Rock damage characterisation from microseismic monitoring

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ABSTRACT: This paper outlines the concepts used to correlate rock failure with microseismic events and presents examples of microseismic monitoring together with associated computer modelling of the rock failure. This study is motivated by the need to develop improved ways to reduce ground control hazards in underground mining. Toward this end we present and compare results from numerical modelling and microseismic monitoring studies conducted at several different mine sites. Emphasis is on integrating results obtained with these tools to characterize, and thus increase our understanding of, important mine deformation processes. The ultimate goal is to use this knowledge to design mine structures, and develop mitigation measures, that minimize specific ground control hazards.

1 INTRODUCTION

The location of microseismic energy release associated with mining activities is well advanced and is practiced regularly. In Australia the method has been used in conjunction with in situ monitoring and computer modelling to research ground failure characteristics and caving mechanics about longwall panels in underground coal mines. In the USA this approach has been used in similar situations and also within underground limestone mines to assess ground failure in regard to mine design.

At the various field sites in Australia and the USA, in situ instrumentation consisting of various combinations of surface to seam extensometers, pore pressure cells, rock stress change cells, support pressure monitoring was used to better understand strata movement and stresses. Computer modelling of the stress distributions, rock failure modes and ground displacements during longwall extraction was undertaken to better understand the rock fracture characteristics and caving mechanics developed within various geological environments. Microseismic monitoring was undertaken to locate rock failure during mining and provide information on the nature of the failure. The majority of this seismic information related to source location, frequency and relative magnitude. Focal plane solutions were available from a limited number of selected events.

The combined investigation approach adopted in these studies, while individually independent, provided very complementary data and allowed confidence in the findings from each investigation method. The nature of rock failure about underground extraction panels has been significantly enhanced by the use of such techniques. Results utilising these techniques in various combinations have been reported by: Gale (1999), Kelly et al., (1999) Iannacchione et al., (2001) Ellenberger & Heasley (2000).

One of the key issues to arise out of this work with regard to microseismic monitoring was to what extent can we characterise the physical nature of the actual rock damage or the type of rock failure represented by the microseismicity. This is the focus of current research as the nature of the failure is becoming of significant interest when interpreting the implications of the microseismic events in terms of mine design and safety. This has involved further work in assessing the magnitude of energy or the stress drop associated with the various rock failure modes and what are the practical limitations of the microseismic method in sensing various failure modes known to occur. The effects of the seismic network configuration and energy transmission while of considerable importance to the problem are regarded as a separate issue in this context and are not part of this discussion.

This paper outlines the concepts used to correlate the rock failure with micro seismic events and presents examples of micro seismic monitoring together with associated computer modelling of the rock failure.

2 ROCK FAILURE MODES AND STRESS MODIFICATION WITHIN THE ROCK MASS

The rock in situ may be considered to experience failure in a number of modes. These are:

1 Shear fracture through intact rock material

2 Tensile fracture through intact rock material
3 Shear fracture of bedding planes
4 Tensile fracture of bedding
5 Remobilisation of pre-existing fractures.

The failure criteria for these can be obtained from relationships determined in laboratory testing. The criteria for the failure modes above are presented in Figure 1 and Figure 2.

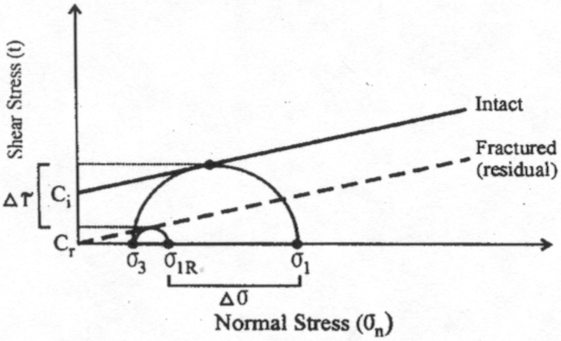
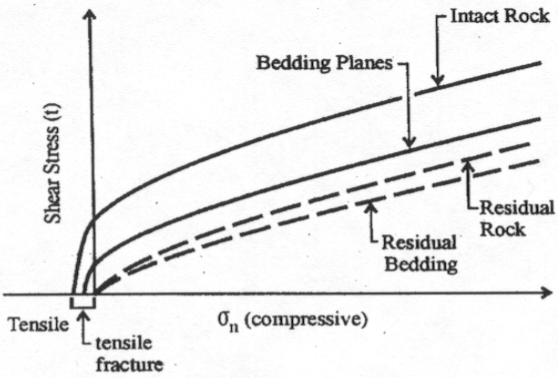


Figure 1. Mohr failure criteria and associated stress modification.

