Three Dimensional Microseismic Monitoring of a Utah Longwall

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ABSTRACT: The National Institute for Occupational Safety and Health (NIOSH) has continued the research role of the former US Bureau of Mines (USBM) to engineer techniques that will reduce the hazards in the mining work place associated with coal bumps. Recent research focused on a longwall coal mine in Utah with overburden greater than 750 m (2,500 ft) containing several massive sandstone units. The primary field instrumentation at the site was three-dimensional, full waveform, autonomous microseismic arrays placed underground and on the surface in order to surround the active multi-panel longwall district. The purpose of these arrays was to help investigate the strata mechanics associated with the redistribution of stress and the associated gob formation of the longwall. Specifically, the seismic arrays were used to determine the timing and location of the failure in the strata surrounding the active mining. Overall 13,000 seismic events were detected and located with on-site processing during the five months the panel was being mined, including a magnitude (M_L) 4.2 event. Of these, a smaller subset of 5,000 well-located events was selected during post-processing to form a consistent data set for analysis in this paper. From this data set, it was observed that the seismic events generally occurred in advance of the longwall face, both above and below the panel, consistent with failure of the strata in the forward stress abutment zone. Also, the occurrence of the M_L 4.2 seismic event within 150-180 m (500-600 ft) of a deep cover longwall face with no associated bump caused a re-evaluation of the nature of the connection between seismic activity and coal bumps.

1 INTRODUCTION

Coal mine bumps, sometimes referred to as outbursts, bursts, or bounces, have been recognized as a serious problem in mining for more than 75 years. For the purposes of this paper, a bump is defined as a sudden release of strain energy that results in the expulsion of coal from a rib, pillar, or floor in a catastrophic manner. Beginning as early as the 1930's, the US Bureau of Mines (USBM) conducted research investigating the causes and potential mechanism of bumps in order to avoid injuries in coal mines (Rice 1936). Research conducted by the National Institute for Occupational Safety and Health (NIOSH) continues to focus on the reduction of bumps and bump hazards.

In the past, bumps have been acknowledged as having a greater likelihood of occurrence at depths greater than 300 m (1,000 ft), in the presence of a strong stiff roof and/or floor, and when an unusually massive unit exists in the main roof (Rice 1936; Iannacchione and Zelanko 1995; Zelanko and Heasley 1995). Miners working under one or more of these conditions need to be constantly aware of the possibility of a coal bump. Recently, the US coal industry experienced several consecutive years with no fatal accidents resulting from bumps, until November of 1996, when three fatalities and five additional serious injuries occurred in a two week period (MSHA 1996a,b).

Coal bumps are often associated with seismic events that are large enough to be registered by regional seismic networks. However, 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 seam level. In reality, coal bumps are just one subset of mine-induced seismicity, and like mine-induced non-bump events, they can exhibit a wide range of magnitudes and energy releases. Also, there are considerably more documented mine-induced, non-bump, seismic events than there are documented coal bumps. In fact, the seismic network in Utah has found the most active seismic area since 1962 to be in the vicinity of the active coal mining with hundreds of mining-induced events ($M>2$) recorded each year (Arabasz et al, 1996).

Recent bump research in NIOSH has centered on a Utah longwall mine. At this site, the rugged topography reached overburdens greater than 750 m (2,500 ft) and contained massive cliff-forming sandstone units. This combination of depth and strong geology indicated a high likelihood of bumps. In order to investigate the rock failure associated with the redistribution of stress and the associated gob formation of the longwall in this bump-prone situation, a microseismic system for "listening" to the rock was chosen. The microseismic system consisted of three-dimensional arrays placed underground and on the surface surrounding the active mining area. The initial analyses of the geologic, geometric and mining parameters, and the associated seismicity from this site are presented in this paper.

2 GEOLOGY

This research was conducted at a longwall coal mine in Utah, situated in the area of the Book Cliffs and the eastern Wasatch Plateau in the northwest corner of the Colorado Plateau. In this area, the coal seams are located in the Blackhawk Formation of the Mesa Verde Group (Figure 1) (Barron et al. 1994). The subject mine is primarily in the Castlegate 'D' Seam; however, over part of the area studied where the seams coalesce, the mine operates in the joined Kenilworth Seam and the Castlegate 'D' Seam. Normally, the Kenilworth Seam lies below the Castlegate 'D' and above the Castlegate 'C' in a cyclic sequence of coal bearing rocks (Barron, 1994). In the Blackhawk Formation the primary interburden consists of a series of regressively deposited sandstones which were reworked. The coalbed at the mine 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 geology immediately above and below the seam consists of thinner (<3 m (< 10 ft)) layers of siltstones, mudstones, shales, sandstones, and coal. Above the coal bearing portion of the Blackhawk Formation, approximately 150-180 m (500-600 ft) of braided stream deposits with numerous lenticular channel sandstones occur. These lenticular deposits make up the immediate and main roof over the mine.

