Microseismic monitoring and analysis of induced seismicity source mechanisms in a retreating room and pillar coal mine in the Eastern United States

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Abstract

A microseismic monitoring system was installed in an underground room and pillar coal mine in the Eastern United States to analyze the occurrence and characteristics of induced seismicity during the retreat of two panels in the mine. This study is the first microseismic monitoring effort at an underground coal mine in nearly 30 years. During the retreat of the first panel, an array of eight uniaxial geophones, installed 10 ft. into the roof, recorded events and their magnitudes. The second panel was monitored using an array of twelve uniaxial geophones and two triaxial geophones, also installed 10 ft. into the roof. Comparing the results of these studies, it has been found that the magnitude of seismic events is minimally affected by immediate roof geology or depth of cover. However, it was observed in both studies that the rate at which seismic events occurred did vary with changing roof geology and depth of cover. Using the seismic data from the second panel retreat, focal mechanism solutions were generated for 50 hand-picked events in order to determine if the failure was in compression, tension, or shear. Results of the focal mechanism solutions show that stress relief resulting in dilational events occurs at significant depths, 150–200 m in this case, beneath the active mining face.

1. Introduction

Ground control is a major issue in underground coal mines. The "soft" nature of the rock, nearby bedding, and seam depth are just a few of the factors that make coal extraction dangerous. In the United States between 2006 and 2012, over 3300 injuries (fatal, non-fatal days lost, no days lost) were reported as a result of a fall of a roof or rib in the underground coal mine industry. This repre-sents over 16% of all reported underground coal incidents during this period (MSHA, 2015). Forty-two of these inju-ries resulted in deaths. In comparison during this same time frame, underground metal mines had 13.5% (240 injuries) and underground nonmetal mines had 6.7% (55 injuries) of all injuries resulting from the fall of a roof or rib. Over the years, the number of injuries have decreased, but as of 2012 there were still 376 yearly injuries in underground coal mines across the United States.

Commonly accepted mining methods, such as longwall and room and pillar retreat, allow overburden to cave. This creates highly variable stress conditions that can be difficult to predict. From both the safety and production point of

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view, unplanned ground falls resulting from these conditions are unacceptable. Not only can fatalities and injuries occur, but falls can obstruct escape ways, block ventilation, cause stoppage in operations, damage equipment, and cause lost ore reserves. Proper mine design and safe operating procedures are critical to prevent ground control issues from happening.

2. Literature review

2.1. Microseismic monitoring

2.1.1. Introduction to microseismic monitoring

A common way of determining instability and changing stress conditions in underground mines is to monitor mining-induced microseismic events. A microseismic event occurs when a rock under a critical amount of stress fractures and emits an energy wave of short duration and small amplitude (Obert & Duvall, 1967). Each waveform contains a grouping of elementary wave signals that represent particle velocity initiated by individual pulses of stress wave energy (Descour & Miller, 1987). The energy pulse's shape details the amount of stress released at the source and the effect of non-uniformities in the rockmass along its travel from the source to a microseismic sensor such as a geophone. The polarity of a waveform from both man-made and natural sources can be used to determine whether an event's driving force was shear or compressional (Swanson, Stewart, & Koontz, 2008). Individual waveforms are analyzed to determine the time, location, and magnitude of a single event. A seismic event with a moment magnitude of typically less than 2.0 is considered "micro" (Spence, Sipkin, & Choy, 1989). Over time, the failure process of a monitored area can be studied from the progression of the located events.

At least three microseismic surveys have been completed and analyzed in longwall coal mines (Alber, Fritschen, Bischoff, & Meier, 2009; Ellenberger, Heasley, Swanson, & Mercier, 2001; Luo, Hatherly, & McKavanagh, 1998; Swanson et al., 2008). These studies and analyses verified that microseismic monitoring is a useful tool for understanding stress redistribution in an underground coal mine setting. In contrast, room and pillar retreat mines have had only one published microseismic study. This study, completed in 1987 by Descour and Miller, monitored various parts of a retreat mine section over a 10 month period. The mine layout however was not the same as what is currently found underground. Modern rectangular retreat panels, which incorporate five to seven entries encompassed by barrier pillars on both sides, were not employed. Instead, an entire section of the mine was extracted. Much smaller barrier pillars, approximately the size of 10 production pillars, were placed in vital areas of the section.

Microseismic events are the results of changes in the stress distribution of a rockmass, where the physical event is a slip or shear of the rock. These events are too small to be felt on the surface of the earth but can be detected and measured by equipment such as geophones or accelerometers. This is considered a passive method as the instruments are monitoring seismic activity already taking place, also known as induced seismicity (ESG Solutions, 2016). This monitoring can provide results in real-time, providing knowledge of what is happening underground at exact points in time (Ge, 2005).

Microseismic monitoring can reveal information such as when and where the microseismic event occurred underground, and the event's magnitude (Ge, 2005). The main goal of such monitoring is to observe these events over time and identify patterns and correlations between events and production activities. Monitoring seismic activity in mining operations can improve mine safety through risk management, and be used to study overall ground conditions.