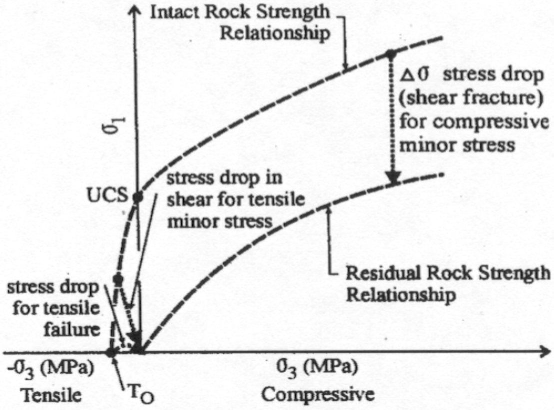


LEGEND

σ_1 = Maximum Principal Stress
σ_3 = Minimum Principal Stress
$\Delta\sigma$ = Normal Stress Change
σ_{1R} = Maximum Stress after Rock Fracture
C_i = Intact Cohesion
C_r = Residual Cohesion
$\Delta\tau$ = Shear Stress Change

Figure 2. Mohr representation of failure criteria.

The stress modification within the ground resulting from rock failure is different depending on the mode of failure and the physical scale of the fracture. The process of failure/fracture causes a reduction in the stress sustainable across the fracture from that which was within intact material to that which is governed by the strength properties of the rock fracture. The difference from the initial stress to the residual stress is termed the stress drop in the following discussion. This concept is presented in Figure 3 and it can be seen that the stress drop associated with tensile fracture is significantly less than shear failure. The general relationships would indicate tensile stress drops are 8-12% of those generated by shear failure. Also, for stressfields where the minimum stress is tensile, but not sufficient to induce tensile failure, the stress drop associated with shear fracture may be significantly less than if the minimum stress is compressive.



LEGEND

UCS = Unconfined Compressive Strength
T_O = Tensile Strength
σ_1 = Maximum Principal Stress
σ_3 = Minimum Principal Stress
$\Delta\sigma$ = Normal Stress Change

Figure 3. Stress drop associated with various failure modes.

Stress drops for bedding plane shear and bedding plane tensile failure will be different again depending on the rock properties. Reactivation of pre-existing planes will provide only small stress drops associated with asperities or stick slip geometries created by fracture networks.

The stress drop ($\Delta\sigma$) can be calculated from the various failure modes of the rocks within the stressfields developed about mining panels by computer modelling, however a general approximation is obtained from:

$$\Delta\sigma = (\sigma_1 - \sigma_{IR}), \text{ or}$$

$$\Delta\sigma = K\Delta\tau$$

where K = 2 in the ideal case as shown in Figure 1, or

$$\Delta\sigma = T_o$$

The resultant stored strain energy released due to failure is:

(0.5) x ($\Delta\sigma$) x (area of fracture) x (displacement across fracture during rupture).

This can be related to the typical stress strain characteristics of rock in Figure 4. In this diagram the area shaded is proportional to the energy released during rupture.

