THE RELATIONSHIP OF ROOF MOVEMENT AND STRATA-INDUCED MICROSEISMIC EMISSIONS TO ROOF FALLS

A.T. Iannacchione, P.R. Coyle,
L.J. Prosser, and T.E. Marshall
NIOSH
Pittsburgh, PA

J. Litsenberger
Better Materials
Connellsville, PA

ABSTRACT

For the first time in an underground stone mine, the relationship between roof movement and microseismic emissions was examined in conjunction with two distinct roof fall areas. As roof monitoring increases in acceptance and monitoring technology advances, the goal of providing reliable roof fall detection systems to enhance the safety of underground mine workers moves closer to reality. Instrumental to reaching that goal is the ability to interpret accurately and completely roof movement and microseismic emissions, which can serve as precursors to roof falls. This paper examines the capabilities of convergence and microseismic monitoring systems to better understand roof rock failure mechanics and to anticipate roof falls. An understanding of how these techniques are used and how they interact with each other is critical in developing the most effective ground control strategy for our nation's mines.

INTRODUCTION

Typically, when roof rock fractures it produces audible microseismic emissions of different magnitudes that are transmitted through rock as elastic waves with varying degrees of propagation. If sufficient fracturing occurs, the roof rock begins to deflect into the mine opening. Factors influencing the rate of roof rock movement have been discussed by several authors (Parker, 1973; Maleki and McVey, 1988; Altounyan, et al., 1997; and Iannacchione, et al., 2000). Generally, microfracturing begins to occur as strain levels approach 50% of the rock's ultimate strength (Hardy, 1975). As individual layers of roof rock move closer to their ultimate strength, they begin to fail by rupturing or cracking in shear or tension (Obert and Duvall, 1967; Gale, et al., 2001). As more rock fractures occur within a defined volume of rock, the potential for the roof rock failing increases (Hardy, 1975; Brady and Haramy, 1994; Iannacchione, et al., 2001).

Both microseismic emissions and roof-to-floor convergences were measured by a NIOSH monitoring system installed within an underground limestone mine in southwestern Pennsylvania. The unstable conditions at this mine site provided a unique opportunity to examine the behavior of unstable roof rock and the relationship between roof rock fracturing and movement.

In the study area, the room-and-pillar technique is used to mine rooms 45 ft wide and 30 ft high within the Loyalhanna Limestone (Figure 1). The Loyalhanna Limestone is a very strong rock unit with unconfined compressive strengths as high as 30,000 psi. Locally, the Loyalhanna ranges from 50 to 70 ft thick with dips between 1 to 5 degrees. The rock mass characteristics of this unit consist of horizontal bedding planes spaced from 1 to 5 ft apart, widely spaced vertical joints, and extensive crossbedding within the individual rock layers (Iannacchione and Coyle, 2002). Approximately 1,000 ft from the study area and under 400 ft of overburden, very high horizontal stresses were measured, reaching a maximum value of approximately 8,000 psi in the N 60° E orientation. The above factors are particularly important because the behavior of this roof rock is dominated by stiff, relatively thin rock layers and the levels of horizontal stresses contained within them.

As part of this research, four electro-mechanical roof-to-floor convergence stations, consisting of a steel wire wound around a potentiometer, were attached to the roof and floor. As the roof and floor converge, a voltage change occurs and is transmitted to a data acquisition system. The data can then be used to produce a unit of distance by multiplying the voltage with a calibration factor. Currently within U.S. underground mines, variations of this technology are used to gather information concerning roof rock stability conditions, and, in some cases, are being used to warn of roof failure. However, this technology suffers from a practical constraint in that there is an inability to cover the underground mining environment with an adequate number of convergence stations. Therefore, significant issues exist concerning where and when to deploy convergence monitoring systems.

In addition to the convergence stations, 23 4.5-Hz 630-ohm uniaxial geophones were connected to a DOS-based microseismic system. All but one of the geophones were mounted on the roof about 30 ft above the mine floor. One geophone was placed 69 ft beneath the mine floor within a borehole. The heights of the events above the mine roof could not be determined because almost all geophones were located along the same vertical plane within the mine. Unfortunately, there is little research within this country over the last decade that supports the use of microseismic monitoring techniques to anticipate roof falls, and thus they are rarely used for this purpose. As commercial microseismic monitoring systems increase in reliability and become more robust, the potential use of this technology needs to be re-evaluated.

Observation data were collected which consisted of the date and location of roof falls and face advances (Figure 1 and Figure 2). From March to June 2002, roof-to-floor convergence was measured during several periods of unstable roof rock conditions. In addition, about 2,400 microseismic emissions were recorded that represent the development of new rock fracture surfaces. Knowledge was gained on roof rock failure patterns and the capabilities of the roof monitoring systems. The goal of this research is to develop a more complete understanding of the mechanisms that cause roof failures and to improve warning techniques for unstable roof rock conditions. These advancements would lead to safer and less hazardous working environments for our nation's miners.