2.1.2. Planning the monitoring system

Efficient mine microseismic monitoring can be summarized in three aspects: monitoring planning, data processing, and event location (Ge, 2005). Thorough planning is essential for establishing an efficient and lasting monitoring system. In planning, it is important to assess monitoring objectives, including target areas, accuracy, and conditions of the area being monitored. The size of the monitoring system is another important aspect to the design. The degree to which a monitoring system is effective is proportional to its ability to pick up signals. Large channel systems, therefore are the most effective as they can record more signals a relatively higher number of signals due to the decrease in distance between potential event locations and sensors (Ge, 2005). Initial and regular calibrations should be conducted on the sensor array to ensure the most accurate data. As mining environments are very dynamic and potentially harsh on monitoring equipment, regular equipment and signal checks should be performed to allow for uninterrupted data collection.

2.1.3 Event location and processing

These microseismic events are detected in the form of an energy wave that travels from the point of origin outward through surrounding rock (ESG, 2016). The waves travel by elastic deformation of the rock medium, creating compressive and shear stresses. The types of waves that are monitored are called body waves. There are two types of body waves: P-waves, or primary waves, and S-waves, secondary waves. P-waves are fast traveling seismic waves, and move through a medium in the longitudinal direction by compression, pushing and pulling the material. S-waves are much slower and move through material causing vibrations perpendicular to the direction of the wave propagation, as opposed to parallel with P-waves. P-waves can move through solids and fluid, while S-waves can only travel through solids. Because P-waves travel faster, the greater the distance between the arrivals of the two waves, the greater the distance between the sensor and location of the microseismic event (ESG, 2016).

The efficiency of a microseismic monitoring system is generally measured by the accuracy of event locations (Ge, 2005). A suitable source location code is necessary for a reliable monitoring system. There are many different approaches to source location, but in general there are four aspects that should be considered. First, the searching algorithm should have a good convergence character so that the divergence problem is less likely to occur and the system will not be interrupted. Second, is the ability to use P- and S-wave arrivals simultaneously. This allows for better use of the data, as both arrivals are not always detectable, and provides a better method for reducing error in source location. Third is the ability to limit the impact of errors, by array and data optimization. The least-squares and absolute-value methods are the most commonly used for defining the error. The fourth aspect necessary for an effective mine monitoring system is a reliability analysis of the source location result. In determining reliability, the residuals, sensitivity, and hit sequences are analyzed (Ge, 2005).

Processing microseismic data from a mine site is usually very complex. There are often large levels of background noise from the mining operation that interfere with microseismic signals. One of the primary tasks of data processing is the filtering of the background noise. If the frequency range for the signals is different from that of the background noise, frequency filters can be used to clear the background noise. Another important aspect of data processing is the identification of arrival types. First arrivals may be P-waves, S-waves, or outliers, which are arrivals not due to the physical source. If these arrivals are not properly identified, the database would contain many systematic errors (Ge, 2005).

2.1.4. Seismic characteristics of rock failure and mechanism solutions

In-situ rock masses may fail in five different modes (Gale et al., 2001):

1. Shear fracture through intact rock.
2. Tensile fracture through intact rock.
3. Shear fracture of bedding planes.
4. Tensile fracture of bedding.
5. Movement of pre-existing fractures.

The stress levels before a failure depend on the strength properties of the intact rock, and after the failure this stress is reduced to an amount dependent on the strength properties of the fractured material. The difference between these two stresses is known as the stress drop. Shear failures create much larger stress drops than tensile failures. Similarly, much more strain energy is released in shear failure than tensile failure (Gale et al., 2001).

During monitoring, the direction of the P-wave can be used to differentiate between shear and tensile failure. Movement both towards and away from the source reflect shear failure, while P-wave motions moving toward the

source at all sensors represents tensile failure (Swanson et al., 2008).

When analyzing the characteristics of seismic activity, focal mechanism solutions are used to display the mechanism of failure occurring in the rock. A focal mechanism solution is derived from analyzing waveforms generated by seismic activity (Cronin, 2010). As seen in the graphic created by the US Geological Survey (public domain), the focal mechanism is a spherical ball with two black quadrants and two white quadrants, also known as a beach ball. The full-circle arcs that divide the quadrants represent two nodal planes, one of which represents the plane on which the failure actually occurred. Local geologic knowledge is usually required to differentiate between the planes (Cronin, 2010). The color of the quadrants represents the movement of material during the failure (USGS, 2016). Material moves in the direction toward the dark quadrant from the white quadrant, meaning compression towards dark quadrants and tension away from the white (see Fig. 1).

2.2. Retreat mining

Room and pillar mining is a traditional mining method for underground coal extraction used in the United States. This method is effective for relatively flat coal deposits, and coal recovery is usually around 60%. Panels are driven out from the mains in a checkered pattern created from entries
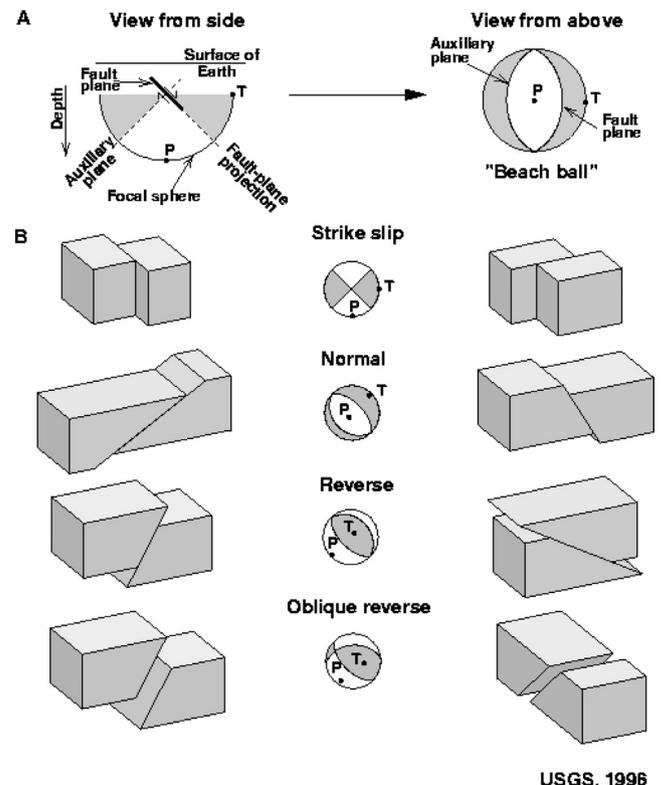