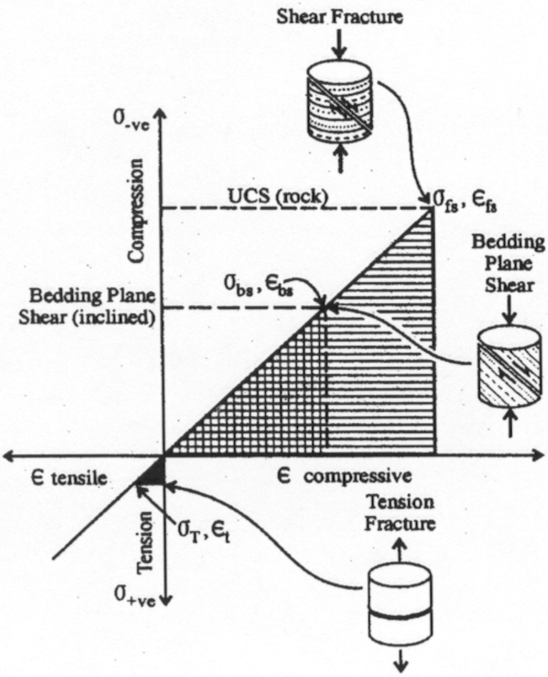


Figure 4. Strain energy release for various rock failure modes.

The relevant parameters are displayed for a range of failure modes for unconfined conditions. It is apparent that shear failure modes will generate significantly greater energy than tensile modes and it will depend on the strength characteristics of the particular rock type as to the energy release per area of rupture.

It is assumed in the model, that the seismic events measured result from the stress drop associated with the formation of fractures. Such events are considered to be "instantaneous" rupture and displacement surfaces which generate the P and S waves measured. The "instantaneous" rupture surface or network is expected to propagate at a similar speed to the shear wave velocity.

Remobilisation of existing fractures in a stick slip mode would be recorded as the rapid energy release associated with failure of asperities or areas which have caused previous "lock up" along the fracture, together with any associated rapid movement along the fracture in the vicinity of the asperity/lock-up zone. The seismic energy released from these fracture/slip sources represents, at most, a few percent of the total energy released (McGarr, 1993). Depending upon the local stability conditions, these same deformation processes can also occur without generating any detectable seismic energy.

Similarly, elastic deflection of overburden is not expected to be recorded seismically, but such deflection may contribute to the loading system which subsequently causes a sudden rupture of the ground.

3 SEISMIC RESPONSE TO GROUND FAILURE

The resultant effect of the failure on mining and in seismicity is related to the ability of the rock to redistribute the stress drop about the boundaries of the fracture. This will to a large extent be dependent on the regional stiffness contrasts in the ground.

In the case of a "stiff" loading system (where the stiffness of the ground generating the stresses causing rock fracture (regional stiffness) is greater than the stiffness of the fractured rock zone), controlled rock fracture geometries are expected in the form of individual fractures in a stable mining geometry.

In the case of a "soft" system (where the regional ground stiffness is significantly less than the stiffness of the fractured rock) then rapid failure and networking of fractures to form a large unstable fracture zone is likely. This type of failure is most likely to be manifest in large scale mine geometries where overburden movement is involved in the loading.

The seismic response envisaged for the stiff system would be numerous independent low energy responses whereas the soft system would produce a single or limited number of high energy responses as a single fracture zone propagates. In reality, a range of responses will be expected depending on the strength and stiffness of the ground about excavations.

4 SIGNATURES OF SHEAR AND TENSILE FRACTURES

The nature of the failure that is occurring within the rock mass can also be inferred from microseismic data. The Commonwealth Scientific and Industrial Research Organization (CSIRO) has undertaken 13 microseismic monitoring studies of longwall extraction at Australian longwall mines. Typically the events that are recorded occur ahead of the face and may occur within the floor strata as well as the roof. These events exhibit strong P- and S-wave motions and examination of their polarisation suggests that shear failure is occurring.

Microseismic events caused by tensile failure have proved much more difficult to detect but this is to be expected given the reduced energy associated with such events, and the need for the seismic wave propagation to occur through more highly absorptive broken ground. However some events that are interpreted to be due to tensile failure have been observed. These typically have amplitudes about a factor of 10 less than the shear events, the P-wave motion is dominant (but not exclusive) and the polarisation of the P-waves suggests that there is first compression in all directions (i.e. the expansion associated with tensile failure). It has been found that these events need to be within 50m of geophones to be recorded (where as the hundreds of meters of propagation are possible for shear events) and their locations are typically behind the face.

5 COMPUTER MODELLING OF LONGWALL EXTRACTION IN COAL AND SEISMIC MONITORING CASE STUDIES

Computer modelling with the FLAC codes (Itasca, 1998) was undertaken at various mine sites to simulate the rock failure modes and caving characteristics about the central zone of the longwall face. The longwall mining process in the central portion of the face is simulated as a two dimensional longitudinal slice by progressively excavating a web of coal and allowing the ground to cave behind the longwall supports.

