Forecasting Roof Falls with Monitoring Technologies – A Look at the Moonee Colliery Experience

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ABSTRACT

There has been a persistent need to forecast roof falls so that miner's exposure to hazardous underground environments can be minimized. Several monitoring techniques have been developed and are used today with varying levels of acceptance in the mining industry. This paper examines the potential for monitoring microseismic emissions activity as a means of forecasting roof falls. The use of this activity to forecast roof falls has drawn only limited attention, resulting in a lack of published field performance data. This deficiency is being partially addressed by analyzing data obtained during longwall mining at Moonee Colliery in 1998. The Moonee data base contains a wealth of information concerning roof fall forecast parameters and the seismic alarm criteria used to develop these forecasts. Four seismic alarm criteria were developed and used by Moonee with varying degrees of success. Roof falls were forecasted 73% of the time with average forecast times of 54 minutes. Ninety percent of the predicted roof falls had a warning time, i.e., the time between warning and roof fall event, of greater than 1 minute. The fraction of forecasted roof falls decayed logarithmically as a function of warning time, until only 20% of events were predicted more than 100 minutes prior to roof falls. False alarms occurred in 50% of the warnings. Many of the false alarms were quickly followed by a cessation in mining which could have temporarily halted the on-going failure process. If mining had continued immediately after the false alarms, a roof fall may have occurred soon after. The microseismic activity collected from Moonee Colliery demonstrates that techniques to forecast roof rock instabilities in underground mines are possible.

INTRODUCTION

Monitoring technology and techniques to provide early warning of hazardous roof fall conditions have been a longstanding goal for safety engineers and practitioners working in the mining sector. Roof-to-floor convergence monitors are perhaps the oldest and most common method of measuring roof deflection as a means to detect roof rock instabilities. This type of instrument consist of an anchor device mounted on the mine roof and floor and connected by a ridged bar or a metal wire. The relative movement of the anchor points is measured with either mechanical or electro-mechanical devices.

Multipoint extensometers installed in boreholes have been used to detect roof movements and have seen use in the United State, the United Kingdom, and Australia (Gale, et al., 1992; Siddall and Gale, 1992). Homemade mechanical extensometers, consisting of a top and bottom anchor, steel wire or rigid tubing, and some kind of micrometer or dial gauge, have been used for decades in metal mines in Michigan, Missouri, and Idaho (Parker, 1973). In 1999, the National Institute for Occupational Safety and Health (NIOSH) introduced a modified mechanical extensometer called the RMSS which had the added capacity to be read remotely (Iannacchione, et al., 2000). Some common commercially available mechanical extensometer monitoring devices are the Miners Helper and the Guardian Angel (Name brand references to a specific product does not imply endorsement by NIOSH).

In addition to extensometers, coal mines sometimes use telltales to warn miners of strata movement. The telltale was first introduced in France during the early 1970's (Bigby and DeMarco, 2001). It consists of a rigid bar anchored into the roof. A small section of rod protruding from the borehole is monitored to determine roof deflection. Altounyan, et al., (1997) found that falls of ground in British coal mines were reduced from 267 to six between 1990 to 1995, partially due to the use of telltales.

All of the instruments discussed are classified as roof deflection monitors and are a significant part of any thorough ground control plan. Field evaluations have shown (Petersen and Shaffer, 2000; Parker, 1973; Maleki and Chaturvedi, 1999) that roof deflection measurements aid in monitoring mine opening performance and in determining where, and often when, a roof fall may occur. At some mines, this kind of information is routinely used by operations personnel to assess the stability of localized roof rock. Widespread industry acceptance of this technology may be limited by the need for extensive and costly instrument coverage. Each roof deflection instrument is capable of assessing the behavior of only localized sections of the immediate roof. These areas can be as small as tens-of-square meters to as great as hundreds-of-square meters. Since the average underground mine often maintains thousands of square meters of active working areas, very large numbers of instruments could be needed to obtain adequate coverage.

The use of monitoring microseismic emissions to warn of roof falls has only had limited investigations. The first evaluation of this technology was in the 1940's by Obert and Duvall (1945a and

1945b) as a means of tracking general stability conditions. Later, Leighton and Stebley (1975) demonstrated that increased noise rates, from a system capturing events in the 36 to 44 kHz range, preceded the failure of a coal mine roof by as much as 15 minutes. Unfortunately, the ultrasonic frequencies attenuate rapidly, requiring geophone placement very close to roof fall events. These kinds of system requirements have presented numerous operational issues.