TWO DISTINCT ROOF FALL AREAS

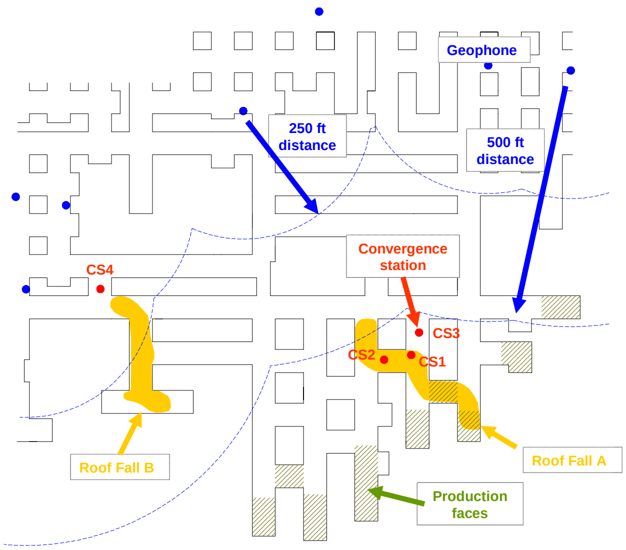

Figure 1. Location of geophones, roof-to-floor convergence stations, and production faces advanced between March and June 2002.

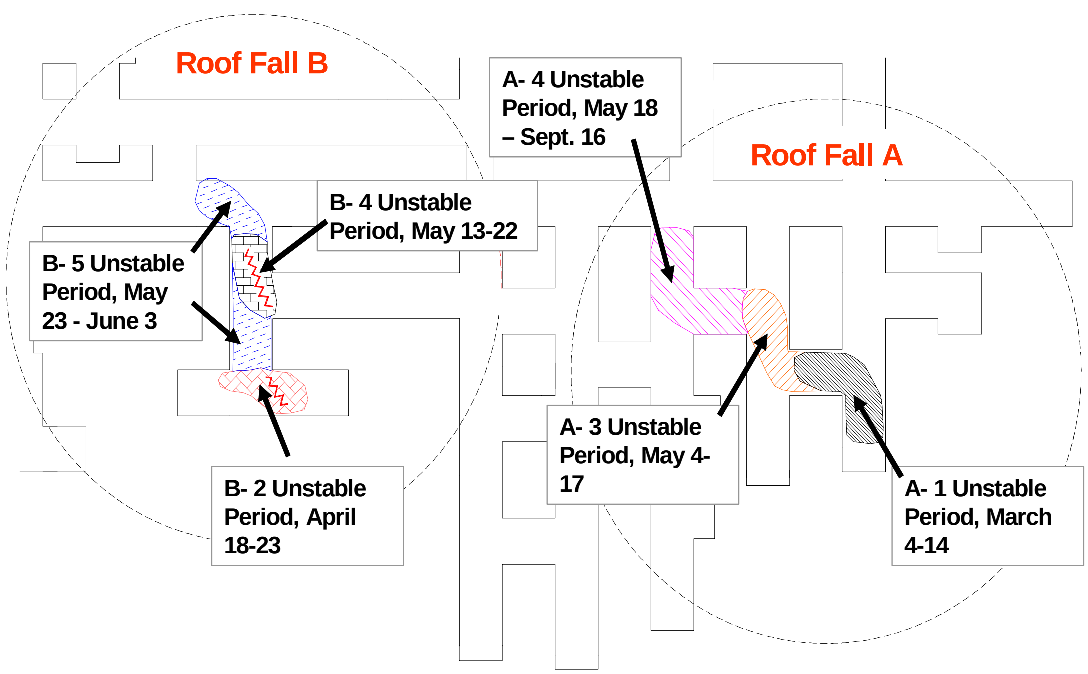

Figure 2. Location of Roof Fall A and B areas. Also shown are the locations and dates of the distinct unstable roof rock periods. Note: Periods A-2, B-1, and B-3 are classified as semi-stable roof rock and are discussed later in the paper.

Two major roof falls occurred during this study. Each of these falls comprised numerous individual roof falls that fell either as one mass or in distinct segments during different periods of time. Roof Fall "A" occurred in the southeast corner of the mine while Roof Fall "B" occurred approximately 500 ft to the west-northwest of Roof Fall A (Figure 2). From March to June 2002, 48 face cuts were advanced by blasting in the study area (Figure 1). The circles surrounding the two roof falls (Figure 2) represent the approximate area where most of the microseismic events occurred.