The model represents the central zone of the longwall panel and is most appropriate for panels of supercritical width to depth geometry. The supercritical width to depth ratio of an extraction panel is typically 1.2-1.5. In a supercritical geometry, the overburden can cave and the goaf may load in the central zone of the panel without any significant influence from the pillars at the edges of the panel. The model does not simulate the behaviour close to the gate-ends. While the two dimensional simplifications are easiest to use for supercritical panels, it is still possible and appropriate to investigate the behaviour under subcritical panel widths. The results from many models have been compared and validated against field measurements and have been found to provide a good estimation of the ground behaviour (Gale 1998, Sandford 1998, Kelly et al 1998).

The rock fracture, stress geometry, ground displacement and support loading/convergence as mining occurs is recorded in the model. An example of the results of the modelling is presented in Figure 5 where the location and type of fractures about a longwall panel are presented. The stress drop associated with the fractures, which occurred during the last mining cycle, is presented in Figure 6. These results provide one information source to assess the ground failure mechanics and the types of rock fractures associated with the micro seismicity.

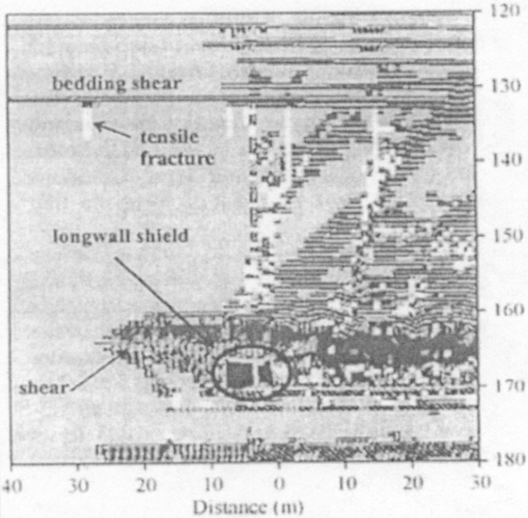


Figure 5. Rock failure mode and fracture geometry modelled about the faceline of a longwall panel.

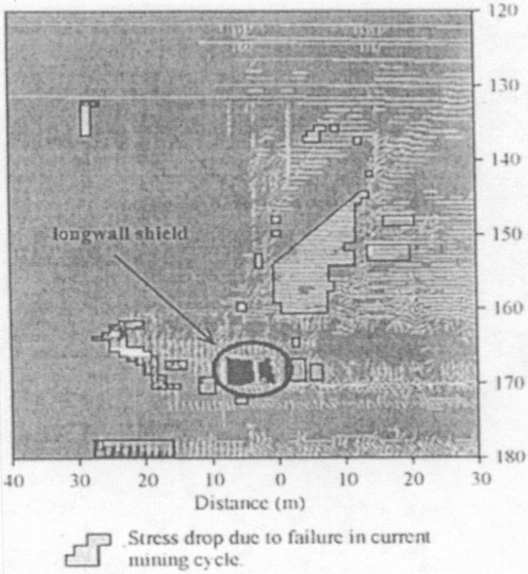


Figure 6. Stress drop zones associated with rock failure which occurred during the current mining cycle.

6 CASE STUDY OF GORDONSTONE MINE

CSIRO conducted a microseismic monitoring study at Gordonstone Mine (Queensland, Australia). The geology of the mine is described by Kelly et al, (1999). The German Creek Seam (3m thick) is mined at 230m depth within weak (5–20MPa) laminated siltstone and mudstone. Some stronger sandstone bands occur but are relatively thin. The microseismic study was reported by Hatherly et al (1995), Kelly et al (1999). The key findings from a rock mechanics viewpoint, were:

1 The rock fracture was recorded well ahead of the mining face within the roof and floor strata.
2 The dominant rock failure modes recorded were

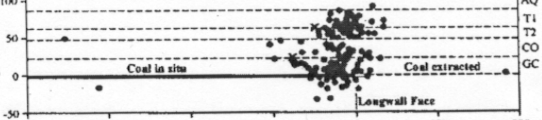


Figure 7. Microseismic events distribution about the centre of the faceline relative to a fixed face position in side view.

shear fracture of rock and bedding.
3 The relative absence of caving related failure recorded within the strata.
4 Focal plane solutions for key events confirmed the mode of rock failure and geometry.
5 The magnitude of events was typically low.