Fig. 1. Schematic diagram of a focal mechanism. Source: USGS, public domain.

and crosscuts. Developed rooms are open areas where coal has been mined out, while blocks of coal, known as pillars, are left between rooms in order to support the mine roof. Some room and pillar mines use the practice of retreat mining where once the panel is driven to its extent, the pillars are extracted upon retreat back towards the mains, and the roof is allowed to fall, further increasing the coal recovery percentage (CSM. Coal Mining Methods., 2016).

2.2.1. Ground control

Coal mines are operating at increasingly greater depths, which create higher stress conditions that complicate ground stability practices (MSHA. U.S. DOL., 2016). According to U.S. legislation, mining operations are classified as deep cover operations when overburden exceeds 450 m (Mark, 2009). However, mine workings at depths greater than 200 m have also been considered deep cover operations (Chase, Mark, & Heasley, 2002). Specific deep cover ground control issues identified by NIOSH include pillar design and recovery sequences, coal bumps, and multiple seam interactions (Mark, 2009). Risk associated with deep cover pillar extraction is categorized in two main groups, global and local stability (Mark, Chase, & Pappas, 2003).

2.2.2. Global and local stability

Global stability involves pillar conditions and failure of a section, and is largely addressed through the mine design. In mine planning and pillar design, empirical design programs such as ARMPS and numerical modeling software such as LAMODEL can be very useful (MSHA, 2016). When using these programs, it is critical that input parameters are appropriate to the situation, and actual in-mine conditions should be considered. It is also useful to review the history of ground control for any nearby mining operations that worked in similar ground conditions. Common risk factors associated with global stability include pillar squeezes, bumps, and massive collapses (Mark et al., 2003). Pillar squeeze is a slow process where the pillars are too small for the load of the overburden, and results include entry closure, rib spalling, floor heave and roof failure. Pillar bumps occur when highly stressed pillars rupture without warning, which sends coal and rock flying. Geologic characteristics, the ability to store strain energy, and mine design are major parameters that affect coal bumps and bursts (Haramy & McDonnell, 1988).

Local stability deals mainly with the stability of the mine roof in working areas. In retreat mining, important factors in roof stability include the cut sequence which the retreat is using, the final pillar stump or pushout, and supplemental roof supports (Mark et al., 2003). The cut sequence is the method for pillar extraction upon retreat. The most popular methods are classified as "left-right" or "outside lift". These methods are used primarily because extra roof bolting is not needed, as the sequences allow for the greatest support while recovering the pillars. The final pillar stump design is another critical factor of local stability,

as the greatest amount of stress is concentrated on the smallest amount of support at the end of the retreat. Some operations will recover the final stump, adding additional risk, while other operations leave it in place (Mark et al., 2003).

2.2.3. Supplemental roof support

While proper mine planning can compensate for most of the stress of overburden, additional roof supports are commonly needed in the retreat of a room and pillar mine and it is important to have the extra support prior to the stress increase caused by retreat (MSHA, 2016). Mobile roof supports, timbers, and roof bolting may be used to support the load once held by the pillars. Timbers are simple and inexpensive, but must be manually moved and have limited load bearing and deflection capabilities. Mobile roof supports have greater load capacity and flexibility than timbers and are remotely operated, but are more expensive and limited to thicker seams. Roof bolting is a widely practiced form of supplemental roof support, and usually is the only overhead protection for miners during pillar recovery. There is no widely accepted method for roof bolting, and many roof failures have come from inadequate roof bolt designs. Other factors that can add risk to roof stability include roof geology, intersection span, depth of cover, multi-seam interaction, recovery of old pillars, and non-uniform pillar design (Mark et al., 2003).

3. Summary of microseismic monitoring studies

3.1. Site description

The monitoring study took place in a room and pillar retreat mine in the Eastern United States. The retreat of Panel A was monitored in the first study (Conrad, 2015), and then the subsequent Panel B was monitored in the second study (Westman, Molka R., & W., 2016). The panels were approximately 1000 m long by 120 m wide, and had seven entries. The coal seam thickness averaged about 1.5 m, with the cut heights of approximately 2 m to cut the rock underlying the coal. All pillars were rectangular, and the panels measured 38 pillars long by 6 pillars wide. Depth of cover for the panels ranged from 180 to 300 m.