Unconformably overlying the Blackhawk Formation is the Castlegate Sandstone. The Castlegate is a massive, cliff forming sandstone that is 120 to 180 m (400 to 600 ft) thick and approximately 200 m (680 ft) above the "D" seam in the mine area, with the basal 90 m (300 ft) being more compact and massive than the upper portion of the unit. Overlying the Castlegate is the Price River Formation, consisting primarily of sandstone with interbedded conglomerates and sandstones. The Price River Formation is also about 180 m (600 ft) in thickness. The uppermost rocks exposed at the site are lacustrian deposits of the North Horn Formation, consisting of interbedded claystones, mudstones, limestones, siltstones, and sandstones. Overall, the overburden at this mine reaches up to 900 m (3,000 ft) (Figure 2).

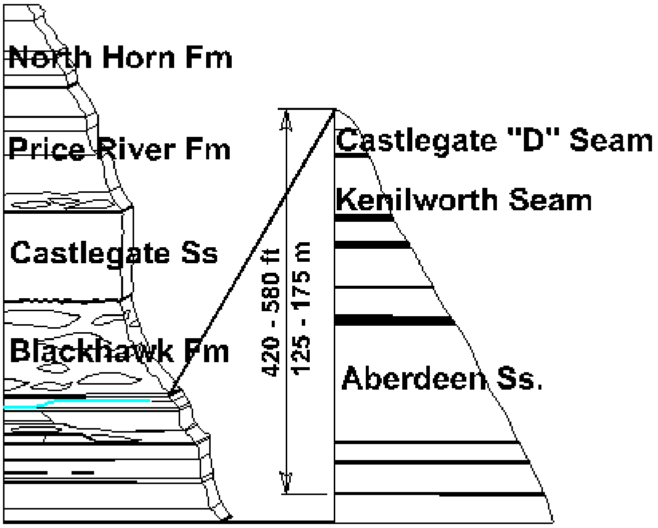

Figure 1. Generalized stratigraphy.

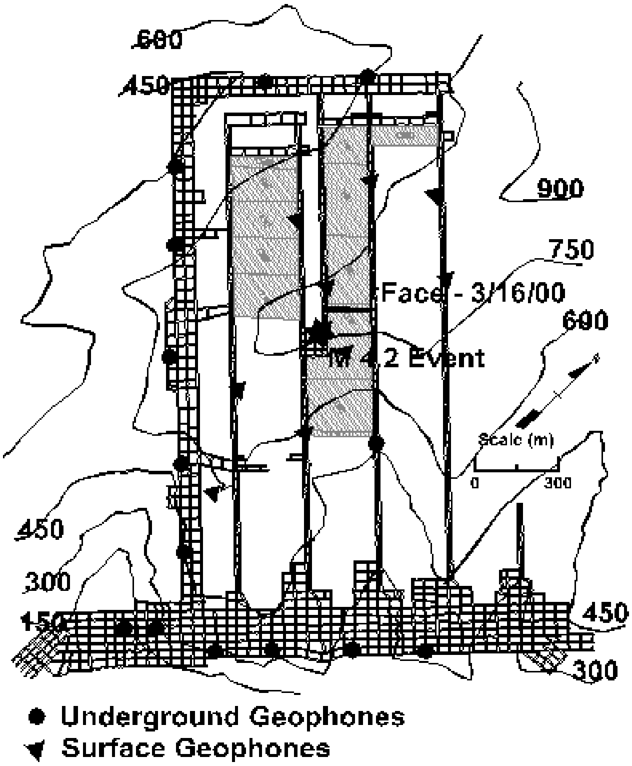

Figure 2. Plan view showing mine layout, overburden, geophone arrays, and the location of the M_L 4.2 event

3 MICROSEISMIC FIELD SITE

The primary objective in this field effort was to instrument a deep, bump-prone longwall mine with a three-dimensional seismic monitoring system in order to examine the behavior of the main roof, gob, and floor. This microseismic system "listened" to the rock and determined the timing and location of the failure of the rock strata surrounding the longwall. 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 order to mitigate dangerous bump occurrences.

