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MICROSEISMIC ACTIVITY ASSOCIATED WITH A DEEP LONGWALL COAL MINE

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ABSTRACT

A deep longwall coal mine was instrumented with a three-dimensional microseismic system in order to help determine the exact strata mechanics associated with the rock failure, redistribution of stress and the associated gob formation from the longwall. Overall, 5,000 well calibrated seismic events were recorded during the mining of the panel. Analysis of these events showed a close correlation between the seismic activity and advance rate, and that the majority of the recorded seismic activity occurs in the immediate area of the advancing longwall face.

INTRODUCTION

In recent years, microseismic systems have been used in coal mines in Australia and the United States to gain a better understanding of the ground failures and rock mechanics involved with longwall mining (Ellenberger et al., 2001; Gale et al., 2001; Kelly et al., 1998; Luo et al., 1998; Swanson, 2001; Westman et al., 2001). These microseismic systems "listen" to the rock and determine the timing and location of the failure of the rock strata surrounding the longwall panel. The recent hardware and software advances in microseismic systems have allowed this geophysical monitoring technique to provide practical geomechanical measurements at operating mines (Swanson, 2001). The results from these measurements have been insights into longwall geomechanics that are somewhat outside of previous strata mechanics understanding. For instance, the microseismic events and associated rock failure have mostly been recorded from well in front of the longwall face, with a noticeable lack of seismic activity coming from the gob area. The seismic events have been distributed fairly evenly above and below the seam and the predominent fracture mechanism has been shear failure (as determined from focal analysis and numerical modeling (Gale et al., 2001)).

The primary objective of the field work presented in this paper was to examine the strata failure behavior of a deep, bump-prone longwall mine using a three-dimensional seismic monitoring system. By analyzing the observed rock failure, we hope to increase our knowledge of the processes governing caving of the massive main roof, the compaction and load acquisition of the gob, the failure of the floor, and the stress redistribution in the coalbed and surrounding strata. The application of this knowledge will enable better mine designs in the future in order to mitigate dangerous bump occurrences and unexpected failures of the massive overburden.

The study mine primarily operates in the Castlegate ‘D’ Seam of the Blackhawk Formation. The coalbed ranges from 2.4 to 6.0 m (8 to 20 ft) in thickness with an extraction thickness of 2.4 to 3.0 m (8 to 10 ft). The immediate and main roofs of the mine consist of braided and lenticular Blackhawk shales, siltstones and sandstone deposits for some 120 to 180 m (400 to 600 ft). Overlying these deposits is the Castlegate Sandstone, a massive, cliff forming sandstone that is 120 to 180 m (400 to 600 ft) thick with the lower 90 m (300 ft) being more compact and massive than the upper portion of the unit (Barron et al., 1994). On top of the Castlegate, another 540 m (1,800 ft) of rugged sedimentary deposits bring the maximum overburden up to 900 m (3,000 ft) (figure 1). The geology immediately below the seam consists of thinner (<3 m (< 10 ft)) layers of siltstones, mudstones, shales,and coal, with the Kenilworth and Aberdeen sandstones being near seam massive units.

The microseismic monitoring array installed at the mine consisted of 23 geophones, 14 geophones in the mine entries and 9 geophones on the surface above the mine. The array had lateral and vertical extents of 2.2 and 0.8 km (1.4 by 0.5 mi), respectively, and essentially surrounded the first two longwall panels (figure 1). The signals from the geophone array were ultimately collected by the main data analysis computer at the mine office. Here the signals were automatically analyzed in order to calculate the event locations. These locations were then automatically displayed on a computer generated mine map for real time use by mine personnel. Over 13,000 seismic events were automatically detected and located during the mining of panel 2.

