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Coal bursts that occur during development: A rock mechanics enigma

Christopher Mark

Safety and Health Administration, Pittsburgh 15236, USA

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ABSTRACT

Coal bursts are typically associated with highly stressed coal. Most bursts occur during retreat mining (longwall mining or pillar recovery) in highly stressed locations like the tailgate corner of the longwall panel. Others are associated with multiple seam interactions. However, a small but significant percentage of coal bursts have occurred during development or in outby locations unaffected by active mining. Most development bursts have been relatively small, but some have been highly destructive. No theory of coal bursts can be complete if it does not account for this type of event. This paper focusses on the development mining coal burst experience in the US, putting it into the context of the entire US coal burst database. The first documented development coal burst occurred almost exactly 100 years ago during slope drivage at the Sunnyside Mine in Utah. Sunnyside subsequently had a long history of bursts, mainly during retreat mining but also during development. Several Colorado mines have also experienced multiple development bursts. Many, but by no means all, of the development bursts in these western US coalfields have been associated with known faults. In the Central Appalachian coalfields, most development bursts have occurred in multiple seam situations. In some of these cases, however, there was no retreat mining in either seam. The paper closes with some lessons from this history, with implications for preventing such events in the future.

1. Introduction: overview of coal bursts in the US

The long history of coal bursts in the US has been well-documented. Iannacchione and Zelanko analyzed the US Bureau of Mines (USBM) database of 172 bursts that had occurred between 1936 and 1993 [1]. The bursts included in the database were serious enough to warrant USBM investigations and reports, and together they resulted in 87 fatalities and 163 injuries.

Iannacchione and Zelanko reported that 24 of these events, 14% of the total, occurred during development [1]. All 24 incidents were reanalyzed for this study, and it seems they fall into three categories:

(1) events that occurred at the Mid-Continent mines, located in Colorado, which were likely gas outbursts rather than coal bursts ($n = 12$),
(2) events that occurred at several mines in Central Appalachia, which were affected by nearby goafs or multiple-seam interactions ($n = 9$),
(3) three events at the Sunnyside No. 2 and Deer Creek mines, both in Utah, that were purely development bursts.

In the US, coal mines must report to Mine Safety and Health Administration (MSHA) any "coal or rock outburst that causes withdrawal of miners or which disrupts regular mining activity for more than one hour" (Code of Federal Regulations, Title 30, Part 50.2). Between 1983 and 2017, 283 bursts were reported to MSHA. Seven of these resulted in a total of nine fatalities; two on longwalls, and seven during five pillar recovery events.

Fig. 1 shows the number of bursts reported each year to MSHA. The long-term declining trend is very pronounced. During the early 1980s, approximately 14 bursts were reported each year, but, in recent years, the number has averaged less than three. The number of development bursts has also declined, with just one reported since 2010.

Fig. 2 shows that 42% of the bursts during the 34-year period occurred on the longwall face. Another 12% affected the tailgate entry at the corner of the longwall face, and 18% occurred during retreat mining. All of these locations are subject to very high stresses, and they are directly affected by mining activity and might be considered likely locations for bursts. On the other hand, 20% of the bursts occurred during entry development, and another 8% affected pillars in the headgate, bleeder, or other outby locations.

Fig. 3 shows regional trends. In Utah, 58% of the total 149 events occurred on the longwall face, and another 17% occurred either in the longwall tailgate or during pillar recovery. Similarly, in Central

E-mail address: mark.christopher@dol.gov

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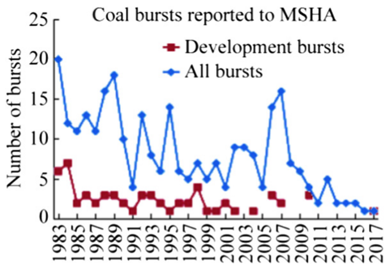

Fig. 1. Coal bursts reported to MSHA.

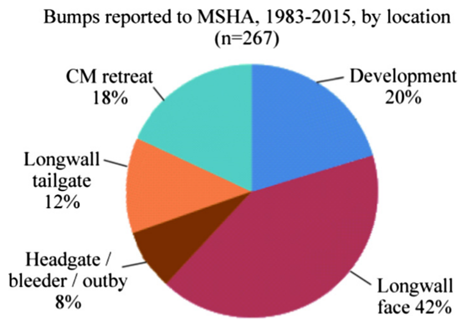

Fig. 2. Bursts reported to MSHA, 1983–2015.