Mine-wide microseismic monitoring technology has the capability to collect and analyze a share of the total energy released as localized strata fractures prior to, during, and after roof falls. This technology has the advantage of continuous detection and relatively low instrument-to-coverage area ratios. For example, geophone coverage areas are likely in the range of hundreds-of-square meters. However, microseismic monitoring systems have higher purchase costs and their data can be more ambiguous to interpret than roof deflection measurements. Perhaps an even greater problem is the lack of published field data which supports the use of this technology to warn of roof falls. Monitoring strategies to implement roof deflection technologies are being addressed by many organizations around the world. The use of microseismic technology in concert with other monitoring technology is currently being addressed in the United States by NIOSH. In a related effort, CSIRO is currently examining changes in microseismic resonance modes prior to roof falls as a possible forecasting tool (King, 2005).

It is important to note the differences between the use of microseismic technology to detect and warn of roof falls and its deployment in many countries around the world to warn of violent, dynamic failures of rock. Rock bursts, coal bumps, and gas outbursts are associated with large releases of energy, occur in most major mining countries, and are a major cause of traumatic injuries to mine workers. The literature is filled with examples of both successes and failures in using microseismic monitoring technology to warn of these intense, but relatively infrequent failures. Mitigating these hazards requires practitioners to forecast the areas of most risk and, in some circumstances, the time of their occurrence.

Dynamic failures, by their nature, are associated with a significant release of energy, producing large seismic events. Forecasting the largest magnitude events, the ones that can do the most damage, is the principal focus. The largest events represent a very small portion of the total population of microseismic activity occurring at any one site. For example, of the 9,580 microseismic events collected from the first longwall panel at the Moonee Colliery, only one was greater than 2.0 on the moment magnitude scale (Figure 1). The moment magnitude scale is roughly equivalent to the commonly used Richter earthquake magnitude scale. The vast majority of the events are less than 0. The difficulty in forecasting these large but relatively rare events is obvious. In contrast, forecasting roof falls relies on the total population of microseismic events to identify the on-set of the collapse.

So by analyzing microseismic emission activity and roof deflections associated with roof falls, forecasting methods can be evaluated. Improving forecasting techniques to detect roof rock instabilities in underground mines is seen as a positive step towards lowering miner exposure to hazardous environments.

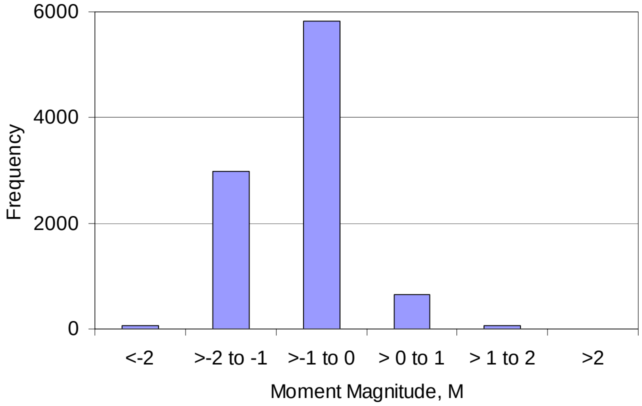

Figure 1. Moment magnitude distribution of microseismic events collected during the mining of Longwall Panel No.1 at the Moonee Colliery.

THE MOONEE COLLIERY AND ROOF FALLS

NIOSH has embarked on an effort to collect and analyze data on the use of monitoring technology to forecast roof falls. One study was recently completed at the Springfield Pike Mine in Pennsylvania and a second was initiated at the Burning Springs Mine in West Virginia. At these underground limestone mines, attention is focused on the onset of intense, localized microseismic activity that rise-up from periods of relative quiet. These kinds of rock failure processes are classified as progressive, indicating that once failure is initiated the potential exist for accumulating failures that can progress towards a roof collapse (Iannacchione, et al., 2005). Roof rock failures that are sudden and lack some progressive development will most likely be undetectable by monitoring techniques discussed in this paper.

Roof fall Characteristics - The Moonee Colliery is a longwall mining operation in the Great Northern Coalbed of the Newcastle Coal Measure, north of Sydney, Australia. Overburden ranges from 90 m in the north to 170 m in the south of the mine (Hayes, 2000). 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. The massive Teralba Conglomerate is the main reason why Moonee's longwall strata doesn't continuously cave as the longwall face 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 (Edwards, 1998). The non-continuous caving of the roof is most likely influenced by low overburden, narrow panels (<100 m), and strong abutment strength of the adjacent solid longwall panels.

