Characteristics of Mining-Induced Seismicity Associated with Roof Falls and Roof Caving Events

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ABSTRACT: The National Institute for Occupational Safety and Health (NIOSH) evaluated microseismic activity from three field sites to compare and contrast the characteristics of microseismic emissions from very different geologic, stress, and mining environments. Recently, NIOSH has embarked on a research program to evaluate the use of microseismic monitoring information to identify roof fall failure processes and to assess its potential to warn of unstable roof conditions. Large roof instabilities, such as roof falls and certain roof caving events, have proven difficult to anticipate representing an increased risk to miners working in these inherently hazardous areas. When local failure processes are better understood, appropriate control measures can be engineered to mitigate these hazards. This study used microseismic emissions to help identify three local rock failure processes. It was also shown that analysis of microseismic emissions can aid in assessing the degree of instability associated with these local rock failure processes.

1. INTRODUCTION

Roof falls and roof caving events represent a serious hazard to miners working underground. The development of roof fall hazard recognition, monitoring, and control techniques is highly dependent on a sound understanding of the failure processes responsible for roof falls and roof caving events. Recent NIOSH studies in a limestone mine [1] have found that tracking the signatures emanating from strata transitioning from stable to unstable states aids in identifying roof failure mechanisms and monitoring for roof stability conditions. In the earliest stages of this transition, the rock strata fail by fracturing in both shear and tension. Generally, one or more significant large events and dozens of smaller events are observed on a daily basis during unstable roof states. As more fracturing occurs and existing fractures coalesce, the ground softens, increasing the potential for roof collapse. Slip can also occur along fracture planes or pre-existing bedding planes as strata move toward the developing roof fall cavity. Finally, the impact of the falling rocks onto the mine floor produces a wide range of seismic signatures that help characterize the rock fall mass and the condition of the surface upon which the rock has impacted.

1.1. Microseismic Monitoring and Analysis

This study analyzed microseismic emissions from three mine sites: Springfield Pike Quarry, Moonee Colliery, and Willow Creek Mine. Springfield Pike and Willow Creek used a microseismic system developed by NIOSH [2] and were analyzed using techniques discussed by Iannacchione et al. [3]. The Moonee field site employed a microseismic system developed in South Africa by ISS International. Emissions from the Moonee Colliery were collected by the operating mining company, Coal Operations Australia Limited, and provided to NIOSH for this study.

In all three study sites, care was taken to determine accurate event locations. Typical rock fracture events have distinct first arrivals which allow for easy P wave identification, an essential characteristic for accurate event location. The size of rock failure events is established by calculating the moment magnitude (M). The moment magnitude scale, developed by Hanks and Kanamori [4], is consistent with the more familiar Richter magnitude scale and is currently used by seismologists as a measure of seismic source size. Moment magnitude is based on the static seismic moment, M_o, by the relationship:

$$M = \frac{2}{3}\log(M_o) - 6.0, \quad (1)$$

where M_o is expressed in SI units (N-m).

The static seismic moment [5] is determined from the observed Fourier displacement amplitude spectrum of body waves, the rock density at the source, the body wave velocity, the body wave radiation pattern, and the distance between the seismic source and the receiver. The seismic moment is also important because it is a measure of the dynamic inelastic deformation, or non-recoverable deformation, associated with a seismic source.

1.2. Rock Failure Process

In this study, three general classes of rock failure mechanisms are identified as progressive, episodic, and continuous. The roof in room-and-pillar mines is generally stable until a localized increase in stress or a loss in strength disturbs the local equilibrium condition and initiates failure. After the onset of rock failure, additional failures are possible as the adjacent rock layers adjust to the changing conditions. In this way, a progression of rock failure is established until the surrounding rock mass reaches a new state of equilibrium or until it results in a roof fall. This process is termed progressive rock failure.

When mining creates expansive extraction zones where stresses and deformations are concentrated at panel edges, such as those found in longwall coal mining, the roof rock fails in a continuous incremental fashion. As support is removed from beneath the overlying strata, the strata break apart and eventually cave into the void made by mining. In this case, the failure process is highly dependent on the extraction effort. If the extraction effort is slow, the failure process is correspondingly slow. Rock failure progresses more rapidly as the mining rate increases. In this way, the failure process assumes a continuous incremental pattern that closely matches the daily extraction rate.

An intermediate condition exists between the progressive and continuous failure process. When mining takes place in panels of limited size or under thick competent strata, the stresses and deformation gradient at the face are reduced in comparison to continuous incremental failure. In this case, strata failure and gob formation do not immediately occur after an increment of face advance, and the expanding area of supported overlying strata becomes larger. As a result, when failure does finally occur, it does so over a wide area. This type of failure can be thought of as an end member of the continuous failure process where the increments, or episodes, are very large and not tied very closely to the short-term mining rate. With additional mining the failure progresses, much like the room-and-pillar rock failure process, until the overhanging rock mass becomes unstable and falls as a large mass. Hence, this type of rock failure is episodic in nature. These three rock failure processes provide an opportunity to examine microseismic information as it relates to the stability of underground structures.