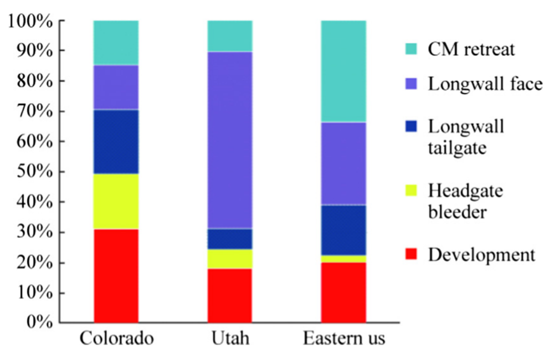

Fig. 3. Regional trends of coal bursts.

Appalachia, 78% of the 23 reported bursts occurred on the longwall face, tailgate, or pillar line. In Colorado, on the other hand, nearly half of the bursts occurred during entry development or in the headgate, bleeder, or other outby location. Although 46 of the 64 Colorado events took place in longwall mines, only nine occurred on a longwall face.

Looking in more detail at the 63 development and outby bursts, none resulted in a fatality. About half involved injuries, mainly minor ones. Only five resulted in serious bone fractures that required more than three months of lost time.

The development and outby bursts occurred at a surprisingly large number of mines. The 24 events in Colorado occurred at nine separate mines, six North Fork Valley (NFV) mines and three Mid Continent operations. A total of 32 development and outby events occurred in 13 different Utah mines. All of the western mines that reported development or outby bursts also reported bursts during retreat mining (longwall or pillar recovery). However, only three Central Appalachian mines reported development or outby bursts, and only one of those mines ever reported a burst during retreat mining.

2. Sunnyside Mine, Utah

The Sunnyside Mine is one of the best known burst-prone mines in the US. It operated in the Book Cliffs region of Utah for nearly a century, before closing in 1994. In response to the bursting that plagued its pillar recovery operations, Sunnyside pioneered longwall mining in the West in the early 1960s. Sunnyside also developed the two-entry yield pillar system, which has become the Utah standard for longwall burst control [2].

The overburden at Sunnyside was predominantly strong sandstone, with some beds more than a hundred meters thick. The immediate roof above the coal was generally poor, however, consisting of shales, sandy shales, thin laminations of sandstone and shale, and rider seams. The floor was a strong sandstone 6–15 m thick. The depth of cover at Sunnyside was severe even in the early days, with the 600 m cover line just 800 m from the coal outcrop due to the cliff-forming sandstones [3]. Numerous faults are present, most prominently the Sunnyside fault system which parallels the outcrop (Fig. 4).

In the early 1900s, bursts were already common in pillar workings under heavy cover at Sunnyside and at other mines within the same region [4]. Most of the really severe events were associated with the main Sunnyside fault [3]. The first significant encounter at the mine with development bursts occurred in 1918. In that instance, bursting started soon after two slopes penetrated a fault having a 5.5 m displacement. As the slopes were driven still further down the pitch, the face would blow out to a depth of 2 m, filling the entry with pea-sized pieces of coal. No further disturbances were noted after a second fault was crossed.

In the early 1940s, slope and entry headings in a virgin development burst violently, although the nearest pillar workings were 450–750 m away. They were of such magnitude as to break the top, knock out timber support, and cause roof falls, some of which were very extensive. Cover over these development workings ranged from 230 to 600 m [3].

In January of 1957, a series of events caused great damage to the main slope area near the fault. A heavily bolted section of roof in the track slope settled on the bolts throughout 150 m of track entry, and the railroad on the same slope was heaved and thrown out of line for a distance of 400 m. This same area had been damaged in bursts in 1944 and 1952.

In December of 1957, a pillar in the same area burst again, filling the manway with rock for a distance of 70 m. The entry had caved previously, and the cave had been used as fill and graded over, so the event was actually rock burst rather than a coal failure (Fig. 5). The tremor was felt at the Sunnyside Town site and was

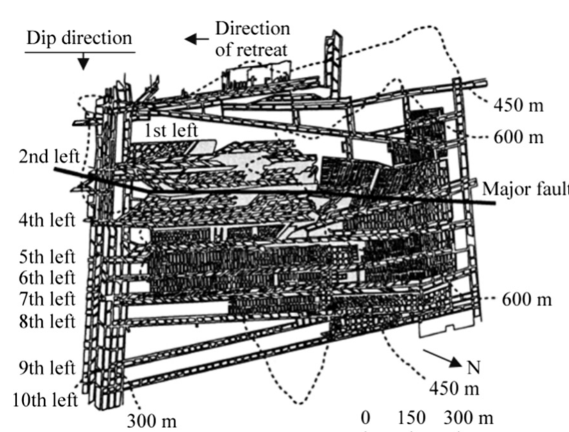

Fig. 4. A portion of the Sunnyside Mine that was mined in the 1950s, showing the Sunnyside Fault (labeled "Major fault" on the right) [2].