Roof Fall A developed from three unstable roof rock periods. The first period occurred from March 4 to 14 and can be described as failing in several distinct stages (Figure 2, period A-1). The initial observed stage of unstable roof rock period A-1 occurred when a shear failure was noticed by mine officials around 3 am on March 7. By that afternoon, a small shallow fall extended approximately 2 ft into the roof. Sometime during the evening of March 7 the roof fall cavity extended across the intersection and approximately 10 ft into the roof, encountering the soft red shales of the Mauch Chunk Formation. From late March 10 into the morning of March 11, the roof fall extended to the southeast where it was stopped by the unmined limestone perimeter. During the morning of March 12, the roof fall extended to the northwest, causing the roof bolts to fail in tension followed by the collapse of a large section of roof. Small rocks dribbled from the roof fall until March 14. The roof fall cavity created during this period extended over 125 ft in length and up to 20 ft in height (Figure 3a). After the March 14 event, the area around the roof fall seemed to stabilize.

A second unstable period occurred in the Roof Fall A area starting on May 4. The period was defined by a series of small roof falls and ended on May 17 with a fairly large roof fall extension (Figure 3b). At this time the roof fall cavity occupied the area shown in Figure 2, period A-3. On May 18 roof rock to the northwest of A-3 began to slowly fail over a four-month period until September 16 when a large roof fall occurred (Figure 2, period A-4).

Roof Fall B was located some 500 ft away from Roof Fall A and included three distinct periods of unstable roof rock conditions. The first unstable period occurred from April 18 to the 23, when a shallow roof fall encompassed an entire intersection (Figure 2, period B-2). This area had experienced some roof rock fracturing in the past and a period of relative stability followed. About two weeks later a series of instabilities occurred that resulted in several major roof fall extensions. First, a large shear

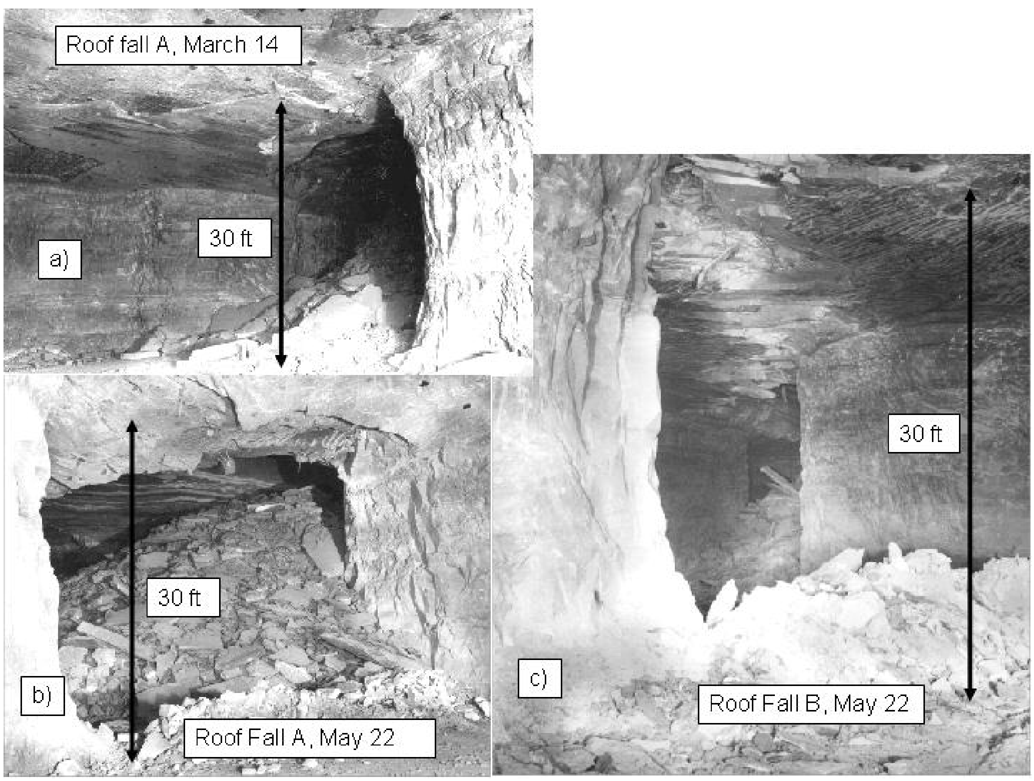

Figure 3. Photographs showing the size and character of the roof falls within the study area. Note: Dates on photo refer to the date when the picture was taken.

failure propagated rapidly across an entry on May 6. By May 22 the entire intersection had fallen (Figure 2, period B-4 and Figure 3c). Two weeks later on June 6, this roof fall extended both to the south and the northwest (Figure 2, period B-5). By mid-June, Roof Fall A extended almost 250 ft in length, while Roof Fall B was closer to 300 ft in length.

As a result of these observations and in combination with data from convergence and microseismic monitoring systems, it is possible to establish periods of semi-stable and unstable roof rock conditions. Six periods of unstable roof rock conditions were identified, three in each of the two roof fall areas. In addition, three periods of relative stability, herein referred to as semi-stable, were observed.

