Ground Failures in Coal Mines with Weak Roof

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ABSTRACT

Coal miners who work and travel under supported roof expect to be protected from rock falls. However, rock fall accidents and injuries continue to occur in coal mines that have been supported according to the roof control plan. Experience at coal mines with large numbers of falls indicates that many have weak roof. Control of this roof may require additional ground control measures. An understanding of the geologic and stress conditions which lead to roof falls is necessary to assess the risk of failure and to design roof reinforcement to improve stability. Six common roof fall types, with attached field examples, are described. Roof support practices for each fall type are also described.

INTRODUCTION

Unplanned roof failures in coal mines can be caused by a number of different factors. These include geologic defects in the roof rock, moisture degradation of shales, extreme loading conditions under high cover, multiple seam mining, and inadequate support to name just a few. A large step toward a solution in any engineering failure is to understand the causes of the failure. Sometimes the causes of a roof fall cannot be determined, but often an investigation of the fall cavity, the condition of the surrounding roof, and the geotechnical environment can reveal the root causes.

NIOSH has investigated roof failure in a number of coal mines in order to illustrate the causes and conditions leading up to a roof fall. Roof fall surveillance data indicate that a disproportionately large percentage of roof falls come from mines with weak roof [Pappas and Mark 2010]. Weak roof is here defined as a roof sequence with a Coal Mine Roof Rating (CMRR) of ≤40, or roof rock with an unconfined compressive strength (UCS) of ≤3,500 psi [Mark et al. 2004a]. Geotechnical data was collected from a total of 22 mines (Table 1). Mines were selected for investigation based on high roof fall rates, or their geographic location in areas like the Illinois or northern Appalachian Basins, which are known to have difficult roof conditions. Seventy percent of all CMRR values ≤ 45 included in a NIOSH database were from mines located in the Illinois Basin or the Northern Appalachian Basin [Molinda 2010]. Of the 22 mines included in the study, 9 had roof fall rates in the highest 10% of all underground mines [MSHA 2007]. The mines were located in 8 states representing five different coal basins and 11 coal seams. The database includes 5 long wall and 17 room and pillar mines. The roof geology covers a wide range of typical roof lithologies including black shale, gray shale, sandy shale, fireclay, stackrock, sandstone, and limestone. The Coal Mine Roof Rating (CMRR) ranges from 30-83 and averages 44. The depth of cover ranges from 25-900 ft and averages 325 ft.

Coal mine roof that falls before the installation of roof bolts can be hazardous. From 1995-2008, 24 miners were killed while travelling beneath unsupported roof [MSHA 1995-2008]. In that same period, 59 miners were killed and 5,143 were injured while under permanently supported ground. Additionally, 19,625 non-injury falls of roof were also reported to MSHA. This situation represents inadequate support, often caused by a failure to recognize hazardous geology. When roof falls occur and miners are killed under supported ground, roof diagnostics, failure mechanisms, and support procedures must be re-examined.

Empirical methods rely on estimations of the effect of key geotechnical parameters to build a roof stability model which can then be used to design mine openings and prescribe roof support. These parameters include roof geology and stress regime. This approach has been successful in developing the Analysis of Roof Bolt Selection (ARBS) [Mark *et al.* 2001] and other NIOSH ground control tools including Analysis of Longwall Pillar Stability (ALPS) [Mark 1992], Analysis of Retreat Mining Pillar Stability (ARMPS) [Mark and Chase 1997], and Analysis of Multiple Seam Stability (AMSS) [Mark et al. 2007]. Difficulties arise when local geologic and stress conditions change and the changes are difficult to detect. In these instances, knowledge of the roof fall geology and stress history is necessary to provide input for entry design and support.

Roof Fall Types

An investigation of roof falls (rock pile and cavity) and adjacent entries may reveal clues to the causes of the roof fall [Molinda 2003]. Field investigation of numerous roof falls has resulted in a list of common roof fall types. The following is a list of observations and indications from roof fall examination.

- Rust-stained shear surfaces indicate water inflow which may have weakened the roof.
- Roof shears or slickensides may indicate severed roof beams.
- Small rock fragments (<12 in across) in the rock fall pile may indicate rock failure between bolts.
- Mud bands or rider coals at the top of flat-topped falls may indicate weak zones that separated above anchorage.
- Cutters leading into the roof fall may have initiated roof failure due to roof compression.
- Long, running, and linear trends in roof falls may indicate a poor mining orientation with respect to the local horizontal stress regime.

These roof defects and mining conditions indicate the failure history leading to the roof fall. Once a roof fall failure type is recognized, it is easier to design the appropriate roof support. Most roof falls can be grouped into one of the following 6 roof fall types, which are described in turn, with individual case studies also presented.

Stackrock Delamination

Stackrock is a mining term for a sequence of roof rock composed of interbedded sandstone and shale layers. The "stack" looks like a tall column of telephone books or news papers **(Fig. 1).** The interbeds can vary from alternating thin beds (0.1 in) to beds up to several inches thick. While this rock unit can be relatively strong perpendicular to bedding (CMRR = 40-60), it is often very weak parallel to bedding. Typically, thick stackrock sequences become unstable when subjected to horizontal stress. Stress concentrates in the stiffer sandstone beds, causing downward deflection, delamination, and crushing of rock at the rib abutment (cutter roof) [Molinda 2003]. Cutter roof is a compressional failure which begins on the entry corner and propagates upward into the roof, or begins up in the roof and cuts downward. The shear angle bounding the roof block dips at typically 60 degrees and extends upward, often to a strong layer which resists shearing. At this point, the cantilevered beam separates from the strong layer, shears the opposite wall of the entry, and falls (Fig. 2).

Figure 1: Roof fall in a stackrock sequence.