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Fig. 5. 1957 burst site in the main slope at the Sunnyside Mine [7].

picked up by the University of Utah seismograph [3]. Three miners were killed in this burst [5]. Another miner was killed in 1959 when a burst caused a 30-m-long roof fall that covered several pieces of track equipment [6]. In that instance, a fault with 2 m of throw was mapped just 6 m away from the victim's location.

The US Geological Survey measured movements on faults located within the Sunnyside fault zone before and after bursts. In one instance, roof bolts located on opposite sides of several small faults moved an average of 0.82 cm following a violent bump in 1961. Railroad track on the surface was observed to deform in a broad area that crosses the Sunnyside fault zone [7].

In 1976, the same fault that had been associated with the severe bursts in the 1950s was encountered again. This time bumping affected the working faces of the two-entry longwall gate drivage. The frequency and severity of the bursts increased until mining had passed through the fault zone [2].

The burst database shows that 16 events were reported to MSHA during the last decade of the Sunnyside mine operation. Ten of the 16 reported events resulted in injuries, at least two of which occurred during development. One non-injury event was described as follows: "a bounce occurred in 3 of 4 entries that caused considerable damage to the roadway beltline and track. A cave resulted from this, causing floor and rib damage for about 130 m in 3 entries."

3. Deer Creek Mine, Utah

The Deer Creek Mine was located in the Wasatch Plateau region of the Utah coalfields. Together with its sister Cottonwood Mine, Deer Creek extracted coal from two seams primarily using longwall mining with two-entry yielding pillar systems. During a 25-year period, the database shows that 7 burst injuries were reported to MSHA, all of which occurred on the longwall face.

In January of 1991, however, an extremely unusual event occurred. Miners developing a set of main entries felt a sudden blast of air and the conveyor belt stopped. They walked 240 m outby to investigate and found that a large coal burst had occurred. Two coal pillars had blown out and an overcast had collapsed (Fig. 6). The report on the event noted that the depth of cover was approximately 480 m, the overburden consisted predominantly of massive sandstone, and there was a major fault located approximately 60 m from the outburst area. No retreat mining or multiple seam interactions were located anywhere near the burst [8].

4. Bowie Mine, Colorado

The Bowie Mine is located in the North Fork Valley (NFV) of the Gunnison River, in west-central Colorado. The area is characterized by extremely mountainous topography, and the maximum depth of cover exceeds 600 m. Past mining also gives rise to multiple seam interactions in some areas.

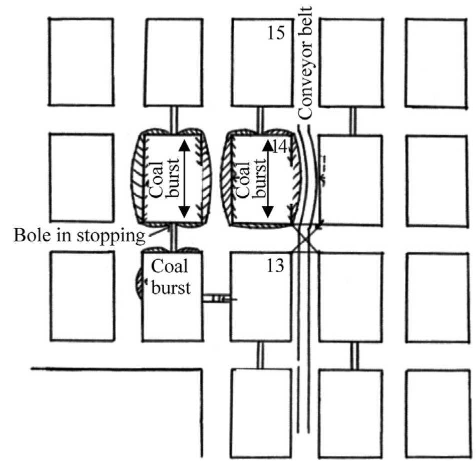

Fig. 6. Burst pillars along the belt line, 240 m outby the development faces at the Deer Creek Mine [8].

The geology of the NFV differs from most burst prone mining districts in that the immediate roof of the most common mining horizons is weak to moderate strength. At Bowie, the roof is usually composed of interbedded siltstone, fossiliferous shale, and thin layers of sandstone. Coal mine roof rating (CMRR) values typically range between 40 and 60, with typical UCS values of 50–80 MPa [9,10]. The immediate floor usually contains a considerable thickness of coal. Massive sandstone units, with strengths exceeding 100 MPa, are typically at least 15–30 m above or beneath the seams [11]. Faulting and joint zones are present throughout the coalfield, and active tectonism continues to occur in the region today [12].