Roof fall caving events began to occur at Moonee after the initial 200 m of face advance within the first longwall panel. Six miners were injured on January 22, 1998, from a windblast associated with the fifth longwall panel roof fall (Mills and Jeffrey, 2001). This roof fall produced a fallen material geometry similar to half a cone with stepped surfaces (Figure 2). 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 2). The top of the roof fall cavity was comprised 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

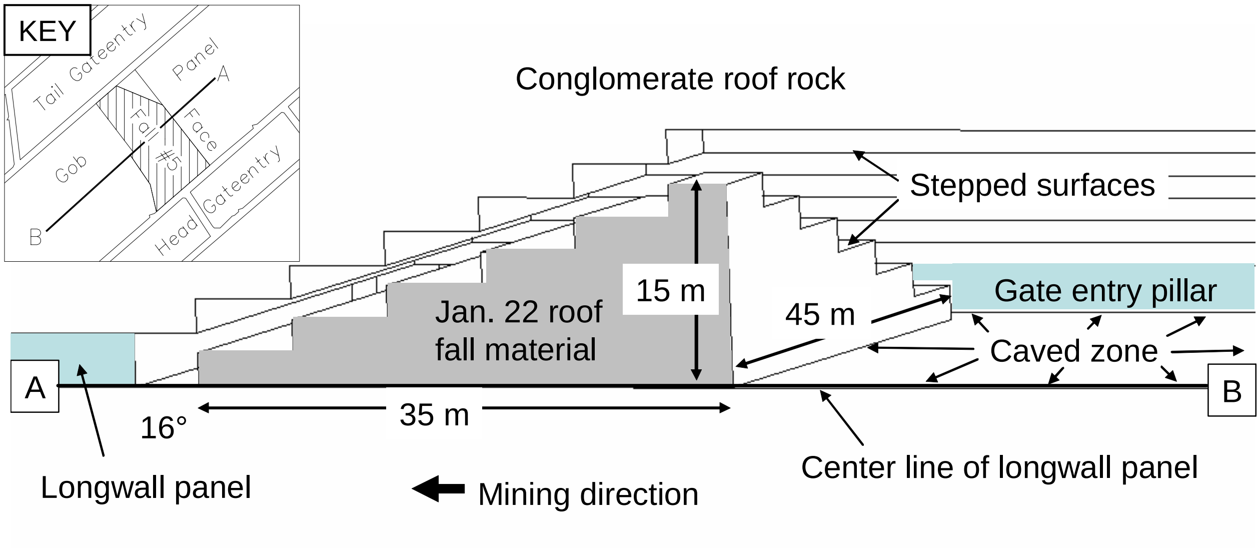

Figure 2. Generalized sketch of the Jan. 22 roof fall (Fall No. 5), longwall panel No.1, Moonee Colliery.

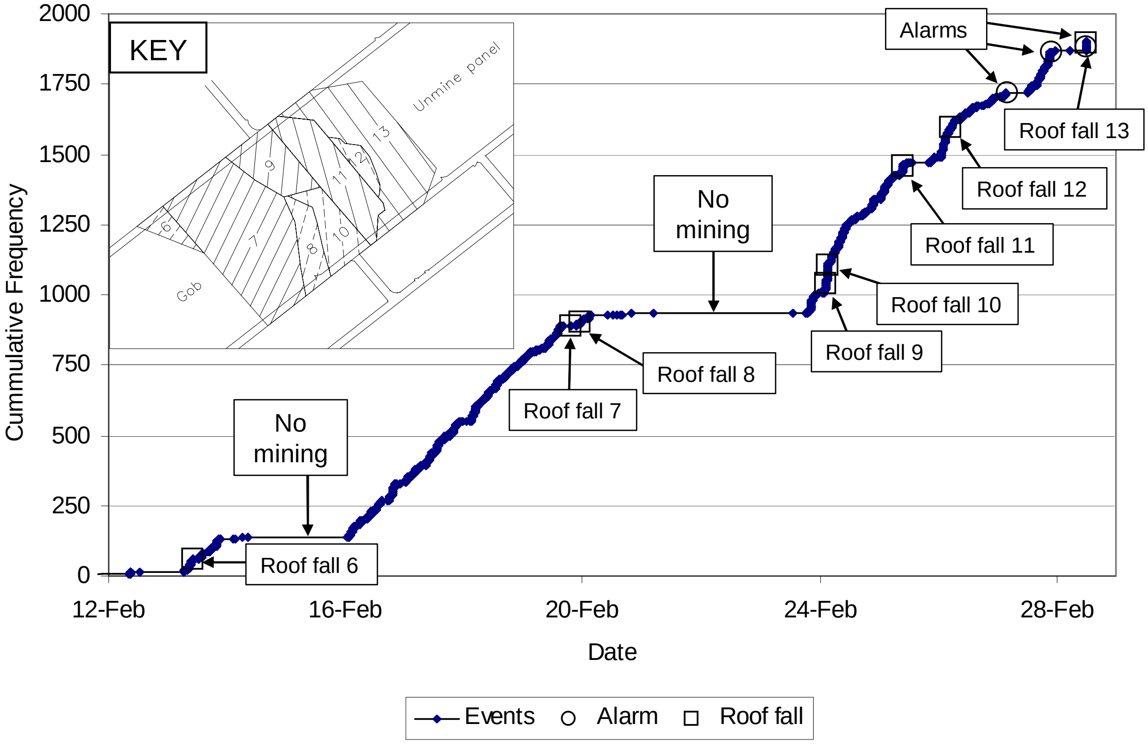

Figure 3. Cumulative frequency of microseismic events during the initial phase of monitoring. Note dashed lines symbolize non-significant roof falls and continuous lines symbolize significant falls.

