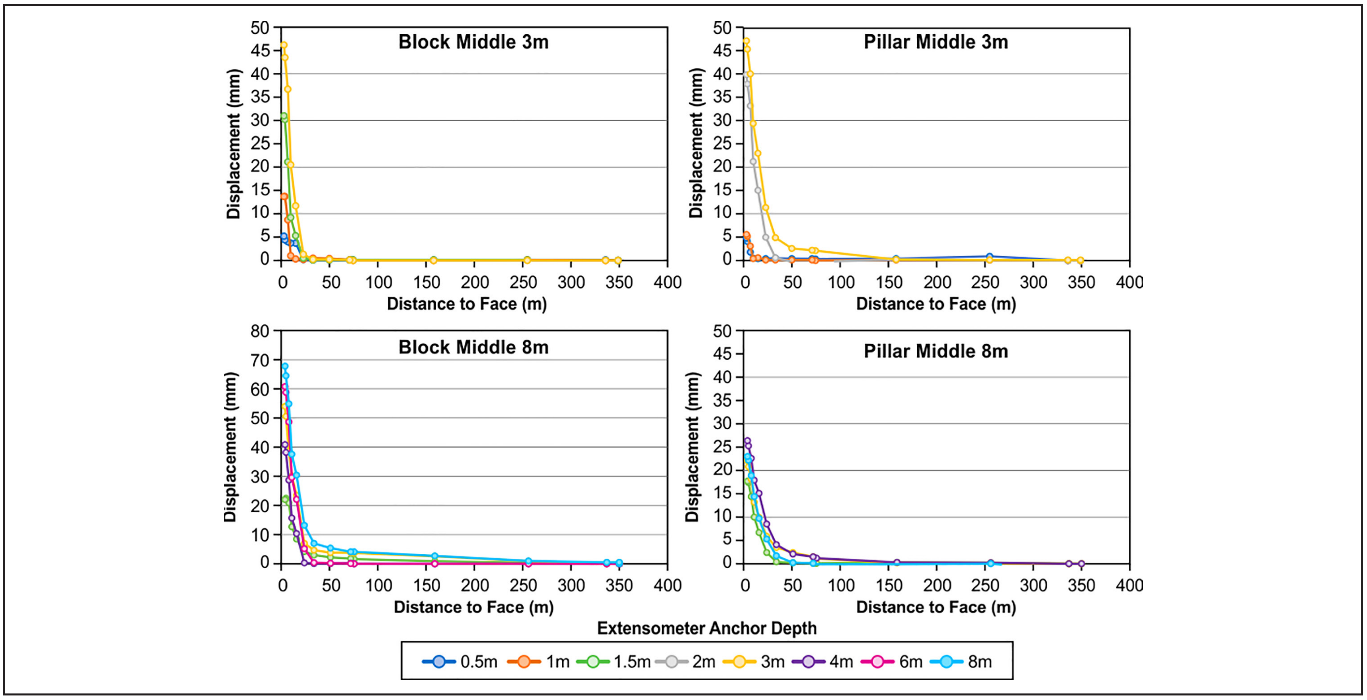

Figure 15. Rib extensometer data in relation to face distance for the mid-pillar ribs at Appin Mine.