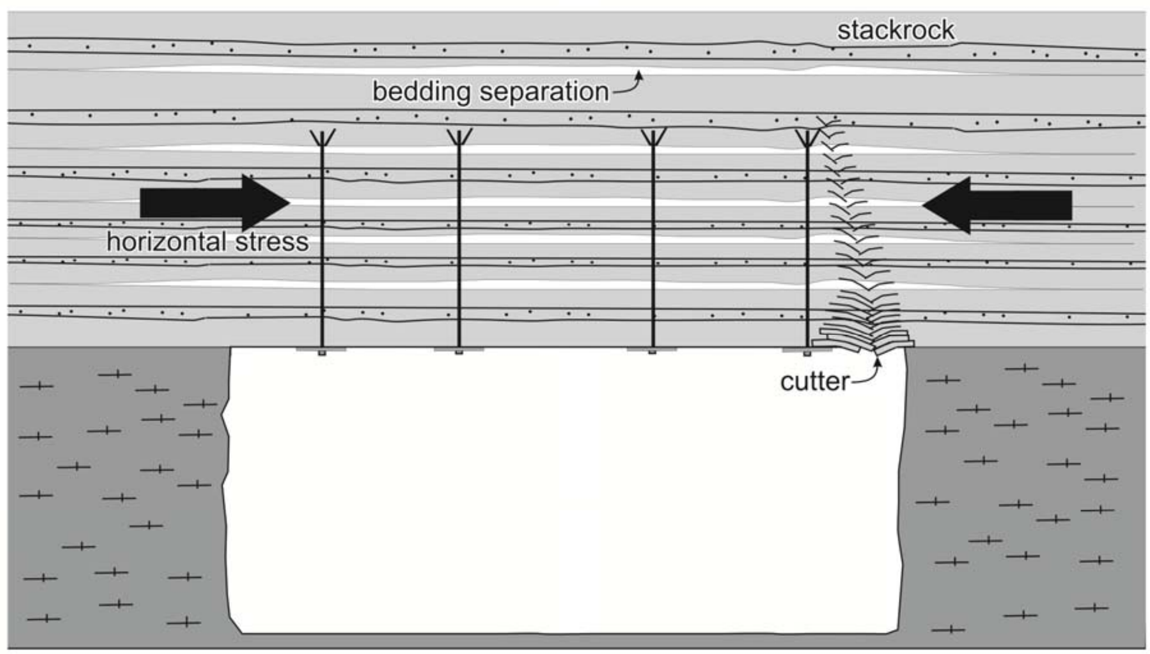

Figure 2: Stackrock delaminates and cutters form when roof is subjected to horizontal stress

Six of the mines visited reported problems with stackrock in the roof. Three of the mines are in the Illinois Basin and three are in the Northern Appalachian Basin. Since stackrock is a relatively stable sequence in the absence of horizontal stress, roof falls related to stackrock may indicate an increased horizontal stress is attacking the roof. The average depth of cover over the 6 mines is 280 ft. This relatively shallow cover indicates that the horizontal stress is related to a regional, in situ stress field. Eight of 22 mines visited report moderate to severe horizontal stress damage to the roof **(Fig. 3).** Damage from horizontal stress can be difficult to control and require a reorientation of the mine workings to reduce damage.

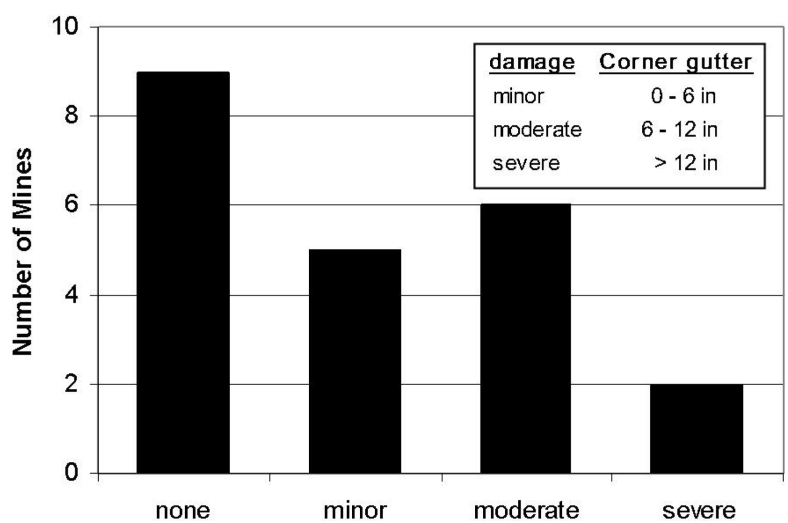

Figure 3: Distribution of horizontal stress damage in study mines.

The stackrock is a result of overbank deposits from river channel flooding and is often an indication that sandstone is nearby in the roof. The stackrock may coarsen upward or grade laterally to sandstone. Stackrock is often termed "adverse' in the roof control plan, and secondary support must be installed to control it. Roof falls in stackrock are often high (25-30 ft) and the rock pile is characterized by large slabs spanning bolts or thick sequences of rock which has fallen intact.

Some mines track the occurrence of stackrock with test holes which are required at intervals, usually every intersection or sometimes as frequently as every 20 ft. Other data can be obtained from longwall face maps, and regular face mapping in advancing room and pillar mines. Surface exploration holes provide less useful data because they are too widely spaced. Often maps based on data from surface exploration holes feature large "bullseyes", indicating that the data is insufficient for meaningful contouring [Mark *et al.* , 2004b]. Such mapping may even mislead engineers as to the nature of the stackrock deposit.

At a mine in the Upper Freeport seam in eastern Ohio, massive sandstone lenses (20-50 ft thick) invade the roof intermittently (Fig. 4). The mine is also subjected to a high horizontal stress oriented E-W. When the sandstone forms the immediate roof, conditions are excellent. Massive sandstone roof that has been exposed by mining for 40 years has survived with very little damage. Along the margins of these channel lenses however, the stackrock sequences occur at various levels ranging from immediate roof to 10-20 ft into the roof. Horizontal stress attacks these sequences resulting in roof falls oriented N-S. The strong E-W stress field is also indicated by roof cutters and roof falls ripping N-S despite having to jigsaw around pillars. Cutter roof is common and often leads into roof falls. Where stackrock approaches the roof, stress damage is more frequent. In addition, water associated with the sandstone may also begin to drip through the roof, further weakening the rock.

Figure 4: Stackrock sequence occur on the margins of sandstone channels.

At the Ohio mine, roof cutters are worse where roof bolt spans to the rib are large. Roof bolts were observed to be up to 48 in from the rib in some places. Installing bolts close to ribs will help to control cutter roof and prevent its propagation. Angling longer corner bolts through the cutter to anchor over the rib is also a preferred control for cutter roof. Some mines have added an additional “cutter” bolt to the row pattern just to fulfill this function. In difficult cases, roof trusses have been effective, provided they maintain contact with the roof and have adequate surface control.