In late 2007, a series of three bursts occurred at Bowie while developing a five entry mains in the B seam. In this area, the overburden was approximately 530 m, and the base of the 30 m thick C Sandstone was 27 m above the B seam. The development was crossing beneath a D Seam mains located 100 m above when the first event occurred, causing 1 m of rib failure and 1 m of floor heave around three pillars. It also caused an air blast and damaged ventilation stoppings for 7 breaks outby the face and registered $M = 2.1$ on the local seismic monitoring system.

In response to this first event, the mine ramped up to leave more coal in the floor and rock in the pillar for reinforcement. A second event occurred that required significant cleanup though it only measured just $M = 1.1$. The third event was the largest of the three, registering $M = 2.9$. It reactivated the earlier floor heave and also caused extensive new floor heave, as much as 1.5 m in some places. The development headings were abandoned at this point.

All of these events occurred beneath developed D-seam pillars which, if they had any effect at all, should have reduced the vertical stress and transferred it to the solid coal on either side (Fig. 7). All the events also occurred well outby the B seam development faces and were not triggered directly by coal cutting activities. It seems likely that the most significant factor was the presence of a zone of steeply dipping northwest trending joints, interpreted as remnants of a fault zone that had been mined through without difficulty in the D seam [13]. Another hypothesis is that the D seam pillars might have themselves failed, providing a dynamic trigger to the events encountered in the B Seam [12].

The next event occurred one year later, in 2008, just to the southeast of the previous events. The location was a longwall headgate, outby the longwall face, and involved sudden floor heave that injured five miners. The $M = 2.5$ event did occur above the boundary between those same abandoned D Seam mains and a barrier

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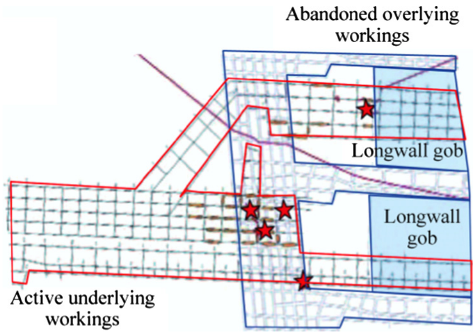

Fig. 7. Location of four development bursts and one headgate burst at the Bowie Mine.

pillar, but about 100 m inby the longwall face had passed beneath a D Seam longwall stop line without incident. The fault zone associated with the earlier events, which was here expressed as a highly jointed zone, extended directly through the area where the greatest damage occurred [13].

The fifth event occurred in late 2008 approximately 600 m to the northeast of the first three. It was centered directly beneath a D seam longwall stop line and within a major northeast trending fault zone. The $M = 2.3$ event took place seven months after the area was developed and was not subject to any B seam retreat mining stress abutments. Some limited de-stress floor blasting had even been conducted to reduce the burst hazard [14].

Two further events occurred in mid-2010 about 1200 m to the west of the first five. Room-and-pillar mining, without pillar recovery but including benching the floor, was being conducted under approximately 480 m of cover. The pillars were substantially larger than in the nearby workings in an attempt to inhibit floor heave. Although the area was bounded by two parallel faults, no faults or joint zones were observed in the immediate vicinity. The second of these two events was $M = 2.9$, and it caused significant amounts of coal to be ejected from the ribs of four pillars in an idle and outby area. The event also damaged ventilation controls over a large area. After this event, further mining in this part of the reserve was abandoned.

5. Other North Fork Valley mines, Colorado

5.1. Elk Creek Mine

The Elk Creek Mine was located approximately 10 km northeast of Bowie. Late in 2009, the mine began longwalling in a new district, at depths that consistently exceeded 600 m. The first major coal burst occurred midway through the second panel, causing extensive pillar failure and floor heave over a large area in the tailgate. The $M = 3.1$ burst was centered at least 150 m outby the tailgate corner, so it is unlikely that front abutment stresses were a significant contributing factor. The burst did occur within the projection of the densely jointed and slicken sided zone that extended across the mine reserve, one of a series exhibiting an approximate N 70° E trend.

Another joint zone, trending the same direction, was associated with a development burst that resulted in an injury. The miner's injuries were so severe that a plate was surgically inserted in his back because of his broken bones. The burst occurred during development of the headgate for the third panel in the longwall district. A year later, during longwall mining, a second burst occurred on another headgate pillar just inby this area.

A final $M = 2.9$ burst occurred inby the headgate corner of the next panel, filling 300 m of two entries with bumped coal to within 1 m of the roof. Shortly afterwards the mine was abandoned.