2. FIELD DATA

NIOSH evaluated microseismic activity from three field sites: Springfield Pike Quarry, located in southwestern Pennsylvania; Willow Creek Coal Mine, located in eastern Utah's Wasatch Plateau; and Moonee Colliery Coal Mine, located in New South Wales 100 km north of Sydney, Australia. Each of these sites exhibits a rock failure process that resulted in different microseismic emission characteristics. Of the three sites, only the microseismic system at Moonee Colliery was designed and utilized to provide real-time roof instability warning information.

2.1. Springfield Pike Quarry: A Case of Progressive Failure

The Springfield Pike Quarry is an underground room-and-pillar mining operation in the Loyalhanna Limestone. Overburden in the study area is approximately 100 m. The Loyalhanna Limestone makes up the mining horizon and approximately 2 m of the immediate roof. Above the Loyalhanna is the Mauch Chunk Formation containing alternating layers of weak claystones, shales, siltstones, and thin sandstones. The Loyalhanna Limestone has an unconfined compressive strength ranging from 130 to 200 MPa and a high horizontal stress field ranging from 14 to 55 MPa [6].

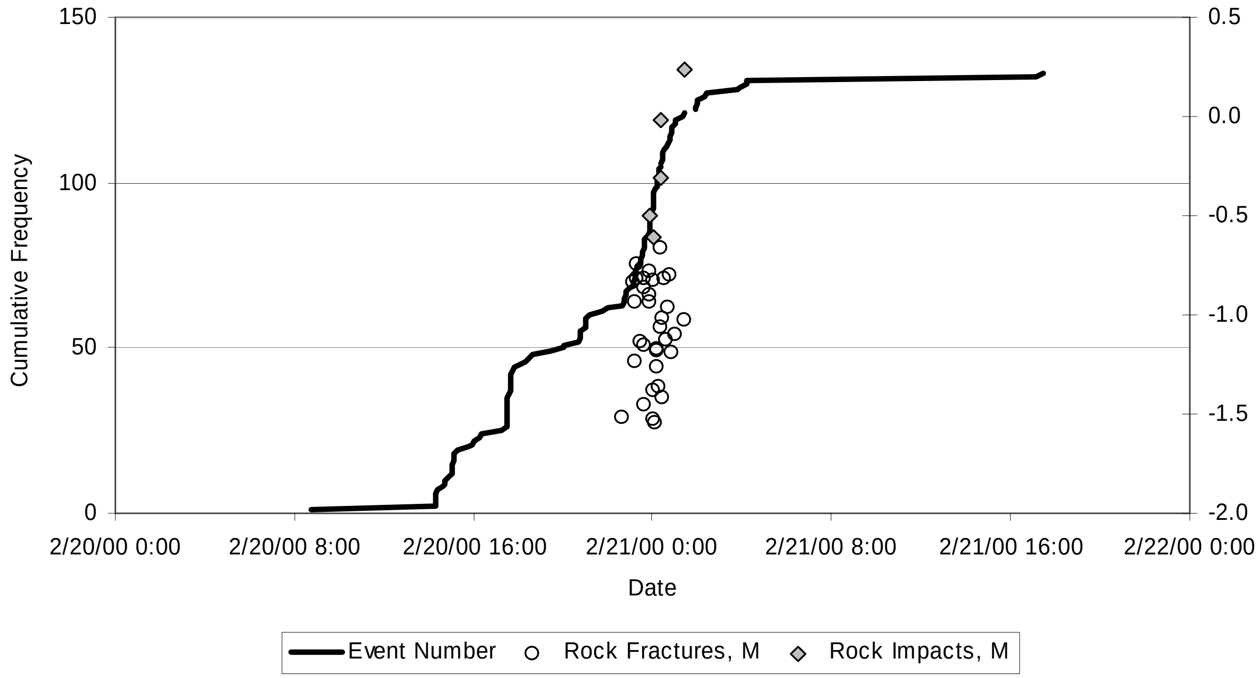

Fig. 1. A plot of the cumulative frequency of the 136 rock fracture events and five rock impact events associated with the February 21, 2000, roof fall at the Springfield Pike Quarry. Moment magnitudes were also calculated and displayed for 32 of the 136 rock fracture and for all five rock impact events.

At the site, 4.5-Hz three-component geophones are used in a single-component configuration. The geophones are mounted on the roof some 8 m above the mine floor. During the course of seismic monitoring at the study site, several thousand seismic events, including several roof falls, were recorded and located [6]. Events involve medium size rock impacts and relatively small rock fracture events. In general, the smallest rock fracture events are typically recorded only by geophones in the immediate vicinity.

On February 20-21, 2000, a series of rock impact events were associated with a major roof fall. This fall extended over 50 m in length, 13 m in width, and as much as 9 m in height. The seismic characteristics of these impacts are similar to those previously discussed by Iannacchione, et al., [3] in that they contain higher seismic moments than rock fractures, are long in duration, and emergent in form. Although it cannot be definitively determined, the authors believe the majority of the energy contained in these events comes from the rocks impacting the mine floor as opposed to the release of the rock from the roof.