Since stackrock, when coupled with horizontal stress, results in roof falls, finding the optimum mining orientation is the first job in improving roof conditions. This can be accomplished by first determining the local horizontal stress field. Roof fall orientation analysis and mapping of roof pots and cutters can provide the determination [Mark and Mucho 1994; Mark and Gadde 2008]. The optimum orientation can then be determined by using the Analysis of Horizontal Stress in Mining (AHSM) program developed by NIOSH. Development as close to parallel to the regional stress field as possible will minimize entry corner damage and roof pots.

MINE A – CASE STUDY OF STACKROCK ROOF

The study mine is a room and pillar mine located in the Illinois Basin and is mining the No. 5 seam. The depth of cover ranges from 150-350 ft with a mining height of 7-8 ft. There are three different roof geologies. 1. Black shale/limestone 2. Thick Dykersburg Shale 3. Stackrock. The stackrock presents the most difficult roof conditions. The mine maps sandstone in the roof and has identified complete coal seam washouts where the coal has been replaced by thick sandstone paleochannels. No mining takes place in proximity to these areas. To access reserves, a set of main entries was driven between the two sandstone washouts (Fig. 5). Numerous roof falls occurred and roof conditions were generally poor, requiring supplemental support. Between the sandstone washouts the roof consists of approximately 10 ft of Dykersburg shale overlain with 20-40 ft of stackrock (Fig. 6). Water associated with the sandstone and stackrock sequences drips through the roof and acts to weaken the soft shale below. A number of roof falls expose this stackrock in the fall cavity. There is evidence of an East-West regional stress field attacking the mine roof. A number of roof falls are oriented in N-S crosscuts on a separate development. Some falls have cutters leading into the roof fall cavity and some floor heave provides additional evidence of horizontal stress. Buckling and crushing of the stackrock sequence is seen on the intact margins of the roof falls (Fig.7). The stress field appears to be concentrated in the stackrock sequence above the shale, causing buckling of the underlying weak shale resulting in a roof fall. There does not appear to be stress damage in the roof where the shale is thicker than 20 ft or there is no evidence of overlying stackrock or sandstone.

Figure 5: Poor roof conditions occurred when mining in stackrock between two channel washouts.

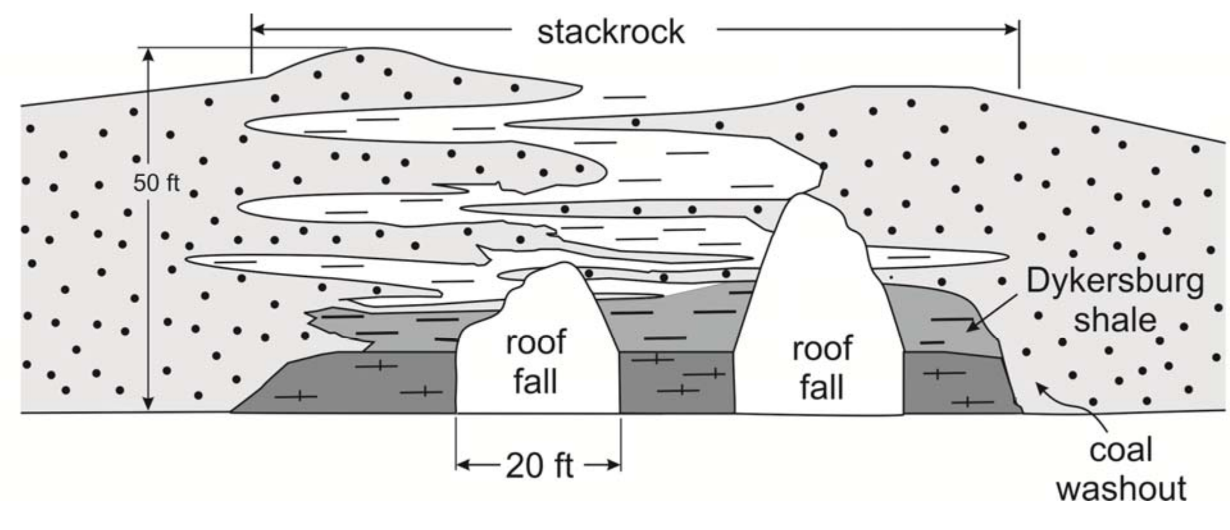

Figure 6: Cross section of stackrock sequences causing poor roof conditions on the margins of paleochannels.

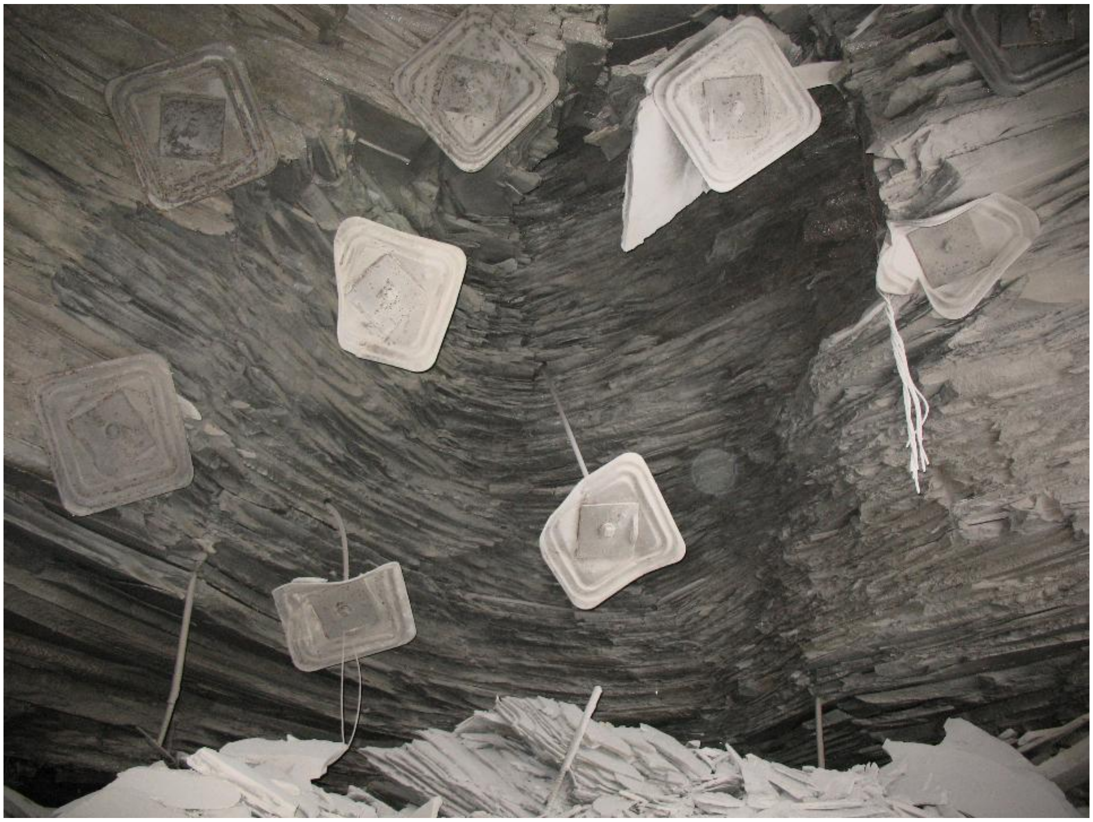

Figure 7: Roof buckling and cutter roof due to horizontal stress.