5.2. Sanborne Creek Mine

Sanborne Creek was located just east of the Elk Creek Mine. Initially opened as a room and pillar mine, pillar recovery operations suffered from numerous coal bursts [13]. Largely because of the difficulties encountered during pillar recovery, in the late 1990s, Sanborne Creek shifted to the longwall method of production.

Six large bumps were reported at depths in excess of 450 m between 1996 and the mine closure in 2003. Three of these took place during development, one in a bleeder, and two in a headgate. None occurred in the tailgate or on the longwall face. Several of the bursts were associated with a low-angle fault zone, defined by strongly parallel coal cleat, joints with water inflow, and low-angle bedding plane faults that strike N 70° E.

5.3. Mine Y

Mine Y is located just south of the Elk Creek Mine. When it initially entered an area where the depth reached 750 m, the mine encountered a series of water and methane inflows from fault-fracture systems. The most severe of these inundated the section with 500 l/s of geothermal water (approximately 83 degrees F). Studies showed that faults extended into the Rollins sandstone located 15 m beneath the mining horizon [15].

Several major bursts were reported at Mine Y over the next few years, all of them in or near mapped faults or prominent, discrete (generally less than 3 m wide) joint zones. At least one was shown to be an extension of a scissors fault identified previously by the mine geologist. Not all such features were associated with bursts, however. The bursts all occurred in association with longwall mining, but none occurred along the face or at the tailgate corner.

6. Mid Continent mines, Colorado

Mid-Continent Resources operated several small metallurgical coal mines near Redstone, CO, between 1956 and 1991. In 1969, two continuous miner operators were killed in separate burst incidents while advancing main entries at the Dutch Creek No. 1 Mine. Two more miners were killed at the L. S. Wood Mine in 1975, and that mine experienced nine bursts during development of the Main Slope section between July 1980 and April 1982. All these events were associated with overburden greater than 600 m, and five occurred under more than 750 m of overburden far from the gob. These bursts are included in the USBM burst database and were discussed by Iannacchione and Zelanko [1].

These bursts are unique in US experience in that each event was accompanied by a major inrush of methane. The miners at the time called them "pushes", and contrasted them with the "bumps" or stress bursts, which in their experience occurred during pillar recovery. "Pushes" were not as violent as stress bursts; the development face simply pushed out 10–20 m horizontally releasing immense quantities of fine coal and gas. A push was accompanied by a series of loud, staccato "booms", which lasted three to five seconds [16].

While it seems that these events should properly be called gas outbursts, the Mid-Continent operations did also have traditional coal bursts (though they were seldom reported to MSHA). A 1969 report on one fatal outburst noted that "it is not unusual for bumps to occur during continuous mining operations, particularly when mining in the vicinity of faults" [17].

7. Manalapan No. 17 mine, Kentucky

Manalapan No. 17 is located in Harlan County, Kentucky, in the Central Appalachian coal mining region. Bumps have been frequent

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events in Harlan County for decades. Rice notes that "eight men were killed and a number injured by bumps in the first 4 months of 1934" [18]. Harlan County is very mountainous, containing the highest mountain in the state of Kentucky, and Rice noted that bursts rarely occurred when the depth of cover was less than 300 m. While Harlan County remains the most burst-prone area in the eastern US, bursts have only been reported at eight mines there since 1983, out of more than 250 room-and-pillar mines that were active in the county [19].

Nearly all Central Appalachian coal bursts have occurred during or in close proximity to pillar recovery, or at a least multiple seam interactions involving pillar recovery. For example, USBM describes a burst that occurred at an International Harvester Mine in Harlan County [20]. The burst occurred when the development workings crossed over an island remnant barrier pillar located between gob areas the underlying coal seam 23 m below (Fig. 8).

The series incidents at the Manalapan No. 17 Mine appears to have been an exception, in that the two largest events were not associated with pillar recovery either in the active seam or the underlying abandoned one. Manalapan No. 17 was extracting the Kellioka Seam, which was located 50 m above workings in the Harlan seam [21,22]. The first two events, in 1999 and 2001, occurred in five entry developments on 24 m × 24 m pillar centers. The depth of cover at both locations was about 510 m.