ROOF-TO-FLOOR CONVERGENCE FROM MARCH TO JUNE

The first roof-to-floor convergence station, CS1, was installed on March 14 (Figure 4). At this point in time, station CS1 was approximately 75 ft to the northwest of the March 4 to 14 roof fall (period A-1). Immediately after the installation, the convergence rate decreased. By March 20, convergence reached a steady rate of approximately 0.03 inches/day and remained so until May 3. At this time, approximately 1.71 inches of cumulative convergence had occurred. From May 4 to May 17, the second unstable period during Roof Fall A produced an additional convergence of 2.82 inches (Figure 4, period A-3). Station CS1 operated until May 16 at which time it was destroyed by a rock fall.

On March 29, convergence station CS2 was installed approximately 50 ft west of CS1. Because of the greater distance from the roof fall, less than 0.11 inches of cumulative convergence occurred until May 18. On this day, the roof around station CS1 failed and the roof rock to the northwest entered a long period of instability that lasted from May 18 until September 16 (Figure 4, period A-4). Because of conditions at this site, mine personnel relocated the convergence stations on June 1 to ensure mineworker safety.

Convergence station CS4 was installed on May 22 approximately 100 ft away from Roof Fall B (Figure 4, period B-4). The convergence rate remained steady at 0.26 in/day until May 28 at which time it dropped to approximately 0.07 in/day. This station was in operation until June 13 when it was relocated farther away from the fall area.

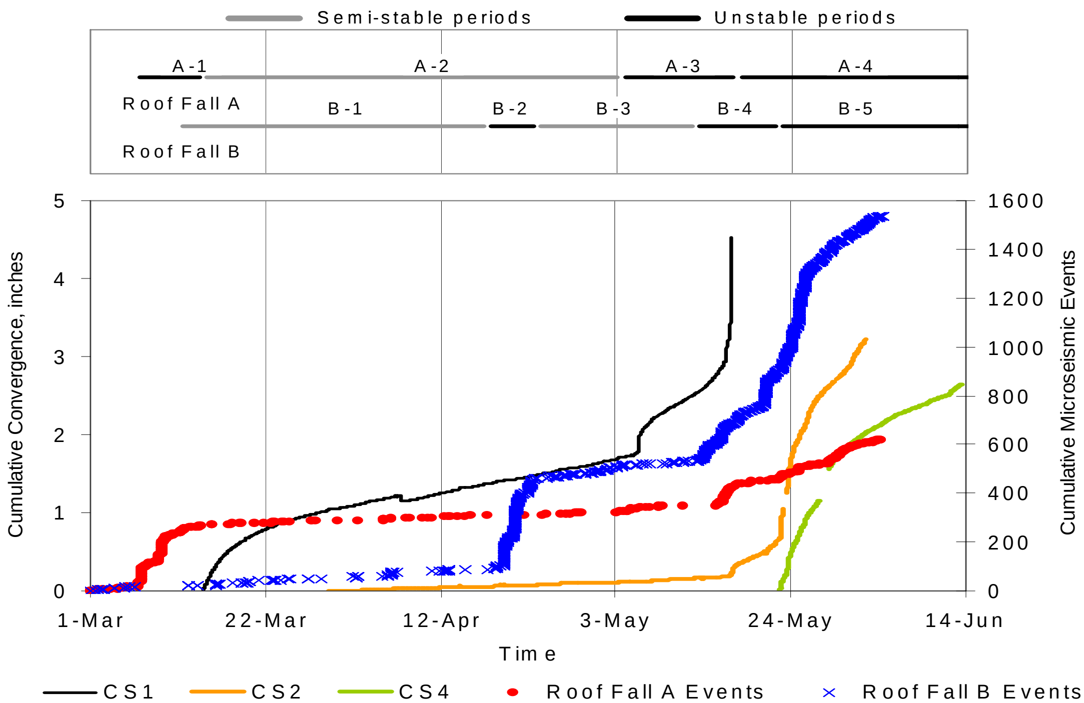

Figure 4. Cumulative convergence and microseismic emissions from Roof Fall A and B areas with associated stability periods.

