Preprint 07-103

AN EVALUATION OF MICROSEISMIC ACTIVITY ASSOCIATED WITH MAJOR ROOF FALLS IN A LIMESTONE MINE: A CASE STUDY

J. Ellenberger, NIOSH, Pittsburgh, PA
T. Bajpayee, NIOSH, Pittsburgh, PA

Abstract

Microseismic monitoring and evaluation is one aspect of the National Institute for Occupational Safety and Health (NIOSH) research program. Roof falls are often preceded by a period of elevated microseismic activity, but not all periods of elevated activity result in a roof fall, nor do all roof falls occur after some amount of elevated activity. The objective of this study is to review periods of elevated microseismic activity and determine whether fracture activity rate can be used to anticipate the initiation of roof falls. The study was carried out at an underground limestone mine where major roof falls are associated with excessive horizontal stress. The progression of roof falls was detected by the microseismic signature produced by the rock falling from the mine roof onto the mine floor, which is termed a roof fall impact event.

A total of nine elevated fracture activity periods that resulted in seven major roof falls were examined. It was observed that elevated fracture activity preceded the initial roof fall impact event in three out of four major roof falls. The initial impact event was not identified for the remaining three roof falls.

Fracture event rates were analyzed and a roof fall alarm trigger of five fracture events in a ten minute time period was established for this test case. The fall alarm trigger was tested against six of the elevated activity periods. Four roof falls occurred in the six periods of elevated activity, and two would have triggered the alarm before the roof fall occurred, while two false alarms were generated.

The results show that limited success would have been achieved by the microseismic system as a roof fall alarm trigger. However, the trigger would have been successful at warning of the onset of elevated activity, allowing mine employees to respond appropriately.

The study highlighted some issues with implementing such a system in an operating mine, including the need for real time identification of fracture related microseismic signals among mining induced signals, and accurate location and identification of fracture clustering.

Introduction

This study was conducted under the NIOSH objective to reduce traumatic injuries of miners and promote safer workplaces. One of the goals of the mine safety program is to reduce ground fall injuries in underground mines. One effort focused on the use of roof deflection and microseismic emissions to help forecast unstable roof conditions (Iannacchione et al., 2004). The microseismic emissions prior to the initiation of major roof falls and the progression of roof fall episodes were examined at an underground limestone mine in Pennsylvania. If miners can detect an area of mine roof that is about to fall, they are more likely to take corrective actions and avoid injury.

The traditional role of seismic analysis has been to locate the hypocenter and determine the size of earthquakes or manmade tremors. Mining has been recognized for over a century as a cause of ground vibrations (Atkinson 1903, Davison 1905). Techniques were developed to monitor acoustic emissions resulting from rock fractures in mines and laboratory (Obert and Duval 1945a, 1945b). The instrumentation to examine the noises was first applied by amplifying signals in the audible range so that rock fracture activity could be observed in mines. An increase in the rate of microseismic events have also been recognized as a precursor to failures of pillars or roof (Brady, 1978). More recently, the Goafwarn[1] device made by the Council for Scientific and Industrial Research uses light emitting diodes mounted on a device that will flash when a preset number of events are sensed (Makusha, 2005).

A roof fall can be viewed as the culmination of deformation and rock fracturing events. In elevated stress situations, rock fracturing is likely to be a dominant mechanism causing instability. Each fracture event serves to create or extend a ruptured surface, thereby diminishing roof stability. As more events occur, the roof becomes progressively less stable and increases the likelihood of progression to a roof fall.

The microseismic records related to roof falls are rock fracture and roof fall impact events. A roof fall impact event occurs when a rock strikes the mine floor. Impacts associated with major falls can be detected by the geophones located on the roof from vibrations that are transmitted through the mine floor and pillars (Iannacchione et al., 2005).