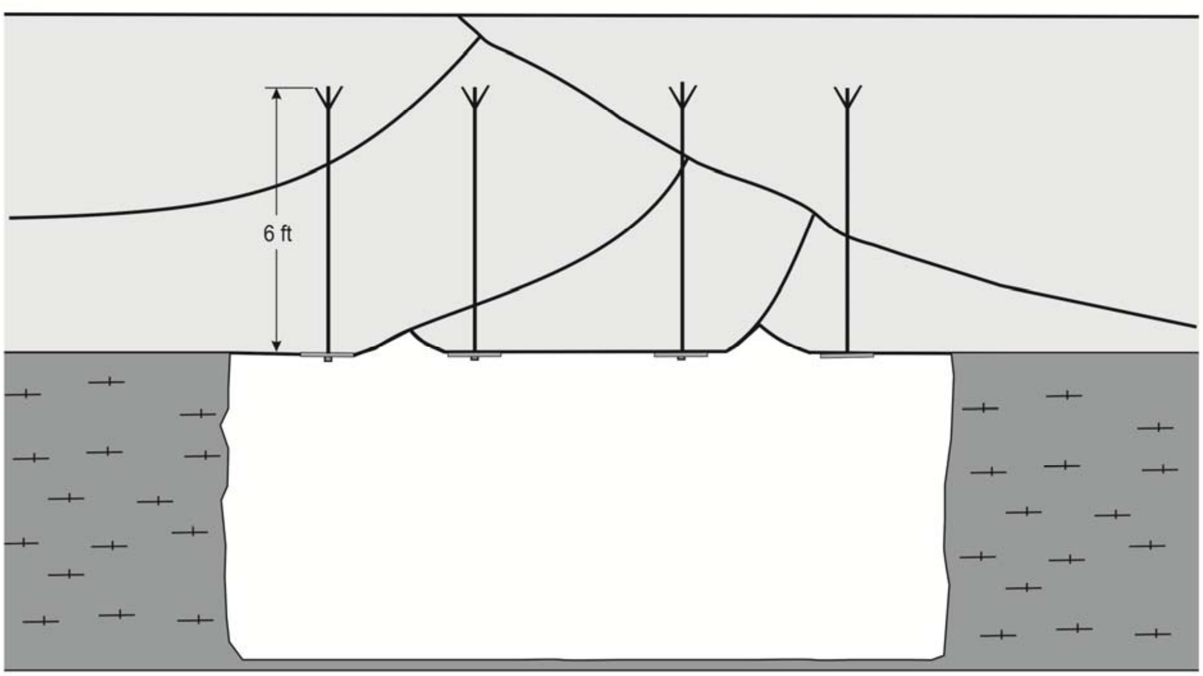

Figure 8: Roof shears can destroy the continuity of the roof beam.

In another area where the stackrock comes right down on the coal seam, large domed falls reaching 20-30 ft high occur (Fig. 1). Horizontal slippage and failure along bedding causes mid-entry crushing leading to the roof falls. The two channel sandstone washouts of the coal seam are part of the same surface drainage system present at the time of coal deposition. The stackrock sequences represent overbank transition zones along the margins of the channels and intersect between the channels (Fig. 6). When sandstone channels come close to the coal seam, stackrock sequences can be expected in the vicinity.

Cable bolts were installed in the travelway of the mains between the two sandstone washouts. The travelway had two rows of cable bolts with a third row added in the intersections. There were very few falls in the travelway and numerous falls in the adjacent uncabled entries. Cable bolts are soft supports that stretch to allow some roof beam movement while the support is maintained intact, thus preserving the beam. Since stackrock delamination is often accompanied by bedding slippage, another bolting strategy may be to try to prevent bedding slippage with a dense pattern of large diameter (7/8 in.), fully grouted bolts concentrated in the intersections. If the roof beam can be maintained intact, it may be suspended with long cables should separation occur above roof bolt anchorage.

Roof Defects

The second failure mechanism is characterized by defective roof. These defects, or discontinuities, destroy the continuity of the roof beam, leading to key block failure. Many of the structures that occur in coal mine roof were created during deposition and compaction of peat or shortly thereafter. These include paleochannels, clay veins, kettlebottoms, slips, shears, pinchouts, lag deposits, concretions, rolls, or small faults [Molinda 2003; Molinda and Ingram 1991; Ingram and Molinda 1990; Ingram and Chase 1987; McCulloch et al. 1975]. The size of the features that most often affects coalbeds can be measured from inches to tens of feet. Roof bolt support of flatlying coal measure rocks relies on the strength of a clamped beam or the suspension of a clamped beam. When a structural defect (crosscutting or parallel to bedding) partially or completely severs or splits the beam, roof failure can occur (Fig. 8). A number of mines in the Illinois basin have large faults which are intersected by mining. The faults are most often normal faults caused by a tensional tearing of the crust (Fig. 9). Other faults are hinge faults or scissors-like faults that have large vertical offsets (20-30 ft) which reduce down to nothing at the hinge. Developments are often stopped at these faults, and roof conditions can be hazardous.

Figure 9: Normal fault causes roof damage in an Indiana coal mine.

Figure 10: Slickensided failure planes cause hazardous roof conditions.