The monitoring array consisted of 23 geophones deployed both underground and on the surface. 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 longwall panels (Figure 2). The underground seismic array consisted of 14 geophones in the mains and bleeders around the longwall panels. The underground geophones were cabled to a central underground computer where the signals were collected and transmitted via fiber-optic network to a main data analysis computer in the mine office (Figure 3). On the surface above the mine, another 9 geophones were distributed over the panels (Figure 2). The signals from the surface network were digitized and transmitted by radio to a digital data acquisition system residing on the same network as the main data analysis computer at the mine office (Figure 3). In the data analysis computer, the microseismic event signals were automatically analyzed in order to calculate the event locations, which were then displayed on a computer generated mine map for use by mine personnel. Using this automatic field location process (Swanson 2001), over 13,000 seismic event were detected and located during the mining of panel 2.

In order to obtain a consistent data set of event locations for this preliminary analysis, the raw waveform data were reprocessed in the laboratory. The lab processing utilized an improved seismic velocity model. Seismic velocity data from sonic logs obtained in nearby boreholes were used to create a starting model. Then a number of calibration blasts and other control events with known locations (which were largely at the accessible periphery of the array) were used to further constrain the layered velocity model. This process culminated in a layered seismic velocity model which best fit the available data, although there still appears to be notable spatial variations in the seismic velocity structure that are not considered in the simple uniform layered model. Finally, only the events with a minimum of 8 stations (with at least 3 surface stations and 3 underground stations) reporting good first-arrival picks were kept in the database. This post-processing procedure winnowed the original 13,000 events down to a good quality data set consisting of approximately 5,000 events from panel 2.

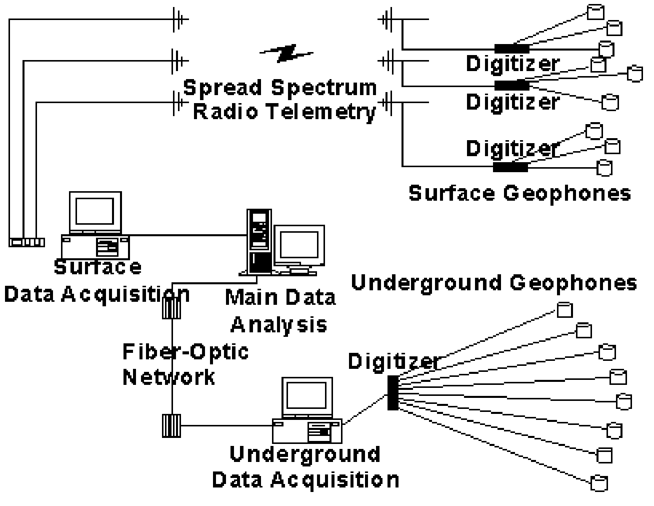

Figure 3. Schematic representation of the microseismic system.

Taking an overall look at the results of the post-processing procedure, a shift of the events by as much as 75 m (250 ft) toward the headgate and away from the tailgate is exhibited. This shift is thought to result from deviations of the actual heterogenous, anisotropic, seismic velocity structure from the assumed homogenous, isotropic, layered velocity model. For instance, we know that the geology is highly variable horizontally, and that the previous gob on one side of the panel influences the seismic velocity. So in analyzing the seismic locations, it must be remembered that the overall event locations can be shifted a little horizontally or vertically by a change in the velocity model. However, the final velocity model applied to the data is the best compromise that minimizes the mismatch between calculated event locations and known source locations for a certain number of events. In addition, the relative location of the events are fairly consistent and can be used confidently in making inferences. Development and use of a spatially heterogeneous, time-dependent, three-dimensional seismic velocity model for event locations is beyond the scope of the present work.

4 SEISMIC EVENTS

The final set of 5000 events from panel 2 were analyzed in two groups since the face width increased from 165 to 245 m (550 to 820 ft) when the barrier pillar separating panels 1 and 2 ended at approximately three quarters of the length of the panel (Figure 2). A review of the data revealed that the number of events were somewhat evenly divided between the two groups with 2,447 events occurring in the initial “narrow” three quarters of the panel, and 2,577 events occurring in the final “wide” one quarter of the panel. To initially visualize the recorded seismicity, the locations of the events were normalized to the advancing longwall 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. All of the events from each end of the panel are plotted on all three orthogonal plots for that end of the panel. The results of this initial visualization process are shown in plan view in Figures 4 and 5, in a vertical view parallel to the advance direction in Figures 6 and 7 and in a vertical view parallel to the longwall face in Figures 8 and 9.