Newman examined the 2001 burst area and observed that the bump impacted six pillars, with the greatest damage centered in the belt entry, two breaks outby the active face. Roughly 3–4 m of the pillar ribs on either side of the belt entry failed, and, the belt entry two breaks outby the face was filled with fine coal in the center of the entry. The coal in the remaining portion of the pillar was separated from the roof creating a void space, approximately 3 m deep into the pillar. The height of the void space was roughly 0.3–0.5 m at the edge of the remaining portion of the pillar, grading back to contact with the roof. Although no roof falls were visible, wide spans in excess of 12 m resulted from the void space that formed between the top of the bumped pillars and the immediate roof [21].

No unusual geologic features were noted in the vicinity of the burst. Fig. 9 shows the conditions after the burst.

Both burst events were underlain by first workings in the Harlan seam (Fig. 10). An ARMPS version 6 evaluation of the Harlan Seam pillars showed that the stability factor (SF) of the Harlan seam pillars exceeded 2.0, which would normally suggest a stable pillar system. Nonetheless, investigators at the time of the events inferred that the Harlan Seam pillar systems created a pseudo gob that transferred stress onto the adjacent barriers [23]. Even more surprisingly, other Manalapan workings were underlain by

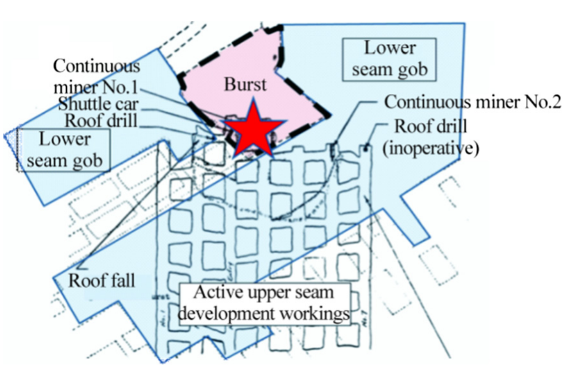

Fig. 8. Development burst in upper seam workings above an island lower seam barrier pillar (outlined with thick dashed line) in a Harlan County, KY mine (after USBM, 1970).

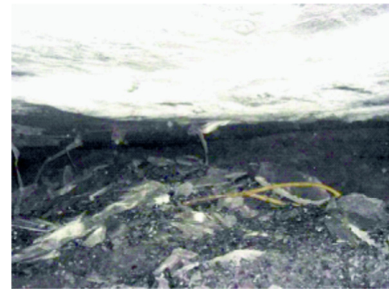

Fig. 9. Conditions after the burst in the Manalapan No. 17 Mine.

Fig. 10. Locations of burst events in the Manalapan No. 17 Mine (black) relative to underlying Harlan seam workings (magenta and green).

full extraction in the Harlan seam (see areas noted as "Harlan Gob" in Fig. 10), yet no bursts had occurred when mining above them.

After the 2001 event, no further mining was allowed in areas where the depth exceeded 460 m and where underlying barriers were present. The subsequent development burst in 2002, which occurred at a traditional gob-solid crossing at 425 m depth of cover, led to further mining restrictions for depths greater than 300 m. Yet another coal outburst occurred during development mining in 2006, which knocked an employee into a roof bolting machine.

It is worth noting that the Kellioka seam is heavily mined in Harlan and adjacent counties, often at depths greater than 450 m. Severe multiple seam interactions are routinely encountered, yet these are the only bursts known to have occurred during development mining.

8. Rivers Edge Mine, West Virginia

Rivers Edge was located in Boone County, West Virginia, in the Central Appalachian coal mining region. Boone County has produced more than 700 million tons of coal, most of it by underground methods, yet only a handful of bursts have ever been reported [24]. One part of the explanation is that the depth of cover rarely exceeds 360 m.

Rivers Edge was extracting the Powellton seam. In 2006, while advancing an eight entry main, a burst occurred in a pillar located two crosscuts outby the faces. At the bumped pillar, Gauna and Phillipson observed the following: …a deep cavity of indeterminate depth above the bumped pillar where coal had been blown into the entry. Mounds of coal were deposited in a wavy, undulating expanse that almost filled the entry. The exposed sandstone

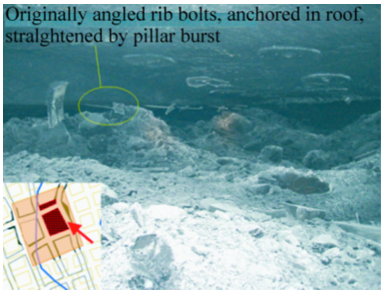

Fig. 11. Conditions in the entry adjacent to the pillar that burst at the Rivers Edge mine [25].

