International Experience with Airblasts and its Relevance to Underground Stone Mines

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ABSTRACT
Recent pillar collapses have caused five large airblasts in underground U.S. limestone mines. One of these events injured three miners, but all of them put many other miners at risk. To better understand the hazards, Mine Safety and Health Administration (MSHA) conducted a comprehensive review of the international literature on airblasts. More than 40 airblast cases have been documented, in a wide variety of minerals. Experience shows that miners that are in the direct path of the air as it moves towards the mine exits are at the greatest risk. The paper describes a risk management methodology that can be used to evaluate the level of hazard throughout the mine and aid in the selection of controls to reduce the risk. The paper concludes with a detailed case history of an actual pillar collapse and airblast.

INTRODUCTION

On April 29, 2015, three limestone miners were waiting in front of the portal for their shift to start. Suddenly they were engulfed in a powerful airblast caused by the collapse of 35 pillars underground (Esterhuizen et al., 2019). The outrushing air severely injured all three miners, two of whom had to be life-flighted to a nearby hospital.

Five years later, a crew of miners at a Tennessee limestone operation heard a series of crashing sounds that emanated from an abandoned area containing more than 40 benched pillars. They evacuated the mine and were waiting outside the mine office when they felt the ground shake. Within seconds they watched as enormous clouds of dust, driven by hurricane force winds, rolled out of the nearby portals (Figure 1). Less dramatic airblasts were also associated with three pillar collapses at two other Pennsylvania limestone mines in 2020 and 2021 (Rumbaugh et al., 2022).

Airblast has been a hazard in underground mining for nearly two centuries (McPherson 1980). During the past 50 years, airblasts have been documented in at least 40 mines around the world (see Table 1), and undoubtedly many others were not described in the literature. Airblasts have occurred in a variety of minerals, although coal seems to be the most common.

Each of the airblasts described above were caused by the collapse of an entire array of pillars. In other mines, airblasts have been caused by large caving events during longwall mining, pillar recovery, block caving, or similar types of operations.

AIRBLASTS IN UNDERGROUND STONE MINES

Before 2015 pillar collapses were highly unusual events in stone mines. Esterhuizen et al. (2011) did not find even one example of a area-wide pillar failure in their studies of historic pillar performance at 34 limestone mines. They did identify two pillar collapses in abandoned mines, but neither was well documented. They also observed a handful of individual pillars that had failed without triggering area-wide collapses.

Phillipson (2013) described a pillar collapse and airblast that occurred at a marble quarry in Georgia. At this mine, employees on the surface felt vibrations that they thought were from a shot being fired underground. Later they found that a portable toilet inside the mine and a tag-in board outside the portal had been knocked over by an apparent airblast. Further investigation revealed that 19 pillars had had collapsed in a benched area that had been abandoned in the early 1990s (Figure 2). There were no injuries, and damage to underground infrastructure was minimal.

Two major pillar failures have been documented in mines extracting lead-zinc ore hosted in dolomite. The failure at the Magmont Mine began with the failure of four centrally located pillars and spread over six months to include approximately 25 pillars, before culminating in the sudden collapse ninety pillars over an area of approximately 400 feet by 600 feet (Dismuke et al. 1994). The final failure caused a significant airblast but caused no injuries. A 1972 failure at the Bautsch Mine, near Galena, IL, apparently progressed over several months, punctuated by larger incidents (Touseull and Rich 1980). Airblast is not mentioned. At this mine, the irregularly shaped pillars were 93 feet high and 32 feet wide, with unsupported spans exceeding 75 feet

PILLAR COLLAPSES IN OTHER NON-COAL MINE*S*

One of the most extensive pillar collapses in the history of mining was in 1995 at the Solvay Chemicals trona mine (Swanson and Boler 1996; Goodspeed and Skinner 1995). The collapse generated a magnitude 5.3 seismic event and involved an area measuring 0.75 square miles. The associated airblast blew out approximately 200 stoppings and reversed the air flow in the intake shaft for 17 minutes. Dense clouds of dust and high concentrations of gases were liberated.

Fifty-five miners were underground at Solvay Chemicals at the time of the event. Most of them apparently reported the same observations: they felt the ground roll (with mostly vertical motion), then a moment later they heard the noise and felt the airblast. Five miners working in the 1S–13W Panel directly adjacent to the collapse (Figure 3) experienced "severe upward and downward movements as the floor heaved violently and rib and roof material fell on top of and around them." Accounts of the event do not indicate that any injuries were directly associated with the airblast, though one miner who was trapped underground for nearly two days succumbed to ammonia and carbon dioxide poisoning.

A second major pillar collapse occurred just five years later at the same Solvay Chemicals mine (MSHA 2000; Board et al. 2007). The pillar collapse encompassed an area approximately 1,800 feet by up to 5,200 feet and generated a magnitude 4.3 seismic event. One miner was injured when he was "showered with rocks." This area of the mine was a "Controlled Closure" experimental area, designed to allow the roof to subside in a controlled manner to eliminate the potential of massive pillar collapse.

Zipf and Mark (1996) list four other historical incidents of pillar collapses in U.S. non-coal mines. The damage from the airblast in each instance was either minor or unknown.