Slickensided roof, often called “horsebacks”, features a slick, glassy failure zone caused by small scale faulting of clay minerals in shale. These features are hazardous because they have low cohesion and bound roof blocks, which can fall without warning. In 14 of 59 rock fall fatalities that occurred from 1995-2008 in supported ground, horsebacks or slips were identified as contributing to the rock fall. Horsebacks can be hazardous on several different levels [Molinda 2003]. Often the slickensides loosen and fall immediately when undermined. This creates an uneven and lumpy roof which is difficult to bolt. (Fig. 10, 11). Another hazard occurs after defective roof blocks are bolted up. With time these blocks can loosen and fall between bolts. Fatalities have occurred when roof blocks bounded by shear planes have fallen between roof bolts. If horsebacks are large, the failure plane reaches above the roof bolt anchorage and massive roof falls can occur. All of the mines visited for this study had slips and horseback occurrences in the roof, but numerous mines in the Illinois Basin had particular difficulties with these features.

Figure 11: Slickensided failure planes cause hazardous roof conditions.


Figure 12: Joints in black shale can loosen with time causing spalling roof.


Figure 13: Siderite nodules present roof hazards.

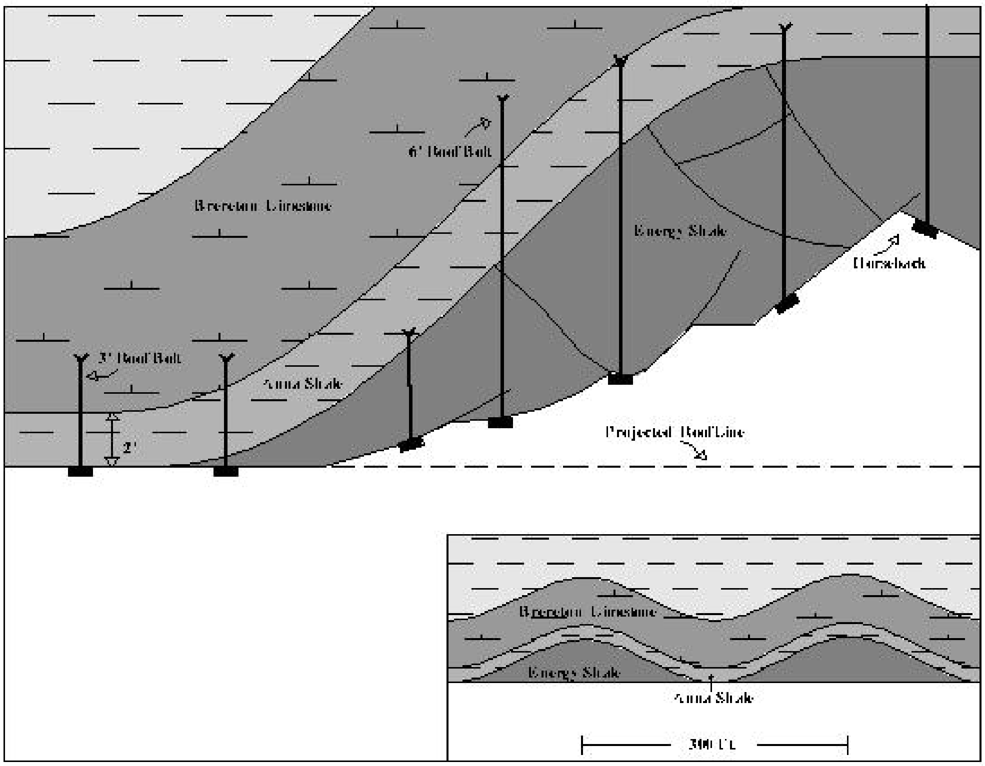

Figure 14: Energy shale wedges are marked by large shears which form horsebacks.

One mine in western Kentucky has poor roof conditions beneath surface stream valleys. Horsebacks and shears tend to increase under the valleys. Very little evidence of horizontal stress damage is seen in the mine. Overburden is in the 200-250 ft range so the poor conditions are not likely due to active horizontal stress concentrations under the valleys. Valley stress relief causes buckling and overthrusting beneath valleys as overburden pressures are transferred laterally into the unconfined strata under the valley [Fergusen and Hamel 1981; Molinda *et al.* 1992]. In addition to broken roof, these structures allow access to surface and formation water, further weakening the roof.

Clay veins (or clay dikes) have long plagued underground coal mines from Illinois to Virginia. At the time of deposition and initial burial, tensional failure in the roof sediments caused an inflow of soft clays. During burial and compaction, these zones form slickensides and can become glide zones as horizontal stresses deform the roof. Damberger attributed these zones to earthquakes occurring shortly after peat deposition when the coalbed was still in a gel-like phase [Damberger 1973]. Clay veins affect both the No. 5 and 6 seams in the Illinois Basin.

A number of mines in both the #5 and #6 seam have black shale as the immediate roof strata. The black shale is highly resistant to moisture-induced deterioration and so resists slaking [Molinda et al. 2008; Molinda and Klemetti 2008, Molinda *et al.* 2006]. However, black shales in general are characterized by well-developed vertical jointing (spacing approx. 4 in) (Fig. 12). With time the joints relax, separate, and the rock between them falls away from the roof. This causes loss of bolt tension and also exposes moisture-sensitive shales above to mine humidity. The black shales also are well known for the occurrence of bands of siderite nodules. These nodules can be up to 3-4 ft across and are extremely hard to cut and drill. Continuous miner bits have been broken off when contacting the nodules (Fig. 13).

Discontinuities bound isolated blocks in the roof and promote key block failure. These blocks can fall out due to gravity unless some restraining force acts on them. Some residual horizontal stress can benefit the roof beam and act to confine the blocks in compression, as long as it is not great enough to damage the roof.

Roof reinforcement for discontinuities should first start with detection. While it is impossible to detect slips with surface holes, mapping of adjacent entries can allow projection of roof defects in advance of mining. Once discontinuities are detected, roof bolt density should be determined by the frequency and spacing of the defects. High coverage steel screen can also provide confinement to detached blocks and prevent progressive unraveling leading to roof fall. Roof trusses can also be considered for increasing surface coverage and rock confinement.

MINE B – CASE STUDY OF ROOF DEFECTS

A room and pillar mine located in the Illinois Basin is mining the Herrin No. 6 seam under approximately 200 ft of cover. The mine operates a single super section with a mining height of 5.3 ft. There are two types of roof geology:

1. Roof type #1 - 1.5 ft of Anna shale overlain by 4-5 ft of Brereton limestone.
2. Roof type #2 - thick Energy shale

There is rarely a roof fall in the black shale/Brereton limestone roof (roof fall rate = 0% in the study area) because the limestone is generally thick and strong enough to be self-supporting. The limestone is typically within 1-2 ft of the roof. Where the limestone is present within 2 ft of the roof, 3 ft bolts are installed and are required to anchor at least 12 in into the limestone. The limestone roof accounts for approximately 60% of exposed roof and is easily detected by drilling. The operator documented the limestone roof areas by using the 3 ft bolts as indicators. The underlying black shale is mechanically weak and sags with time. Steel screen is holding a substantial amount of rock and helps to maintain the roof line.

