MECHANICS OF RIB DEFORMATION AT MORANBAH NORTH MINE – A CASE STUDY

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ABSTRACT: The risk of fatalities from rib failure is still prevalent throughout the coal mining industry which prompted further industry research into understanding rib deformation and rib support interaction. This paper provides the results of a rib deformation monitoring project at Moranbah North Mine as part of ACARP project C25057. Moranbah North Mine provided funding and mine site access to assist this research into the risk of rib failure within the industry. Two rib monitoring sites were installed to monitor rib and roof deformation and rib bolt loads under both development and longwall retreat stress scenarios. The monitoring highlighted the progression of rib deformation from the minor deformation and bolt loads experienced on development, through to the significant deformation observed under longwall abutment loads. The stability of the Tonstein Band (10 to 15 cm claystone/siltstone band located approximately 1 m above the floor), was highlighted as a key factor in the rib deformation both on development and retreat. The monitoring provided observations of the progression of deformation and highlighted a step change in rib stability. The rib deformation stepped from near rib deformation within the bolted zone to a significant increase in depth of softening under longwall abutment loading. It was inferred from the monitoring data that shear failure along the Tonstein Band in the lower section of the rib resulted in the increased deformation for the middle and upper rib. Computer modelling was also used to examine the failure mechanisms.

INTRODUCTION

The current risk of rib fatalities in the coal mining industry has prompted further research into understanding the mechanisms of rib failure. Moranbah North Mine (MNM) assisted further research by providing the mine for rib deformation studies as part of the Australian Coal Association Research Program (ACARP) project C25057. This paper provides the results of the rib deformation monitoring project at MNM. MNM is however currently effectively managing rib failure risk through support design and Trigger Actions Response Plans.

An approach of monitoring rib deformation and rib support loads was used to measure and characterise the dynamic rib deformation for mining cycles of 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 rock failure. 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.

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MNM is located 16 km north of Moranbah in the Bowen Basin Coalfield in Queensland, Australia (Figure 1). MNM mines the Goonyella Middle Seam (GMS), using retreating longwall extraction methods. The GMS is a thick seam of approximately 5 m to 6 m, leaving approximately 2 m of coal in the roof. The depth of cover for current mining typically ranges from 300 to 350 m.

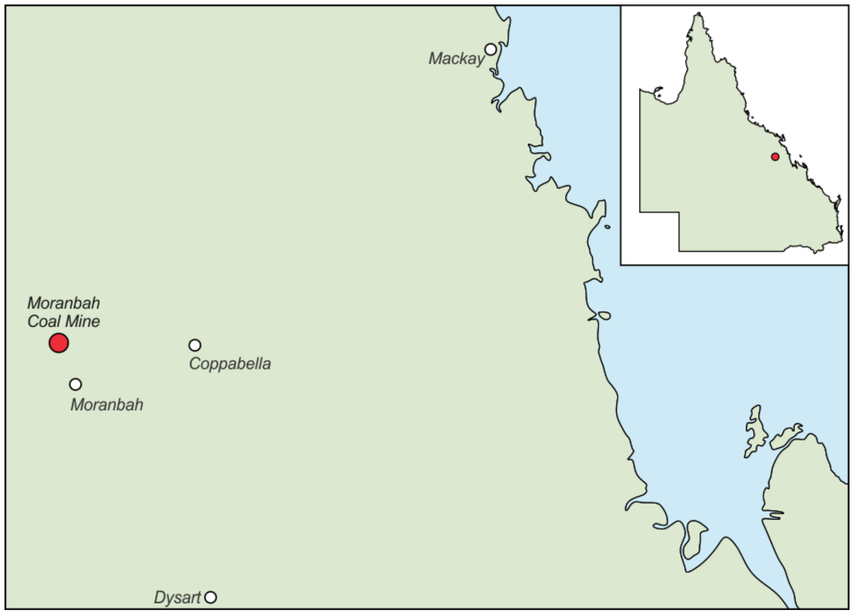

Figure 1: Location map of Moranbah North Mine

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 et al (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. One of the key missing seams from this dataset is the GMS. This paper provides a publically available dataset on rib deformation for the GMS in the Bowen Basin.

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 et al, 1992; Colwell, 2006
		South Bulli	Bulli Seam	Fabjanczyk et al, 1992
	Western Coalfield	Springvale Colliery	Lithgow Seam	Gale and Fabjanczyk, 1999
		Angus Place Colliery	Lithgow Seam	Fabjanczyk et al, 1992; Colwell, 2006
	Newcastle Coalfield	West Wallsend Colliery	West Borehole Seam	Colwell, 2006
		Wyee State Mine	Fassifern Seam	Fabjanczyk et al, 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

MECHANICS OF RIB DEFORMATION

In underground coal mining the types of rib failure are typically understood as 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. The instability of the wedge may be a combination of:

1. Discontinuities including cleat and bedding
2. 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
3. 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 the 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.

MONITORING ARRAY

A rib and roof monitoring array was implemented to define and measure the progression of deformation in response to the dynamic mining process on both development and longwall retreat. Two monitoring sites were installed. Their locations are presented in Figure 2 and described as follows:

- Development site – MG112 A Heading, 10 m inbye 39 Cut-through, 350 m depth of cover
- Longwall retreat site – mid-pillar MG111 26 Cut-through, 330 m depth of cover

The major horizontal stress direction is approximately north-northeast in the location of LW111 and LW112 creating higher stress concentrations on the cut-throughs. However, the thick seam allows for a coal roof which reduces the stress concentration in the immediate roof.

The instrumentation array in the ribs consisted of sonic extensometers, strain gauged shear strips (measuring vertical shear in the rib) and instrumented bolts. A sonic extensometer was also located in the roof in addition to roof convergence monitoring for the longwall site.

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 longwall abutment loading and monitored during the approaching and passing of the longwall. The instrumentation array for the development and longwall sites is presented in Figure 3.