More recently, a massive pillar collapse occurred at the Mosaic Potash Carlsbad Mine in Eddy County, New Mexico. The collapse measured approximately 1,700 feet by 3,000 feet and generated an airblast that knocked three miners off their feet in an adjacent section. The event registered 2.4 on nearby seismic systems. Another event, at the Troy Mine in Montana, began with the failure of about 12 pillars in a 750- by 750-foot area. It eventually spread until it caused the entire mine to be abandoned. Fortunately no miners were injured.

AIRBLASTS ASSOCIATED WITH PILLAR COLLAPSE IN COAL MINES

The Crandall Canyon Mine disaster was the largest coal pillar collapse in recent times. It involved hundreds of pillars over an area of approximately 2,500 by 1,000 feet, and it generated a magnitude 3.9 seismic event. The resulting airblast destroyed or damaged stoppings for an additional 1,500 feet. Several miners were travelling in the mine at the time of the pillar collapse and they experienced the airblast differently, depending on their proximity to its source (Gates et al. 2008). The two miners nearest the pillar collapse area were driving separate trucks, and the force of the airblast slid one truck sideways and pelted the other with dust and pieces of foam sealant from destroyed ventilation controls. A mile outby another miner felt a large gust of air that peppered him with small rocks and injured his eardrum. Another mile outby two miners were working just inside the portals, and they did not notice anything.

The largest coal mine pillar collapse in history occurred at the Coalbrook Mine in South Africa in 1960. An area greater than 1.2 square miles collapsed, trapping 438 miners whose bodies were never recovered. Other miners who were working in the vicinity of the pillar collapse "became aware of increasing thunder-like noises from Section 10 and increasing methane emissions. They withdrew but before they could reach a safe place, were overtaken by a hurricane of dust laden air accompanied by crashing like thunder. The gale swept through the mine for 10 minutes with great force and then at diminished force for a further 45 minutes. Men were blown over, and a general exodus from the mine ensued" (van der Merwe 2006). Seismic records show that the pillar collapse occurred over a period of 5 minutes.

Numerous other pillar collapses have occurred in South African coal mines, including at least 23 since Coalbrook (van der Merwe 2006). Despite an extensive literature on the pillar design aspects of those incidents, there is very little mention of the airblast hazard. However, van der Merwe (2006) notes that the average age of the post-Coalbrook collapsed pillars was 21 years, which implies that most of these failures occurred in long-abandoned areas.

Mark et al. (1997) describe 13 pillar collapse cases that occurred in the U.S. during the 1980s and 1990s. All happened suddenly and without significant warning, and most resulted in airblasts that damaged the ventilation systems. Figure 4 shows the map of a typical failure involving pillars that had been split on retreat. Other failures occurred in areas where floor coal had been mined on retreat, or where pillars were developed on very small centers. The effects of some of airblasts generated by these events are detailed below:

- Three weeks after second mining was completed in a panel, an area measuring approximately 450 by 500 feet and containing 107 fenders (remnant split pillars) collapsed. The airblast knocked miners to the floor on a nearby section. One miner was bounced off a steel rail and required 26 stitches to his head.
- An airblast resulted from the collapse of fenders in a panel that was being retreated. A roof bolter operator said that he and his coworkers were knocked to the floor, and 103 stoppings were destroyed.
- When 94 pillars that had been developed on small-centers collapsed, the airblast blew out 37 stoppings as far away as 800 feet from the collapse area. The airblast threw 30-lb cinder blocks 500 feet. Fortunately, the pillar collapse occurred on an idle shift and no one was in the mine.
- At a mine in Utah, floor was being recovered in a thick coal seam, resulting in remnant pillars that were 40 feet wide by 18 feet high. A worked-out area measuring 500 by 1,600 feet collapsed while the section was being actively mined. The force of the airblast hurled three miners for distances of 40–100 feet, causing one severe head laceration. The airblast also blew a two-ton shop car through a permanent stopping, caused extensive damage to ventilation controls, and scattered concrete blocks from for distances up to 100 feet. It also stalled the main mine fan and temporarily reversed the airflow in the mine.

Galvin (1996) presented a database of 13 Australian coal mine pillar failure case histories. At least four occurred suddenly and caused "major windblasts." Sharma and Fowler (2004) mention the "violent" pillar failure at the Muswellbrook No. 2 Colliery that resulted "one of the most severe windblasts in underground coal mines." No fatalities occurred in any of these events.

AIRBLASTS ASSOCIATED WITH CAVING

The Northparkes block caving operation in New South Wales (NSW), Australia, suffered four fatalities in 1999 when an enormous plug of ore and overburden caved at once (see Figure 5). At the time of the collapse, the caveback (the crown) extended from the surface down approximately 650 feet. Below the crown the maximum air gap height was around 500 feet, and the caved ore column (muck pile) height varied from 270 to 500 feet above the extraction level (Ross and As 2005). When the crown caved all at once, approximately 13 million tons of material collapsed into the air gap and rapidly displaced 4 million cubic yards of air.

The destruction and damage caused by the massive air-blast was confined to the direct flow path of the air (Ross and As 2005). Extensive damage was caused to decline services, ground support, ventilation barricades, light vehicles, and hoisting shaft cabling. The most severe damage occurred in the 1 Level heading that directly accessed the air gap below the crown. The collapse propelled such a powerful airblast through 1 Level that a large pump weighing 5 tons was transported over 600 feet and rotated through 180 degrees from its original position. The airblast killed all four miners that were in this heading.