The location of events in a section about the central zone of the longwall panel is presented in Figure 7 and the focal plane resolutions are presented in Figure 8.

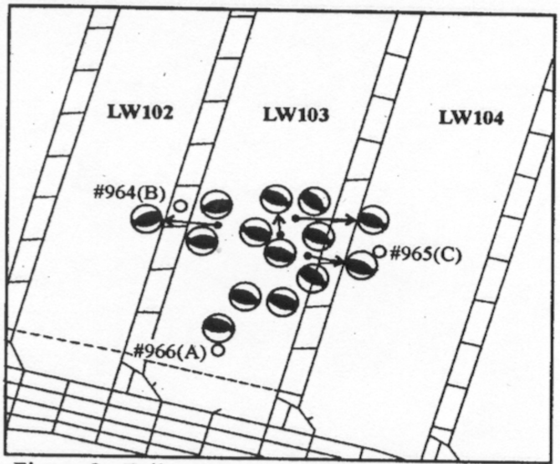


Figure 8. Failure mechanisms for 14 events. Shade areas are under tension and the open areas are under compression.

Computer modelling of the site was undertaken and reported within Kelly et al (1999). The key findings of the study were:

1 Shear fracture and bedding plane failure occur well ahead of the faceline;
2 The geometry of the shear fractures was very similar to that from the focal plane solutions;
3 Coupled fluid pressure within the rock failure criteria is a major factor in the failure characteristics of weak material.

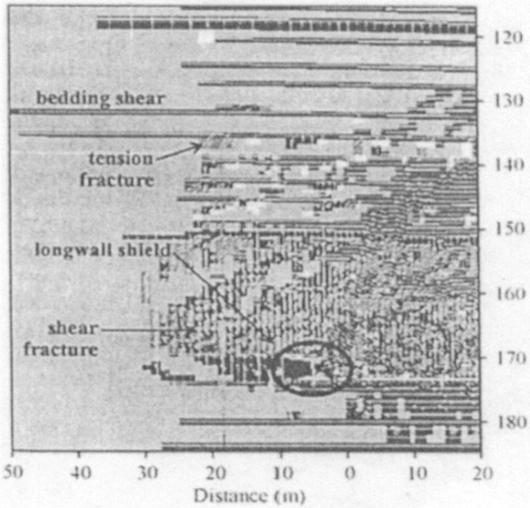


Figure 9. Rock Failure modes and fracture orientations about the central zone of the faceline.

The zones of rock fracture about the central zone of the longwall panel is presented in Figure 9.

Overall, the computer simulation and the microseismic monitoring show very similar and complementary results. At the time these results were contrary to the more conventional rock fracture geometry based on tension fracture of the ground behind the mining face, however subsequent investigations have confirmed these findings.

7 CASE STUDY OF A UTAH LONGWALL MINE

NIOSH (National Institute for Occupational Safety and Health) recently studied a mine located in Utah USA at a depth of 500-600m. The strata about the mine are typically strong interbedded siltstone and sandstone of 60–120MPa together with thin coal seams. Higher within the overburden a thick unit named the Castlegate sandstone exists which is a laminated sandstone in the strength range of 40–60MPa. Above this more interbedded and carbonaceous material exists. A more detailed discussion of the geology is presented by Ellenberger et al. (2001).

A microseismic monitoring study was conducted in 1999 and was reported by Ellenberger et al. (2001). The key aspects of this study were:

1 Microseismic activity occurred well ahead of the mining face within the roof and floor;
2 The fractures typically were not within the traditional caving zone;
3 The largest magnitudes of the events ahead of the face ranged from M_L 2.0 to 2.5.
4 A large scale seismic event was recorded (M_L4.2) within the overburden which was considered to be associated with large scale overburden movements.