An example of a typical geophone trace resulting from a fracture event is shown in figure 1. The fracture of the rock produces a signal that is sharply defined, and the amplitude generally decays rapidly, often in a fraction of a second (Iannacchione et al., 2005). Figure 1 also shows an example of a geophone trace resulting from a roof fall impact event. Impact events differ from fracture events in that they are emergent wave forms that are often several seconds in duration. Exact locations of impact events are not readily identified from P and S wave arrivals. This is because the irregular wave paths and the emergent nature of the wave distorts the P and S arrivals, but the geophone closest to the event is easily identified, to establish the location of the roof fall. Large roof fall impact events can be seen across the entire microseismic network. When the initial roof fall impact event is identified, the time of the event can be placed among the fracture events to show when the initial roof fall occurred relative to the fracture activity.

The objective of this study is to evaluate the potential for anticipating major roof failures from the rate of roof fracture events. Roof falls are classified as major falls when they extend above the 8 ft (2.4m) roof bolted interval.

Field Site and Microseismic Monitoring Network

The study site is the Springfield Pike mine, an underground limestone mine located in southwestern Pennsylvania. The mine produces crushed stone from the Loyalhanna Limestone Formation, which is 70 feet (21 m) thick in some areas. The mining zone averages 30 feet (9 m) high during development and consists of horizontal beds that range from 3 to 5 feet (1-1.5 m), containing widely spaced vertical joints, and extensive cross bedding (Iannacchione and Coyle, 2002). The Loyalhanna is overlain by the Mauch Chunk

[1] Mention of company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

Formation, consisting primarily of interbedded shales and calcareous sandstones, and underlain by the Pocono Sandstone. The intact strength of the Loyalhanna ranges up to 30,000 psi (200 MPa) unconfined strength, but geologic structures and discontinuities can significantly reduce the overall rock mass strength. Throughout the mine, the roof is supported with 8 foot bolts.

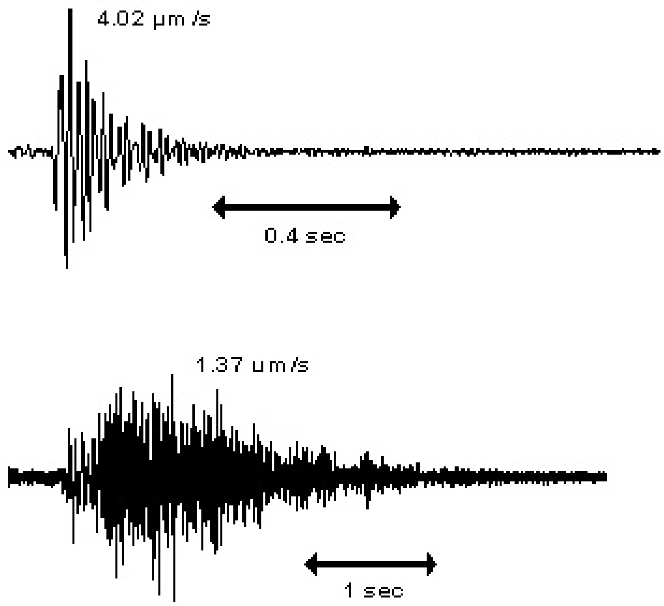

Figure 1. Example traces for a rock fracture (top) and impact (bottom) events.

Roof falls in the mine display the characteristics of falls caused by excessive levels of horizontal stress (Iannacchione et al., 2001). The falls are often elliptical in plan, are initiated by roof guttering similar to cutter roof seen in coal mines, and are aligned perpendicular to the maximum horizontal stress. Hydrofracturing tests at the mine indicate the existence of very high horizontal stresses, ranging from 2,200 to 8,000 psi (15 to 55 MPa).

The monitoring system consisted of 12 uniaxial geophones oriented in a North-South direction, mounted on the mine roof approximately 30 feet (9 m) above the mine floor. Figure 2 shows the location of the geophones relative to the study area. The geophones were distributed across two active areas of the mine with average separations of about 300 feet (90 m). Data acquisition, filtering, and analysis equipment was located in a trailer, and cables were connected to the geophones. The sensors connected to the system were 4.5-Hz, 630 ohm, uniaxial geophones (Iannacchione et al., 2001).