The airblast did not appear to affect areas outside its direct flow path, even immediately adjacent areas. On 1 Level empty plastic bottles and 5-gallon fluid containers were completely undisturbed in a crosscut only 160 feet from the main entry point of the blast. Both the undercut and extraction levels were undamaged, and 57 miners were safely evacuated later in the day (Ross and As, 2005).

Two other airblasts in block caving operations in Chile and the Philippines are discussed by Fowler and Hebblewhite (2003). The same authors also describe crown pillar failure at the Epoch Mine in Zimbabwe that resulted in a major airblast.

Violent caving events have also disrupted several Australian longwall coal mines, particularly ones located in the Newcastle coalfield of NSW. The roof there often consists of massive 100-feet thick conglomerate directly above the coal seam. In addition, the two-entry longwall gate systems employed at Australian mines limit the number of flow paths that are available to an airblast. During the late 1990s, the Moonee Colliery suffered a series of airblasts which caused numerous injuries and resulted in the mine's temporary closure. Moonee only reopened when hydraulic fracturing proved capable of delivering "caving on demand" (Hayes, 2000).

Fowler and Hebblewhite (2003) also list five NSW mines, some longwalls and some room and pillar, where "skeletal injuries [caused by airblasts] have included broken necks, ribs, arms and legs, and severe facial trauma, while internal injuries have resulted in the surgical removal of a lung and spleen." It is not clear whether all of these were due to goaf falls, or whether some may have resulted from pillar collapses. In South Africa, eight miners were injured over one four-year period by airblasts associated with roof caving behind the longwall at the New Denmark colliery (Makusha and Minney, 2005).

The U.S. has limited published experience with airblasts on longwall faces. At the Kopperston Mine in 1989, the longwall had advanced 180 feet from the set-up room without a cave when approximately half of the 500-feet-wide face fell at once. One worker was killed and four suffered minor injuries (Bowman 1989). More recently, one miner was propelled 80 feet and very severely injured by an airblast caused by an initial caving event at the Bull Mountain longwall mine in Montana (Federal Mine Safety and Health Review Commission, 2015).

Chinese experience with airblasts in gob areas of room and pillar mines was described by Song and Xu (1992). The most severe problems occurred in the Datong coalfields where the roof is a thick conglomerate, like that in the Newcastle coalfields of NSW. In the four examples described, the sudden caving involved areas ranging from 70 to 400 thousand square feet. Two of the events resulted in fatalities (including one devastating airblast that resulted in 14 deaths and 19 injuries (McPherson et al. 1995), and all four damaged ventilation and equipment. Song and Xu (19920 state that two mitigation techniques have been employed, one being induced caving and the other "leakage roadways" that allow the impacted air to flow quickly to the surface.

No discussion of the airblast hazard would be complete without mentioning its association with explosions in coal mines. At least six explosions or fires in coal mines have been associated with large caving events, one each at the Endeavor and Moura No. 4 collieries in Australia (Fowler and Hebblewhite, 2003) and two each at the Willow Creek and Buchanan mines in the U.S. (Brune, 2013).

AIRBLAST MECHANICS

The NSW Department of Primary Industries (NSW DPI) (2006) defines an airblast as "a rapid displacement of large quantities of air, often under pressure, in a constrained underground environment caused by a fall of ground or other material. It is often characterized by significant overpressures and air velocities which can result in fatal injuries to persons and cause severe damage to equipment and infrastructure. The extent of the consequences of such an airblast depends on the amount of air that is compressed and the rate of that compression."

Researchers at the University of New South Wales (UNSW) made the most extensive measurements of airblasts underground more than a decade ago (Sharma and Fowler 2004). The measurements were primarily conducted at Moonee Colliery, and they show that a "wind blast" (the Australian coal mining term for airblast) comprises a rapid rise in absolute pressure to a maximum (positive compression phase), followed by a similarly rapid fall to below ambient atmospheric pressure (expansion phase 'suck back'). At around the same time, although not necessarily in phase with the overpressure, the wind velocity also rises rapidly to a maximum and then exhibits a sudden reversal into the 'suck back' phase. Each event usually lasts for a few seconds. Sharma and Fowler (2004) also make the following observations:

- The overpressure pulse in a single heading attenuates with distance as it propagates outby. The attenuation is predominantly related to air viscosity, although other factors, such as flow through crosscuts (spreading) contribute.
- The rate of propagation of the airblast typically equals the speed of sound.
- There appears to be an upper bound to peak overpressure with increasing goaf/fall area.
- Wind blasts with peak wind velocities greater than 45 mph are hazardous because they can result in injuries to mine personnel according to Fowler and Torabi (1997).
- Hurricane level wind speeds have been measured in mine roadways but not exceeding Mach 1 values.
- Empirical scaling laws for wind blasts, based on explosive equivalency, could not be well defined due to the unpredictability and the variability associated with the roof fall, the caving mechanism in the goaf, and the geotechnical properties of the coal measures involved in the caving process.

The measurements also show a clear relationship between larger areas of caving ground and higher overpressures and wind velocities. In addition, NSW DPI (2006) state that "the potential energy, and therefore the magnitude of the consequence of an airblast, increases proportionally with the height of the void."

The Saffir-Simpson Hurricane Wind Scale may be helpful in evaluating the potential consequences of an airblast, though it was primarily developed to estimate property damage. While even a Category 1 hurricane produces life-threatening winds in excess of 74 mph, hurricanes rated Category 3 and higher are known as major hurricanes. Major hurricanes, with wind speeds above 111 mph can cause devastating to catastrophic wind damage and significant loss of life simply due to the strength of their winds. A Category 5 hurricane is defined as one with winds greater than 157 mph (NOAA 2022).