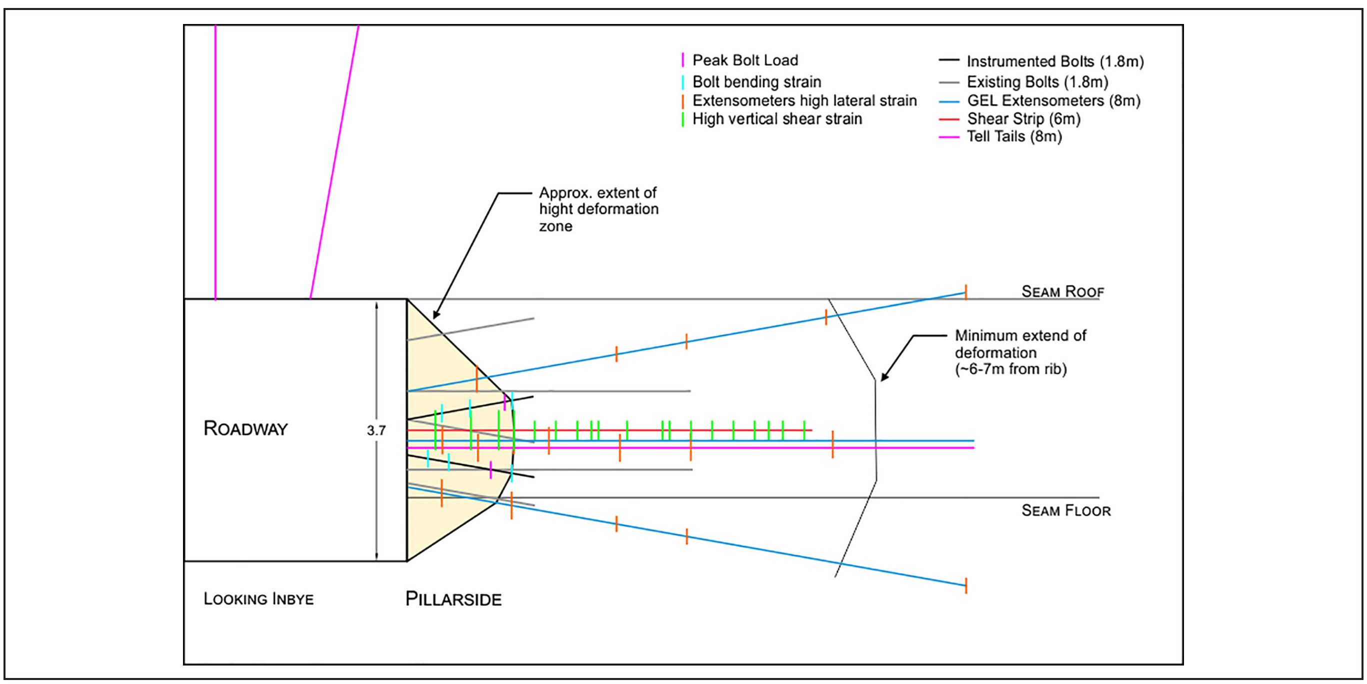

Figure 16. Interpretation of the Appin Mine longwall retreat site deformation.

the abutment load is increasing further into the rib and that the abutment load peak is, therefore, deeper into the pillar than the shear strip is installed, nominally 6 m.

DISCUSSION: WHAT IS THE ROLE OF RIB SUPPORT?

Rib support in most Australian Coal mines is systematically installed at depths greater than approximately 150 to 200 m overburden depth. The rib support design typically has a density of 1.5 to 3 bolts per meter for typical roadway heights of 3 to 3.5 m. Increased secondary support often introduces tendons to approximately 4 m into the rib. The geometry of rib support design is fairly consistent across Australian mines. The main variations in rib support design patterns are the density of bolts, number of bolt rows, and the geometry of a star or grid bolting pattern, notwithstanding the bolt type and bolt length. Mesh is typically a key part of rib support design where any form of deformation is observed. Some mines choose to shotcrete ribs as another method of confinement.

The rib support design geometry is largely controlled by the operational range of the bolter on the continuous miner. Rib bolt designs typically locate a row of bolts in the top 0.5 m of the rib, a row roughly in the centre of the rib and, if the design allows, a middle row of bolts between the two. This creates a design that is focussed in the top half of the rib that may not consider the mechanisms of rib deformation. The lower portion of the rib, however, is typically overlooked in rib support design due to the restrictions of the bolters on the continuous miners.

The seemingly generic rib support design for the variation in observed mechanisms of rib deformation then poses the question: What is the role of rib support? If the mechanisms of rib deformation are not considered in rib support design, what is rib support controlling? Is the purpose of the current rib support design to control kinematic failures or to generate confinement to increase the overall strength of the fractured coal? Should rib support design take into account the mechanisms of rib deformation?

The key roles of rib support are outlined in the following sections.

Rib Support to Control Kinematic Failures

Where discontinuities are present or where discontinuities interact with mining-induced fractures, kinematic failures can form with the smallest stress changes or dilation within the rib. Rib support is effective if rib bolts are located in the correct location to control the kinematic failure. However, the generic rib support design often does not control kinematic failures due to the location of the failure relative to the bolt location. Rib mesh is an important factor in controlling kinematic failures in these situations. Rather than installing a generic rib support design, an improvement could be to understand what mechanism is driving the kinematic failure and then designing the rib support to control this driver.

Rib Support to Generate Confinement and Increase Overall Rib Strength

Bolts are designed to generate confinement of the rock around the bolt to increase the strength of the roof or rib. Confinement increases the strength of rock that is either intact or already failed. Confinement of intact rock can prohibit the rock from failing due to the increased strength generated from the confinement. Similarly, confinement of failed rock acts to increase the strength of the rock from zero residual strength if unconfined. The increased strength generated from confinement both controls kinematic failure and limits the progression of rib yield further into the rib. Rib bolt length can also assist in improving confinement of the rib.

Rib Support to Control the Progression of Rib Deformation Further into the Rib

The progression of deformation further into the rib can be a result of the kinematic failures and inadequate generation of confinement in the rib. If the skin deformation is not controlled, then the rib face effectively moves further into the pillar as the rib slabs away. The depth of softening then progresses further into the rib as the fresh coal face forms the new rib further into the rib. By appropriately controlling the initial skin failures that are often driven by another mechanism other than discontinuities, the perpetuating failure into the rib can be controlled.