3.2. Panel geology

The coal at the mine is bituminous, containing 5% ash content, less than 1% sulfur content, and is 25% volatile matter. The seam at the panels has an average dip of 1.7% towards N16°W, with a strike of N74°E. The face cleat is orientated at N68°E, while the butt cleat lies at N15°W. Principal stresses have not been gathered at the site. A regional thrust fault has created a flat lying detachment fault surface within the coal bed due to lateral movement. As a result of faulting, drag folds, which are slickensided inclined fractures, are present in the seam itself

and lay roughly at 45° angles. Above and below the coal seam are alternating layers of shale and sandstone.

3.3. Monitoring arrays

The array installed for monitoring Panel A consisted of eight uniaxial geophones, six located along the long axis of the panel, in the entry closest to Panel B, and two in the main entries at the end of the panel. All geophones were anchored 3 m into the roof above the seam. After 1.5 months of monitoring, about 3000 events with acceptable location errors of less than 30 m were recorded.

For the retreat of Panel B, the same eight uniaxial geophones were used again, along with a new array consisting of four uniaxial geophones and two triaxial geophones located on the opposite side of Panel B. The retreat was monitored for a period of about 3 months, however data was only collected by all 14 geophones simultaneously for 3 time periods within the 3 months, and events within these periods were analyzed. The second data set contained data of a higher quality since the geophones were located on both sides of the panel. During the monitoring of both Panels A and B, the event locations, magnitudes, and rates were recorded.

4. Focal mechanism solution generation method

Microseismic monitoring studies provide very useful information about seismic event magnitudes and the rate at which they occur in relation to a mining operation. The mechanism of failure for a seismic event can also be determined using the data recorded during microseismic monitoring. Using the data from the Panel B retreat, 50 events were handpicked to generate focal mechanism solutions. These events all occurred during one of the periods when data from all geophones was being recorded. For uniaxial geophones, first-arrival P-waves were hand-picked. Observing the waveforms generated by the triaxial geophones, P- and S-wave arrivals were able to be hand-picked as well. Along with picking the arrival times, the first motion polarities of the waves were designated, either negative or positive which indicated movement away or toward the source. With these conditions set for an event, a focal mechanism solution was generated for the event. The polarities of the waveforms and generated raypaths from the geophone to the event location determine the behavior of the failure. A uniform velocity model is assumed for this study. Of the 50 events that were picked, only 5 events were well constrained in their solution. With the mechanism solutions generated, the type of failure occurring during a seismic event was analyzed.

5. Results and discussion

To analyze the microseismic data gathered during the retreat of Panel A, event rates per hour (Fig. 2) and moment magnitude (Fig. 3) were plotted against time. Each

plot uses Greenwich Mean Time (GMT), which is five hours faster than Eastern Standard Time (EST) where this data was recorded. The panel was paused during retreat from March 16th until March 20th. This period is shown as a black outline in both figures. While noticeable gaps appear in the data collection, several observations can be made concerning the progression of event rates and resulting magnitudes.

Two event per hour peaks occur on fully monitored days. One hourly event rate peak occurs during the early morning hours of third shift, typically between 3:00 am and 7:00 am EST. The second daily peak occurs in the afternoon, between 12:00 pm and 4:00 pm EST, and is larger than the previous. At the mine site, third shift is set aside for maintenance while first and second shifts are used for production. First shift begins physically mining at approximately 7:00 am and continues until 2:00 pm EST. Second shift begins mining at 3:15 pm and continues until around 11:20 pm EST. One full pillar line is typically mined every day. The shifts typically switch halfway across the face in entry five as mining progresses from entry seven to entry two.

Before the larger peak in event rates, events per hour tend to exponentially rise daily until a maximum is reached, then sharply fall, resulting in a cycle that exhibits a skewed left appearance. Peaks during the afternoon hours are possibly attributed to a buildup of stress as mining progresses halfway across the face, the pause for shift change, and the continual mining across the face towards entry two, resulting in a critical failure point in the roof that releases the stress accumulation. Exact face locations and better wave arrival picks are needed though for indisputable conclusions. Fig. 4 (period 1) and Fig. 5 (period 2) show closer views of the peak cycles with their respective peaks identified by time. When viewing the magnitude versus time plot in Fig. 3, the larger afternoon peaks tend to have more spread in magnitude than the peaks that occur during the morning hours and other monitoring.

Figs. 4 and 5 also display a noticeable change in event rates per hour between the continuous monitoring periods of March 2nd to 8th and March 11th to 15th. At an overall mining rate of approximately two pillar lines every three days, retreat would have changed from under a more brittle shale roof, to a mixture of sandstone and sandy shale on or around March 10th. The event rates per hour between March 2nd and 8th were much higher than those experienced between March 11th and 15th. Event magnitudes shown in Fig. 3 are not significantly different for the two periods of differing geology.