McPherson (1995) and Lin (1997) developed mathematical predictions of airblast pressures using a "leaky piston" model. Their focus was on the potential temperatures generated by such an event rather than air velocities. Logan and Tyler (2004) developed a wind gust model specifically for the Ridgeway block caving mine. This model predicts air inrush velocities resulting from a massive cave back failure as a function of (1) the expansion void, (2) muck pile thickness, (3) permeability of the broken rock pile, (4) nature of collapse, (5) number of exit paths, and (6) measurement error. The model is very site-specific.

MANAGING THE AIRBLAST RISK

The worldwide experience with airblasts clearly indicates that air velocity is the main hazard. As Logan and Tyler (2004) put it: "High air pressures are converted to wind gusts when they find an escape pathway to areas of lower pressure (e.g., surface). High wind gusts become hazardous when the paths of rapid air flow coincide with working location of people and/or infrastructure."

On the other hand, without wind, the pressure pulse by itself does not appear to pose a significant hazard. Based on their extensive research, Fowler and Hebblewhite (2003) concluded that "amongst the published reports of personal injuries occasioned during wind blasts in coal mines, there are no instances of eardrum rupture.[*] As the threshold of such injuries is usually taken to be a rapid increase in pressure of 5 psi it is considered that wind blast overpressures at the working place are unlikely to have significantly exceeded this value."

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[*] Fowler and Hebblewhite completed their work prior to the 2007 Crandall Canyon disaster, where one miner apparently did suffer a ruptured eardrum as described earlier.

According to the NSW DPI (2006), if there is a potential source for an airblast, then foremost consideration should be given to the pathways of least resistance through the mine that an airblast may follow to vent to the atmosphere. Considerations include:

- the number, location, and size of openings,
- the path of least resistance should an airblast occur,
- any concentrated effect along its pathway,
- access to a void (source of airblast), and
- potential connections to the surface

NSW DPI (2006) continues by saying that the next step is to identify zones where a potential airblast could affect personnel and/or infrastructure. This should include determining the air velocities and secondary effects (debris becoming airborne) in potential pathways the vicinity of persons or infrastructure. Steps can then be taken to minimize the exposure of persons in the highest risk zones.

Strategies suggested by NSW DPI (2006) to reduce the potential airblast velocities in headings where the exposure of personnel cannot be eliminated include:

- Deliberately planned zones of high resistance in airways to help dissipate an airblast's energy. These could include a series of broken rock piles placed in the heading. However, these must be constructed so that loose rock will not become airborne and travel with an airblast through the mine,
- Planning separate pathways of least resistance, where persons would not be located, which would take most of the airblast flow,
- Layouts that incorporate as many entries as are possible on all sides of a potential collapse area to dissipate the velocity/pressure effects of a windblast, and
- Leaving blasted or fallen material in the mined-out area to reduce the height of the void to cushion or dissipate the energy from an airblast, should it occur.

NSW DPI (2006) also recommends that planning for a potential airblast should also address:

- Effects on the surface (a surface exclusion zone could be considered),
- The ingress and egress headings, and the effects on egress from the mine should they be blocked after an airblast has occurred, and
- Effects on ventilation fans and all other infrastructure.

NSW DPI (2006) discusses "safe havens" where personnel could go if an airblast appeared imminent. Experience indicates that if persons go into a nearby dead-end crosscut or heading they would be protected because they would not be in the pathway of the high-velocity air. But a "safe haven," or a mine evacuation strategy for that matter, is only useful if there is sufficient warning. A seismic monitoring system or an array of convergence monitoring stations could conceivably provide sufficient warning, but those approaches are unproven at this time. Without remote monitoring there is often little warning of a pillar collapse, particularly if it occurs in an inaccessible, abandoned area of the mine.

NSW DPI (2007) states that, for coal mines, "The most severe consequence of windblast is a gas and/or coal dust explosion. For such an explosion to develop, fuel and an ignition source are needed, both of which can be provided by a windblast." This concern does not apply to stone operations.

CASE HISTORY

In July of 2021, a massive pillar collapse occurred at a limestone mine in central Pennsylvania. The pillar dimensions and other details of the collapse event are discussed by Rumbaugh et al (2022). There were no eyewitnesses to either the collapse or the airblast because all of the miners that were underground were working in inby areas when the collapse occurred.

Two weeks after the collapse Technical Support conducted an underground investigation to determine the extent and degree of airblast damage underground. We found that the airblast traveled west towards the mine openings, causing the most severe damage along east-west corridors (Figure 6). Severe damage to ventilation curtains was observed around the perimeter of the collapse area. The heaviest damage was observed near area (A), close to the collapse, where a piece of communication equipment weighing over 100 pounds was blown over, and signs posted in the area were found several hundred feet outby.

Moving outby along the travelways, the most severe damage was a toppled chain link fence. However, other sensitive features in this area, including signs and mirrors, did not appear damaged from the airblast. Similarly, older ventilation curtains were blown down while newer curtains appeared to be largely unaffected. The evidence suggests that the force of the blast was largely dissipated by the time it reached (B).