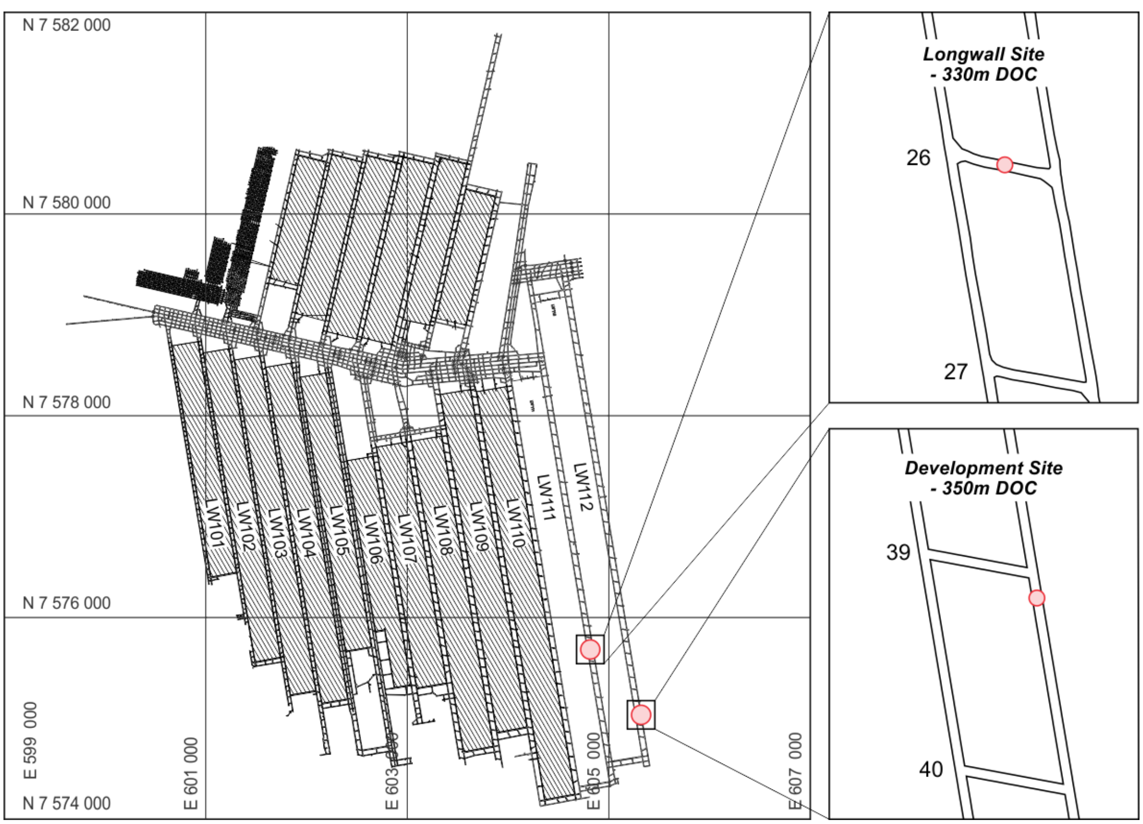

Figure 2: Monitoring site locations at Moranbah North Mine

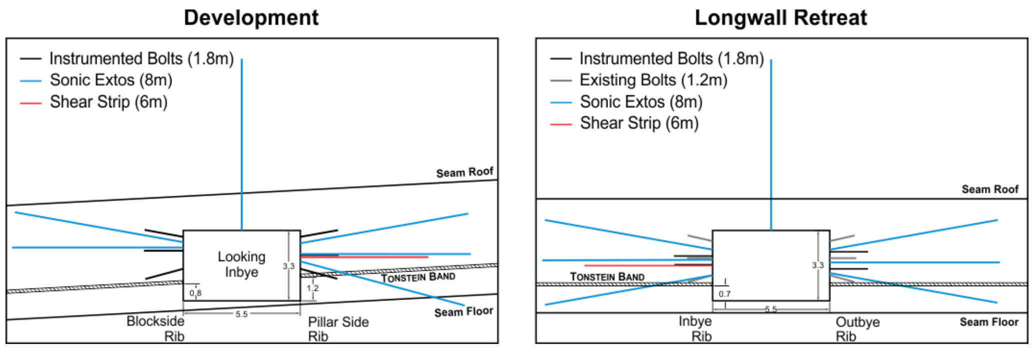

Figure 3: Installed instrumentation layouts

DEVELOPMENT RESULTS

The extensometers showed that minimal deformation was initially observed on development in the first 30 m of continuous miner advance. The measured mid rib depth of softening was 0.8 m to 1.1 m into the pillar side rib only. The lower rib deformation with a depth of softening at 1.7 m into the rib coincided with the location of the Tonstein Band. The pillar side deformation was focused on the mid to lower rib with 15 mm deformation. No deformation was monitored on the lower extensometer of the block side rib, due to damaged extensometer tubing at the location of the Tonstein Band.

The bolt loads, presented in Figure 4, showed high strain zones at the top of the rib, showing the importance of the top rib bolt. The lower rib bolt load and lower rib extensometer showed high strain zones about the Tonstein Band. This suggests that the Tonstein Band, combined with no support at this location is a driver for rib deformation.

During 30 and 200 m of continuous miner advance, the rib continued to deform with greater magnitude of strain in the lower rib. This is observed in the bolt load data in Figure 4, particularly in the lower rib bolts where they show the most significant deformation. In the case of the lower rib bolt on the block side, these changes were significant enough to destroy the strain gauges on one side of the bolt. The calculation of the bolt loads are an average of strain on opposing sides of the bolt, thus the load and strain results were not able to be calculated in this instance. The shear strip data in Figure 5 also shows a change in the rib behaviour associated with this step change in lower rib deformation. The vertical shear displacement shows the near rib moving in a downwards direction, relative to further into the rib.

An increase in rib deformation beyond the initial dynamic stress during tributary loading, could be due to either a change in stresses or a change in rock properties, typically due to water activity. Given the adjacent longwall was approximately 1.5 km to 2 km from the development site during the monitoring period, stress change is not considered to be related. Therefore the observed movement may indicate clay and water activity occurring on the Tonstein Band to cause deformation well beyond changes in the stress environment.

With the inference that the Tonstein Band has weakened due to a time related change in geotechnical properties, the simultaneous changes observed in the mid-rib are likely to be related to the deformation occurring on the Tonstein Band. It is inferred that the Tonstein Band sheared, in turn reducing the ability for the lower rib to generate confinement, and allowing the mid-rib to deform. Strong roof, floor and bedding contacts in a pillar, or in the rib, increases the pillar's ability to generate confinement and the overall coal strength of the pillar and rib.