The depth of cover between the two periods examined are slightly different, but may have still influenced results. Between March 2nd and 15th, the depth of cover ranged from 225 to 300 m, compared to a range of 210–245 m between March 11th and 15th. Furthermore, no conclusions could be made when retreating under 300 m of cover in crosscuts 31–33 because of inconsistent data collection and unknown exact face locations.
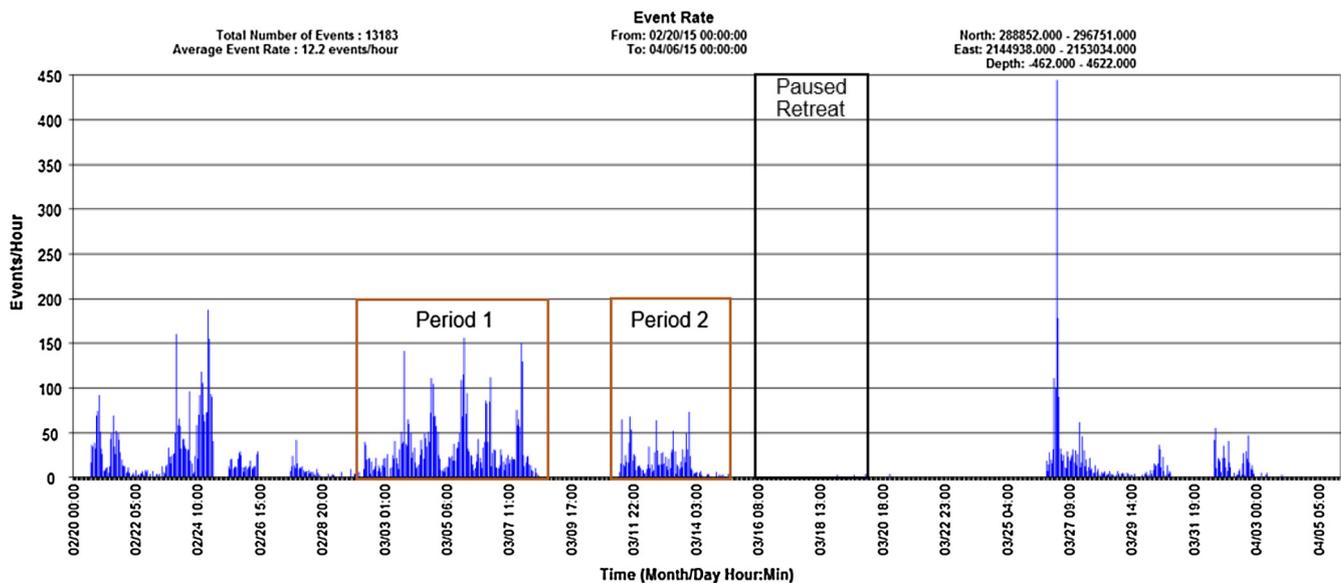
Fig. 2. Event rate (per hour, GMT) for all located events during Panel 2D retreat.
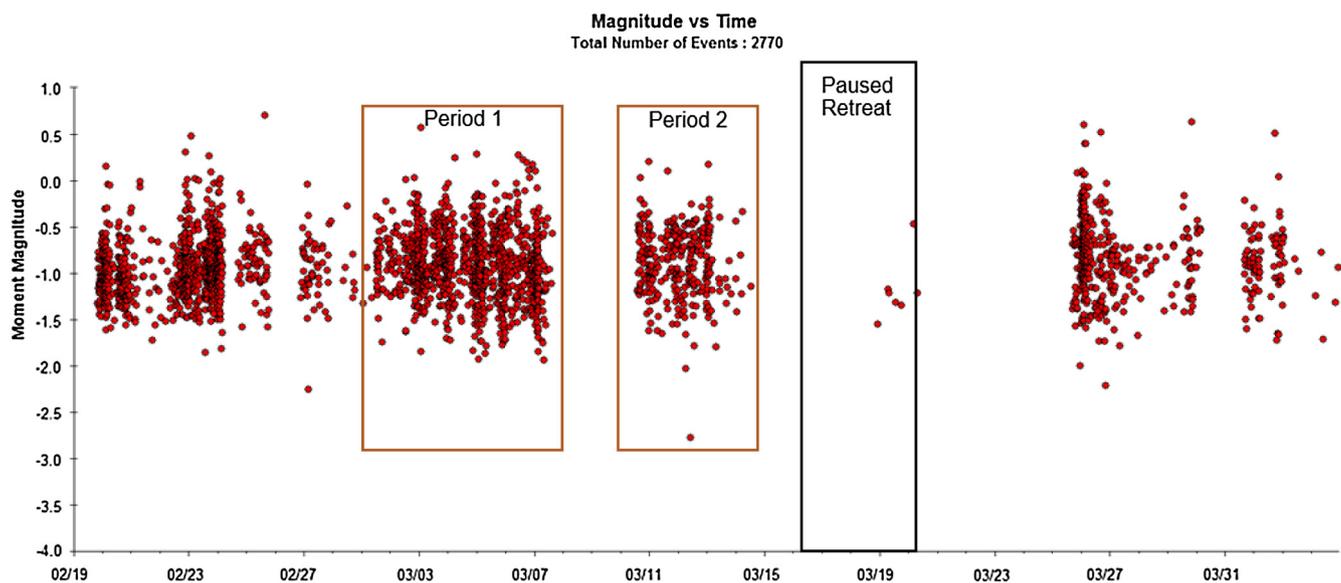

Fig. 3. Magnitude verse time (GMT) chart for all located events during Panel 2D retreat.

Another element of Fig. 2 is that it displays one hour of an extremely high rate of events on March 26th. There were 444 events that occurred between 5:00 pm and 6:00 pm. It should be noted that figure displays that the magnitudes of these events were roughly similar to those experienced during other periods of retreat. When an estimation of the face location (crosscut 12) on this day is overlain on the roof geology and depth of cover, no abnormal observations can be made. Pillaring was taking place under a sandy shale roof at 700 ft.–800 ft. (213–m) of cover. Retreat would have been outby the sandstone roof channel by two to three crosscuts. A large section of hanging roof could have failed, possibly causing the large peak in events per hour, but documentation of individual caving

events was not available from the mine site. The five day pause in retreat would not be expected to influence this high event rate, as pillaring began again on March 20th, six days before the high event rate was encountered.