planes were associated with the local jointing, spaced a few meters apart (Mills and Jeffrey, 2005). 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 previously caved rocks, was approximately parallel to the longwall face but arched toward the longwall face. Mills and Jeffrey (2005) have indicated that the general pattern described above was typical of longwall panel No.1's roof falls.

As a result, when these failures finally occur, they do 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 until the overhanging rock mass becomes unstable and falls as a large mass. Hence, this type of rock failure is episodic or periodic in nature (Iannacchione, et al., 2005).

Microseismic Monitoring - Microseismic monitoring occurred at Moonee from 1998 until 2002 when a decision was made to close the mine, due to factors other than those related to the windblast issue. Many researchers worldwide are aware of the unique site conditions at Moonee and the exceptional field data that was collected there. After the mine closed, NIOSH purchased the microseismic database and began re-analyzing the data.

Microseismic monitoring was introduced to Moonee soon after the Jan. 22, 1998 roof fall as a way to predict the onset of caving with sufficient warning to enable miners on the longwall face to take shelter in a safe location prior to the associated windblast (Edwards, 1998). The microseismic system was manufactured by ISS International from South Africa and used 14-Hz 3-component geophones throughout the study. Four geophones were mounted in 10 m roof boreholes surrounding the longwall face and continuously moved as the face advanced. 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 (Brink and Newland, 2002; Hayes, 2000).

Initial Monitoring - An initial period of microseismic monitoring collected 1,903 microseismic signatures from February 11 until February 28, 1998 (Figure 3). Many of these signatures were not located and some may not be associated with rock fracturing. Techniques were perfected during this period to accurately locate and classify events and to calculate an array of seismic parameters. As these techniques developed, the mine began to evaluate alarm criteria and formulated a plan for managing the microseismic information.

Eight roof falls were observed during the initial monitoring period (Figure 3). Three were considered significant (Nos. 7, 11, and 13, Figure 3). Significant roof falls were defined as those events that had an area greater than approximately 2,000 m^2, and that had, by calculation, the potential to generate dangerous windblast. This definition implies that the roof came down, more-or-less, as one continuous mass. Five of these roof falls (Nos. 6, 8, 9, 10, and 12, Figure 3) were considered non-significant. In all, 27 roof falls were classified as significant during the mining of longwall panel No.1. The median area of all significant roof falls is 4,350 m^2.

Conversely, 14 roof falls were classified as non-significant. With the exception of roof falls Nos. 30 and 34, all non-significant roof falls were relatively small with a median area of 460 m^2. These two roof falls were deemed non-significant because they did not produce a caving event that tripped the windblast monitoring device in the main gate entry. However, it is possible that these roof falls directed their air blasts into the gob and, therefore, may have been significant. Most non-significant roof falls occurred before the face advanced 20 m from the last roof fall.

A geologist/microseismic operator was responsible for processing incoming events and continually updating trends. After two false alarms, the first successful alarm occurred 2 minutes prior to the roof fall No. 13 (Figure 3).

MICROSEISMIC ACTIVITY AND ROOF FALL ALARMS

After the initial period of microseismic monitoring ended with the successful alarm for roof fall No. 13, a seismic alarm criterion was implemented to assist in producing actual warnings of roof falls that could potentially create windblasts. The actual warning alarms issued by the operator were derived from a number of different sources including: shield pressure, audible noise, miner input, and seismic information. The seismic alarm criterion was comprised of four individual computed or appraised criteria:

- Frequency1 (F1) – based on the capture of 6 events or greater in a 10 second period. The computer automatically initiated an alarm to the operator.
- Frequency2 (F2) – based on the capture of 5 multiple events in 1 minute. Multiple events have more than one distinct signature per record. The operator was required to monitor event characteristics.
- Magnitude (M) – based on more than one event with a moment magnitude greater than -1.0 in a 2 minute period. Since 68% of the events measured during longwall panel No. 1 were greater than -1.0 (Figure 1), many events could be considered in this criterion. The operator was required to process events to determine event magnitudes.
- Trend (T) – based on interpreted trends in microseismic activity, usually focused on changes in four seismic parameters. One of these parameters, Apparent Volume, is a cumulative indicator of seismic activity based on both the frequency and magnitude of successive events. The Energy Index, Seismic Viscosity, and Seismic Schmidt Number can all be likely indicators for the onset of roof rock failure (Mendecki, van Aswegen, and Mountfort, 1999). The relationship between the Apparent Volume and the Energy Index were key indicators, along with some consideration of Seismic Viscosity and the Schmidt Number, to balance the problem of wild swings in individual parameters. These parameters were displayed in continuously updated system history windows available to the operator.