The locations and dates of the three major roof falls and the extension of two major falls that occurred during this study period are shown in figure 2. It should be noted that all three major falls occurred in an area approximately 300 feet (90 m) wide in an E-W direction by 500 feet (150m) in the N-S direction. The February 20 fall was approximately 130 feet (40 m) long and trended NW-SE. The March 7 fall was approximately 150 feet (45 m) long, trending N-S. The June 26 fall was the extension of a previous fall, and was the only roof fall outside of the 300 foot (90m) by 500 foot (150m area). The October 28 fall was approximately 170 feet (50 m) long in a N-S direction, and the major fall of November 14 extended the October fall approximately 110 feet (35 m) in a NW-SE direction.

Approach

The microseismic records from February through November 2000 were the subject of an earlier report (Iannacchionne et al., 2001). Since this original work, improvements in analysis techniques and software capabilities have identified an increased number of locatable events. The recognition of roof fall impact events permitted the initial episode of a major roof failure to be accurately located in the progression of fracture events. A series of roof fall impact events are often identified during the time when the roof is failing, but the first impact event is significant because it signals the start of the major fall. However, it must be recognized that smaller undetected fall episodes may precede a major roof fall.

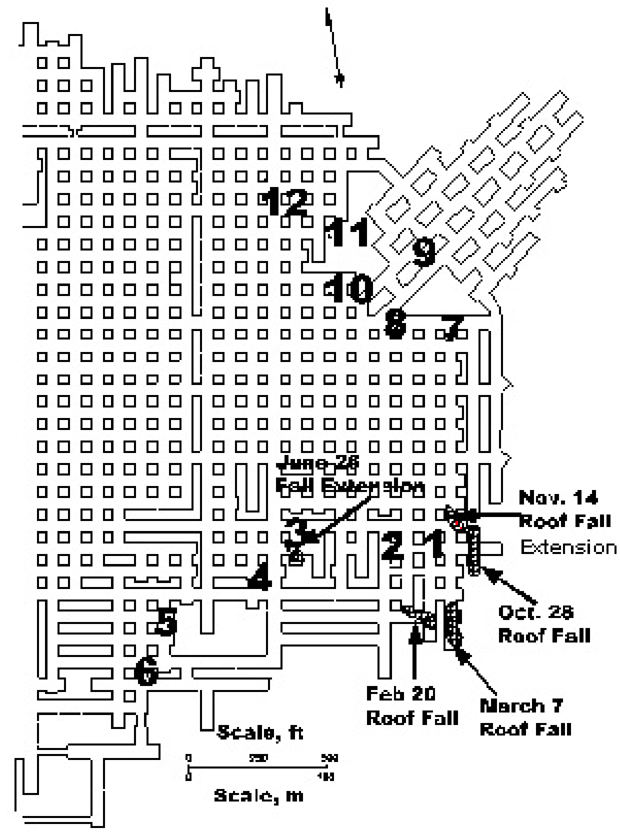

Figure 2. Mine map showing the locations of geophones, three major roof falls, two roof fall extensions and dates.

Because the microseismic records had been reviewed earlier (Iannacchione et al., 2001), and periods of elevated activity were already identified, the records were examined in two groups. In the first group, all records were examined to establish normal background fracture rate and precursor trends associated with roof falls. In the second group, only records from elevated activity periods were reviewed.

The first group included all the microseismic records in a period of 140 days from July through November 17, 2000, a total of 13,801 microseismic records. These records were individually classified as fracture, impact, blast, electrical, or mining induced. From this total, 670 fracture events were identified and located. Impact events were also identified and associated with the roof falls that occurred in this period. This group of events was then analyzed to establish an alarm trigger rate for the second group of elevated activity periods. The trigger rate is the number of events occurring in a specific time window that may signal the beginning of a roof fall episode.