MICROSEISMIC ACTIVITY FROM MARCH TO JUNE

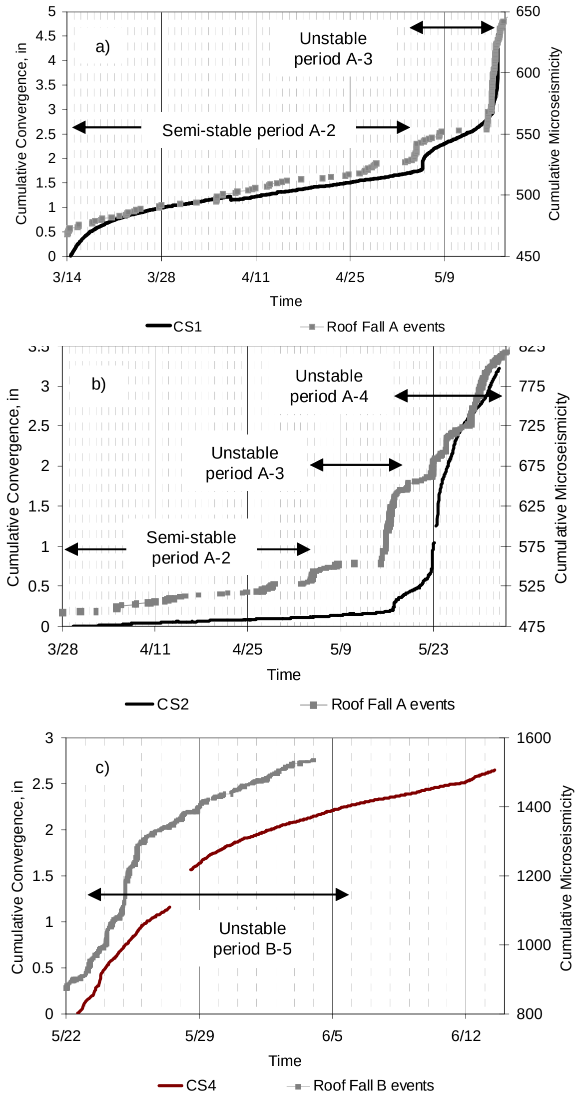

Figure 5. Comparison between convergence, microseismic event frequency, and local stability conditions.

Almost 2,400 microseismic events were located in the two roof fall areas. Approximately 800 occurred in Roof Fall A area and another 1,600 in Roof Fall B area (Figure 4). In Roof Fall A area, 473 events produced a rate of 43 events/day in association with the March 4 to 14 roof fall (period A-1). During the semi-stable roof rock period from March 15 to May 3, microseismic activity was reduced to an average of 1.2 events/day (period A-2). On May 4 and again on May 15 and 16, activity increased in conjunction with local roof instabilities (period A-3). After this time, microseismic activity assumed a higher rate of 10.8 events/day. The roof in the area surrounding station CS2 also experienced increased rates of convergence (Figure 4).

Microseismic activity did not occur in the Roof Fall B area until immediately after the activity associated with the Roof Fall A March 4 to 14 episode diminished (period B-1). A semi-stable rate of 1.9 events/day was maintained from March 12 until April 17. Over the next six days, 373 events were recorded, producing an average rate of 62.2 events/day (period B-2). Again, a period of decreased activity, averaging 3.9 events/day, followed until May 13 (period B-3). This time span included the initial shear roof failure that occurred on May 6. From May 13 to 22, 375 events were associated with a large roof collapse (period B-4). Activity continued at a high rate of 52 events/day in conjunction with the roof fall extensions that occurred between May 22 and June 6 (period B-5).

COMPARISON BETWEEN CUMULATIVE CONVERGENCE, MICROSEISMIC ACTIVITY, AND ROOF ROCK STABILITY CONDITIONS

All of the data presented represents conditions other than stable. Stable conditions imply no measurable roof deflection that would result in roof sag or roof-to-floor convergence. Additionally, the microseismic activity would be virtually absent in a stable area with rock fracture events occurring only once every few days. Stable roof rock rarely fractures and only minor amounts of elastic beam deflection could be measured.

Comparisons were made between each convergence station, the local microseismic event count, and the local stability conditions for the semi-stable and unstable periods (Figure 5). Clearly, agreement exists between the relative trends in convergence and microseismic activity. In general, periods of semi-stable roof rock conditions are accompanied by lower levels of convergence and microseismic activity. Periods of unstable roof rock conditions are accompanied by higher levels of convergence and microseismic activity. These trends are shown in Table 1. Here the nine different roof rock stability conditions are listed along with their corresponding dates, convergence measurements, and microseismic event counts. Microseismic events were

Table 1. Convergence and microseismic event data for the nine different roof rock stability conditions observed during the study.

Stability State	Period	Convergence CS1			Convergence CS2			Convergence CS4			Microseismicity		
		Days	inches	in/day	Days	inches	in/day	Days	inches	in/day	Days	Events	Events/ day
Unstable A-1	March 4 - March 14										11	473	43
Semi-stable A-2	March 15 - May 3	51	1.71	0.03	37	0.11	0.00				51	61	1.2
Unstable A-3	May 4 - May 17	13	2.82	0.22	14	0.24	0.02				14	119	8.5
Unstable A-4	May 18 - June 3				15	2.87	0.19				17	183	10.8
Semi-stable B-1	March 12 - April 17										37	71	1.9
Unstable B-2	April 18 - April 23										6	373	62.2
Semi-stable B-3	April 24 - May 12										19	74	3.9
Unstable B-4	May 13 - May 22										10	375	37.5
Unstable B-5	May 23 - June 6							15	2.20	0.15	12	624	52.0

measured during all nine periods. This is not the case with convergence because these stations were located in specific areas and only operated during a portion of the periods observed.