Five rock impact events and 136 rock fracture events were recorded at this site (Figure 1). Almost all of the rock fracture events occurred over a 14-hour period from 2:17 p.m. February 20 until 4:15 a.m. February 21. The five rock impact events occurred over a 94-minute period and ended with a final major event at 1:24 a.m. on February 21. The locations of the geophones, rock fractures, rock impacts, and roof falls are shown in Figure 2.

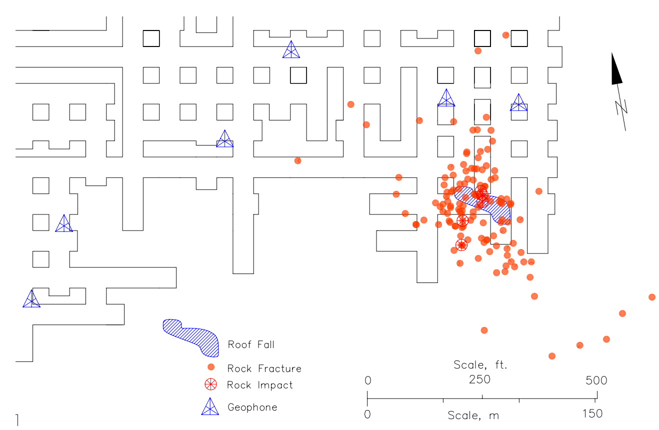

Fig. 2. Location of the 136 rock fracture events, five rock impact events, five geophones, and the February 21, 2000, roof fall at the Springfield Pike Quarry.

The moment magnitude (M) of 32 rock fracture and five rock impact events with the lowest location error measurements are shown in Figure 1. The moment magnitude of the rock fracture events ranged from -1.5 to -0.7, averaging -1.1. The moment magnitude of the rock impact events ranged from -0.6 to 0.2, averaging -0.2. The last rock impact event at 1:24 a.m. on Feb. 21 was the largest (M = 0.2) and most likely represented the biggest mass of falling rock. The magnitude of the event was probably lessened when debris buildup from the previous impacts partially absorbed the energy transfer [3].

The rock failure process in bedded formations with excessive levels of horizontal stress is initiated when the stiffest and thinnest beds in the roof strata begin to buckle from the horizontal loading [1]. When these layers buckle (Figure 3a), shear and tensile rupture between layers and low-angle shears through the intact rock layers can occur (Figure 3b). Eventually the beam begins to cantilever, initiating a tensile failure along the fixed contact area at the edge of the roof fall (Figure 3c). From this point forward, reductions in super- and sub-adjacent layers lower confinement, resulting in additional low-angle shear failures. One-by-one the individual roof beams are strained to failure, shedding their load to adjacent layers which are also strained to failure. The rock failure process is progressive in nature and reduces when the shape of the roof cavity assumes the more stable arch shape. The roof cavity shape is defined by the sub-vertical tensile failures (Figure 3d). Rock failure can be reinitiated at the axial ends of these roof fall cavities where elevated stress conditions sometimes occur.

2.2. Moonee Colliery: A Case of Episodic Failure

The Moonee Colliery is a longwall mining operation in the Great Northern Coalbed of the Newcastle Coal Measure. Overburden ranges from 90 m in the north to 170 m in the south of the mine [7]. The immediate roof comprises 1.6 m of coal and claystone. These layers are overlain by the Teralba Conglomerate with a thickness of 30 to 35 m. Unlike most longwall mines, the Teralba Conglomerate typically does not continuously cave as the longwall advances. Instead, it can hang in place until extensive unsupported spans exist. When it does cave, it can fall as a series of impacts well behind the longwall face or as one continuous mass [8]. The non-continuous caving of the roof is most likely influenced by low overburden, narrow panels, and strong abutment strength of the adjacent solid longwall panels. During mining of the first longwall panel, 41 distinct roof falls occurred with an average hanging span of 46 m. Many of these spans encompassed the entire width of the 100-m-wide panels.

Roof fall caving events began to occur at Moonee after the initial 200 m of longwall face advance of the first panel. Sometimes massive roof falls resulted in dangerous windblasts. For example, six miners were injured on Jan. 22, 1998, from a windblast event associated with the fifth longwall