A similar discussion of the event rates and magnitudes recorded during the retreat of Panels B is contained in Westman et al., 2016. The results show that the event rates and magnitudes for Panel B were approximately the same as those recorded for Panel A. This is significant as it demonstrates that a one-dimensional array can provide this important information without the added cost of a parallel array.

Using data recorded during the retreat mining of Panel B, the source mechanisms for five events were analyzed. An
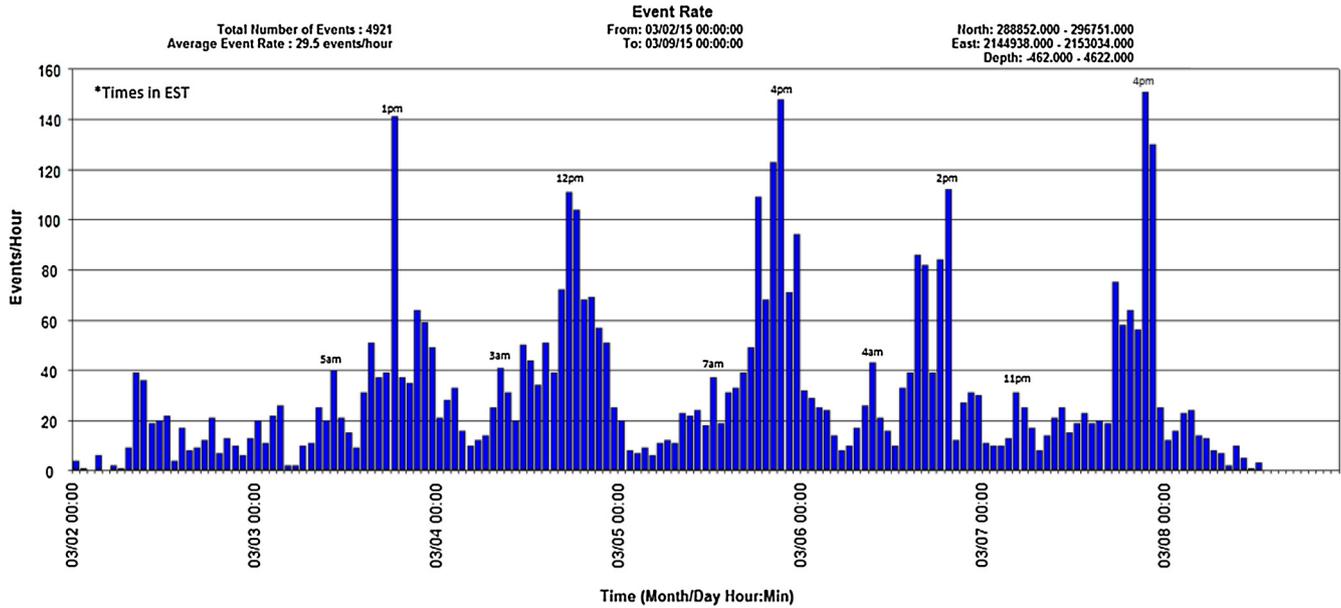
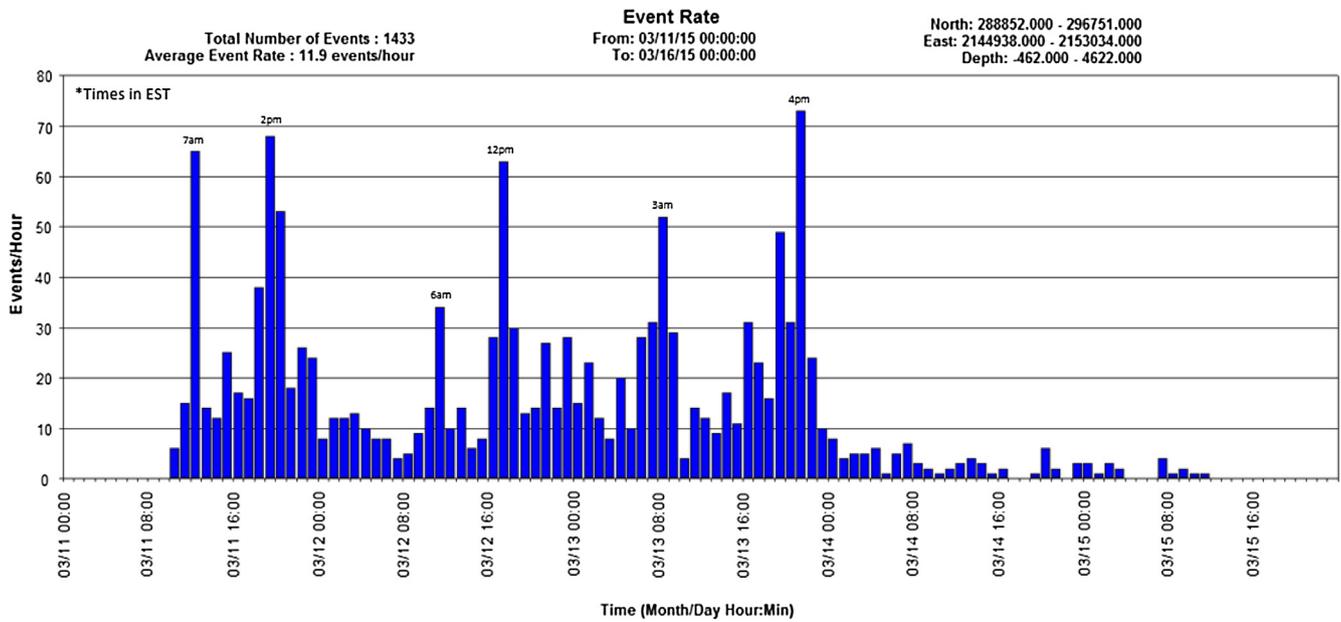Fig. 4. Event rate peaks (period 1) with noted times in EST.