In the portal area (C), ventilation curtains were blown down and a sign was bent. However, other signs, cones, and curtains in the area were undisturbed. This suggests that the primary exit path of the airblast may have been through the ventilation adits (D). The portal area was apparently protected from damage by its distance from the pillar collapse and the availability of multiple openings for the air to exit the mine.

Located north of the portals, three other ventilation adits were serviced by a fan (E). A ventilation curtain installed above the fan was blown down, but there were no other signs of damage in the area.

The detonator and explosive magazines (F) were largely shielded from the airblast by solid pillar. A cone was overturned in this area, but otherwise sensitive signs and equipment appeared undamaged.

Despite numerous signs, cones, and other equipment that might have been damaged, no evidence of the airblast was found in the belt transfer area (G). A large strip barrier pillar apparently provided protection from the impact of the airblast.

Overall, this example conformed to experience with airblasts. The greatest air velocities, and thus the highest risk, were located near the source of the event. As the air moved through an array of pathways towards several different exits, the air velocity evidently reduced. Locations that were protected by pillars, and thus outside the direct air pathway, were hardly affected at all.

IMPLICATIONS FOR UNDERGROUND STONE MINES

The initial energy released by a pillar collapse depends on the volume of rock that collapses, the distance it falls, and how rapidly the event takes place. The areal extents (plan view) of most of the potential collapses in stone mines are not so large, relative to other pillar collapses that have occurred. On the other hand, the potential fall height is greater only in block caving operations. Pillar collapses in stone mines generally happen so rapidly that they generate a large seismic event. It is clear that pillar collapses in stone mines can release very large amounts of energy.

Where does this energy go? Perhaps the most significant finding is that, unless it is associated with high velocity wind, the pressure pulse resulting from an airblast poses relatively little direct hazard. Therefore, miners inby a pillar collapse (working at the faces for example) would likely not be directly affected. (Indirect effects, such as disruption of ventilation, or blockage of egress, are still possible, however.) On the other hand, those miners located in the direct path of the air as it made its way to the portals could be at high risk. The magnitude of the risk seems to be directly related to the velocity of the air.

Explicit, quantitative prediction of those air velocities seems to be an extremely complex undertaking. However, it is possible to estimate the qualitative risk posed by the airblast. The process involves:

- Identifying the likely flow paths of the air leading to the portals,
- Evaluating the number, location, and size of the openings in each flow path, and
- Considering the likely dissipation of energy as the air travels through the mine.

Based on these considerations, it should be possible to identify those locations where personnel would be at highest risk. Risk mitigation can include reducing the potential air velocity or redirecting its flow (using techniques such as barriers, seals, or pressure relief pathways), or removing personnel to safer locations.

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TABLE 1.—Worldwide Airblast Incidents, 1960-Present.

Mineral (number of mines)	Location	Date	Type of Failure	Size of Collapse Area	Effect on Miners	Effect on Mine	Reference
Limestone (5)	PA, TN	2015	Pillar Collapse	500 by 650 feet	2 severe injuries		Rumbaugh et al. 2022
Marble	GA	2011	Pillar Collapse	300*600 feet	none	Minimal	Phillipson 2013
Dolomite (Pb/Zn ore)	MO	1986	Pillar Collapse	90 pillars	none		Dismuke et al. 1994
Dolomite	MO	1972	Pillar Collapse				Touseull and Rich 1980
Trona	WY	1995	Pillar/Floor Collapse	3000*7000	Injuries to miners in adjacent panel	200 stoppings destroyed	McKinney et al. 1995; Swanson and Boler 1996
Trona	WY	2000	Pillar/Floor Collapse	1850*5000			Board et al. 2007
Quartzite (Cu-Ag ore)	MT	2013	Pillar Collapse			Mine is closed	
Potash	NM	2012	Pillar Collapse	1700*3000 feet	3 miners knocked down		
	NSW Australia	1996	Block Cave		4 fatalities	Minimal, except access drifts	Ross and As 2005
Coal	WV	1989	Gob Fall	510*150 feet	1 fatality, 4 injured	Minimal	Bowman 1989
Coal	NSW Australia	1997–2000	Gob Falls (numerous)	60-200 feet * 300 foot longwall face	1 major injury	Minimal?	Hayes 2000

Coal (15)	US—Various	1980–2000	Pillar Collapses	150-700 thousand ft^2	two minor injuries	major to minimal	Mark et al. 1997
Mineral (number of mines)	**Location**	**Date**	**Type of Failure**	**Size of Collapse Area**	**Effect on Miners**	**Effect on Mine**	**Reference**
Coal (4)	Datong China	1960–1975	Pillar Remnant Collapses	220-1250 $*10^3$ ft^2	Two caused fatalities	Major	Jin and Sheng 1992
Non-coal (4)	US—Various	1972–1992	Pillar collapse	110-5400 ft^2	none noted	Minor	Zipf and Mark 1997
coal	NSW Australia	1976	Goaf Fall		1 fatality		Referenced in Sharma and Fowler 2004
coal	NSW Australia		Pillar Collapse				Referenced in Sharma and Fowler 2004
Coal (4)	NSW Australia	various	Pillar Collapse	not given	None noted	"major windblast"	Galvin 1996
Coal	South Africa	2000–2004	Goaf Fall	130 feet longwall face advance	8 injuries in separate events	minor	Makusha and Minney 2005
Coal	South Africa	1960	Pillar collapse	0.75 mile^2	438 killed by pillar collapse, no injuries reported	Stoppings damaged by small precursors	Van der Merwe 2006
Coal (5)	NSW Australia	1983–1999	Goaf falls (?)		All with serious injures		Fowler and Hebblewhite 2003

FIGURE 1 Airblast exiting an underground limestone mine in Tennessee.