During the remainder of mining this longwall panel, 15 significant roof falls were selected and analyzed (Table 1). These roof falls had hanging strata over the longwall gob areas greater than 20 m in length. The 20 m face advance was used in the mine's Windblast Management Plan to determine when protective measures were required (McDonell, 2001). The seismic alarm criteria were used to determine the actual warning 73% of the time and produced an average forecast time of 54 minutes, 12 minutes better than the average for the operators warning alarm (Table 1). The operators alarm types consisted of seismic criteria, shield pressure, and audible noises. The frequency criterion (F1) was the dominant seismic alarm followed by the magnitude and trend criteria. Fifty percent or 15 of a total of 30 alarms were classified as false. Many of these may be due, in part, to a cessation in the episodic failure process when the longwall was stopped as a consequence of the alarm being triggered, i.e., the self-perpetuating threshold had not been reached. Since this paper is focused on the performance of the seismic activity in forecasting roof falls, the following analysis will focus only on the seismic alarms.

Plots of success rate of seismic alarms decayed logarithmically with increasing forecast time (Figure 4). Ideally a forecast window of more than 2 minutes may be needed to give the miners time to seek shelter in a refuge area. Refuge areas were provided for every second longwall support and at several places along the main gate entry (Hayes, 2000). Using this criterion, 80% of the roof fall events would have been successfully forecast. Hayes (2000) reported that the microseismic system was able to give sufficient warning of impending roof falls that could cause windblast in approximately 90% of the cases. The frequency and magnitude criteria were more important in the short forecast windows while the trend-criterion was more important in the longer forecast windows. The short forecast windows became the focus of the seismic alarms, thereby diminishing attention on improving the longer forecasts.

Table 1. – Characteristics of fifteen selected roof falls

Roof fall number	Actual warning		Seismic alarm criteria		No. of false alarms	Face advance, m
	Type	Minute	Type	Minute		
14	NA	6	F1, F2	1,1	4	67
17	Seismic	8	F1, F2, T	8,8,8	2	48
18	Audible	1.5	F1, F2, T	2,2,2	0	41
19	Seismic	9	F1	9	0	20
21	Seismic	2	F2, M, T	3, 3, 4	2	97
23	Audible	2.5	F1, F2, M, T	159,159,159,157	0	95
25	Seismic	13	F1, F2, M, T	36,36,36,36	4	127
26	Seismic	1	F1, F2, T	68, 13, 13	0	28
31	Seismic	24	F1, F2, T	24	0	38
32	Seismic	209	F1, F2, T	206,206,209	0	30
33	Shield pressure	139	F1, F2, M, T	158,258,158,158	1	59
35	Seismic	119	F1, F2, M, T	98,120,98,119	0	27
36	Seismic	90	F2, M, T	89,81,81	0	109
39	Shield pressure	0.1	F1, F2, M T	0.1 (all)	0	69
40	Seismic	0.5	F1, F2, M	1 (all)	2	151

F1 – Frequency1 criterion
F2 – Frequency2 criterion
M –Magnitude criterion
T – Trend criterion
NA – not available

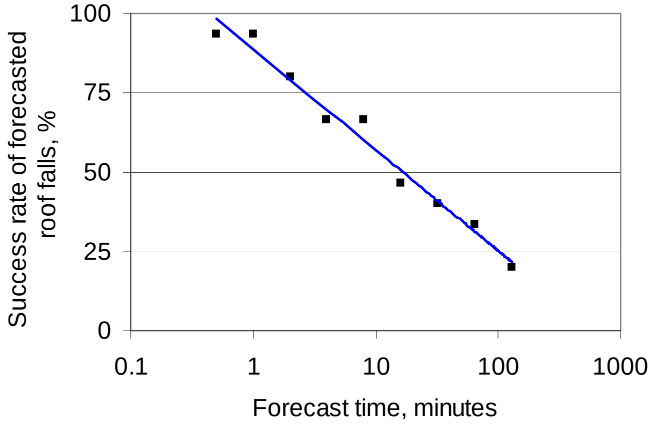

Figure 4. Logarithmic decline of forecast time versus the percentage of successfully forecasted roof falls.