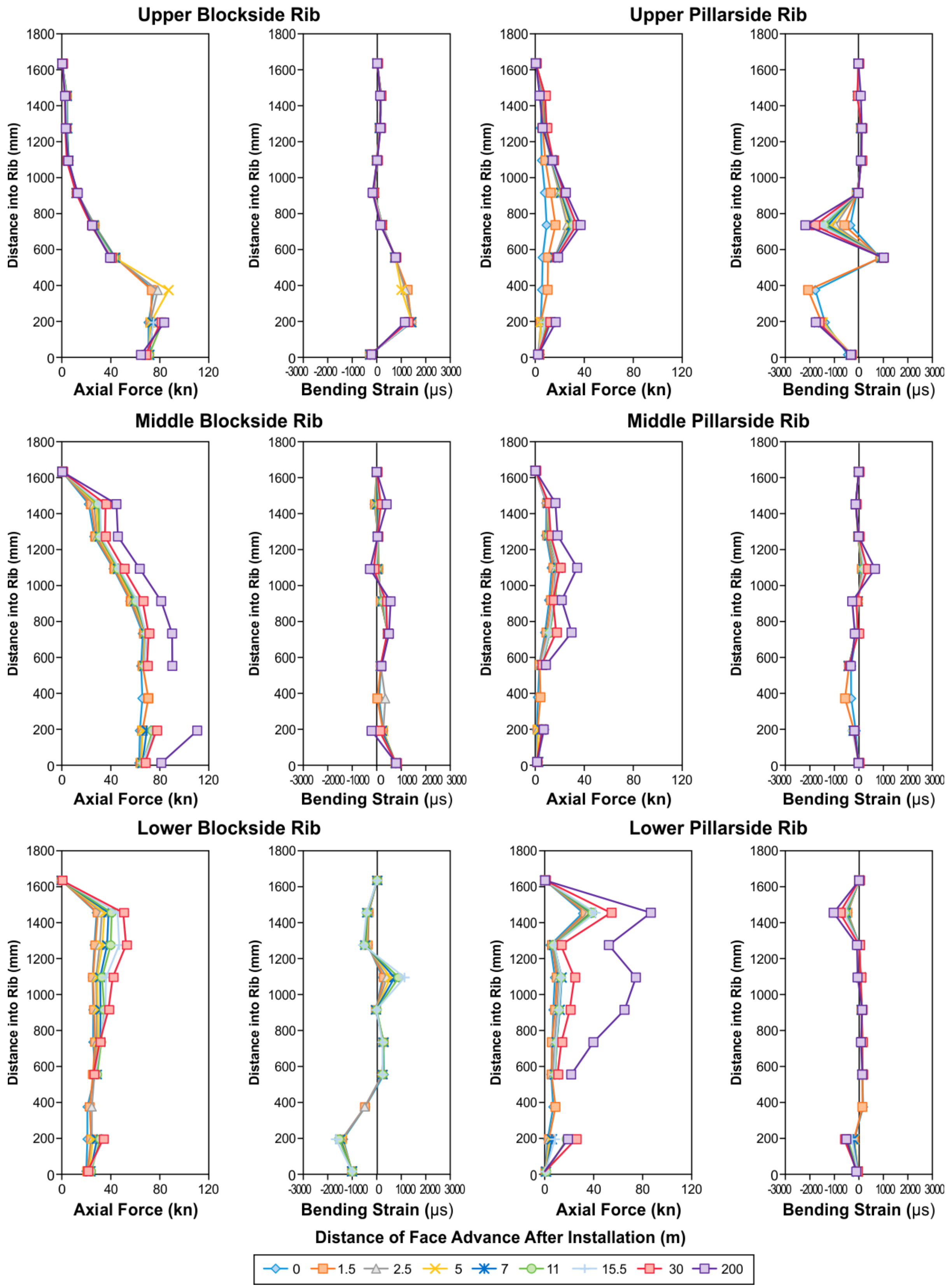

Figure 4: Bolt data for the development site

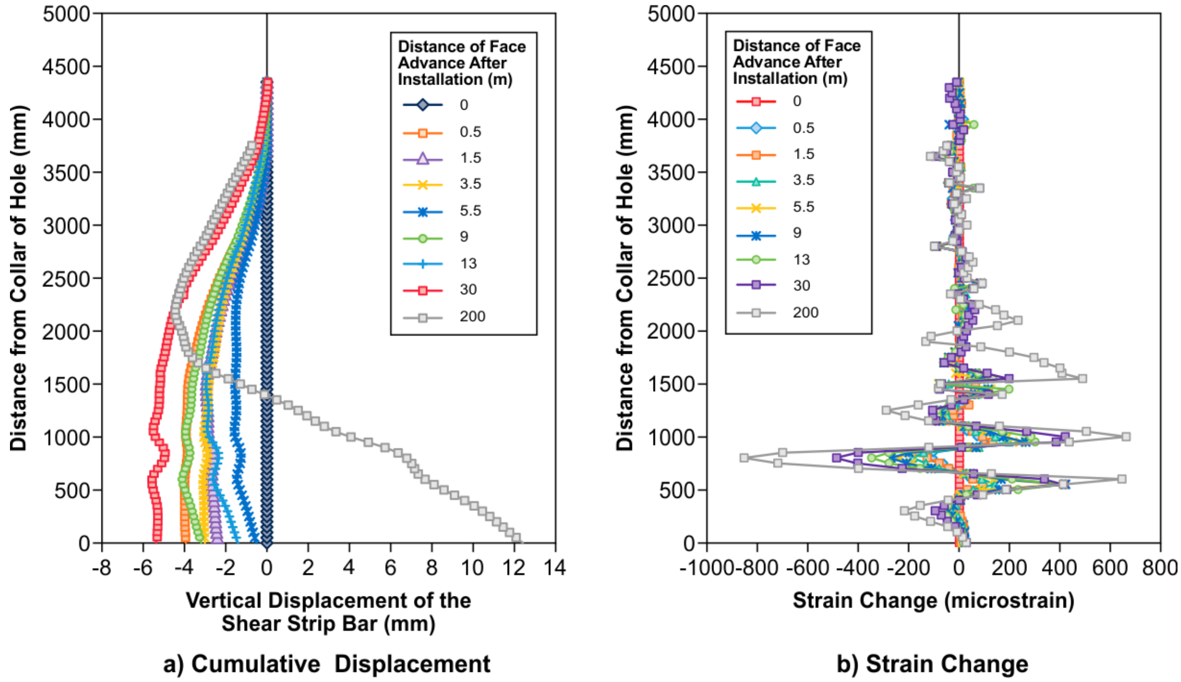

Figure 5: Shear strip data for the development site

Rib spall is often observed about the Tonstein Band at MNM significantly outbye of the initial drivage. The monitoring observations of delayed rib deformation could explain this rib spall experience at MNM.