The three periods of semi-stable roof rock conditions (A-2, B-1, and B-3) have microseismic event rates averaging 1.9 events/day. Convergence was monitored during period A-2 by both station CS1 and CS2. The mean convergence rate for these two instruments is 0.02 in/day. Obviously, the rate for station CS1 is much higher than CS2 because it was much closer to the roof fall during that period. The data suggest that average convergence rates on the order of a few hundredths-of-an-inch per day and microseismic activity averaging only a few events per day are indicative of a semi-stable roof rock condition as defined in this study.

The six periods of unstable roof rock conditions (A-1, A-3, A-4, B-2, B-4 and B-5) have microseismic event rates averaging 30.7 events/day. Convergence was monitored during periods A-3, A-4, and B-5. The average convergence rate for these periods is 0.14 in/day. Again, the rate for station CS1 is much higher than CS2 because of the closer distance to the existing roof fall. The data suggests that average convergence rates of a tenth of an inch or more per day and daily microseismic event rates in double figures indicate unstable roof rock conditions for this study.

UNDERSTANDING ROOF FALL BEHAVIOR WITH COMBINED CONVERGENCE AND MICROSEISMIC MONITORING INFORMATION

The convergence and microseismic monitoring data along with in-mine observations provide a clear picture of the behavior of strong roof rock failing from excessive levels of horizontal stress (Figure 6). The following generalized sequence of events was identified during this study:

- Initial shear failure occurs in individual roof beams subjected to excessive levels of horizontal stress (Figures 6a and 6c).
- Adjacent layers begin to fail in shear as stresses are added from a) dissipated stresses from prior beam failure, and b) layers experiencing volumetric increase in mass as a result of failure (Figure 6d).
- At some point in this process the roof rock can begin to deflect enough that its progress can be measured over a significant area with convergence monitors (Figure 6e).
- The roof begins to fall into the mine opening once enough beam deflection or sag from cantilevering occurs, causing tensile failures along the perimeter of the beam (Figure 6e).
- The roof fall can happen as a single, dramatic event or over a series of smaller events spanning days or weeks.
- The roof fall cavity eventually assumes a stable arch shape (Figure 6b).
- The axis of the roof fall is defined by the orientation

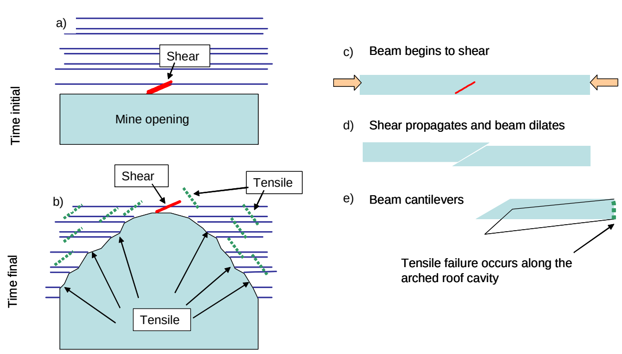

Figure 6. Examples of roof rock failure characteristics in high horizontal stress conditions.

of the horizontal stress field where this axis will be perpendicular to the maximum horizontal stress direction (Figure 7).

- Dissipated stresses from the roof failure process are concentrated at the axial ends of the roof fall and in the remaining competent beams at the crest of the roof fall cavity.
- Higher stresses, rock fractures, and convergence occur in areas adjacent to the axial ends of the roof fall cavity, causing additional rock falls (Figure 7).
- Areas adjacent to the long axis of the roof fall and away from its axial ends have been destressed and are typically stable.
- Roof falls progress as described above until some outside agent causes a reduction in the horizontal stress, the roof is strengthened sufficiently by rock reinforcement, or the roof encounters a solid rock abutment.

The application of the above knowledge suggests that

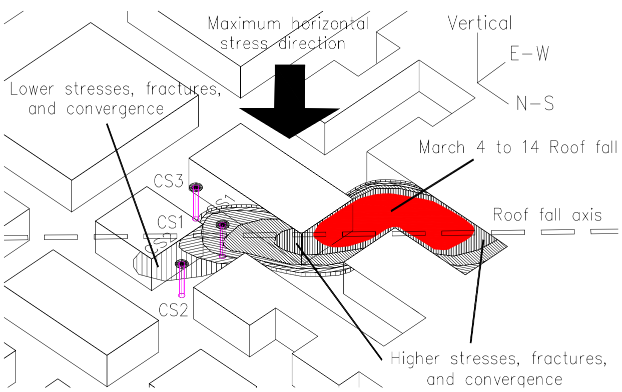

Figure 7. Idealized distribution of roof-to-floor convergence associated with the March 4 to 14 roof fall.

mines with high horizontal stresses will have non-uniform convergence profiles associated with roof falls. Typically, the areas of highest convergence occur along the axial ends of the roof fall where the stresses and the concentration of new fracture surfaces are highest. This knowledge was used to locate the three roof-to-floor convergence stations after the development of a roof fall from March 4 to 14 (Figure 7). Two of the convergence stations (CS1 and CS2) recorded measurable ground movements. As a control measure, station CS3 was placed slightly outside the expected trend of the roof fall and did not measure roof movement. The roof rock conditions immediately adjacent to this station were considered to be stable.