The Energy shale occurs in large wedges and represents overbank deposits from the ancient Walshville channel system which transects the coal in the southern part of the basin [Krausse et al. 1979]. The Energy shale consists of numerous facies including dark gray shales, siltstones, and stackrock. A marine transgression followed Energy shale deposition, causing the black shale/limestone to be deposited over top of the Energy shale wedges nearest the channel floodplain. The Energy shale "wedges" are erratic and very difficult to anticipate. They have only been successfully mapped from underground exposures. The Energy shale is marked with rolls and shear bodies which are highly slickensided and contorted. These intersecting shears and horsebacks bound key blocks ranging from inches across to 10-20 ft across, and cause them to fall out on mining **(Fig. 14).** The shears can also extend over the rib, isolating large brows which can slide into the entry. This can happen on the active section, making them particularly hazardous. The "horsebacks" also can loosen and fall after bolting if they are located between bolts. The falls show some time-dependency, indicating a relaxing of the slip surface.

The roof fall rate (ft of fall/ft of entry) in the study area for the Energy shale is 2% compared to 0% for the black shale/limestone roof. If 1 ft of limestone anchorage cannot be achieved with a 3 ft bolt, then a 6 ft bolt is installed. If a roof crack is encountered during test drilling or the entry is sagging or "adverse", then an 8 ft bolt or cable bolt is installed in the Energy shale, depending on the height of the separation.

The mine has been successful covering the roof with steel screen, with a subsequent reduction in rock fall injuries. In potted and lumpy roof, the screen is formed to cover the roof cavity and prevent subsequent block and slab separation. In fractured roof, cables are more effective if steel screen confinement is provided to slabs between bolts so that the loads can be transferred to the cables. In extreme loading, cables can be post-grouted with polyurethane to consolidate the roof beam. When maintaining contact with the roof, trusses are effective in supporting roof blocks bounded by angled slips. Trusses also benefit from the confinement provided by steel screen. The mine installs a double row of bolts on the last row of a cut in order to prevent "horsebacks" from riding over into the bolted place where the operator stands. In addition to roof cavities, tall ribs are created in the weak Energy shale, posing sloughage problems. Steel screen can also provide rib support.

A number of mines in southern Illinois and Kentucky are intersected by normal faults. These extensional faults have also caused poor roof conditions at the study mine. A normal fault zone, over 1000 ft long, intersects the roof and offsets the coalbed by 2-3 ft. Large vertical fault planes transect the roof over a 600 ft wide zone. An igneous dike has intruded one fault plane. This zone is marked by numerous roof falls. When the vertical fault planes intersect the localized shears in the Energy shale, roof falls occur. Roof bolts and cable bolts installed vertically are ineffective in supporting vertical shear planes. Angled bolts and trusses are more effective in intersecting the fault planes.

Cutter Roof

Cutter roof refers to damage of coal mine roof caused by horizontal compression and crushing of roof rock. This most often occurs at the intersection of roof and rib, but can occur in the center of the entry or anywhere in the entry. The damage is caused by horizontal stress acting to shorten and crush the roof [Gale 1986; Mark 1991; Hasenfus and Su 2006; Mark and Gadde 2008]. The damage is more common in weak rocks but has been documented to occur in stackrock (as described earlier), and even in limestone in near-surface stone mines [Iannachione et al. 2001]. Cutter roof is a progressive failure and can lead to guttering, which is more extensive rock damage along the roof and rib intersection. This guttering can extend above the roof bolt anchorage horizon. In thick shale sequences the roof beam stays intact and the cutter works upward along the ribline causing a cantilevered roof and finally a roof fall (Fig. 2). Cutting usually occurs on the working section either running out of the newly exposed face, or shortly after mining (Fig. 15). While cutter roof often damages the roof at the working face, roof falls may not occur until months after mining when guttering has progressively severed the roof beam. Investigation of the roof surrounding the fall will often show cutter roof leading up to the roof fall, indicating cutter roof to be the cause of the fall. The initial failure, usually begins in an intersection. After the intersection falls out, the fall can progress to long, running falls perpendicular to the direction of maximum principal stress. A number of roof damage features, including potting, stitching, rock flour, cutting, and guttering indicate of the presence of horizontal stress and its orientation [Mark and Mucho 1994] (Fig. 16).

Figure 15: Cutter roof in thick shale roof sequence.