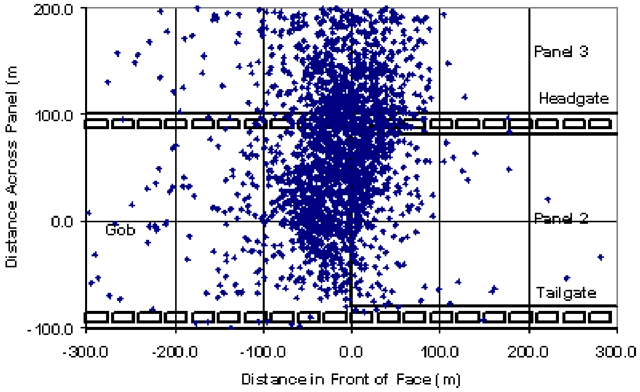

Figure 4. Plan view of the normalized event locations for the first three quarters of panel 2.

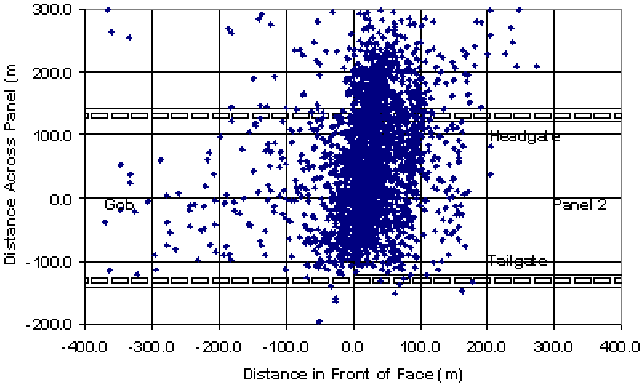

Figure 5. Plan view of the normalized event locations for the last quarter of panel 2.

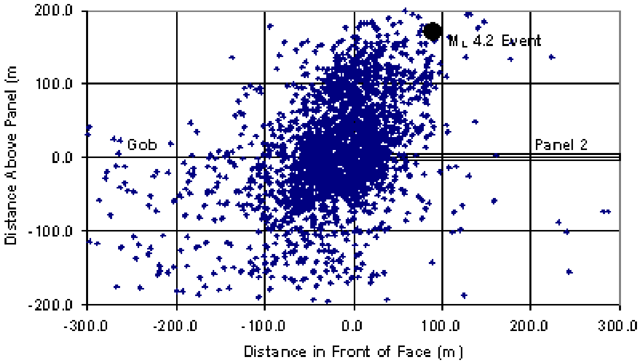

Figure 6. Vertical view parallel to face advance showing the normalized event locations for first the three quarters of Panel 2.

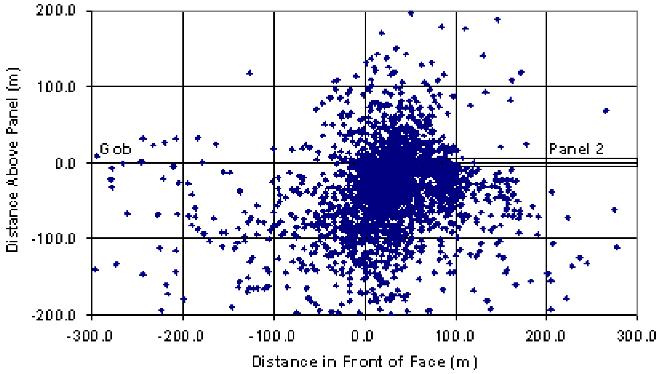

Figure 7. Vertical view parallel to face advance showing the normalized event locations for the last quarter of Panel 2.

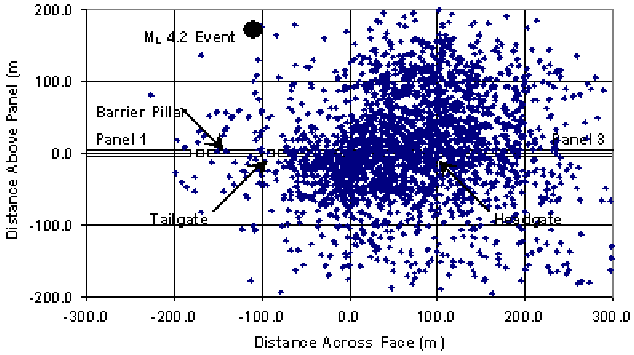

Figure 8. Vertical view parallel to the longwall face showing the normalized event locations for the first three quarters of Panel 2.