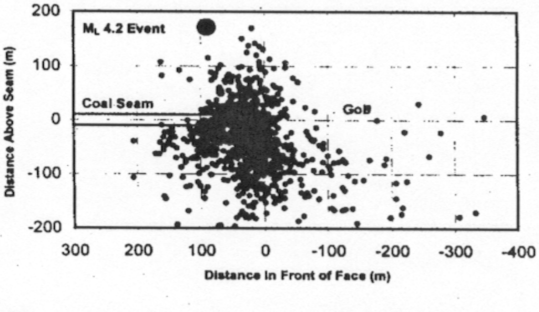


Figure 10. Location on microseismic events in a cross-section view relative to face position.

The location of small magnitude events (typical events) ahead of the faceline is presented in Figure 10 together with the location of the M_L4.2 event.

Computer modelling of the site was conducted to assess the location and type of fractures developed about the control zone of the longwall panel and also to assess the impact of overburden behaviour on multiple panels. The key findings were:

1 Shear fracture of the ground and bedding plane shear would be expected as the primary failure modes.
2 Such fracturing would occur well ahead of the faceline as independent events within a stable system.
3 Under certain mine geometries, a large scale failure zone would be anticipated higher into the geological section as a result of overburden spanning characteristics. A combination of a high angled rock fracture zone and bedding plane shear was noted. The high angle fractures form within a soft loading system and would propagate rapidly. High energy seismic responses would be anticipated.

The rock failure zones anticipated about the face area for a single panel geometry is presented in Figure 11. The stress drop zones associated with the rock fracture is presented in Figure 12. The results indicate shear fracture of the strata and bedding plane shear are common failure modes which develop the potential for many low energy events about the face area. The potential for larger scale events which relate to a larger mine geometry (regional scale) and larger scale ground movements is presented in Figure 13 where the effect on panel interaction was found to allow failure zones to develop in the overburden as panels interacted. The stress drop zones associated with the rock failure is presented in Figure 14 and indicates the potential for large scale failure and seismic events where ground movement in the overburden occurs over a large (regional) scale.

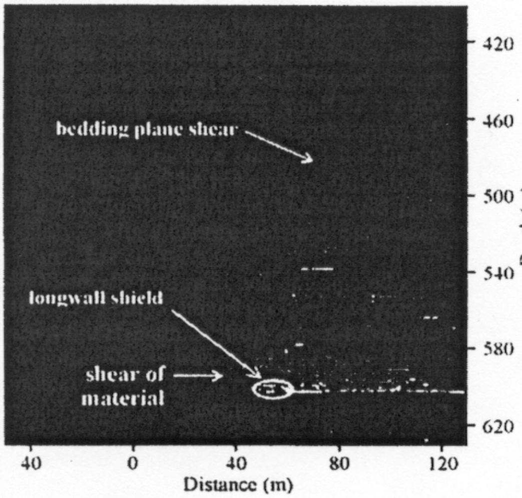


Figure 11. Rock failure zones developed about the central area of the faceline.

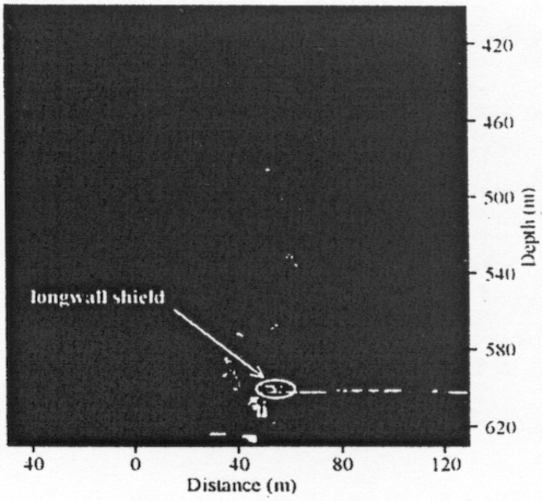


Figure 12. Stress drop zones developed about the central area of the faceline.