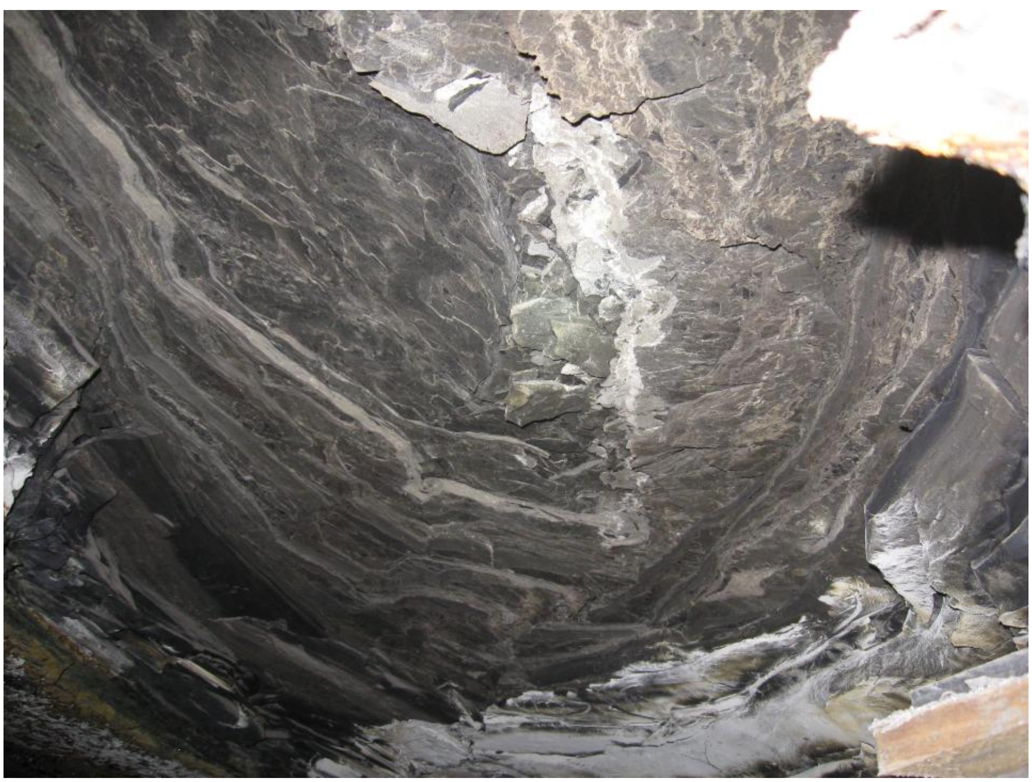

Figure 16: Roof pot and rock stitching caused by horizontal stress.

MINE C – CASE STUDY OF CUTTER ROOF

A mine in the Illinois Basin is working the #9 seam under approximately 350 ft of cover. Seam height is 70 inches with 8-10 inches of drawrock taken, for a total mining height of 80 inches. The roof geology consists of 4 ft of dark gray to black laminated shale, overlain by an 8 in thick mud layer, overlain by a massive, poorly bedded shale. The black shale immediate roof is typically resistant to moisture-deterioration, but the overlying gray shale is moisture-sensitive. The roof is attacked by a horizontal stress field oriented approximately East – West to N. 80 E. This stress field orientation is consistent with other horizontal stress measurements in the basin [Ingram and Molinda 1990] Roof potting, guttering, and other stress damage was observed to lead into roof falls. Crosscuts on the left side of several production panels showed far more damage than crosscuts on the right side. The crosscuts on the left side are oriented at a larger angle to the E-W stress field (62 degrees) than those on the right side of panel (10 degrees). As a result, roof potting and guttering is more severe. (Fig. 17).

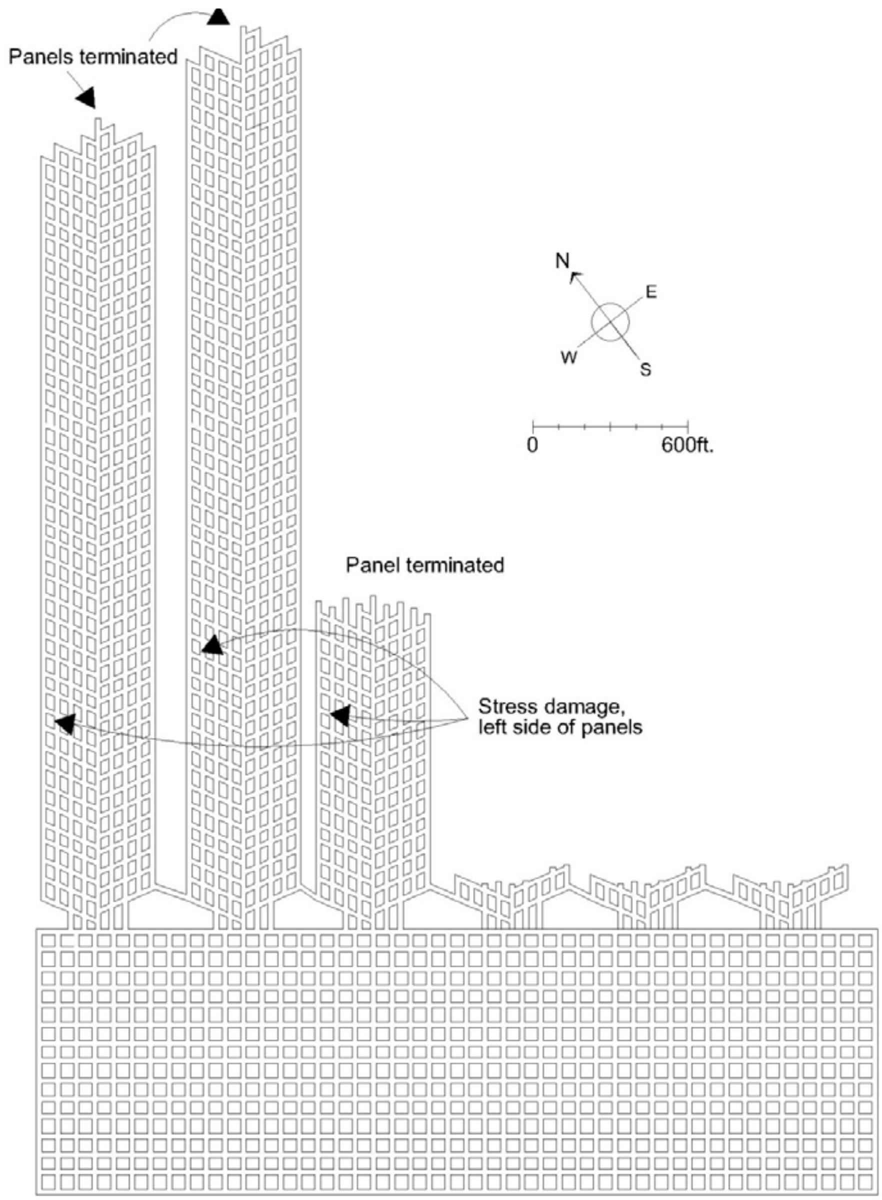

Figure 17: Stress damage is more severe on the left side of a production panel than on the right side.

Although the black shale is unreactive to moisture, it can be damaged and crushed by horizontal stress. Once this shale is damaged and falls away, the overlying mud band and moisture-sensitive gray shale is exposed. This leads to deterioration and chandelier bolts (Fig. 18). This type of failure was observed around the margins of several roof falls.

Reorientation of developments or angling of crosscuts is the first remedy to minimizing damage from horizontal stress. Roof bolts nearest the rib can be angled to intersect the cutter and anchor over the stable rib. Cable bolts are often installed systematically in intersections to suspend the roof beam from a stable anchorage.

Figure 18: Exposure of moisture-sensitive gray shale leads to chandelier bolts.