The second group of data included six periods of elevated activity from February to July 2000. The first roof fall impact event was identified relative to the set of fracture events. This group of events was used to test the alarm trigger rate to forecast an impending major roof fall. Similarly to the first group, all seismic records were reviewed in the elevated activity periods, fracture events were identified and located, and impact events were identified and associated with roof falls. The first impact event associated with any roof fall was identified and placed in its correct position with regard to time of occurrence. This group of events was used to test the alarm trigger rate. The group included two major roof falls.

Determination of Roof Fall Alarm Trigger

The cumulative event plot in figure 3 shows the time relative occurrence of all 670 rock fracture events that were identified during the span of 140 days included in group one. The slope shown in the center portion demonstrates the typical fracture event background activity. This period includes 214 fracture events from July 10 through October 24, a period of 106 days. The steeper slopes on either end represent the periods of high activity associated with roof falls in July, October, and November. Table 1 shows the number of fracture events that occurred per day in each of the background and elevated periods.

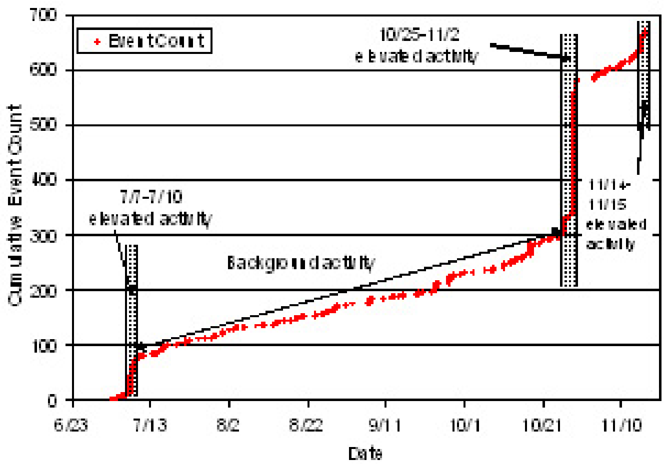

Figure 3. Cumulative event count from July 2 to November 15.

Table 1. Summary of group #1 quiet and elevated activity periods showing the number of events per day and weighted average for similar periods.

Dates	Activity Classification	Duration (days)	Outcome	Events per day
7/2-7/7	Quiet 1	3.9		3.11
7/7-7/10	Elevated 1	2.3	Roof Fall	28.73
7/10-10/25	Quiet 2	106.0		2.03
10/25-11/2	Elevated 2	3.8	Roof Fall	75.29
11/2-11/14	Quiet 3	11.2		4.63
11/14-11/15	Elevated 3	1.5	Roof Fall	23.32
Weighted Average				
	Quiet			2.3
	Elevated		Roof Falls	50.9

Since event frequency is the number of events occurring in a defined period of time, a matrix was developed including the number of times a trigger would occur using the first group of 670 events. Time windows of 5, 10, 15, 30, and 60 minutes were utilized to assess fracture event rates. From the time an event occurred, it remained in the count window for the designated time. The 670 events were time ordered in a spreadsheet, and the time differences between any given event and the next six events were calculated. This effectively created a rolling time window so that the number of events in the time window at any point in time could be evaluated. The plot in figure 4 shows the percentage of the time that two to seven events in a given window of time preceded an initial roof fall impact event. This plot shows that two or three fracture events in a time window of five to 60 minutes may forecast the initial roof fall impact event, but seven to ten false alarms would occur for each actual roof fall. When the alarm trigger is changed to four events in five minutes or five events in ten minutes, the percentage of alarms that are followed by roof falls increase to over 40 percent. Based on this assessment, an alarm trigger was selected as the first occurrence of five events in a period of ten minutes.