DEVELOPMENT INTERPRETATION

The inherent operational constraints in installing rib support mean that the rib support is typically installed approximately 5 m from the development face. The nature of mining induced fractures about roadways is that they form ahead of and around the corners of the development face. As the miner advances through the fractured ground, some of the deformation in the rib has already occurred before rib support is installed. This may be a reason for the low magnitudes of deformation that were observed in the monitoring data.

Despite this limitation of measuring deformation back from the face, the results showed a key finding in the long term stability of the development roadways at MNM. The step increase in deformation some weeks after the roadway was initially driven, highlights a time component of the rib stability. The focus of deformation about the Tonstein Band indicates that the instability of the Tonstein Band is a driver in the mechanics of rib deformation on development at MNM.

The staged interpretation of the development site deformation is presented in Figure 6 and shows the pillar side rib deformation and bolt loads prior to, and after, the interpreted movement along the Tonstein Band.

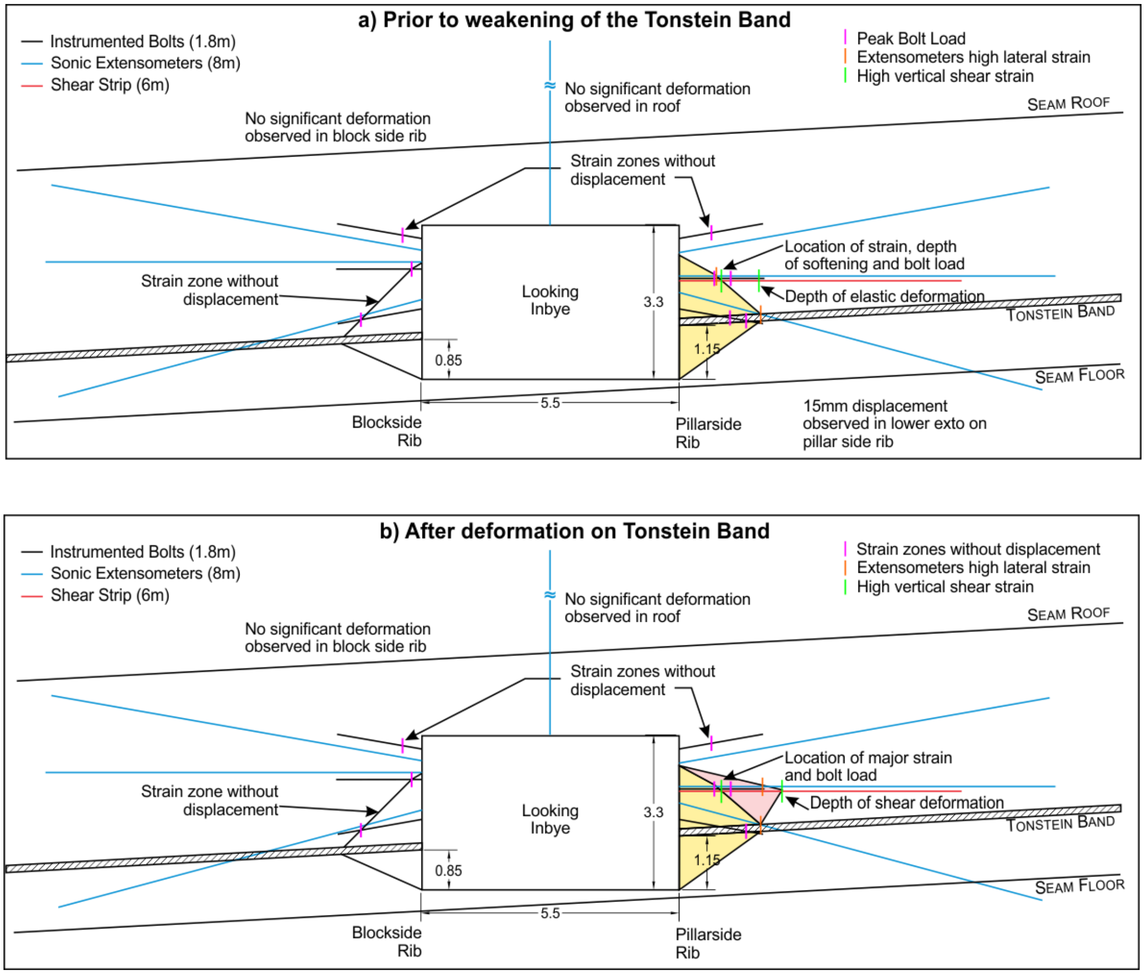

Figure 6: Interpretation of development deformation

LONGWALL RETREAT RESULTS

During the retreat of LW111, the ribs and roof in 26 cut-through were monitored for deformation in response to the progressive longwall abutment loading. The monitoring showed substantial rib deformation and minimal roof deformation. The monitoring also showed a stepped progression of deformation whereby the rib deformation suddenly increased in what appears to be the process of shearing of the Tonstein Band. Similar behaviour was observed on the inbye and outbye ribs of the cut-through, however the timing of the deformation stages was delayed on the outbye rib due to the later loading of the outbye pillar. The results for the instrumented bolts, extensometers and shear strip monitoring are presented in Figure 7, Figure 8 and Figure 9 respectively.