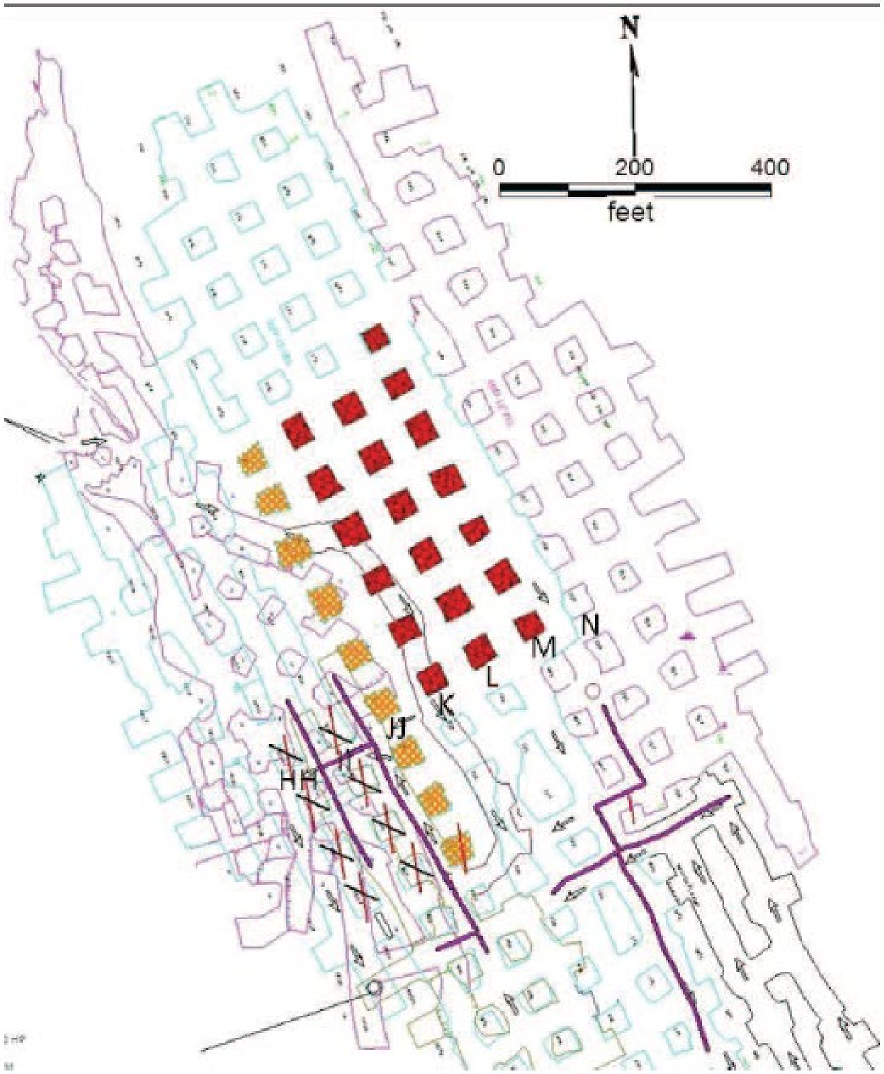

FIGURE 2 Map of the collapse area at the Georgia marble quarry (Phillipson 2013). The red pillars apparently failed, and the orange ones were taking weight.

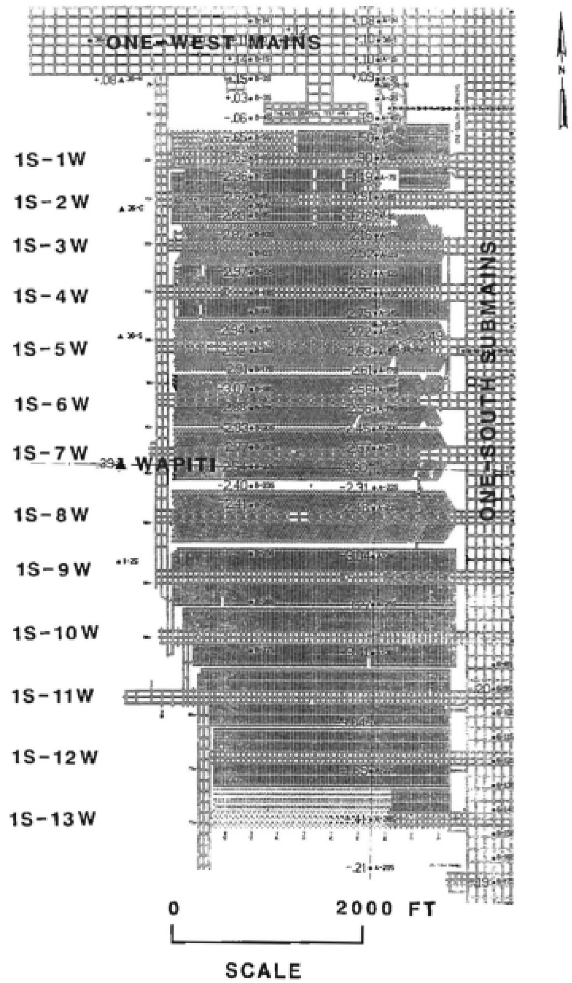

FIGURE 3 Map of the Solvay mine collapse area (Swanson and Boler 1996). The 1S panels from 1W to 12W all collapsed. The crew was in the faces of 13W.