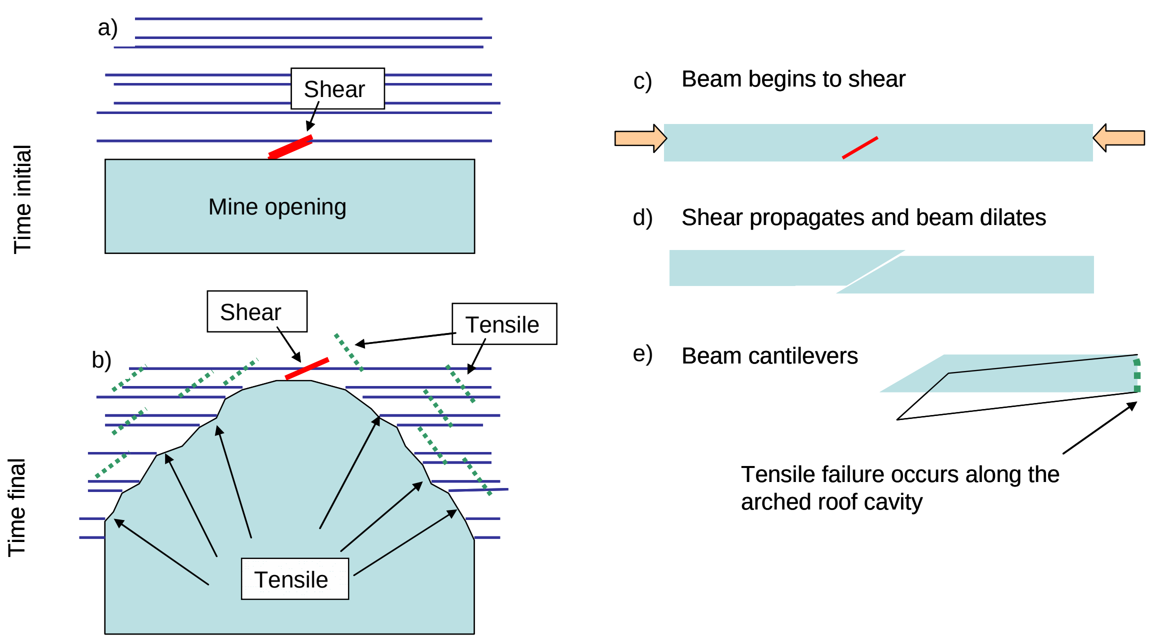

Fig. 3. Generalized sequence in which individual roof beams fail and develop into large roof falls under elevated horizontal stress conditions.

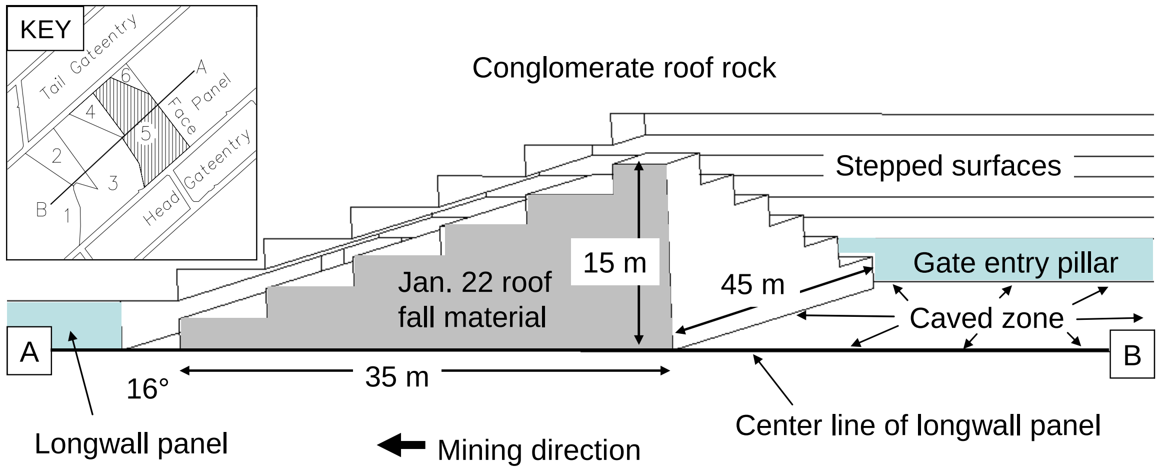

Fig. 4. Generalized sketch of the Jan. 22 roof fall (Fall No. 5), longwall panel No.1, Moonee Mine.

panel roof fall event [9]. This roof fall produced a fallen material geometry similar to half a cone with stepped surfaces (Figure 4). The top of the roof fall failure surface arched approximately 16º over the panel from the longwall face and the two gate entries, reaching a maximum thickness of 15 m in the center of the panel, 35 m from the longwall face (Figure 4). The top of the roof fall cavity was made up of both horizontal and vertical planes that formed a step-like surface. The horizontal planes were most likely associated with local bedding structures within the conglomerate, while the vertical planes were associated with the local jointing, spaced a few meters apart [10]. Above the fallen material, the conglomerate strata continued to bridge across the panel, leaving a 2- to 3-m high air gap. The back side of the fall, facing the previous caved rocks, was approximately parallel to the longwall face but arched toward the longwall face [10]. Edwards [8] and Mills and Jeffrey [10] have indicated that the general pattern described above was typical of longwall panel No.1's roof fall.