As has been demonstrated, the zones of highest convergence are close to the axial ends of the roof fall and dissipate gradually along the axis for distances ranging from 50 to 100 ft. Conversely, convergence decreases significantly perpendicular to the axial trend of a roof fall. This direction is parallel to the direction of maximum horizontal stress (Figure 7). The areas adjacent to the roof fall cavity, but away from its axial ends, have lower stresses and are thought to be within the roof fall's stress shadow. Understanding these trends is important in identifying the appropriate ground control response (Emery, 1964; Parker, 1966; Mark and Mucho, 1994; Iannacchione, et al., 1998).

Perhaps the most intriguing finding in this investigation is that there seems to be some direct and stress-related connection between the two distinct roof fall areas. This statement is supported by the fact that microseismic activity in Roof Fall B area did not initiate until the activity in Roof Fall A area diminshed after the March 4 to 14 roof fall (Figure 4). The data suggest that roof rock failures, and the corresponding high stress conditions that cause these failures, seem to migrate back and forth between the two roof fall areas (Figure 4). These trends imply that stability conditions are very dependent upon what is happening in the adjacent areas of the mine. The complexities of geology, mining layout, and in-situ stress conditions seem to interact in ways not entirely understood to influence the development of unstable roof rock zones.

ANTICIPATING ROOF FALLS WITH COMBINED CONVERGENCE AND MICROSEISMIC MONITORING INFORMATION

Knowledge of roof rock behavior provides a framework for constructing strategies to anticipate impending roof falls. The use of convergence measurements for this purpose has long been studied and represents the state-of-the-art in anticipating roof falls. If the instruments are placed in ideal locations and at the proper time, convergence values can provide an invaluable estimation of the roof rock stability condition. Unfortunately, these instruments are not always placed in the most appropriate locations and often are installed only after some rock failure has been identified in the area. Microseismic monitoring helps to minimize these deficiencies by aiding in determining when and where convergence monitors should be deployed.

Awareness of microseismic activity is critical in knowing when to deploy convergence stations

Perhaps the most important role for microseismic monitoring is that it can provide very early indications of roof instabilities. Detailed analysis of Figure 4 shows that microseismic activity often precedes convergence. Prior to the first signs of roof rock failure on March 7, microseismic activity in Roof Fall A area was already high. From March 4 to 6, more than 200 events emanated from this area. A second example occurred on May 4, when microseismic activity increased significantly in the Roof Fall A area. Approximately one day later, increases in convergence from CS1 were observed (Figure 5a). A third example occurred on May 14, when microseismic activity increased dramatically a full day prior to a significant increase in convergence from CS1 (Figure 5a). This same trend was observed between microseismic activity and convergence from CS2 (Figure 5b).

Trends of microseismic activity proceeding convergence indicate that microseismic monitoring provides an earlier detection capability than convergence monitoring. As would be expected, rock fracturing precedes significant non-elastic roof deflection. This type of information can prove crucial in helping mine personnel to know when to install convergence stations. It is important to place the convergence stations in the earliest stage of semi- or unstable roof rock conditions. Only in this way can a complete cumulative convergence profile be obtained. The greatest value to miner safety is achieved when monitoring data becomes available early in the roof failure process.

Knowledge of local roof rock behavior is critical in knowing where to deploy convergence stations

In order to have complete confidence that no convergence of unstable ground goes undetected, an unrealistic number of stations may need to be deployed. This has been one of the major hindrances to the full utilization of this technology. It therefore becomes essential to place the fewest number of convergence stations in the most optimal locations. In this case, microseismic activity may supply some direct input. If the events can be accurately located, then the source of the instabilities can be identified. Unfortunately, the location of individual events is highly dependent upon the equipment characteristics and the location and number of geophones used. For this study, the locations were accurate within a range of 60 to 100 ft. If enough events are located then the center of the activity will cluster in a location representative of the unstable ground. This is an example of the direct application of the microseismic information to locate convergence stations.

An indirect application comes from the enhanced understanding of roof fall behavior discussed in previous sections. Areas of critical convergence can be predicted with sufficient understanding of the mechanism controlling roof failure. The value of this knowledge should not be understated. Knowing how local roof rock fails is key in knowing where to place convergence stations. As demonstrated in this study, the understanding of roof rock failure processes allowed for the optimal placement of stations.

SUMMARY AND CONCLUSIONS

This paper examines the relationship between the fracturing of roof rock and the corresponding roof beam deflection into the mine opening in an underground stone mine. Both of these pre-roof fall behaviors are compared to local roof rock stability conditions so that more can be learned about using these technologies to better understand and anticipate roof falls in underground mines. A connection between roof rock instabilities and trends in convergence and microseismic activity was demonstrated. Additionally, microseismic emissions were observed sometimes to occur prior to convergence, demonstrating that rock fracturing precedes roof deflection. The results of this analysis suggest that these measurement technologies could be used to better determine the relative stability of local roof rock conditions.