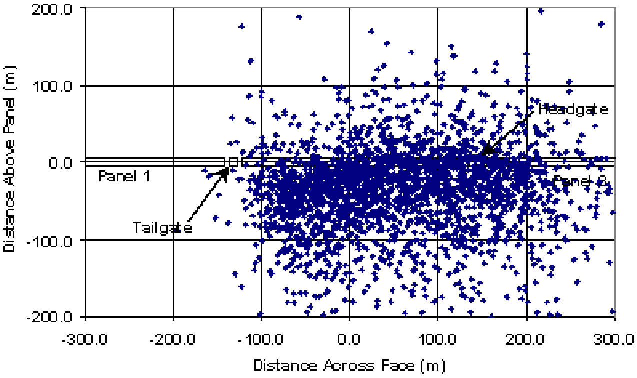

Figure 9. Vertical view parallel to the longwall face showing the normalized event locations for the last quarter of Panel 2.

From the plan view in Figures 4 and 5, it can be seen that most of the seismic activity generally lines up with 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 above.) In comparing Figure 4 to 5, the events appear more dispersed (in relation to the face) in the first part of the panel and generally behind the face. This apparent distribution could be a result of the initial gob formation during the first part of the panel where significant seismic events were occurring above and behind the face as the gob developed to the full sustained height carried throughout the rest of the panel. Or, the relative dispersion could be affected by the reduced constraint on the locations at the beginning of the panel which is at the edge of the array. Also, it is interesting to note that the events in the final wider quarter of the panel are very concentrated in front of the face and occur more frequently (about 3 times more often per given advance). We believe that the linearity of the events in the final quarter of the panel is due to the well established gob and that the increased frequency is a response to the wider panel; however, the affect of spatial variation in event detection sensitivity may also be a factor, but its role has not yet been analyzed in detail.

Figures 4 through 9 indicate that the seismic activity is mostly located in the face area and generally in front of the face. This agrees with seismic data from other coal mining sites (Luo et al. 1998) and has been interpreted to include the failure of the strata in the forward stress abutment zone. 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. From the side view in Figures 6 and 7, it can be seen that the vast majority of the seismic activity is occurring in the face abutment zone, but that there is a notable absence of recorded seismic activity coming from the gob area. Also in Figures 6 and 7, it can be seen that the seismicity is originating both above and below the seam level. This response also coincides well the response observed at other field sites (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 7, a majority of the seismic activity appears to be 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.

Figures 8 and 9 display the distribution of events in a vertical view parallel to the face. In Figure 9, it is important to note that the center of the face has moved 40 m (135 ft) further away from the headgate as the face width was increased on the tailgate side. In Figures 8 and 9, it can again be noted that the events appear more dispersed in relation to the seam in the first part of the panel, and generally more located above the seam. This is consistent with the hypothesis expressed earlier that the higher events were a result of the initial gob formation during the first part of the panel where significant seismic events occur above and behind the face as the gob develops to the full sustained height carried throughout the rest of the panel (or this distribution may be affected by the spatial constraint on event location due to array geometry).

5 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. There was very little indication of 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 US coal mine. This event caused rock slides from critical slopes on the nearby highway and 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 (Figures 2, 6 and 8). 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 & 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.

6 SUMMARY

From examining the seismicity at the site, several general observations can be made. First, the events in the first three quarters of the panel appear to be more dispersed both vertically and horizontally than the events in the last (wider) quarter of the panel. Not only are the events relatively concentrated in front of the face in the last quarter of the panel; but also, the event rate is about three times as high as that at the beginning of the panel (2,447 events for 1,000 m (3,000 ft) versus 2,577 for 300 m (1,000 ft)). We hypothesize that this is a result of the initial gob formation during the first part of the panel versus a well established gob and wider face in the last quarter of the panel. Also, from examining the seismic events, it can be observed that the events generally occur in advance of the longwall face and were approximately evenly distributed above and below the panel. This observation is consistent with the interpretation that the seismic events coming from failure of the strata in the forward stress abutment zone that is vertically symmetric about the coal seam.

A magnitude 4.2 seismic event occurred within an 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 & 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 was never determined. Using the mine-wide seismic system the M_L 4.2 seismic event was relatively accurately located within 150-180 m (500-600 ft) of a deep cover longwall face with no associated bump. This documents a rather dramatic example of how large seismic events do not necessarily result in face damage, and 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 to the working face.

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