Microseismic monitoring was introduced to Moonee soon after the Jan. 22 roof fall as a way to predict the onset of caving with sufficient warning to enable miners on the face to take shelter in a safe location prior to the associated windblast [11]. This system used 14-Hz three-component geophones. Four geophones are mounted in 10-m roof boreholes around the longwall and were continuously moved to surround the longwall face. During the course of this multi-year seismic monitoring project, tens of thousands of seismic events, including numerous roof fall caving episodes, were recorded and located [7, 12]. For example, there were 118 rock fracture events (Figure 5) in the eight-day period that occurred after roof fall No. 20 and prior to roof fall No. 21. Approximately 70% of these seismic events occurred during the last three days of advance. In this case, there was only a weak correlation between advance rate and seismicity. It seems reasonable to ascribe this seismicity to the stepped fracture surface developing in the overlying conglomerate that would soon outline the fallen material for roof fall No. 21 (Figure 6).

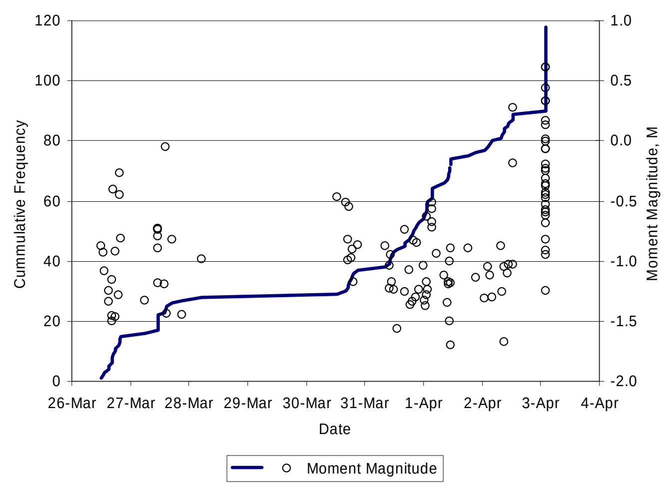

Fig. 5. A plot of the cumulative frequency of the 118 rock fracture events associated with the period between Roof Fall No. 20 and 21 at the Moonee Colliery. Moment magnitudes were also calculated and displayed for all 118 rock fracture events.

By April 3, the hanging roof extended 97 m encompassing a 9,830 m^2 area (Figure 6). The average rock fracture event occurred approximately 16 m above the extraction horizon. Also, a small cluster of rock fracture events occurred along a northwest-southeast trending dyke 150 m from the longwall face. These events may be associated with fracturing surrounding this stiff intact dyke. The moment magnitude of 118 rock fracture events, shown in Figure 5, ranged from -1.7 to 0.6 and averaged -0.9. Three rock fracture events with moment magnitudes between 0.3 and 0.6 occurred approximately three minutes prior to roof fall No. 21.

2.3. *Willow Creek Mine: A Case of Continuous Failure*

The Willow Creek Mine, abandoned since 2001, was a longwall coal mining operation in the Castlegate "D" Coalbed. Overburden in the study area ranges from 750 to 900 m. The immediate roof strata are made up of less than 3 m of thin claystones, shales, sandstones, and coalbeds. Above this is between 150 to 180 m of Blackhawk Formation composed of strong interbedded coalbeds, siltstones, and sandstones with unconfined compressive strengths ranging from 60 to 120 MPa. Capping the Blackhawk is 120 to 180 m of massive cliff forming Castlegate sandstone.

The Willow Creek longwall panels are over a thousand meters long and range in width from 162 to 244 m. The immediate roof strata cave tightly behind the longwall shields as the longwall advances. The continuous caving of the immediate roof is undoubtedly influenced by significant overburden, the wide panels, and the marginal abutment strength of the adjacent longwall gate entries.

A three-dimensional microseismic array used 14 horizontally oriented and 9 vertically oriented surface geophones (4.5 Hz). The underground geophones were mounted directly on the roof and the surface geophones were placed in shallow holes. During the course of seismic monitoring, five thousand high-quality seismic events were recorded and located [13]. The seismicity associated with a typical day of longwall advance is shown in Figure 7. During the early hours of the morning, when maintenance activities idle the longwall, seismicity is very low. Seismicity increases considerably a short time after mining commences.