In order to obtain a consistent, high-quality, data set of event locations for the final analysis, the raw waveform data from the field were reprocessed in the laboratory using an improved layered seismic velocity model which best fit a number of known events. Also, the quality of the seismic data was upgraded by including only events with a minimum of 8 stations (with at least 3 surface stations and 3 underground stations) reporting good first-arrival picks. This post-processing procedure winnowed the original 13,000 events down to a good quality data set consisting of 5,024 events from panel 2 (Heasley et al., 2001).

EVENT TIMING

One of the first aspects of the seismic data that was investigated in detail was the number and timing of the events. During the active mining of the panel, 5,024 good quality events were recorded. This is an average of 29 events per day with a minimum of 0 and a maximum of 136 events per day. However, these events were not evenly distributed over the panel. The data shows three distinct periods of seismic activity (figure 2). From the start of the panel through the first about 300 m (1,000 ft), the seismic activity was fairly low, averaging around 5 events per day (table 1). Generally, these events were relatively smaller and more scattered about the advancing face than in subsequent periods (Ellenberger et al., 2001). A higher level of seismic activity (28 events per day) was noted as the face advanced from 300 to 900 m (1,000 to 3,000 ft) at which point the face was stopped and widened from 165 to 245 m (550 to 820 ft) (figure 1). In the final time period, as the longwall advanced 300 m (1,000 ft) with the wider face, the seismic activity was quite high averaging 64 events per day.

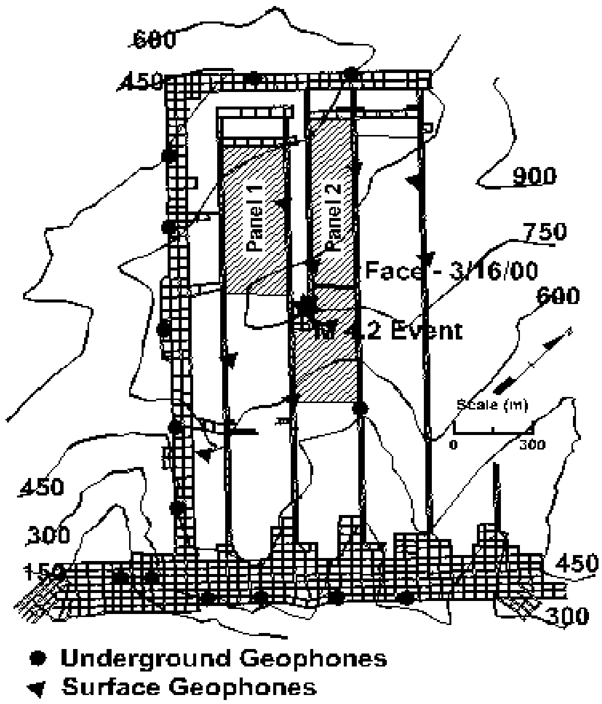

Figure 1. Plan view showing mine layout, overburden, geophone arrays, and the location of the M 4.2 event