The depth of softening on the inbye rib was 1.2 to 1.6 m with a magnitude of displacement of approximately 10 mm until the lower extensometer sheared off at the location of the Tonstein Band. Once the lower extensometer sheared off, the middle and upper extensometers increased in their depth of softening to approximately 3 to 4 m with a corresponding increase in displacement of 45 to 65 mm.

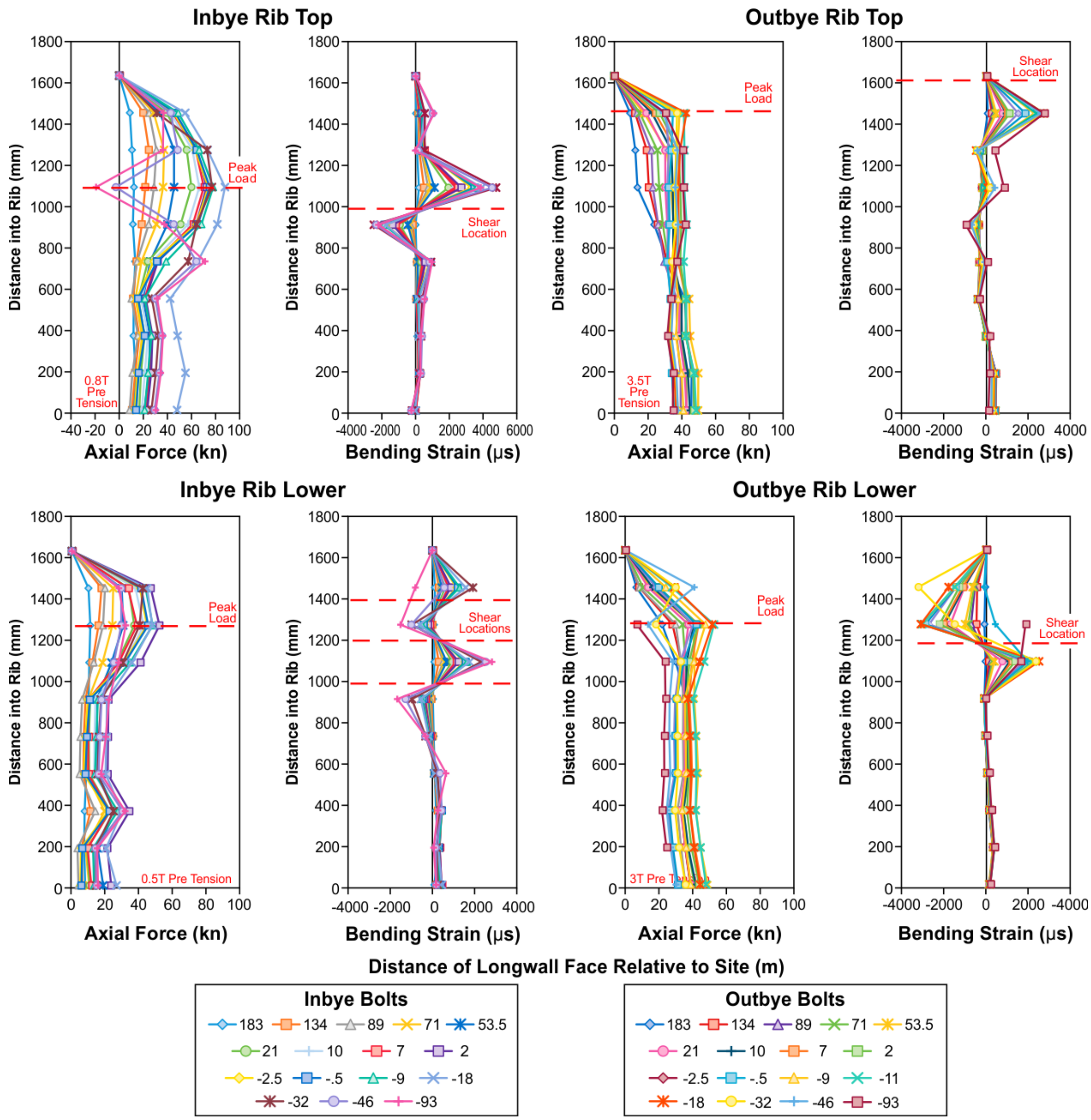

Figure 7: Bolt load data for the longwall site

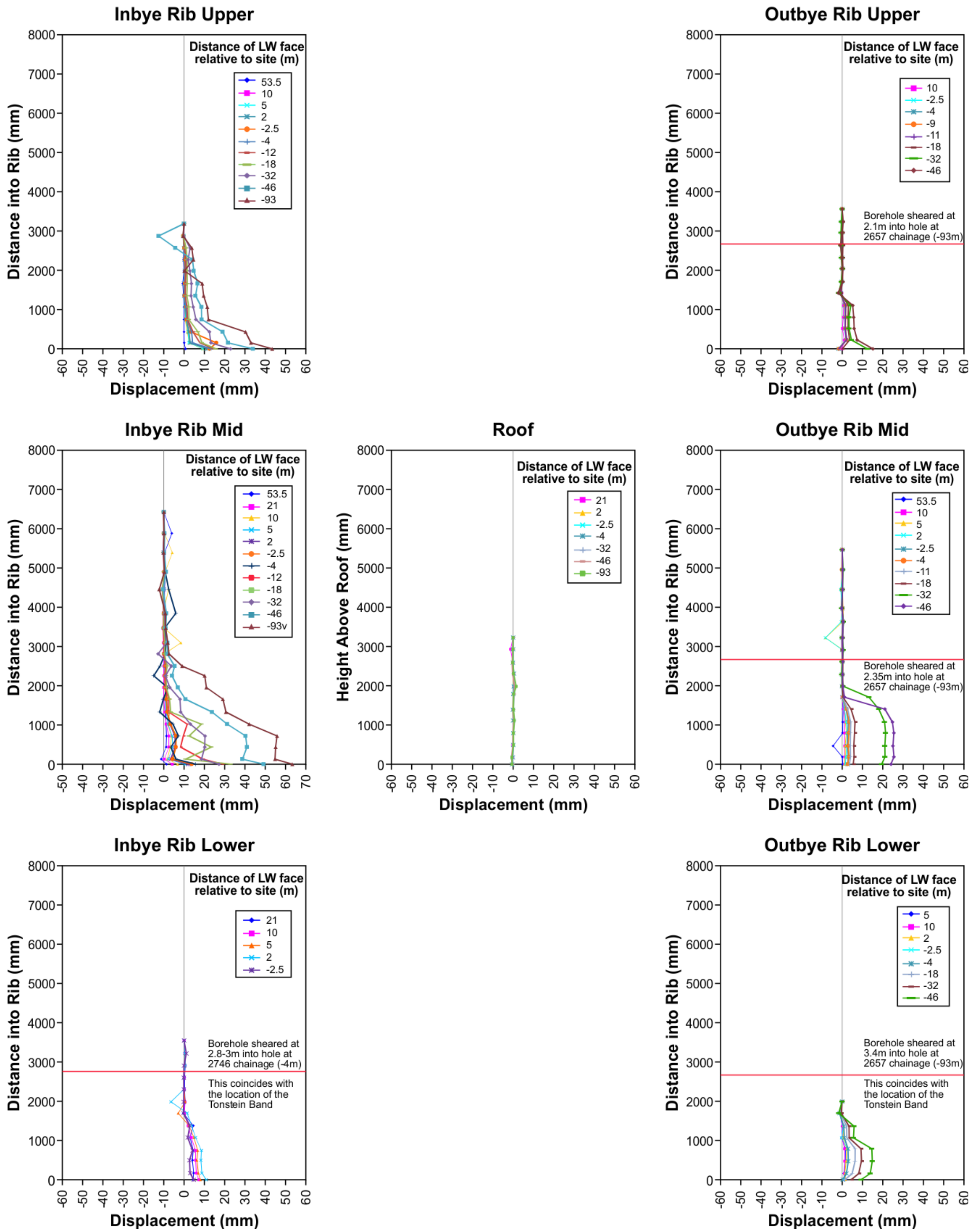

Figure 8: Extensometer data for the longwall site

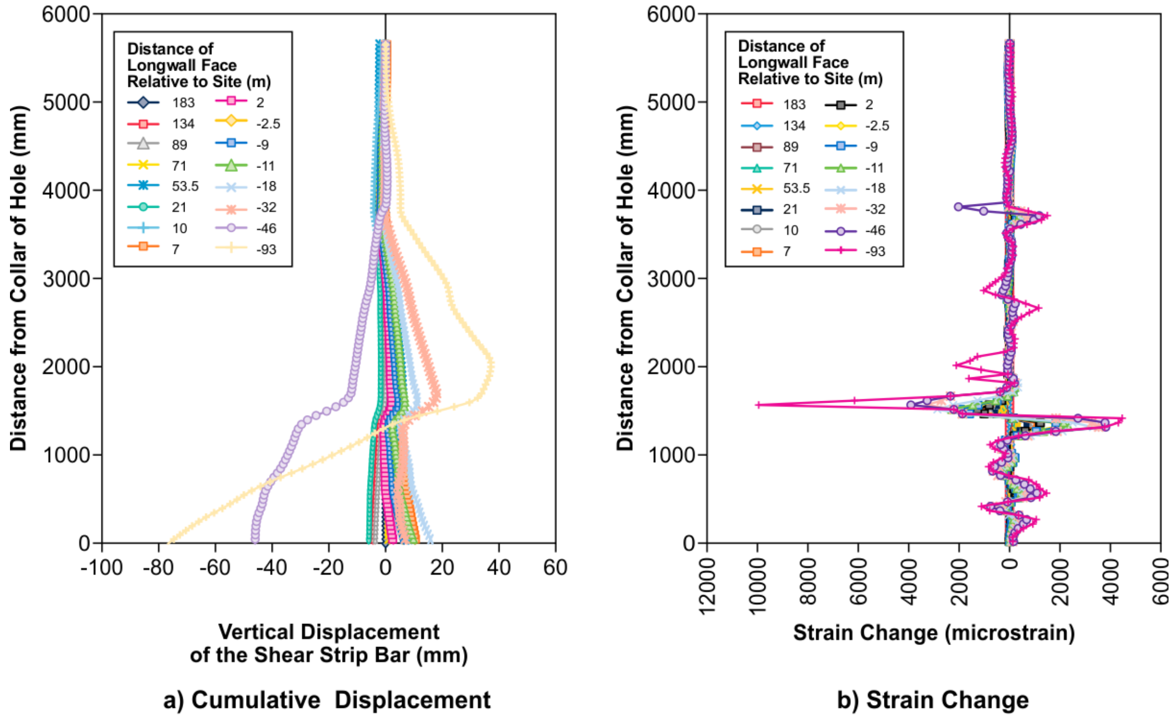

Figure 9: Shear strip data for the longwall site

A major shear plane was observed in the inbye rib on the instrumented bolts and shear strip at 1.4 m into the rib. This corresponds with the initial depth of softening of the rib, and coincidentally corresponds with the depth of the primary rib support.

The outbye rib showed a depth of softening of 1.5 to 2.6 m with a magnitude of displacement of 20 to 25 mm prior to all the holes shearing off. All extensometers in the outbye rib sheared off between longwall locations of 46 m and 93 m past the instrumented site. The location of the shears increased the depth of softening to 2.1 to 3.4 m.

Both ribs exhibited this step change in deformation. The inbye rib however showed the key information whereby when the lower extensometer sheared off, the increase in deformation and depth of softening was observed in the middle and upper rib. As the outbye rib middle and upper extensometers all sheared at the same time, the magnitude of deformation could not be confirmed in this rib.

LONGWALL RETREAT INTERPRETATION

The interpretation of the mechanism of deformation in the rib was inferred from the rib deformation monitoring data. The key element of the shearing of the Tonstein Band, and the step change that it created in the inbye rib deformation, assisted in interpreting the deformation in the outbye rib.

Figure 10 shows the interpretation of the rib deformation due to longwall retreat. The first stage of deformation shows the peak loads, lateral strains and vertical strains with a focus on depth of softening of about 1.5 to 2 m into the rib.