Fig. 5. Event rate peaks (period 2) with noted times in EST.

example of the focal mechanism diagram is shown in Fig. 6 and a table containing information about the events is shown as Table 1. As shown in the table, three of the five events were dilational and two were compressive. Table 1 uses traditional mining terminology to relate the event position to the location of the active face at the time of the event. An event that occurs further into the mine than the active face is termed as "inby" the face while an event that occurs in the direction from the active face out of the mine is termed "outby." Thus events that occur "inby" the

face are occurring above or below the retreated portion of the panel (where the supporting pillars have been mined) while events that occur "outby" the face are occurring above or below pillars that have not yet been mined.

Locations of the events relative to normalized face locations are shown in Fig. 7. Fig. 7A shows the events in a horizontal cross section with the previously-mined, and now caved, panel to the top of the figure and the subsequent panel, still unmined, shown to the bottom. The events are shown in a vertical cross section in Fig. 7B with
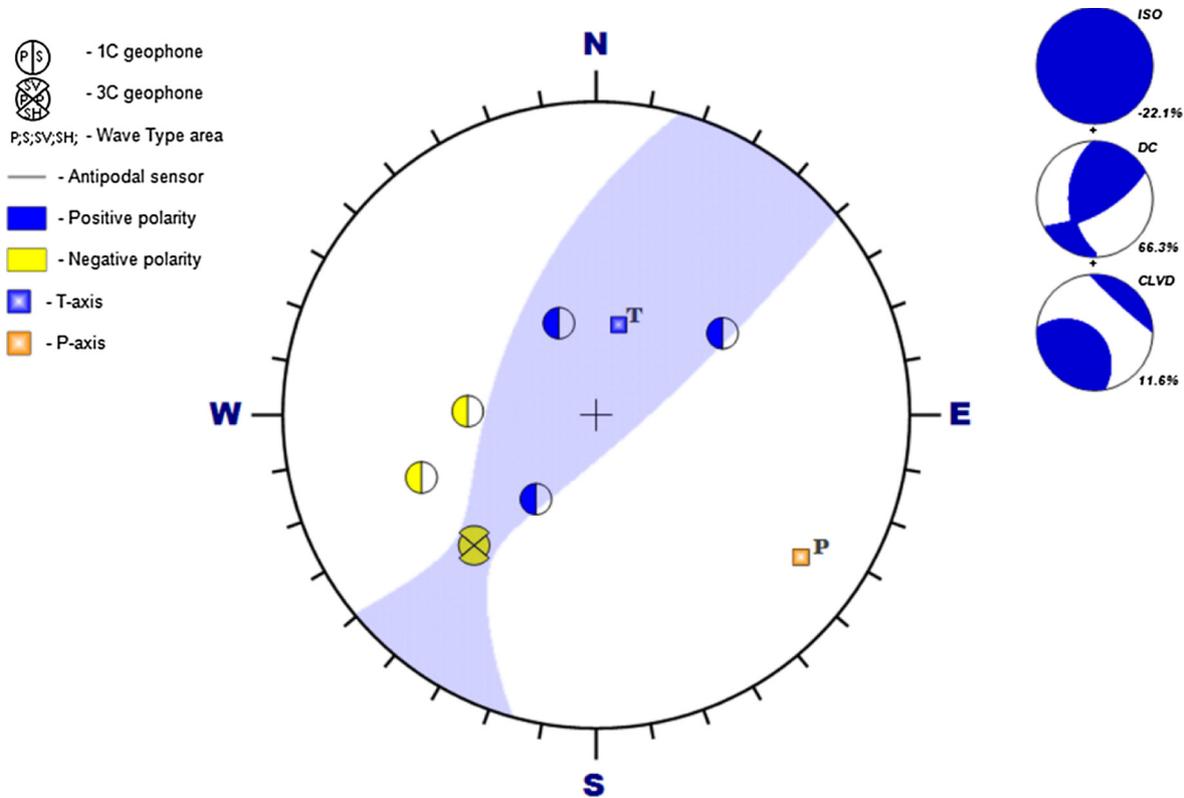
Fig. 6. Example source mechanism plot, for Event 5.

Table 1
Information for events for which a source mechanism was identified.