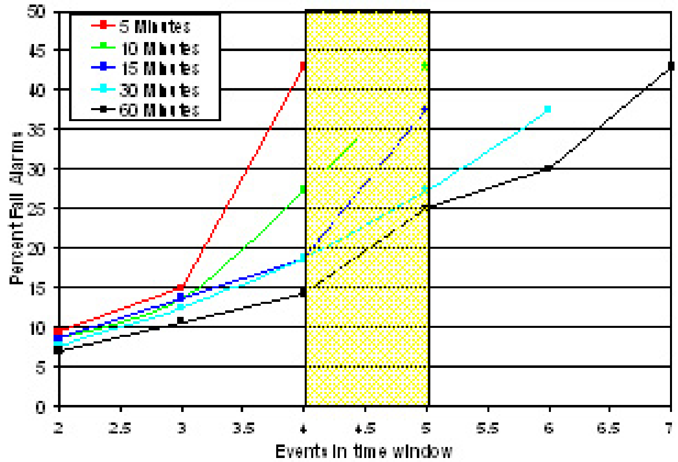

Figure 4. Percent of fall alarms that proceeded roof falls vs the number of events required to trigger the alarm.

Assessment of Microseismic Alarm Trigger

The second group of elevated activity periods was then used to test the effectiveness of the alarm rate of five events in 10 minutes to forecast the onset of roof falls. Six elevated activity periods were evaluated (Table 2). The elevated activity periods were identified during earlier analysis (Iannacchione et al., 2001). These six periods included three major roof falls, two periods of elevated activity that did not result in a fall, and one fall that did not extend beyond the roof bolts. Event records were reviewed for two to three days preceding and during the elevated activity. Initial roof fall impact events were identified in two of the roof falls while no impact events were found in the two other roof falls.

Table 2. Summary of group #2 elevated activity periods used to test the effectiveness of the alarm trigger.

Event window	Number of events	Outcome category	Observed damage	Events/ hr	Warning Time, minutes
2/20-2/21	507	1	Roof Fall	14.60	22
3/7-3/8	66	1	Roof Fall	2.35	131
4/21-4/22	25	4	No damage observed	0.61	N/A
5/27-5/28	51	3	Shallow failure	1.25	N/A
6/24-6/25	30	4	No damage observed	0.66	N/A
6/26	47	3	Fall Extension	2.22	N/A

It was recognized that each of the elevated fracture activity periods would result in one of four outcomes:

1. Elevated activity preceding a roof fall with an identifying impact event (forecastable falls),
2. Initial roof fall impact event coinciding with the onset of elevated fracture activity (roof falls with no microseismic warning),
3. Elevated fracture activity associated with a confirmed roof fall, but without detection of the roof fall impact event, and
4. Elevated fracture activity that resulted in no roof fall.

The first category of elevated fracture activity includes roof falls that may be anticipated before the major fall occurs. Two of the four falls that occurred in group #2 were detected by microseismic activity before the initiation of the roof fall. Elevated fracture activity following the alarm trigger rate of five fracture events in the ten minute time period is shown in figure 5 for these two roof falls. The initial roof fall impact event associated with each fall is also shown on the graph. The elapsed time from the initial alarm trigger (the fifth fracture event) determines the warning time associated with the initial roof fall episode. For these two falls, the warning time was 22 minutes for the February 20-21 fall and 2 hours and 11 minutes for the March 7-8 fall.

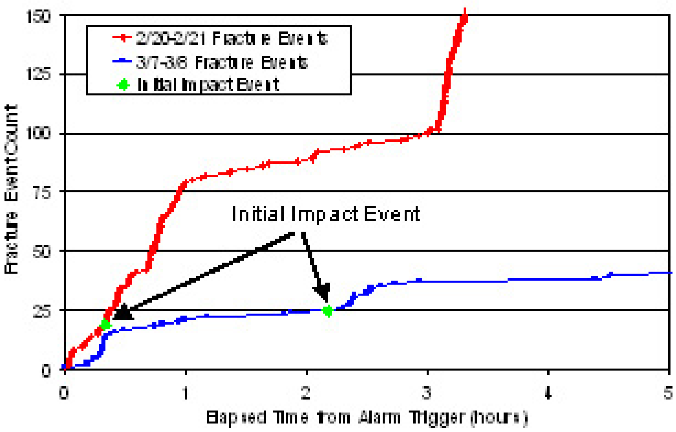

Figure 5. Event count plot of two major roof falls with recorded initial impacts.