Analysis of the magnitude of the events indicates that the M_L4.2 event would be consistent with a rupture zone of approximately 170-200m in diameter. This is consistent with the modelled results and also in general with the mine geometry. The smaller events ahead of the faceline are consistent with fractures in the range of 0.2-2m in diameter. The modelling was done in isolation with the microseismic monitoring and does not directly reflect the specific mine geometry at the location of the monitored M_L4.2 event, however, the ground behaviour and scale of events is consistent with the microseismic monitoring and provides an enhanced understanding of the interaction of seismicity and rock damage.

8 CASE STUDY OF SPRINGFIELD PIKE MINE

NIOSH is in the process of monitoring microseismic activity at Commercial Stone's Springfield Pike

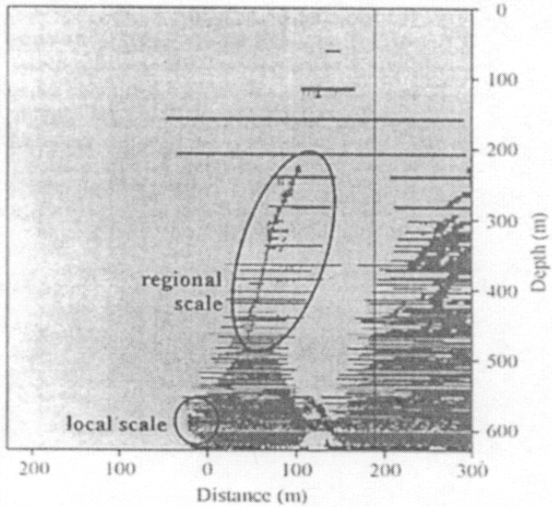


Figure 13. Regional scale rock failure mode about mining panels.

Mine near Connelsville, Pennsylvania, USA. In contrast with the first two examples, this is a room-and-pillar limestone mine. Overburdens ranges from 60m to 120m, with rooms 13.8m wide by 7.6m high and pillars 10.7m square. The limestone is mined by blasting 4m deep V-cuts in various entries along a wide mining front. The Loyalhanna Limestone is approximately 21.5m thick and is overlain by the Mauch Chunck Formation containing interbedded shales and calcareous sandstones and underlain by the Pocono Sandstone. While the strength of intact specimens are very high (UCS 130 to 200MPa), the Loyalhanna Limestone contains a great deal of structure which greatly influences the overall rock mass strength. The largest scale features are reverse faults with several meters of displacement. Large trough beds, which can extend from several meters to tens of meters in length dip at angles ranging from 70 to 20 degrees. Jointing is generally widely spaced but can often extend through the entire mining horizon. Bedding planes can extend over large mining areas and are often sought after to form smooth roof horizons in the mine. These planes are close to horizontal and are spaced at intervals ranging from several centimetres to several metres. The smallest scale structures are crossbeds which dip from 15 to 35 degrees and are spaced at intervals averaging one centimeter.

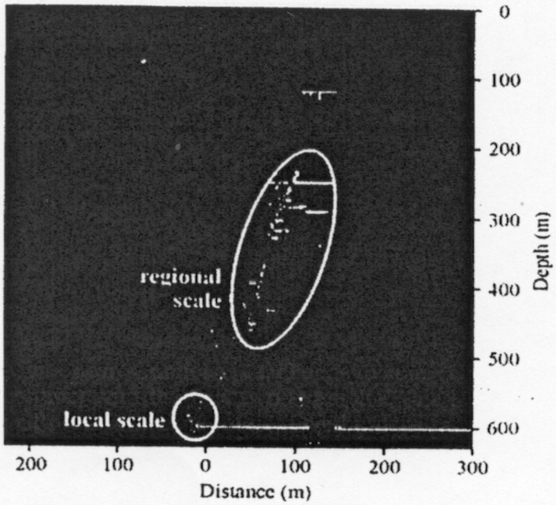


Figure 14. Local and regional scale stress drop zones about mining panels.