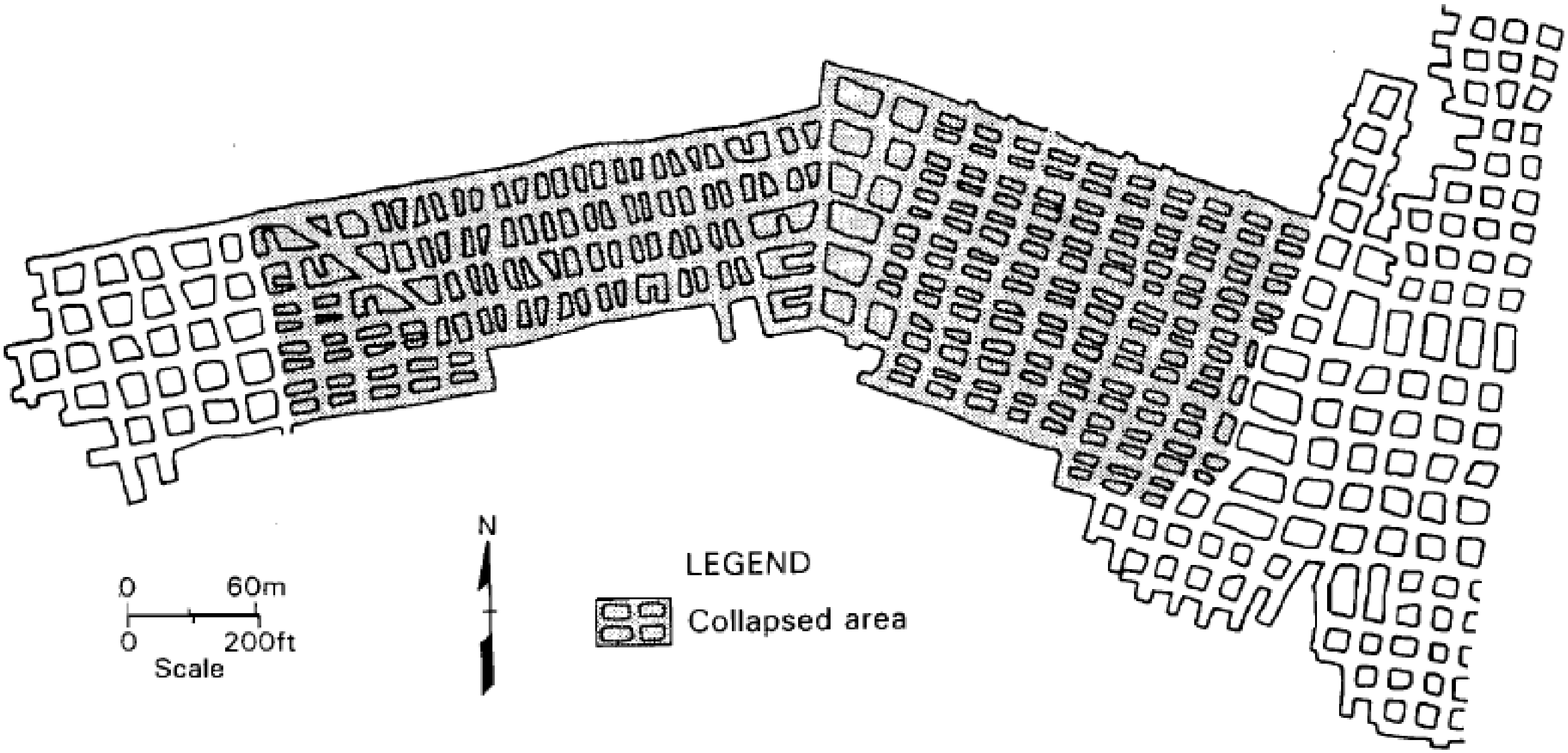

FIGURE 4 Map of a pillar collapse at a West Virginia coal mine (Mark et al. 1997). Pillar splitting on retreat left an array of slender pillars that suddenly collapsed.