The second category of elevated activity can be classified as roof falls that are not immediately preceded by elevated microseismic activity (roof falls with no microseismic warning). In this category earlier fracture events may have deformed and weakened the roof, reducing the number of fracture events necessary to weaken the roof to failure. Roof falls that occur in this category might also be related to geologic structures or discontinuities that have significantly weakened the roof before mining (Iannacchione et al., 2001). These falls are associated with a high level of fracture activity after the fall develops. The microseismic data has value to the operator in locating the fall area, especially if it occurs in remote areas. The cumulative event count plot for the fall shown in Figure 6 shows an example of a roof fall that occurred on July 7-9, which was not preceded by elevated microseismic activity. The plot shows typical background activity for over 100 hours preceding the fall, followed by a similar trend to that of the forecasted major falls in the previous category. However, the initial roof fall impact event is the third event as the activity elevates. A total of 55 fracture events were identified in the elevated activity period.

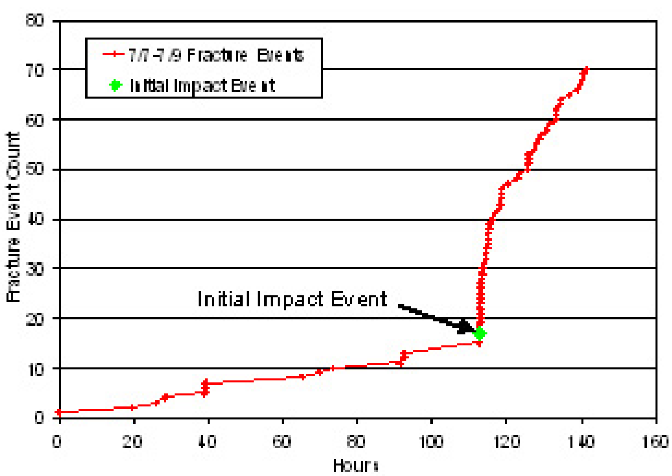

Figure 6. Cumulative fracture event plot of a roof fall with virtually no warning. Note the abrupt change from background to elevated activity.

The third category of elevated fracture activity is one where a roof fall is identified by on-site observation, but the microseismic records did not include a roof fall impact event. Figure 7 shows the cumulative event count of fracture events recorded on June 26, and it is very similar to the plots seen in association with roof falls in figures 5 and 6. Nearly 50 fracture events were recorded between 7 and 11 hours on the plot. The review of the seismic records showed that the events were readily identified as being nearest geophones 3 or 4. A roof fall that was observed to have extended to a greater depth on June 26 is also near geophones 3 and 4. Since the material that fell from the roof to extend the fall probably fell on existing rubble, it is reasonable to assume the impact events were masked from the microseismic system to record the event.

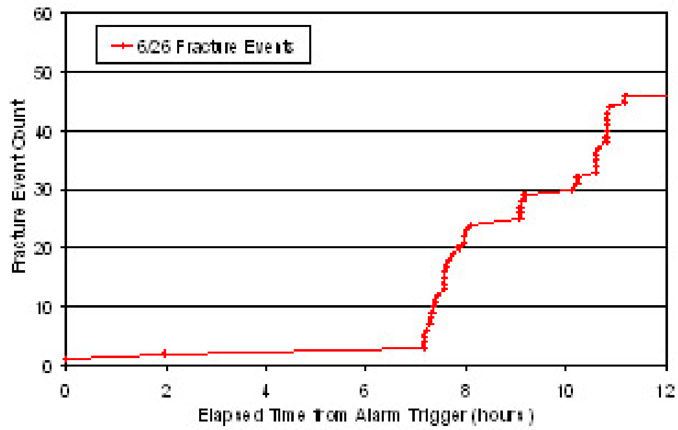

Figure 7. Cumulative fracture event activity with no identified roof fall impact.