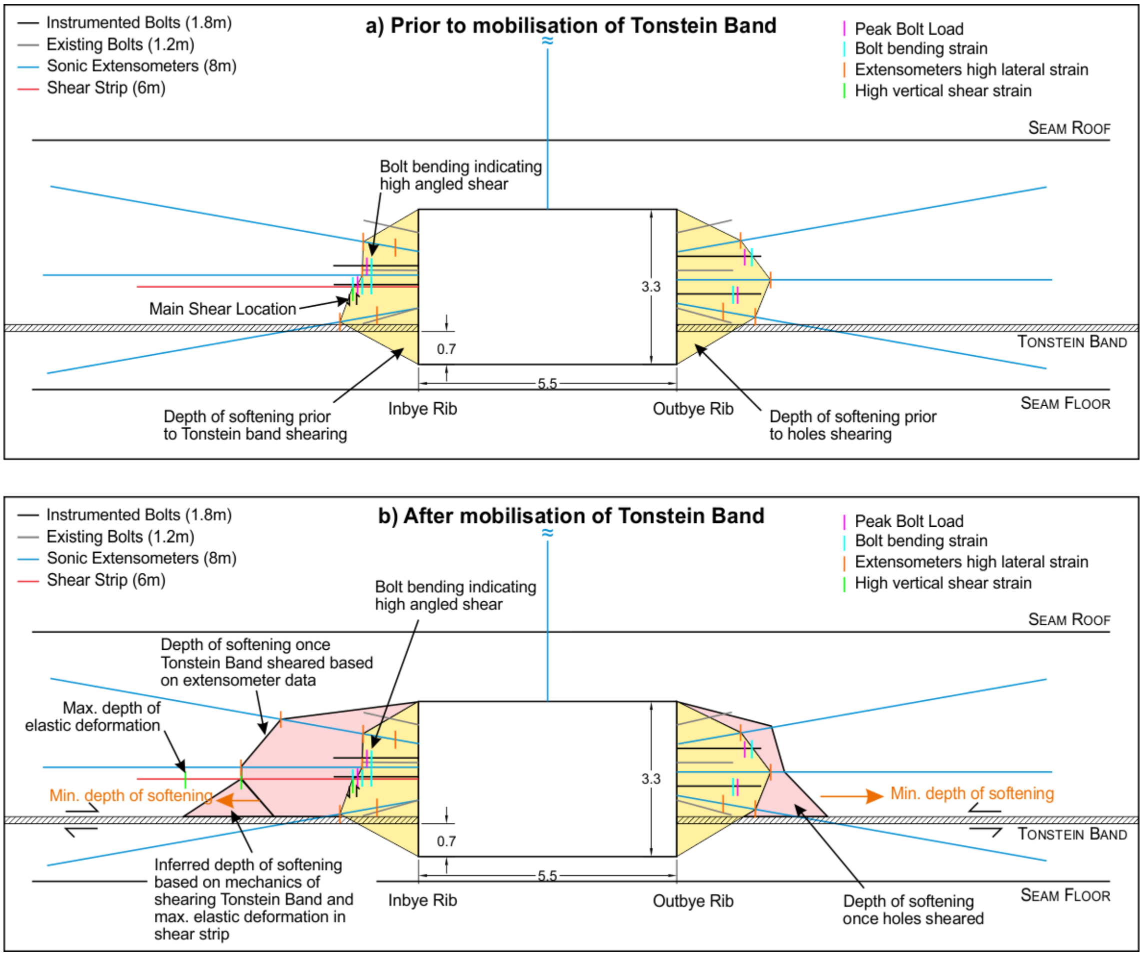

Figure 10: Interpretation of the longwall site deformation

The additional shear stress incurred about the roadway due to the longwall abutment loading causes the Tonstein Band to fail along the bedding plane. Once this plane fails, the lower rib loses its ability to confine the pillar or rib, and the middle and upper rib moves out towards the roadway. This horizontal displacement reduces the vertical stress transfer in the near rib and redistributes it further into the rib. In this case, the stress redistribution created failure of the coal further into the pillar, increasing the depth of softening to 4 m on the inbye rib, and a minimum of 3.4 m in the outbye rib.

The shape of the depth of shearing in the outbye rib shows a greater depth of softening at the Tonstein Band. This supports the inference that the Tonstein Band is a key driver in the mechanics of rib deformation.

MODELLING ASSESSMENT OF RIB DEFORMATION

A modelling assessment was conducted to simulate the behaviour of rib deformation to assist in the interpretation of the monitoring results. The models were rock failure models in FLAC 2D 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 sites, borehole DDH436. The sonic inferred unconfined compressive strength (UCS) used for model inputs are presented in Figure 11. Models were run for the development and longwall retreat scenarios and roadway geometries. Longwall abutment loads based on empirical data were applied to the longwall retreat model.

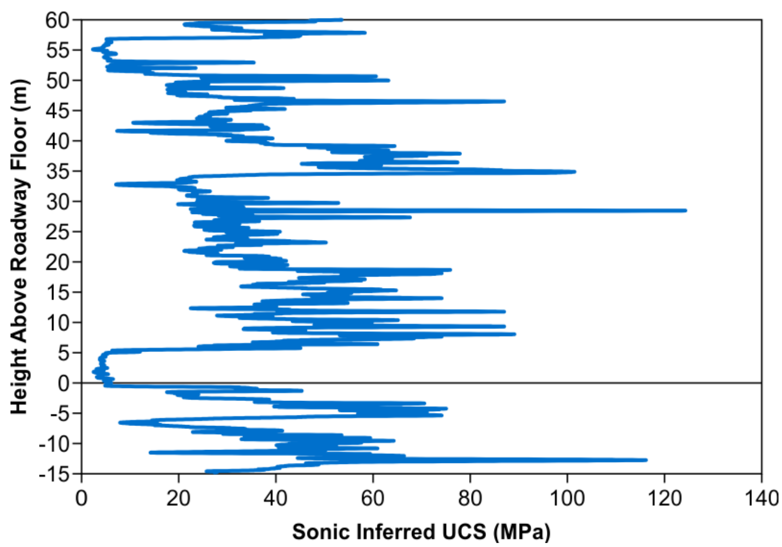

Figure 11: Model UCS inputs based on borehole DDH436 sonic inferred UCS

Although there are many model outputs such as rock failure modes, displacements and bolt loads, the incremental shear strain outputs are presented in Figure 12 to show the general distribution of strain within the rib. The location of high shear strain is significant to the location of peak bolts loads, vertical shear and lateral shear observed in the monitoring data.