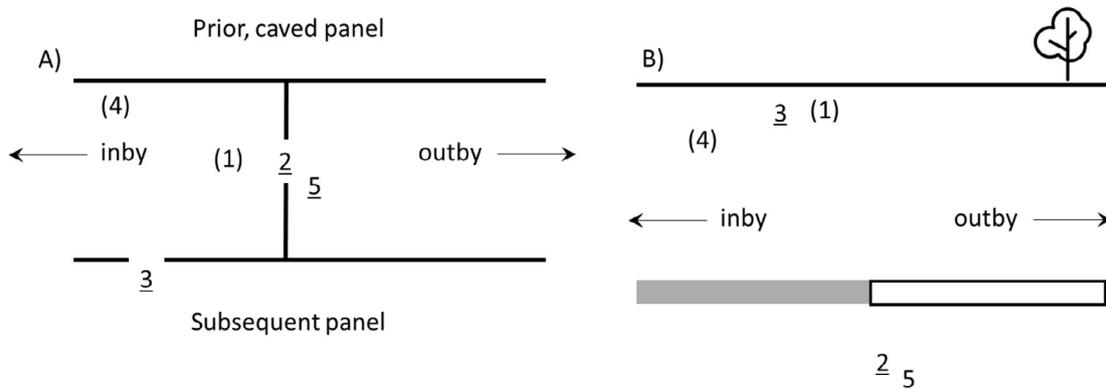| Event number	Distance from mining face	Distance above or below face	Mechanism	Moment magnitude
1	60 m inby	300 m above	Compression	−0.59
2	0 m inby	150 m below	Dilation	−0.49
3	200 m inby	200 m above	Dilation	0.05
4	300 m inby	120 m above	Compression	−1.03
5	30 m outby	200 m below	Dilation	−0.62

Fig. 7. Schematic diagram showing location and mechanism of the five events. (A) Horizontal cross section at level of mined seam, (B) vertical cross section. Actual distances provided in Table 1. Mechanisms shown as: dilation and (compression).

the event locations shown at depths relative to the mined seam. Events shown with red text are compressional in nature while those in blue are tensile.

Several results can be observed in Fig. 7. Fig. 7A shows that four of the five events occur within the panel, the only outlier is Event 3 which is a dilational event that occurs

over the barrier pillar that separates Panel B from the yet-to-be-mined Panel C. The vertical distribution of the events, shown in Fig. 7B, shows that one dilational event (Event 3) and both compressional events occur above the seam and inby the active face, with Events 1 and 3 occurring very near to the earth's surface above the mine. Two events (Events 2 and 5) occur directly underneath the active mining face (Event 2) or 30 m outby the face (Event 5) at a depth of 150–200 m below the seam.

A typical expectation regarding the source mechanisms related to a caving method of mining a coal seam (either retreat mining or longwall mining) is that the stronger, compressional events should occur in advance of the mining face within the forward abutment loading zone and weaker, tensile events should occur behind the face where the gob is being formed by the caving of the overburden. It is also expected that the tensile event associated with gob formation would be of a low enough energy that they may not be recorded by a microseismic monitoring system.

The results observed in Fig. 7 are of interest because they indicate that stress relief resulting in dilational events occurs at significant depths, 150–200 m in this case, beneath the active mining face. Additionally, the dilational events generally had a higher moment magnitude than the compressional events, which is contrary to typical expectations at a retreat coal mine.

These location and mechanism of the events that occur in the overburden can be compared to mining subsidence theory. The general understanding of the distribution of stresses within the overburden caused by subsidence is that a tensile zone exists in the overburden above the boundary between the solid coal and the caved zone while a compressional zone is developed at the inflection point where the subsidence trough approaches its maximum depth. This general distribution agrees with the observed locations of Events 3, and 4. Event 3 occurs above the boundary between the mature caved zone of Panel B and the solid zone of unmined Panel C. Event 4 occurs further inby the face and in the area where surface subsidence could be reaching its greatest depth. Event 1, however, does not conform to the generally-accepted understanding. It is a compressional event very near the ground surface above the mine and 200 ft. inby the active face. The possibility exists that it is a collapse event associated with more immediate surface subsidence than typically occurs. Another possibility is that the subsidence mechanism is not completely understood and that further microseismic analysis can help this to be developed.

6. Summary and conclusions

Microseismic monitoring is a very useful method of observing and analyzing the behavior of surrounding ground during a mining operation. For the first time in nearly 30 years a microseismic system was used to monitor seismicity at a retreating room and pillar coal mine in the Eastern US. Understanding how mining activities disrupt in-situ conditions and how those changing conditions affect the operation can be very important in mine planning and safety considerations. In the studies of the Panel A and B retreats, similar conclusions were drawn regarding event rates and magnitudes.

Results indicated that peaks in the hourly event rate frequently occurred once in the early morning hours during the mine's maintenance shift, and again in the afternoon during one of the two production shifts. Rates typically exponentially grew from a base level around the late evening hours, through the first smaller peak of events in the morning, and until the larger peak in the afternoon. After the large hourly peak in events, rates sharply dropped.

Results also show a disparity in event rates when retreating under a shale roof as opposed to under a sandstone/sandy shale roof. The average event rate was much higher between March 2nd and 8th when retreating under shale than it was between March 11th and 15th when retreating under a mixture of sandstone and sandy shale. Shale roof is more brittle than a sandstone roof, which would account for a higher rate of events. No conclusions could be made when retreating under 300 m of cover because of inconsistent data collection and exact face locations being unknown.

For the first time, source mechanisms have been assigned to seismic events at a retreat room and pillar mine. From analyzing the source mechanisms, it is seen that stress relief resulting in dilational events occurs at significant depths, 150–200 m in this case, beneath the active mining face. Additionally, the observed event locations and mechanisms generally agree with accepted theory about overburden response to tabular seam mining. These new findings provide an improved understanding of the rock mechanics associated with retreat room and pillar mining, both above and beneath the mined seam.

Acknowledgements

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