The fourth category, elevated fracture activity that results in no roof fall, may best be classified as false alarms. In these situations, fracture events occur, and the frequency may reach that of an alarm, but the roof reaches equilibrium without having a failure. Figure 8 shows two elevated cumulative event count periods that were not associated with significant roof damage. These plots include a small number of fracture events following the 5 events in 10 minutes that classified them as triggered alarms, while the roof falls of February 20-21 and October 28-29 included 507 and 244 events, respectively. It should be noted that the elevated activity seen on June 24-25 preceded the fall extension that occurred on June 26 (category two). These episodes of elevated activity do represent the development of fractures and the continued weakening of the roof, and may contribute to those falls described earlier that occur with little or no warning.

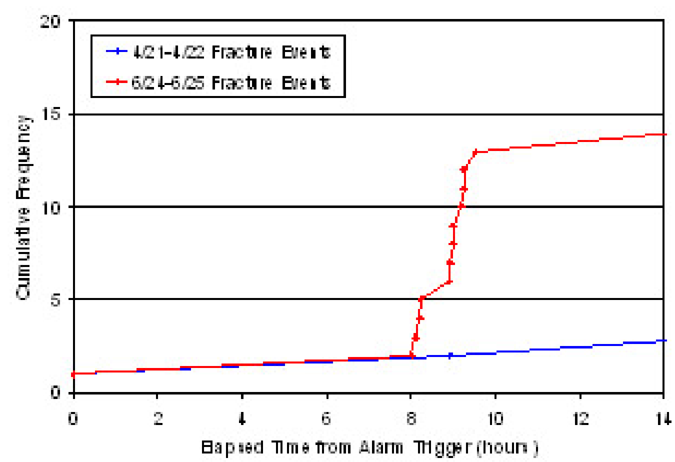

Figure 8. Cumulative fracture count of two elevated activity periods with no identified impact events.

To summarize, the alarm trigger would have provided pre-warning of the two roof falls in which the initial impact event was known. It is not known if the alarm would have triggered prior to the initial impact in the two remaining roof falls, because these impact events were not detected by the microseismic system. The final two elevated activity periods reached the trigger alarm rate and caused false alarms.

Discussion of Issues Related to Microseismicity and Roof Falls

Clearly, several issues still need to be addressed to further enhance the capability of microseismic systems as roof fall warning devices. These issues are discussed below.

A warning system would have to operate in real time. Less than 10% of the events that the system recorded were determined to be fracture events. Some events generated by mining activity are difficult to distinguish from fracture events and typically occur at the workface. A reliable filtering system to automatically exclude these events and only consider rock fracture events is required.

Although roof fall impacts were detected with the microseismic system, it is possible that smaller rock falls occurred prior to the initial identified impact. The focus was to detect the initial large rock fall event. Since almost any size rock can result in a fatal accident in mines where the roof is usually 25 feet or higher, the need to further refine the initial failure is a significant problem.

When a roof fall has occurred, the roof fall may become an impediment to the ability to recognize activity that will result in an extension of the roof fall. First, the roof in the fall extension area has been weakened by fractures that developed at the time of the initial roof fall. The preexistence of these fractures weaken the roof to a near critical state. Then the critical nature of the roof may render the use of a universal alarm trigger impossible. A review of the fracture event plots presented in this study shows that the fracture rates during recognized periods of elevated activity vary considerably.

A roof fall warning system needs to address areal clustering of events in addition to event frequency rate. Events occurring frequently but dispersed over a large area are not necessarily related and do not indicate an accumulation of damage in a local area. Conversely, if the same events do occur in close proximity, it can indicate an impending roof failure. In this study it was observed that four of the elevated activity periods were clustered around major roof fall locations while two were not clustered nor were they associated with a major roof fall.

Summary and Conclusions

Elevated microseismic activity was found to be correlated to major roof falls at an underground limestone mine where roof falls are attributed to high horizontal stress. A total of nine elevated activity periods were associated with seven roof falls. A detailed analysis showed that elevated microseismic activity preceded three out of four of the falls. An evaluation was carried out to determine if the preceding microseismicity could be used as a roof fall warning system.