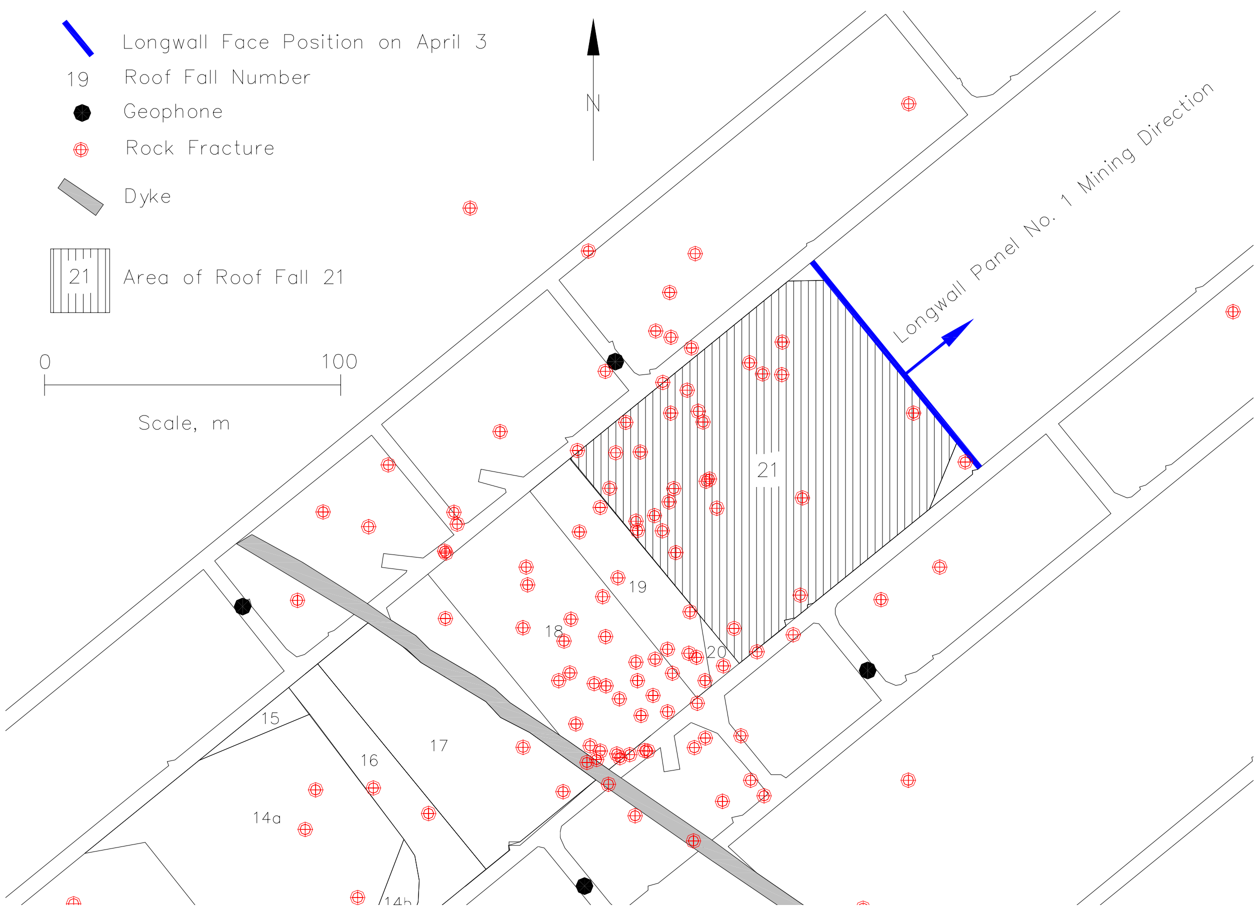

Fig. 6. Location of the 118 rock fracture events, geophones, roof falls, longwall face, and dyke at the Moonee Colliery.

During this period, events occur at a somewhat constant rate until production ceases and then relative quiet returns to the longwall panel. Correlations between advance rate and seismicity rate were documented by Heasley et al. [13] and Westman et al. [14].

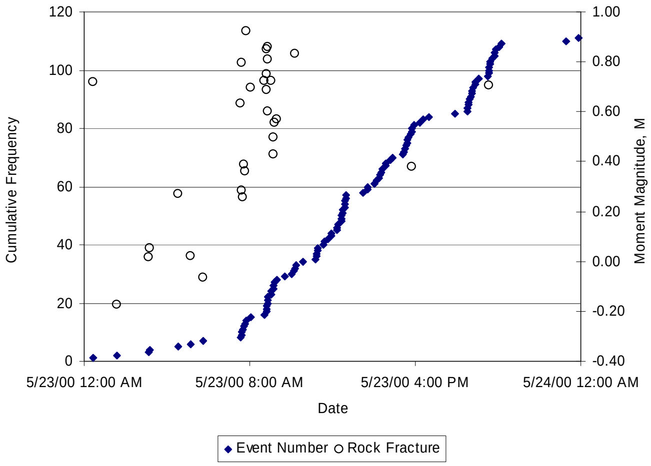

Fig. 7. A plot of the cumulative frequency of the 111 rock fracture events associated with longwall mining on May 23, 2000, at the Willow Creek Mine. Moment magnitudes were also calculated and displayed for 30 of the 111 rock fracture events.

The location of 111 rock fracturing events from May 23, 2000, cluster along the longwall face area (Figure 8). There is a noticeable concentration near the headgate entries. Additionally, the events occur both above and below the mining horizon. In examining the data for the entire longwall panel, Heasley et al. [13] found that the events generally occurred in advance of the longwall face, distributed both above and below the mining horizon.

A majority of the events are associated with the forward abutment stress that fractures the rock in the longwall face area. The forward abutment stress acts along the longwall face area, producing fractures that eventually outline blocks of various size and shapes. These blocks are held together in this area because the longwall face and shields act to supply some level of confinement. As the longwall face advances and the confinement is removed, the blocks begin to separate and collapse forming the broken rock mass known as the longwall gob.