The author considers the control of the progression of failure further into the rib to be the key factor in controlling rib deformation. The role of rib support is, therefore, to control kinematic failures and increase confinement of the already failed coal within 0 to 2 m of the rib.

Rib Support to Control Deterioration of Coal over Time

At a number of sites, ribs are observed to deteriorate over time where coal then falls away from the rib. This deterioration can be controlled by mesh or shotcrete or by re-supporting the rib after a period of time.

DESIGNING RIB SUPPORT TO CONTROL FAILURE MECHANISMS

A modelling assessment was conducted to simulate the behaviour of rib deformation to assist in the interpretation of the monitoring results and assessment of varied rib support design. The models were rock failure models in FLAC2D using "in-house" rock failure routines based on Mohr-Coulomb failure criteria. A description of the model process and validation can be found in Gale and Sheppard (2011).

The models were based on site-specific geotechnical properties and strata from the closest borehole to the monitoring site. The example discussed here within is from MNM and is of a roadway perpendicular to the major horizontal stress, such as a cut-through. The model was run with two scenarios; i) the installed location of the rib support and ii) the lower rib bolt located to control the shear failure of the Tonstein Band.

Although there are many model outputs, such as rock failure modes, displacements, and bolt loads, the incremental shear strain outputs are presented in Figure 16 to show the general distribution of strain within the rib. Figure 17 shows that the model with the lower rib bolt installed through the Tonstein Band controls the high strain along the Tonstein Band to the area between the bolt and the rib. The bolt through the Tonstein Band also controls the lower rib high strain compared with the model with bolts installed off the miner. The lower strain at the near rib indicates that this location of bolt may assist to reduce lower rib spall to maintain confinement further into the rib. This highlights that a rib support design that is tailored to the site-specific mechanisms of rib deformation can act to control rib deformation.

CONCLUSION

The ACARP project C25057 allowed for measurement and monitoring of the dynamic progression of rib support deformation at three mines in three different coalfields in Australia. The characteristics of the rib deformation at each mine highlighted a vast variation in the mechanisms of rib deformation. Despite this, the rib support design applied to most mines is typically similar across different mines and different seams for a similar overburden depth.

This paper poses questions about the role of rib support and whether rib support should be tailored to the site-specific mechanisms for rib deformation. Monitoring to date suggests that the role of rib support is to stop the progression of failure further

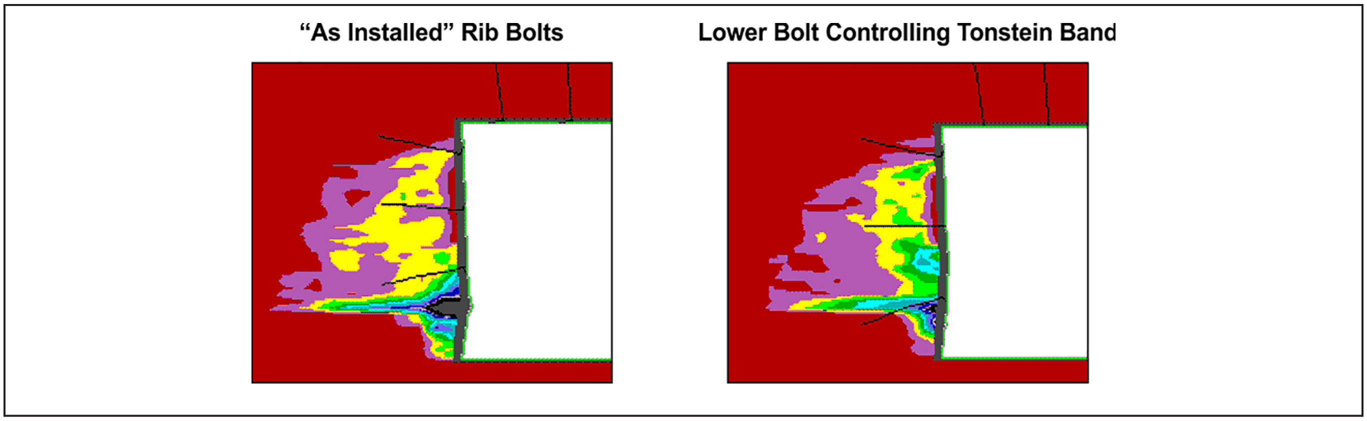

Figure 17. Modelled MNM longwall site output of incremental shear strain for the installed location of the rib support, and the lower rib bolt located to control the shear failure of the Tonstein Band.

into the rib by controlling kinematic failures and generating confinement of the failed near rib. The site-specific failure mechanisms are, therefore, required to be understood in order to effectively implement these controls.

Challenges that lie ahead may include the investigation into the miner bolter geometry design or the ability to vary the mining horizon to allow for potential improvement in rib support design.

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