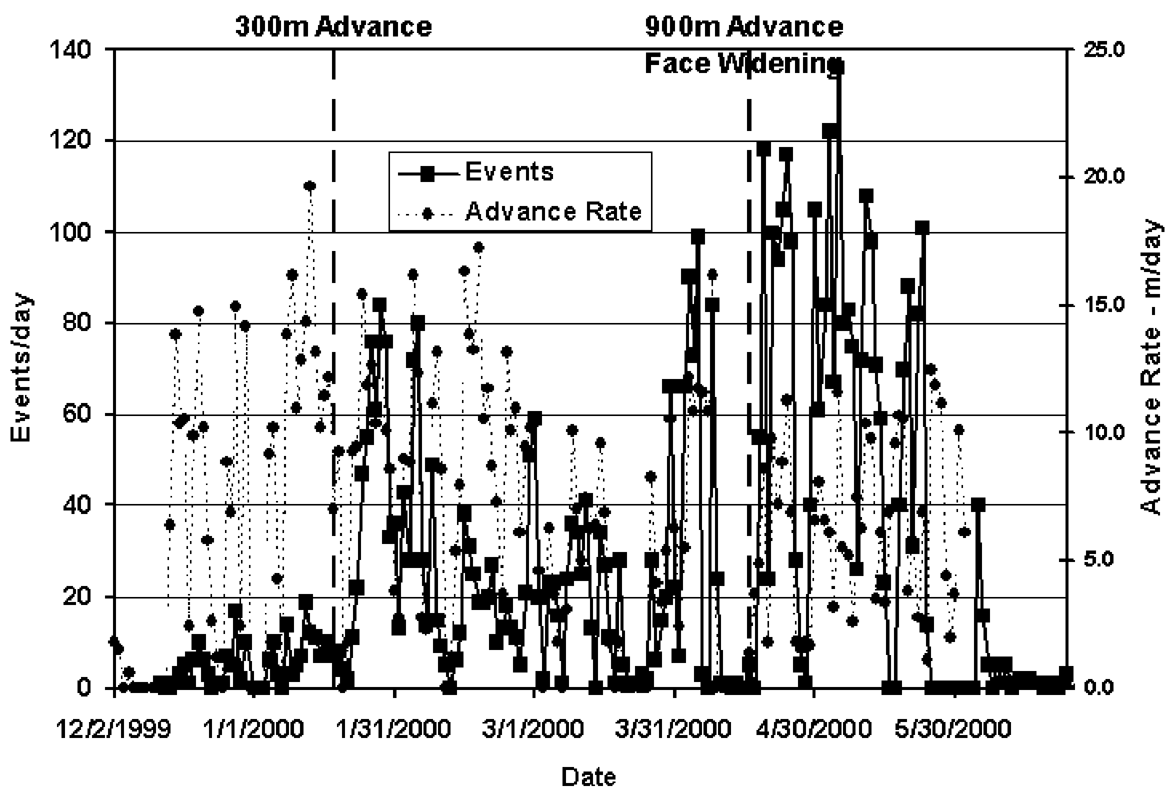

Figure 2. A comparison of the number of events per day with the mining advance rate

Table 1. A comparison of the seismic activity between different parts of the panel

	Advance (m)	Starting Date	Ending date	Total # of events	Average # of events per day	Correlated Events per meter	Correlation coefficient^2
Total Panel	0 - 1200	12/2/1999	5/25/2000	4,930	29	2.81	0.2498
Early Panel	0 - 300	12/2/1999	1/20/2000	212	5	0.70	0.6681
Mid Panel	300 - 900	1/21/2000	4/8/2000	2,232	28	3.10	0.4886
Final Panel	900 - 1200	4/16/2000	5/24/2000	2,486	64	8.34	0.5827

The next investigation was to correlate the advance rate of the longwall face to the amount of associated seismic activity. Previous research has shown a direct correlation between the mining advance rate and the induced seismicity (Arabasz et al., 1997). To perform this analysis, the meters of advance of the longwall face per shift were correlated against the number of good quality seismic events that were detected during that shift (and within 4 hours after the face stopped on an idle shift). The results of this analysis are shown in the right side of table 1. First, looking at the entire panel in table 1, a linear correlation of 2.81 events per meter of advance is determined, but the r^2 value only 25%. However, if the panel is again broken into the same three distinct periods, or section, as above, a much stronger correlation is obtained. In fact, the average r^2 value for the panel divided into the three sections is 58%. This squared value of the correlation coefficient is fairly significant for this type of mining data and signifies that 58% of the fluctuation in the shift-based number of events can be explained by the corresponding fluctuation in the shift advance rate. Mechanistically, this implies that a majority of the seismic events are a direct result of the advancing face. The same relative intensity of the seismic activity as noted before in the three sections of the panel is, of course, evident in the correlation with advance rate. The first part of the panel averages 0.7 events per meter of advance versus 3.1 events per meter of advance for the middle part of the panel and 8.3 events per meter for the final part of the panel.