A noteworthy observation is that microseismic emissions are obvious in the front abutment stress area but not so apparent in the longwall gob zone. This is most likely an issue of event detection sensitivity. A minimum of eight stations with high-quality arrivals were required to satisfy the criterion for locating events plotted in Figure 8. Average source to receiver distance was 1.1 km. Thus, smaller events which did not satisfy this condition were not detected. Numerical modeling studies by Gale et al. [14] support the notion that events representing incremental fracture in the frontal abutment zone should be larger than events in the gob zone. In the two-dimensional models, fracturing behind the longwall shield was generally not associated with microseismic activity because of low stress drop conditions, a corresponding lack of shear fracturing, and poor transmission of elastic energy through the broken rock mass.

The moment magnitudes of 30 selected rock fracture events are also shown in Figure 7. This subset of the May 23 events was selected because of their low location value residuals. The moment magnitudes of the rock fracture events ranged from -0.2 to 0.9 with an average of 0.5.

3. MICROSEISMIC EMISSIONS AND STABILITY MONITORING

The three case studies demonstrated that the local rock failure process, active at each site, could be determined from a combination of observational information and microseismic monitoring. The microseismic information was able to detect and characterize the rock deformations in a way that was otherwise not possible. In each case a distinct pattern of seismicity occurred.

3.1. Stability Assessment at Springfield Pike

At the Springfield Pike Quarry, a period of quiet was interrupted by the onset of microseismic activity lasting approximately 14 hours and culminating in a series of rock impacts followed by the return to quiet. Approximately 12.5 hours of microseismic activity preceded the rock impact events that occurred in the last 94 minutes of this time period. In this case, it appears that the microseismic information could be used to provide warning of impending major roof instabilities.

3.2. Stability Assessment at Moonee

The episodic rock failure process at Moonee Colliery was in many ways similar to the Springfield Pike Quarry with the exception that it was rarely very quiet in the longwall panel area. The almost continuous advance of the longwall face