An alarm trigger was developed using three of the elevated activity periods. The background activity rate was also considered to limit false alarms. A variety of event rates were tested using a range of time windows from five to sixty minutes duration. It was found that a rate of 5 fracture events in a 10 minute window provided the best chance to warn the onset of roof falls at the mine site.

The developed alarm trigger was tested against the remaining six periods of elevated activity, which included four roof falls and two periods that did not result in roof falls. It was found that the trigger correctly warned of two falls, but two false alarms were generated by the elevated periods that did not result in roof falls. The other two roof falls triggered alarms, but the time of the roof fall was undetermined; it is therefore not known if the alarms would have proceeded the roof falls.

While the alarm trigger showed limited success as a roof fall warning system, it would have been successful in warning of the onset of elevated fracture activity. Knowledge of the location of the elevated fracture activities would allow mine employees to take appropriate action, such as inspections to determine if the roof has already fallen or avoidance of the area.

The study has highlighted some of the issues related to the use of a microseismic system as a roof fall warning device. These issues include: a) real time determination of fracture events among large numbers of mining induced events, b) identification of small roof falls prior to the larger impact event recorded by the microseismic system, c) identification of the extension of existing falls, and d) quantification of areal clustering of events.

The potential for false alarms and the reality of roof falls that are not preceded by microseismic activity are further issues that would impede the acceptability of such a roof fall warning system. Notwithstanding the above, microseismic systems can provide valuable information on the onset and location of elevated fracture activity, indicating potentially unstable roof so that appropriate remedial actions can be planned. In addition, the location of roof fall impact events is useful information, especially if they occur in disused areas of a mine.

Acknowledgements

The authors are indebted to A. T. Iannacchione, Ph.D., Principal Research Engineer, Rock Safety Engineering Branch, for constructive guidance and direction in conducting this analysis, and T. E. Marshall, Engineering Technician (retired) for his dedicated work in maintaining the field network and collecting the field data.

References

Atkinson, W.N. (1903), "Report of H.M. Inspector of Mines for the Stafford District for the Year 1903."

Brady, B.T. (1978), "Prediction of Failures in Mines-An Overview," *Bureau of Mines, Report of Investigations No. 8285*.

Davison, C. (1905), "Earthshakes in Mining Districts," *Geol. Mag*, Decade V, 2:219-223.

Iannacchione, A. T., L. M. Burke and M. C. Chapman (2005), "Characterising Roof Fall Signatures from Underground Mines," in *The Proceedings, Sixth International Symposium on Rockburst and Seismicity in Mines, Controlling Seismic Risk, Australia*, March 9-11, pp. 619-629.

Iannacchione, A.T., P.R. Coyle, L. J. Prosser, T.E. Marshall and J. Litsenberger, (2004), "Relationship of Roof Movement and Strata-Induced Microseismic Emissions to Roof Falls," *Mining Engineering,* pp. 53-60.

Iannacchione, A.T. and P.R. Coyle (2002), "An Examination of the Loyalhanna Limestone's Structural Features and Their Impact on Mining and Ground Control Practices," in *The 21st International Conference on Ground Control in Mining,* Morgantown, WV, Aug. 6-8, pp. 218-227.

Iannacchione, A. T., Marshall, T. E., and L. J. Prosser (2001), "Failure Characteristics of Roof Falls at an Underground Stone Mine in Southwestern Pennsylvania," in *The 20th International Conference on Ground Control in Mining,* Morgantown, WV, Aug. 7-9, pp. 119-125.

Makusha, G and D. Minney (2005), "A System to Provide Early Warning on Impending Goaf," in *The 24th International Conference on Ground Control in Mining*, Morgantown, WV, Aug. 2-4, pp. 61-65.

Obert, L and W. I. Duval (1945a), "The Microseismic Method of Predicting Rock Failure in Underground Mining, Part 1, General Method," *Bureau of Mines, Report of Investigations 3797*.

Obert, L and W. I. Duval (1945b), "The Microseismic Method of Predicting Rock Failure in Underground Mining, Part 2, Laboratory Experiments," *Bureau of Mines, Report of Investigations 3803*.