This paper outlined three categories of stability and defines them as follows:

- Stable - No measurable roof deflection that would result in roof sag or roof-to-floor convergence. The microseismic activity would be virtually absent in a stable area with rock fracture events occurring only once every few days. Stable roof rock rarely fractures and only minor amounts of elastic beam deflection could be measured.
- Semi-stable - Relatively low convergence rates in the range of several hundredths-of-an-inch per day and few microseismic events from a specific area per day. During these periods, roof rock failures are typically not observed, but there is a sense from the monitoring data that the roof is only temporarily stable and can move to a state of instability at any time.
- Unstable - Relatively high convergence rates in the range of a tenth of an inch per day or more and many microseismic events per day in the range of at least 10 to 20 events per day. During these periods, a combination of observational and measurement information provides a sense that roof failure is imminent. Roof failures were often observed or noted by increases in the rock piles beneath roof fall cavities.

This study suggests that current state-of-the-art technology in roof fall anticipation could be improved upon. These techniques rely only on convergence monitoring and observational data to develop local ground control strategies. Actual experience has shown that convergence information provides a non-ambiguous picture of local roof rock conditions. However, convergence information suffers from difficulties in knowing the right time and location for placement of instruments. Data presented support the use of microseismic monitoring to improve convergence station placement and to aid in collaborating trends developed from the convergence monitors.

This study also demonstrates the use of monitoring information to better understand roof failure processes. This knowledge is critical in developing the most effective response to combat local unstable roof rock conditions. Better understanding of roof fall behavior and improved techniques to anticipate unstable roof rock conditions are expected to lead to safer and less hazardous working environments for our nation's miners.

REFERENCES

Altounyan, P.F.R., D.N. Bigby, K.G. Hurt, and H.V. Peake, 1997, "Instrumentation and Procedures for Routine Monitoring of Reinforced Mine Roadways to Prevent Falls of Ground," 27th Int. Conf. of Safety in Mines Research Inst., New Delhi, India, pp. 759-766.

Brady, B.T. and K.Y Haramy, 1994, "High Amplitude Stress Wave Generation and Damage Induced by Roof Caving in Mines," Proceedings of the 1st North American Rock Mechanics Symposium, Univ. of Texas, Austin, TX, June 1-3, pp. 1033-1040.

Emery, C.L., 1964, "In Situ Measurements Applied to Mine Design," Proceedings, 6th Symposium on Rock Mechanics, Rolla, MO, pp. 218-230.

Gale, W.J, K.A. Heasley, A.T. Iannacchione, P.L. Swanson, P. Hatherly, and A. King, 2001, "Rock Damage Characterization from Microseismic Monitoring, Rock Mechanics in the National Interest," ed. Elsworth, Tinucci and Heasley, Washington, DC, pp. 1313-1320.

Hardy, R., 1975, "Emergence of AE/MA as a tool in Geomechanics," First Conference on Acoustic Emission-Microseismic Activity in Geologic Structures and Materials, University Park, PA, June 9-11, Series on Rock and Soil Mechanics, Vol. 2, No. 3, By Trans Tech Publications, Rockport, MA, pp. 13-31.

Maleki, H.N. and J.R. McVey, 1988, "Detection of Roof Instability by Monitoring the Rate of Movement," U.S. Bureau of Mines RI 9170, 12 p.

Iannacchione, A.T., D.R. Dolinar, L.J. Prosser, T.E. Marshall, D.C. Oyler, and C.S. Compton, 1998, "Controlling Roof Beam Failures from High Horizontal Stresses in Underground Stone Mines," Proceeding, 17th International Conference on Ground Control in Mining, Morgantown, WV, Aug. 4-6, pp. 102-112.

Iannacchione, A.T., L.J. Prosser, R. Grau, D.C. Oyler, D.R. Dolinar, T.E. Marshall, and C.S. Compton, 2000, "Roof Monitoring Helps Prevent Injuries in Stone Mines, Mining Engineering," Nov., pp. 32-37.

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

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

Mark, C. and T.P. Mucho, 1994, "Longwall Mine Design for Control of Horizontal Stress," U.S. Bureau of Mines Special Publication 01-94, New Technology for Longwall Ground Control, pp. 53-76.

Obert, L. and W.I. Duvall, 1967, "Rock Mechanics and the Design of Structures in Rock," John Wiley and Sons, Inc., New York, pp. 113-188.

Parker, J., 1966, "Mining in a Lateral Stress Field at White Pine," Canadian Institute of Mining and Metallurgy Transactions, Vol. LXIX, pp. 375-383.

Parker, J., 1973, "How Convergence Measurements Can Save Money," Engineering and Mining Journal, August, pp. 92-97.