EVENT LOCATION

Once the optimized velocity model was determined and the final set of good quality seismic events was produced, the location and magnitude of the events were investigated. One of the best means that we found to visualize this “four” dimensional data was to plot the events in three-dimensional space as spheres which are scaled by magnitude (figure 3). Taking an overall look at this figure, a number of observations can be made. First, the lack of events in the first 300 m (1,000 ft) of the panel is evident as is the high density of events in the last 300 m (1,000 ft) of the panel. Second, the events appear to be fairly evenly distributed above and below the panel.

In order to visualize the location of the seismic events in relation to the advancing longwall face, the locations of the events were normalized to the face position and plotted on three orthogonal planes such that the center, or zero point, of the normalized coordinate system corresponds to the center of the longwall face at seam level. In this paper, only the events from the last part of the panel will be specifically presented and analyzed using the relative face position since the events at the other sections of the panel provide similar information (Ellenberger et al., 2001). The results of normalizing the location of the events from the final part of the panel to the face position are shown in a plan view in figure 4 and in a vertical view parallel to the advance direction in figure 5.

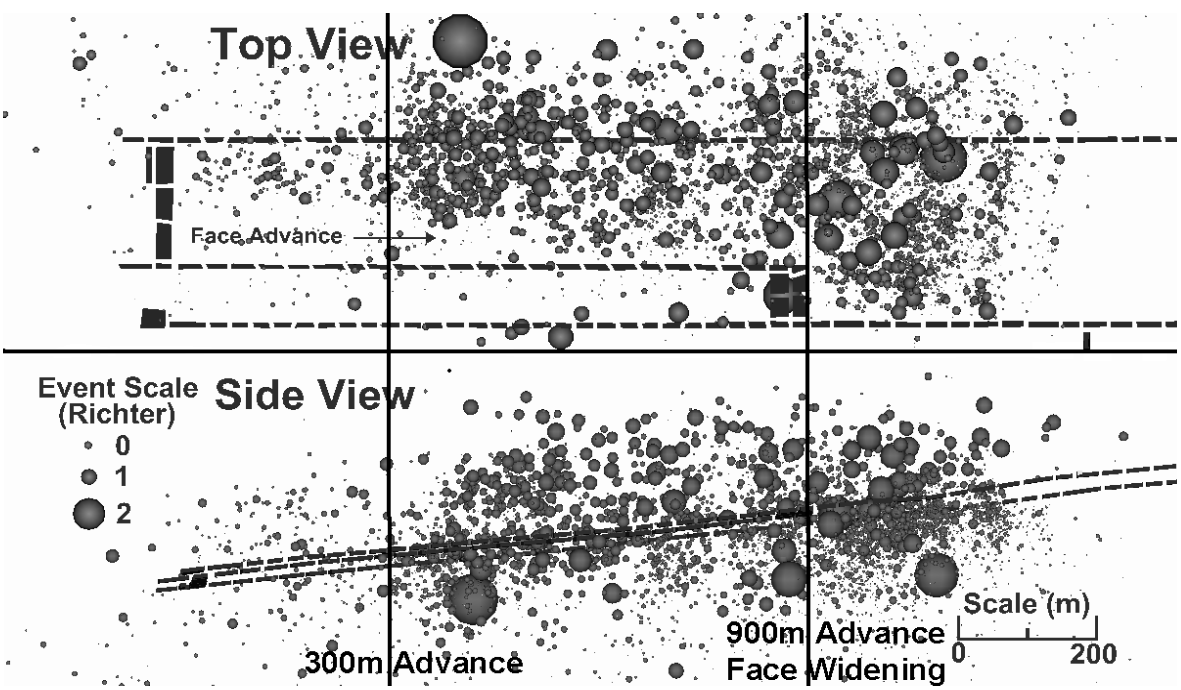

Figure 3. A three-dimensional view of the seismic events with the event size scaled by magnitude he M_L 4.2 event removed for clarity)