WHAT CAN BE LEARNED ABOUT FORECASTING ROOF FALLS FROM THE MOONEE DATA?

The Moonee study is important because the episodic rock failure processes that were observed there are, in many ways, similar to the progressive rock failure that typifies many roof falls in underground mines with strong roof rock conditions (Iannacchione, et al., 2005). The extraction of longwall coal mine panels generally produces strata that cave continuously and lacks dramatic changes in microseismic activity (Heasley, et al., 2001; Westman, et al., 2001). At Moonee, where episodic rock failures are common, the majority of the microseismic activity is apparently associated with the initiation and development of the stepped failure surfaces (Figure 2). These surfaces eventually define the extent of large, distinct roof falls that are similar to that found at the Springfield Pike Mine (Iannacchione, et al., 2004).

What is striking about the Moonee data is that the seismic activity generally increases dramatically, close to the time of the roof falls. For example, figure 5 shows the microseismic activity during the period after roof fall 30 and just before roof fall 31. The seismic activity is maintained at a relatively constant rate, with the exception of the idle weekend, until a short time before the roof fall. Plots of event locations show a dispersed pattern over the most recent longwall gob areas. Most likely this represents the continuous development of the stepped failure surface that will eventually outline roof fall 31. In the 24 minute forecast period between the seismic alarm and the roof fall, an intense period of activity occurred within the gob in the area of roof fall 31 (Figure 5). This flurry of activity probably signals the coalescence of many smaller fracture surfaces into larger destabilizing structures within the roof rock.

This significant change in the rate of seismic activity rate at Moonee might be viewed as a transition from a stable to an unstable condition, much like what is observed in many progressive type roof falls. This point in time can also be considered as the start of the roof fall forecast window. These transitional points between stable and unstable conditions were observed for almost all of the roof falls studied (Figure 6).

The precise character of the forecast window starting points provides insight into the potential magnitude of rate changes expected to signal the onset of a roof fall. At Moonee, the background seismicity ranged from 5 to 15 events per hour (Figure 7). At the start of the unstable periods the seismicity rate at least doubled and in many cases increased by one order of magnitude (Figure 7). This data demonstrates the complexity of patterns associated with the transition from stable to unstable roof rock.

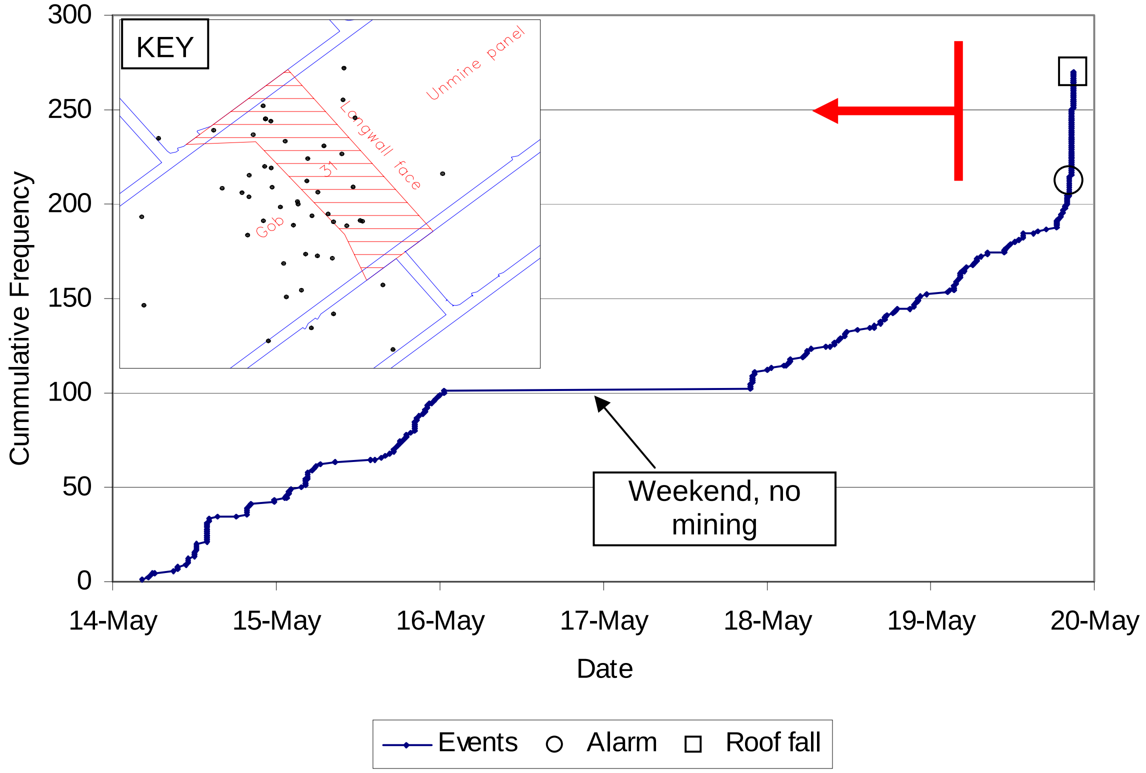

Figure 5. Cumulative frequency of seismic events associated with roof fall 31. The location of events, occurring within the forecast window between the seismic alarm and the roof fall, is also shown.