The development model outputs of incremental shear strain in Figure 12a highlights the high strain zones at the upper corners of the rib and a zone about the Tonstein Band. The majority of rib deformation is observed in the lower rib below the lower rib bolt, where the Tonstein Band is also located. The Tonstein Band strength properties consisted of low shear strength properties of 0.5 MPa cohesion and a friction angle of 10 degrees.

For the longwall retreat model, a sensitivity analysis was also conducted on the geotechnical properties of the Tonstein Band as this is indicated to be a key driver in the total rib deformation. Strong and weak shear strength properties were applied to the Tonstein Band where the weak strength properties appear to match the observed deformation. The strong Tonstein Band properties consisted of bedding cohesion of 2 MPa and friction angle of 20 degrees, while the weak Tonstein Band properties consisted of bedding cohesion of 0.5 MPa and friction angle of 10 degrees.

The two modelled scenarios of strong and weak strength Tonstein Band properties are presented in Figures 12b and 12c, respectively. The shear strain plots highlight the sensitivity of the rib deformation to the geotechnical strength properties of the Tonstein Band. The model with strong shear strength properties in the Tonstein Band shows a general arc shape of rib deformation from the roof to the floor (Figure 12b). With weaker shear strength properties, the Tonstein Band shears along its bedding plane and increases the deformation in the strata above the Tonstein Band (Figure 12c).

It would appear that the deformation of the ribs before the step change is more consistent with the model simulation of the strong Tonstein Band properties where there is minimal shear deformation on the Tonstein Band. This produces a consistent arc shape of depth of softening from the roof to the floor. The observed deformation after the step change creates a shape more closely related to the model where the Tonstein Band has sheared. This produces a depth of softening shape focussed at the Tonstein Band.

The models highlight the mechanisms which create the characteristics of deformation observed at the MNM longwall site. The difference in magnitude between the model and measured deformation could be accounted for with a measured abutment load rather than an empirical abutment load applied in the model.

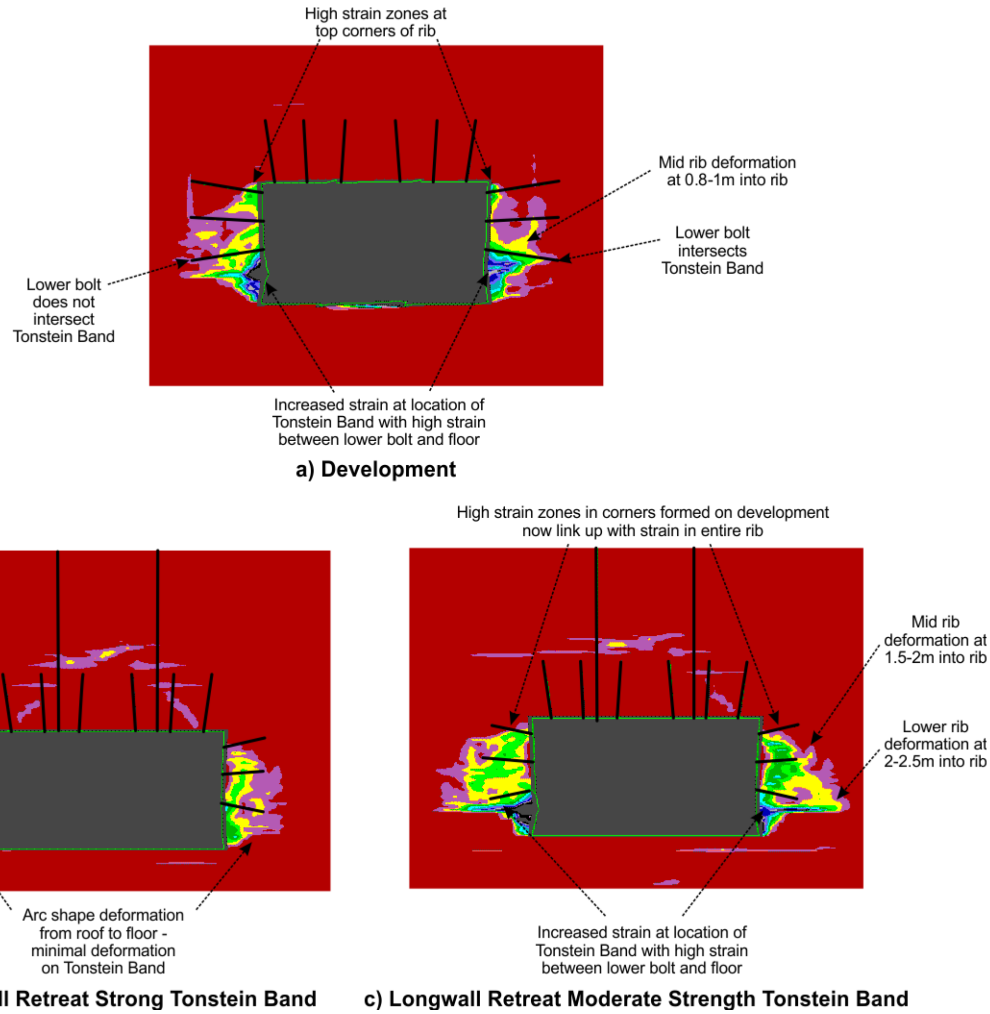

Figure 12: Rock failure model results showing incremental shear strain to highlight areas of deformation

CONCLUSIONS

Monitoring of rib deformation characteristics throughout the dynamic stress environments of development and longwall retreat provided a significant insight into the mechanics of rib deformation at MNM. The mechanics of rock failure within the rib deformation process highlighted the key driver in the rib deformation to be the shear failure of the Tonstein Band. The failure of the Tonstein Band in the lower rib then created a step change in rib deformation in the middle and upper rib. This is due to the reduction in lower rib confinement creating a reduction in rib strength.

An understanding of the mechanisms of failure within the rib can be used to investigate various support design strategies, or mining geometries, that may provide for better support of this failure mechanism.

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