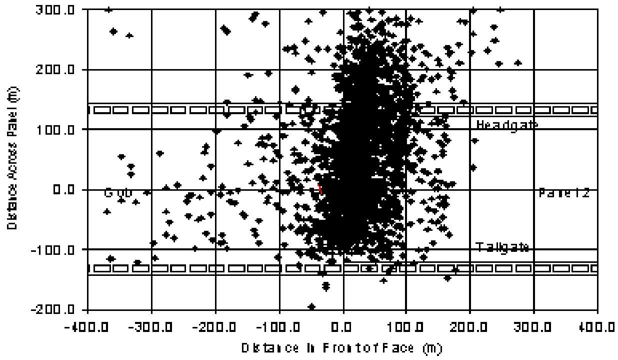

Figure 4. Plan view of the normalized event locations for the last part of panel 2

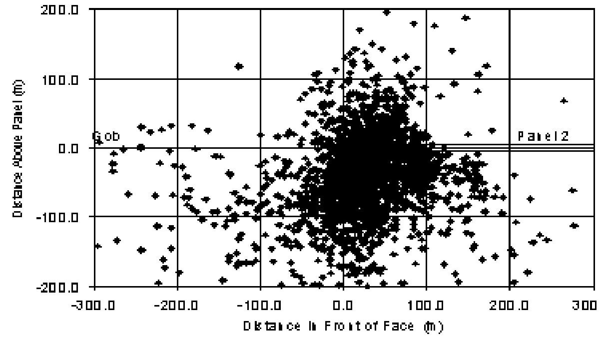

Figure 5. Vertical view parallel to face advance showing the normalized event locations for the last part of panel 2

Figures 4 and 5 indicate that the seismic activity is mostly located in the face area and generally in front of the face. Also, there is a notable absence of recorded seismic activity coming from the gob area. The location of the seismic data in front of the face agrees with seismic information from other coal mining sites (Gale et al., 2001, Luo et al., 1998) and has been interpreted to represent the failure of the strata in the forward stress abutment. It is thought that the rock failures that occur in the confined high stress area in front of the face are well recorded by the seismic system due to the high energy release and good transmission characteristics; however, the low energy, unconfined tension failures of the immediate roof in the gob behind the face are not well recorded because of the low energy release and the high attenuation in this generally broken rock area. Also in figure 5, it can be seen that the seismicity is originating both above and below the seam level. This response also coincides well with the response observed at other field sites (Gale et al., 2001, Luo et al., 1998) and is consistent with a front abutment stress field that is vertically symmetric about the coal seam. In fact, in figure 5, the majority of the seismic activity is coming from the floor. This response may be due to the presence of more competent floor strata or to a shift of the event locations due to inaccuracies in the assumed velocity model, and the lack of an extended geophone array below the coal (Ellenberger et al., 2001; Heasley et al., 2001). From the plan view in figure 4, it can be seen that most of the seismic activity generally lines up in front of the advancing face. There is a little skewness to the event data, with the seismic activity occurring further in front of the headgate than the tailgate. (Also, it can be seen that the events appear shifted towards the headgate. This may be a manifestation of the deviation of the actual velocity structure from that assumed in the model as discussed elsewhere.(Ellenberger et al., 2001; Heasley et al., 2001))

MAGNITUDE 4.2 EVENT

On March 6, 2000, at 7:16 pm, MST, a magnitude (M_L) 4.2 "earthquake" occurred in the overburden above the mine and within the confines of the active mine-wide seismic array. The event vibrations were strongly felt by the miners, but there was very little damage from the event on the working longwall face, and only a few rib spalls were evident in the development entries. This is the first time that such an event has been recorded with this detail and accuracy at a U.S. coal mine. This event caused rock slides from critical slopes on the nearby highway, which damaged automobiles. The train tracks adjacent to the highway at that point were also temporarily blocked. Underground, multiple roof falls occurred in the bleeder entries to the west of the first panel and several seals were cracked around the previously abandoned panel. Also, a significant amount of methane was rapidly liberated resulting in a temporary evacuation of the mine. Fortunately, there were no injuries.