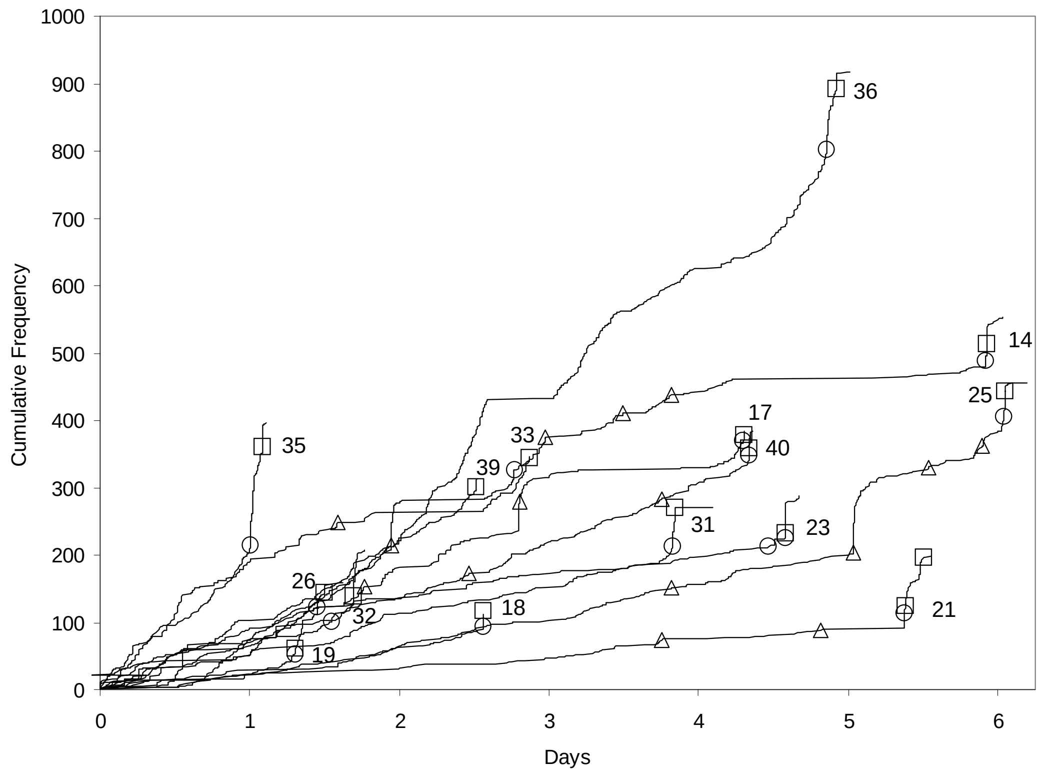

Figure 6. Cumulative frequency plots for 15 selected roof falls. The idle periods associated with weekends have been removed from the data. Roof falls are shown as squares, alarms as circles, and false alarms as triangles.