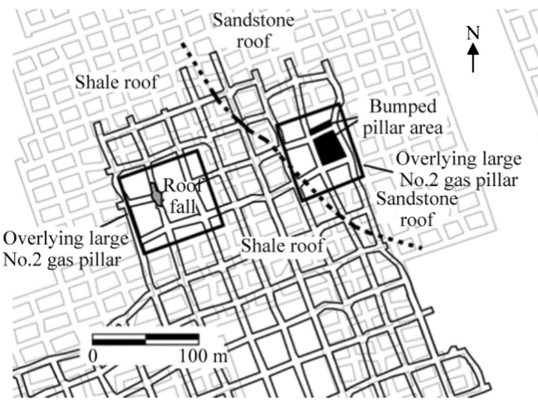

Fig. 12. Powellton seam burst region.

roof above the former location of the pillar was characterized by a rusty red, powdered coloration. Installed pillar rib bolts, angled upward and anchored into the roof, had been bent parallel to the roof horizon by the force of the bump. The roof horizon remained undisturbed and unbroken above the bumped pillar (Fig. 11) [25].

The Powellton seam burst region (Fig. 12) was situated approximately 18 m beneath a large pillar, 73 m × 69 m, which had been left in the overlying No. 2 Gas Seam. The large pillar in the No. 2 Gas Seam was surrounded by much smaller pillars, measuring 12 m × 15 m. The No. 2 Gas Seam small pillars immediately surrounding the remnant barriers had an ARMPS SF over 1.9. SF of these magnitudes normally suggests a relatively stable pillar system. However, it was believed that long-term flooding in the No. 2 Gas seam in a region above the active mining may have softened the overlying pillar system and degraded the load-bearing capacity of the smaller pillars, creating a "pseudo gob" [23]. It was also noted that above the burst pillar, the roof had transitioned to a sandstone channel.

It may seem simple in retrospect to identify the sandstone channel and the pseudo gob as factors contributing to the burst risk. However, it must be noted that millions of tons have been mined on retreat in Boone County, often with sandstone roof and multiple seam interactions, yet there have been almost no bursts. That one of these extremely rare events was a burst that occurred well behind the mining face, on development, seems extraordinarily unlikely.

9. Crandall Canyon Mine rescue

The Crandall Canyon Mine Disaster was the largest pillar failure to occur in the United States in at least a century. The main pillar failure, which occurred on August 6, 2007, has been thoroughly documented and widely discussed [26]. It affected essentially all

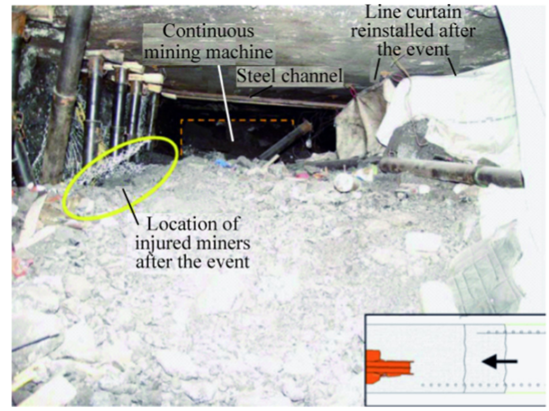

Fig. 13. Entry No. 1 filled with broken coal at the Crandall Mine after the burst on August 16, 2007 [26].

the pillars in an area approximately 1000 m long by 300 m wide. The second, smaller burst, which occurred during the rescue operations, has not received as much attention. However, it (and the other bursts that occurred during the rescue) has potentially significant implications for our understanding of the mechanics of coal pillars and coal bursts.

The main pillar failure filled or partially obstructed all approaches to the trapped miners with burst coal for a distance of 700 m. Therefore, the rescue efforts took the form of "development mining". Initial efforts in the No. 4 entry had progressed only 100 m when a burst refilled much of the path that had been cleared. Fortunately, no rescuers were present at the time. The seismic system recorded the approximately $M = 1.5$ event.

Rescue efforts recommenced in the No. 1 entry. It was completely filled with burst coal and had the appearance of a previously unmined face. The barrier side rib was observed to have shifted horizontally up to 3 m into the entry. At least eleven bursts occurred during the cleanup, but, before August 16, they were either at the continuous mining machine inby the miners, or they were contained by the standing support.