Using the optimized velocity model for the site, this event was located 90 m (300 ft) in front of the active face, 170 m (560 ft) above the coal seam and 10 m (35 ft) in from the edge of the 60 m (200 ft) wide barrier pillar between the active and the previous panel (figure 1). This location puts the event near the top of the Blackhawk Formation and the base of the massive Castlegate Sandstone. The event occurred when the active face was approximately 30 m (100 ft) from aligning with the recovery room of the previous panel.

Using P-wave first motion data from the mine wide seismic monitoring system, three temporary University of Utah stations located near the mine and the University of Utah regional seismic network, a well constrained focal mechanism, which fits all of the available P-wave data, was determined. The preferred focal mechanism indicates oblique reverse faulting on a plane dipping steeply to the south or shallowly to the north-northwest (Swanson and Pechmann, 2000). The focal mechanism of the event is consistent with the roof strata failing and the Castlegate formation falling into the gob. The location and size of the event and the relative locations of the previous and active longwall faces suggest that the M_L 4.2 event was a failure of the main roof essentially over both panels in the vicinity of the base of the Castlegate. Whether a functional failure of the intervening barrier pillar to fully support the overburden may have preceded and helped initiate the major failure of the main roof is not clear at this time.

CONCLUSIONS

From examining the seismicity at the site, several general observations can be made:

The event rate is low at the beginning of the panel, about six times higher in the middle of the panel, and twice again as high at the wider end of the panel (table 1). We hypothesize that this is a result of the initial gob formation during the beginning part of the panel versus a well established gob through the middle of the panel and then a wider face in the last part of the panel. In fact, when the panel width increased by 50%, we see the seismic activity increase by more than 100%. Also, the correlation between the face advance rate and the seismic activity implies that the majority of the seismicity is a direct and fairly immediate response to removal of the coal and the associated stress redistribution. Looking at the location of the seismic events, it can be observed that the events generally occur in advance of the longwall face and are approximately evenly distributed above and below the panel (Ellenberger et al., 2001). This observation is consistent with the interpretation that the observed seismic events come from failure of the strata in the forward stress abutment zone and is consistent with observation at other sites where the predominant recorded failure mechanism was shear fracture in front of the face as opposed to tensile failure in the gob.

A magnitude 4.2 seismic event occurred within the active longwall panel and was recorded by the mine-wide seismic system giving a unique opportunity to characterize important overburden deformation processes. It has long been acknowledged that not every potentially hazardous bump generates a regional seismic event, nor does every mine-induced, regional seismic event manifest itself as a coal outburst at the seam level. Numerous larger (> M 2.0) seismic events have been located near active mines by regional seismic systems (Ellenberger and Heasley, 2000). Some of these seismic events were associated with coal bumps underground, but many of the larger seismic events caused no observable underground damage. Given the location accuracy of the regional seismic systems, the exact proximity of the seismic event to the coal seam and bump location could not have been determined. Using the mine-wide seismic system in this study, the M_L 4.2 seismic event was relatively accurately located some 150-180 m (500-600 ft) above the longwall face. So at least in this one case, we know that the large seismic event was associated with overburden failure and not with pillar or panel failure. Also, since this very large event was within 180 m of a highly stressed longwall face and there was little coal discharge on the longwall face, this instance documents a rather dramatic example of how large local seismic events do not necessarily result in serious face damage. Therefore, this one occurrence suggests that, in order to control coal bumps, mine designers and safety personnel generally need to be more concerned with the seismic events, stress and geologic anomalies that are relatively close (within 30 m (100 ft)) to the working face. Also, the location of this large overburden failure above the intervening “barrier” pillar and the relative closeness of the two longwall faces at the time of the event, suggest that the two longwall gobs were functionally combined at the location of the failure.

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