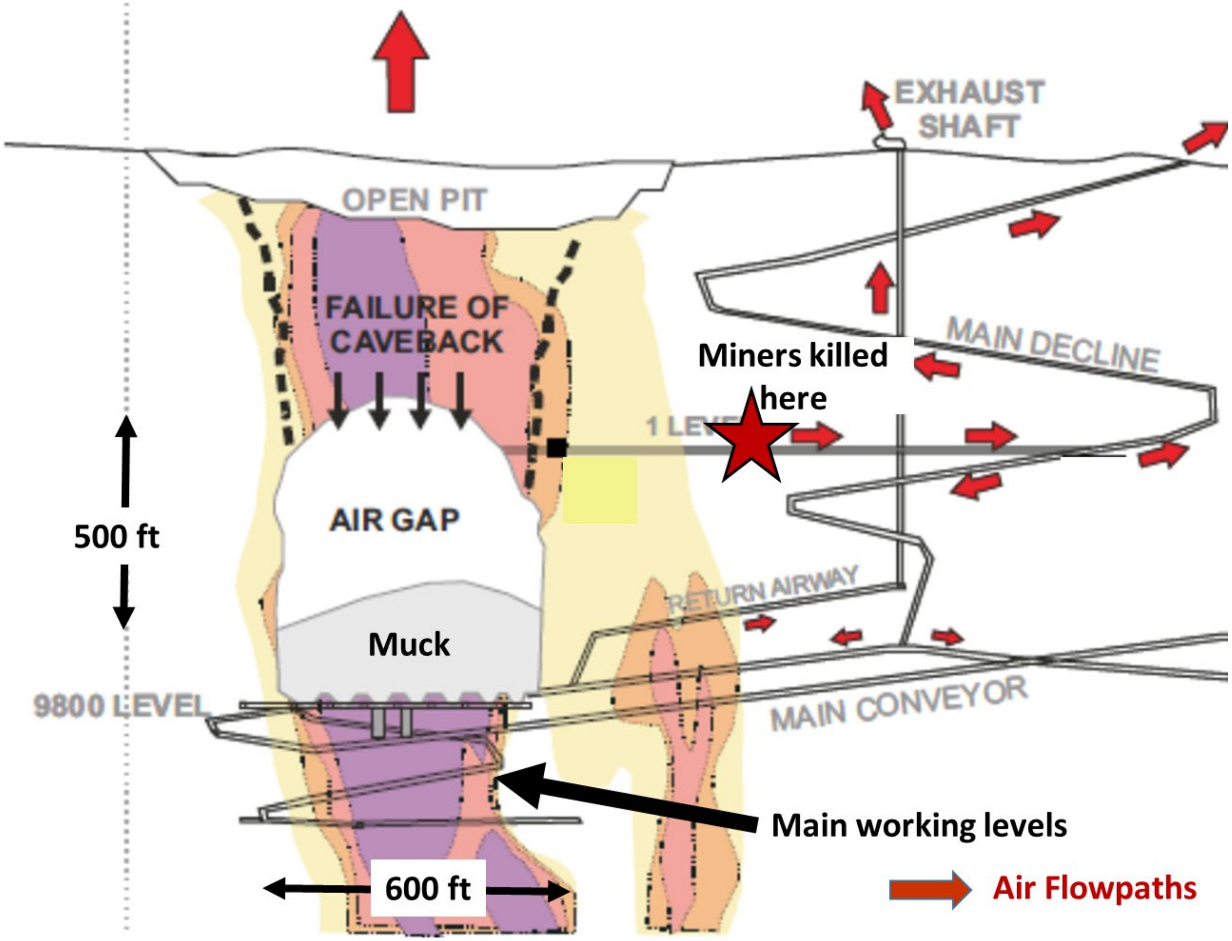

FIGURE 5 Schematic of the 1999 caving event at the Northparkes Mine (afeeter Ross and As 2005). The miners who perished were in the "1 Level" heading. Note that the "air gap" was approximately 500 feet high at the time of the collapse.

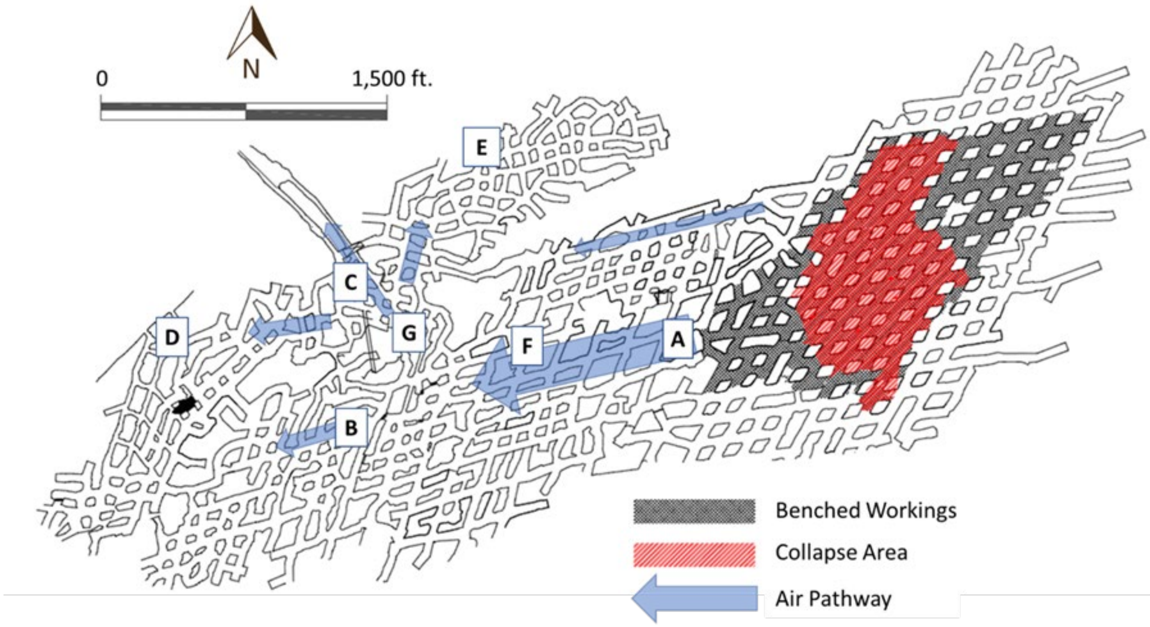

FIGURE 6. Map of the airblast case history mine. The airblast damage observed at locations A through G is discussed in the text.