Horizontal stresses at this mine are extremely large (15 to 55 Mpa) and are thought to contribute to the excessive stress conditions which have produced several large roof falls. These roof falls are thought to contain several of the failure mechanisms previously discussed. Typically, roof failure starts when one of the stiffest and thinnest beds in the roof strata concentrates enough horizontal compressional stresses to initiate both intact shear failure and adjacent tensile bedding plane failures. At this point, low angle shears and the accompanying vertical tensile failures can occur more easily in the remaining intact isolated roof beams, which have had the vertical confinement reduced. As various roof beams fail, stresses are transferred to adjacent beams where the process is repeated. Since these roof falls at the mine range from 6 to 10m in height, a single roof fall could easily have hundreds to thousands of individual shear failures (seismic events) associated with them.

This failure process can be illustrated by examining the microseismic activity from one of these falls. On October 28 and 29, 2000, a roof fall occurred in the southwest corner of the mine. This is presented in Figure 15. In this area, a prominent low angle shear had formed three months before generating considerable microseismic activity. After a period of relative quiet, early on October 28, approximately 50 microseismic events were recorded over a two hour period as presented in Figure 16. It is assumed that numerous thin beds within the immediate roof failed along bedding and through the intact material. This period was followed by another period of relative quiet lasting approximately three hours. Then almost 50 events were recorded over a 20 minute period. This is assumed to be the time when the major portion of the roof collapsed. Again a period of relative quiet occurred for approximately 2 hours. Then, a third period of high activity occurred over the next hour followed by approximately 16 hours of relatively small events at fairly constant rates. It is possible that during this time period both the edges and top of the roof fall continue to increase in size.

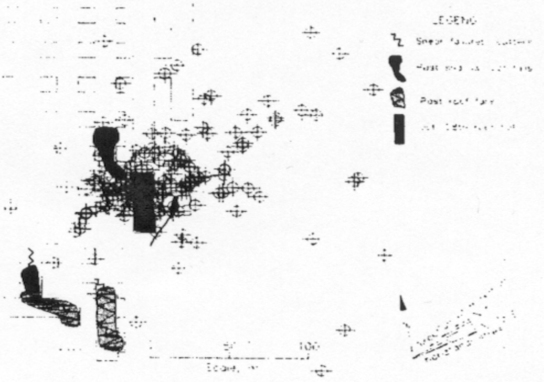


Figure 15. Microseismic locations and mapped rock damage above mine roadways.

9 DISCUSSION

In the monitoring studies undertaken about longwall panels, the notable feature is the distance ahead of the caving front that the fracturing is being recorded. This is consistent with the modelling which indicates that shear fracture of the rock and bedding plane shear would be expected to occur in these areas. These fractures are likely to generate the highest stress drop and strain energy release.

It is also notable the caving related seismicity is typically absent from the surveys. This may in part be related to the microseismic systems, but a significant factor is considered to be the relatively low stress drops and energy release which result from such fracture patterns. Bedding plane tensile failure and tension fracture of small sections of rock as anticipated in the caving zone are unlikely to be recorded. This is also true for small scale rock failure known to have occurred in the immediate vicinity of the gateroad entries which was not picked up at some sites studied in Australia.

The magnitudes of the seismic events about longwall mines are generally consistent with that expected from computer modelling however, further work is being undertaken to better define the relationships of microseismic response with the type and scale of fracture generated.

The monitoring at the Springfield Pike Mine is being analysed in terms of the scale of fracture relative to the energy in a similar manner as the example of the Utah longwall mine.

Ongoing work is aimed at providing a better interpretation of the capability of microseismic monitoring to define the nature of rock damage about mining operations. Knowledge of the energy released by various failure modes will better define the requirements of a microseismic system to monitor the type of rock behaviour required for various mine planning and safety issues.

It is also anticipated that the nature of the rock failure and the stability of the strata in the area of seismic activity will be better defined in ongoing analyses.

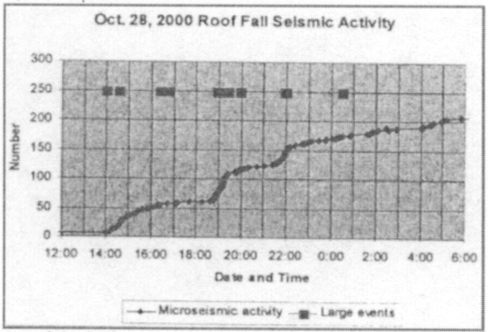


Figure 16. Microseismic events associated with rock failure recorded over a two day period.

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