The rescue efforts were interrupted on the morning of August 16 when a burst occurred in the coal pillar between the No. 1 and No. 2 entries. The burst, which registered as a $M = 1.5$ seismic event, displaced approximately 1.2 m of the pillar rib, filling the entry on the right side of the continuous mining machine to a depth of approximately 0.8 m.

The burst that terminated the rescue operation occurred that same evening. Coal was thrown violently across the No. 1 entry during the magnitude 1.9 seismic event. The burst created a void up to 6 m deep into the right side pillar at the roof line. The dislodged coal threw posts, steel cables, chain-link fence, and a steel channel toward the left side of the entry, striking the rescue workers and filling the entry with approximately 1.2 m of debris (see Fig. 13). Three rescuers were killed and six more were severely injured.

Prior to this event, the assumption had been that a "failed" pillar could not burst. The August 16 accident confirmed that substantial potential energy remained in these "failed" pillars.

10. Conclusions

Development bursts provide an unusual perspective on the coal burst phenomenon. While a high level of stress is the one common characteristic of all coal bursts, development bursts by definition occur at lower stress levels then those encountered during retreat mining. In other words, if only the most highly stressed locations in a mine were liable to burst, then nearly all that mine's retreat faces would burst before any of its development faces did.

Some of the development bursts described here also call into question the conventional wisdom regarding geology. The clearest examples are the bursts in the NFV of Colorado. There, the seams are sandwiched between at least 15 m of relatively weak roof and floor, yet the NFV has seen some of the most powerful bursts ever encountered in the US. Most of the largest bursts have been associated with relatively large seismic events, likely providing an important clue to their origins.

In fact, the frequency with which the presence of faults has been noted in conjunction with development bursts is striking. It is also surely significant that most fault-related bursts appear to have occurred in the seismically active western US rather than the seismically quiescent east. It seems likely that more faults in the west are critically stressed, and thus vulnerable to even very small mining-induced stress changes that may be triggered by development mining.

The conjunction between faults and development bursts may also say something about the role of seismicity in general. Overburden failure is an obvious potential source of seismic energy for retreat mining bursts, but it is not available during development. The fact that so many development bursts appear to require an alternative source of seismic energy may imply that seismic shocks are more central to the coal burst phenomenon than is usually thought.

Development bursts in the Central Appalachian coalfields typically seem to have been associated with multiple seam interactions rather than faults. It is worth noting that at least one study found that multiple seam interactions can be a source of seismic energy release [27].

Development bursts also call into question the concept of a "pillar burst". Certainly most development bursts involve pillars, but usually it is only a rib or portion of a rib that is affected. This is true even when several pillars are affected by a single event. The events during the Crandall Canyon rescue showed that even pillars that appear to have been destroyed by bursts can burst again. We already know that longwall bursts simply involve a certain volume of coal in the longwall face and do not imply anything about the structural integrity of the rest of the panel. It seems likely that most pillar bursts are the same.

The database also shows that most development bursts are relatively small events. Many would not have been reported if an unlucky miner had not been standing in the wrong place at the wrong time. In fact, the distribution of coal burst magnitudes may be similar to that of natural earthquakes, as described by the Gutenberg-Richter relationship: "in any particular region, the logarithm of the number of earthquakes, greater than any magnitude, is proportional to magnitude" [28]. In other words, for every one hundred $M = 1$ earthquakes, one may expect ten $M = 2$ events, and one $M = 3$ event. For mining, where bursts seem to occur in distinct, regional clusters, the most significant implication of this rule can be stated as follows: "Whenever a larger-than-usual event occurs, an even larger event should be considered possible" [29]. This underlines the need to pay close attention to the "precursor" events that have often preceded large, destructive bursts [30].

Finally, however, we are left with a number of questions without satisfactory answers:

(1) Coal mines have developed across many faults in Utah and elsewhere. What was so unique about the Sunnyside fault that it contributed to so many powerful bursts over so many years, many in the same place, and well outby any active mining?
(2) Similarly, what caused the sole significant reported outby burst at the Deer Creek Mine?
(3) In the NFV, why are so many bursts associated with large magnitude seismic events? Why is the area so burst prone when the coal seams are encased in relatively soft rock?
(4) Why were the events at the Manalapan No. 17 Mine so destructive when other nearby operations successfully conducted retreat mining with much more severe multiple seam interactions? Why would several bursts have occurred above the same development workings?
(5) If a burst was going to occur in Boone County, WV, why would it be several breaks behind a development face when there is so much retreat mining under multiple seam conditions?

It might be sometime before there are satisfactory answers to such questions.

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