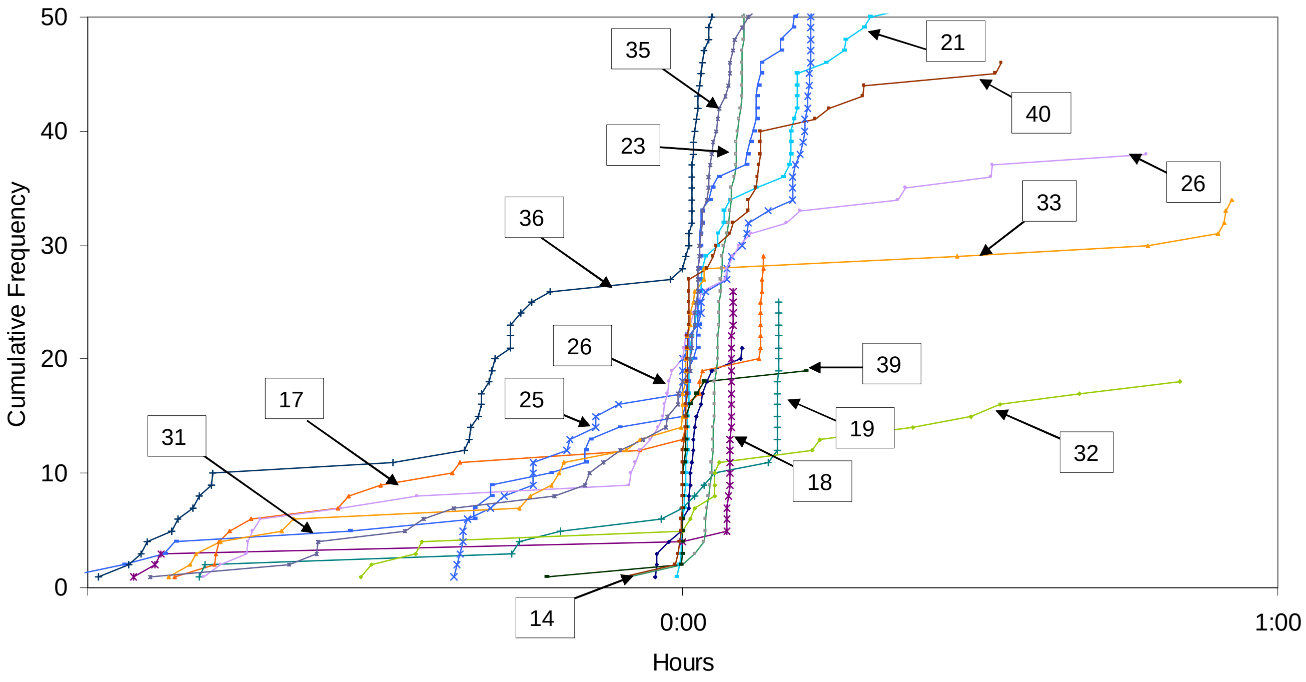

Figure 7. Cumulative frequency plots for 15 roof falls covering a two hour window. The zero hour indicates the beginning of the forecast window where the strata is transitioning from stable to unstable.

SUMMARY AND CONCLUSIONS

Monitoring technology and techniques can provide a means to warn of hazardous roof fall conditions. Measuring roof deflection is the most common method of detecting roof instabilities. These measurements aid in monitoring mine roof performance and in determining where, and often when, a roof fall may occur. Widespread acceptance is limited by the need for extensive and costly instrument coverage. The use of microseismic emissions activity to forecast roof falls has drawn only limited attention, resulting in a lack of published field performance data which supports the use of this technology. NIOSH is interested in providing microseismic emissions activity and roof deflection performance data as a means to address this issue.

Two roof fall failure processes were identified that lend themselves to early roof fall detection:

- Progressive failure – periods of quiet are interrupted by the onset and progression of microseismic activity and marked by significant changes in roof deflection. Both of these measurements signal the progress of rock failures that can eventually lead to a total roof collapse (Iannacchione, et al., 2005).
- Episodic failure – microseismic activity is associated with the initiation and development of the stepped-shaped 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.

Roof falls in conjunction with longwall mining at the Moonee Colliery were classified as episodic and produced a fallen material geometry similar to half a cone with a stepped failure surface. Microseismic emissions from 15 roof falls were analyzed during the mining of the first longwall panel at Moonee. These emissions are apparently associated with the initiation and development of the stepped failure surface associated with each roof fall.

Four seismic alarm criteria were developed at Moonee. Geologists responsible for operating the microseismic system had varying levels of input in the generation of these alarms, ranging from computer initiated auto alarms to trend analysis requiring substantial data interpretation. The seismic alarm criteria were used to successfully determine the actual roof fall warning 73% of the time and produced an average forecast time of 54 minutes. False alarms occurred in 50% of the warnings. Many of the false alarms were quickly followed by a cessation in mining which temporarily halted the on-going failure process. In many cases, a roof fall would probably have occurred if mining had continued after the alarm. The seismic alarm forecast times displayed a logarithmic decay versus the percentage of forecasted roof falls. Frequency based seismic criteria were most important in the short forecast windows while the trend based criterion were more important in the longer forecast windows.

The microseismic activity displayed a rapid increase prior to 15 roof falls with longwall panel No.1, probably signaling the completion of the stepped failure surface associated with each individual collapse. This rapid increase in microseismic activity is thought of as the transitional point between stable and unstable conditions. Background seismicity associated with normal longwall advance ranged from 5 to 15 events per hour. At the start of the unstable periods, the seismicity rate increased from 2 to 10 times over the background rate. If these kinds of rate changes can be observed in the episodic failure modes at Moonee Colliery, there should be a more than reasonable chance for observing similar significant rate changes associated with the progressive type roof falls that plague many underground mines.

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