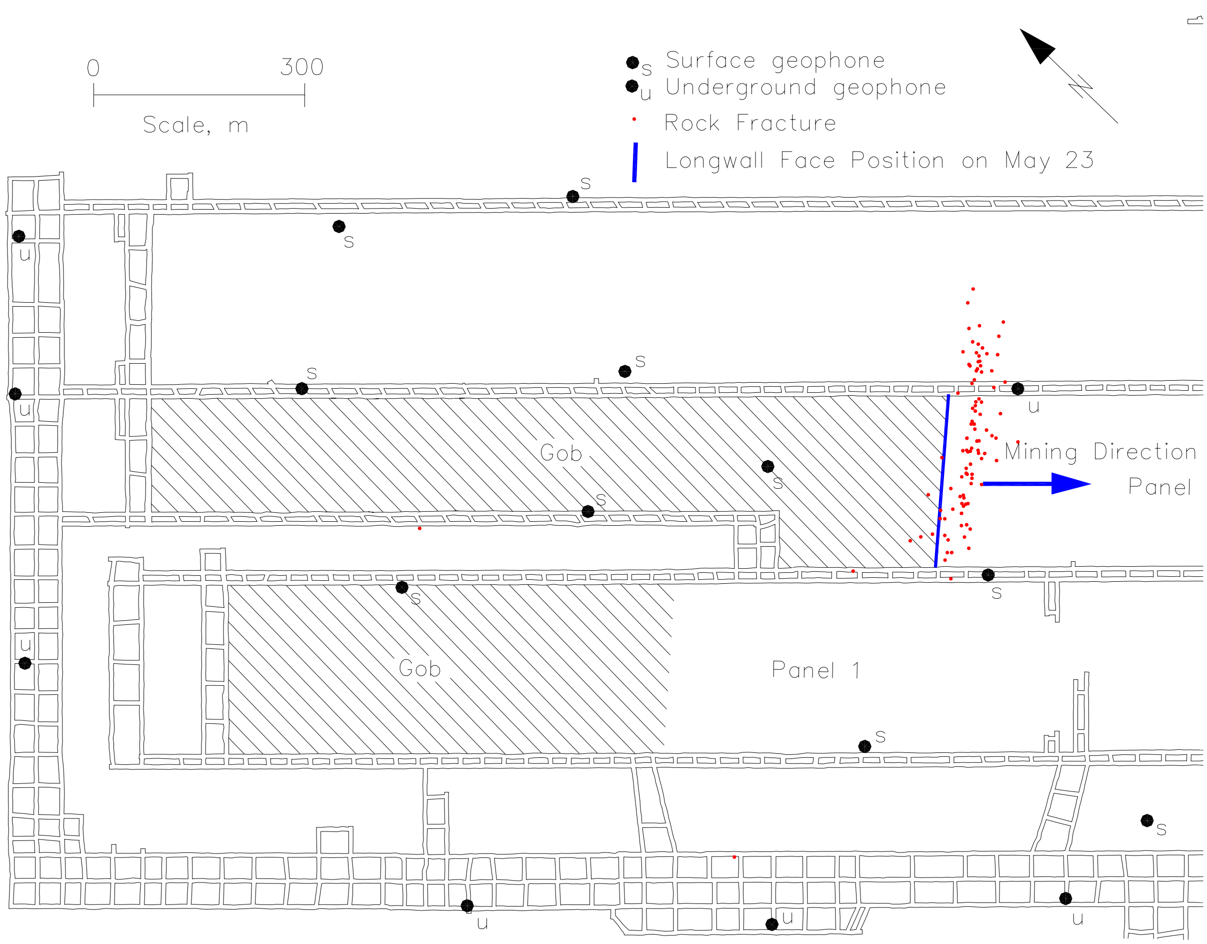

Figure 8. - Location of 111 rock fracture events, geophones, longwall caving zone (gob), and longwall face at the Willow Creek Mine.

acted to destabilize the overlying roof strata above the longwall panel. The majority of the microseismic activity did not cluster around the face. Instead, the microseismic activity apparently represents the initiation and development of the stepped failure surface and accommodation of stress adjustment over a wide area. This final activity just prior to the roof collapse represented a dramatic increase in the occurrence, rate, and, to a lesser degree, magnitude of microseismic events (Figure 5). In fact, Moonee Colliery developed a system of alarms that warned of impending roof falls from observed trends in microseismic activity. These alarms were:

1. Trend Alarms – based on interpreted trends of microseismic activity. Alarms were typically long-term warnings, usually a few hours, that provided sufficient time for the longwall crew to evacuate the face.
2. Frequency or Magnitude Alarms – based on a sudden flurry of microseismic activity. Alarms were typically short-term warnings, usually a few minutes, that provided sufficient time for the longwall crew to move to the safest area of the face.
3. Auto Alarms – based on the capture of six events or greater in a 10-second period. In this case, an alarm was automatically signaled.

Hayes [7] reports that the microseismic system was able to give sufficient warning of impending roof falls that could cause windblast in approximately 90% of the cases.

3.3. Stability Assessment at Willow Creek

The continuous failure process at the Willow Creek Mine is very different from the progressive and episodic processes at Springfield Pike and Moonee. Microseismic activity was associated with the constant caving of the longwall panel. This constant activity was a sign of "normal" mining conditions. While the microseismic information was never used to issue warning of specific hazardous ground conditions, deviations from a continuous failure process may represent the onset of abnormal caving. Recognition of this deviation from normal provides the basis of a hazard warning methodology. Abnormal caving behavior is often associated with coal bumps, weighting of the longwall shields, large roof collapses in the gob, and, in some cases, damaging windblasts.

4. SUMMARY AND CONCLUSIONS

This paper reviews the behavior of two roof fall events and one case of continuous roof caving. Significant differences are observed in the collective seismic character from each site. These differences are related to the interaction of local geologic, mining, and stress conditions. It would be very difficult to develop an adequate understanding of the important failure processes operating at each of these sites without the microseismic information. Three rock failure processes were identified as progressive, episodic, and continuous.

Microseismic information collected from three field sites consisted of:

- At Springfield Pike, 136 rock fracture events occurred over a 14-hour period. The moment magnitudes of these rock fracture events ranged in size from -1.5 to -0.7. During the final 94 minutes of this failure event, five significant rock impact events occurred. The moment magnitudes of these rock impact events ranged in size from -0.6 to 0.2.

- At Moonee, 118 rock fracture events occurred over an eight-day period between Roof Fall No. 20 and No. 21. The moment magnitudes of these rock fracture events ranged in size from -1.7 to 0.6.

- At Willow Creek, 111 rock fracture events occurred during a normal production day. The moment magnitudes of 30 selected rock fracture events ranged in size from -0.2 to 0.9.

In each of the three case studies, the character of the microseismic information helped to identify the rock failure process:

- Progressive – Periods of quiet are interrupted by the onset and progression of microseismic activity which lasted in this case for approximately 14 hours and culminated in a series of rock impacts followed by the return to quiet.

- Episodic – The majority of the microseismic activity represents the initiation and development of the stepped failure surface that outlines the eventual roof fall material. The final surge in activity is associated with the completion of this surface and the collapse of the roof.

- Continuous – Microseismic activity in the forward abutment stress zone was associated with the constant caving of the longwall panel.

It was also demonstrated that the microseismic information provided a useful assessment of the stability of the roof rock. In the case of the progressive rock failure process, the onset of microseismic activity signaled the beginning of unstable conditions. It was also demonstrated that while activity continued, rock impacts were possible. In the case of the episodic rock failure process, trends in the microseismic activity were used to warn of roof falls with a high degree of success. Finally in the case of the continuous rock failure process, the constant uniform activity in the forward abutment stress area was a sign of “normal” conditions. Deviations from normal strata response can provide useful stability information.

Microseismic activity, occurring during and before roof fall and roof caving processes, can be measured and analyzed to characterize local failure processes. Enormous potential exists for application of this technology to assess the stability conditions of underground structures, so that safer mine layouts, monitoring systems, and support systems can be engineered.

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