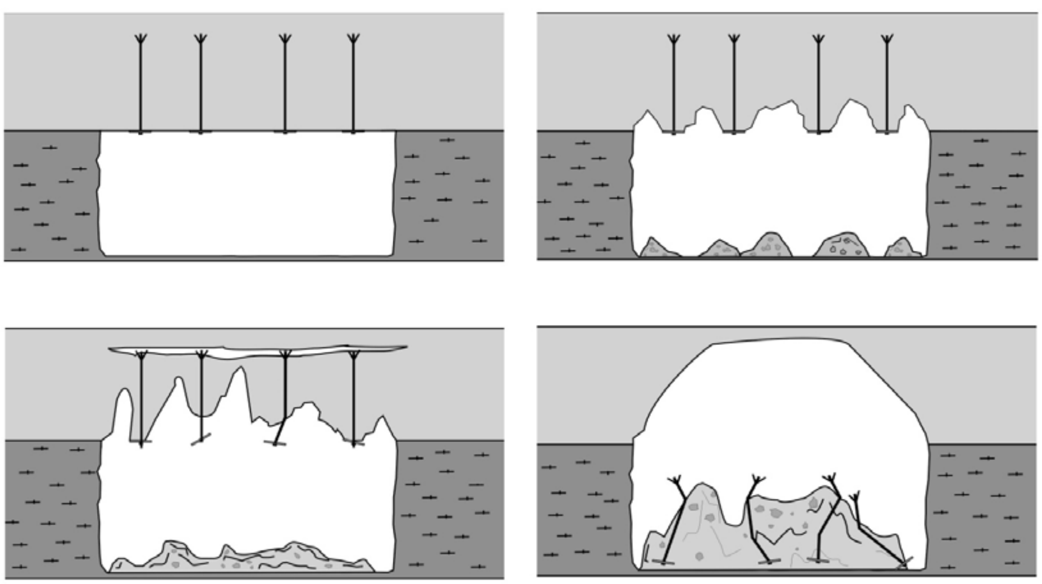

Figure 19: Unraveling of rock between bolts leads to roof fall.

Spalling Roof

Roof spalling is the fall of rock between bolts. It can progress upwards, eventually above the roof bolt anchorage (Fig. 19). Rock spalling between bolts can be due to several factors. Poor bedding cohesion or a weak rock matrix can allow separation and scale to form between bolts (Fig. 20, 21). The separation can be driven by horizontal stress or by gravity. Roof separation above bolt anchorage then compromises the roof beam and can lead to roof fall. The other mechanism is weathering of moisture-sensitive rocks. Moisture can weaken clay-rich shales and cause swelling, creating downward pressure on the roof, fracturing already-weak rocks [Molinda *et. al.* 2006]. This unraveling can eventually progress to a roof fall. A number of mines in the Illinois Basin have time-dependant deterioration of the roof leading to roof falls. Roof falls can continue to happen years after mining. Many studies show that mudrocks weaken with exposure to moisture [Mark *et al.* 2004a; Huang 1986; Cummings and Singh 1981; Aughenbaugh and Bruzewski 1976]. It may be this moisture-deterioration which explains some long-term roof falls.

Figure 20: Progressive roof spalling leads to roof fall.

Figure 21: Weak cohesion in a roof fireclay leads to fall between bolts.

The roof beam must be maintained between bolts as well as across the entry. Typical roof bolt patterns in the U.S. (4 ft x 4 ft) are largely adequate for much of coal measure roof. For a smaller proportion of weak roof, the typical roof bolt patterns may be inadequate. In the case of weak, moisture-sensitive rock in a coal mine, the typical 4 ft roof bolt span, without effective surface control, may lead to unraveling between the bolts (Fig. 22). Van der Merwe [2001] found that 27% of all roof falls studied in South Africa were caused by bolt spacing that was too wide. Increasing the roof bolt density, and/or improving the surface control can help to reduce both rock fall injuries and roof falls in weak rock

Figure 22: Progressive spalling between roof bolts in a moisture-sensitive roof shale.

Figure 23: Rock pile below rib gutter is due to disaggregation of weak roof shale.

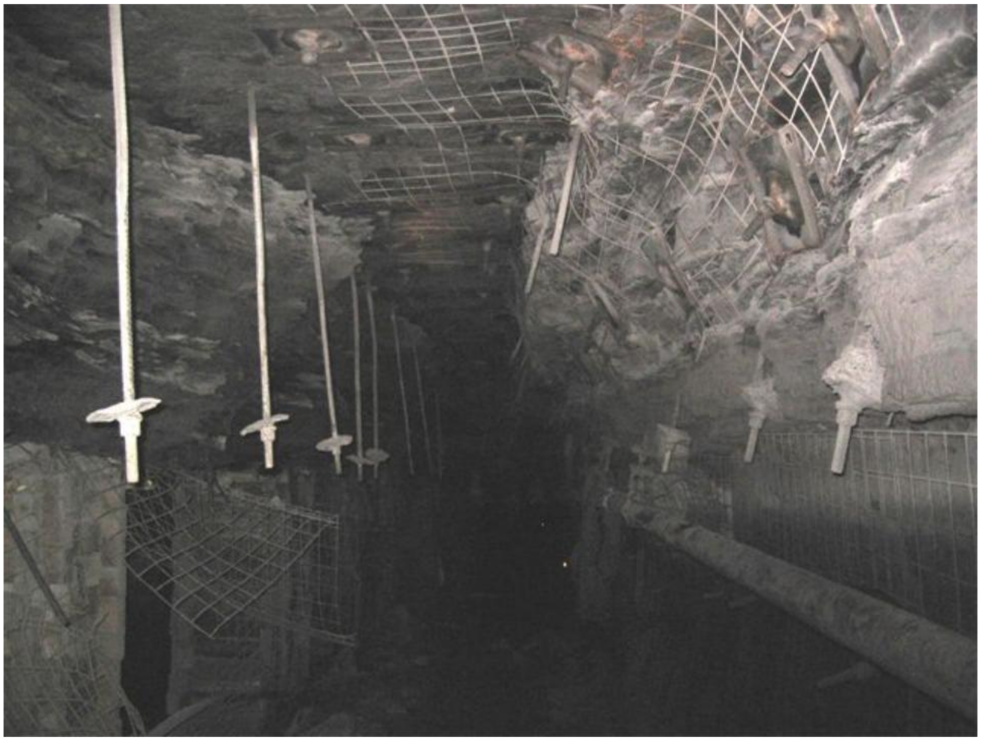

Figure 24: Rock disaggregation between bolts extends nearly to bolt anchorage.

Figure 25: Deterioration of black shale exposing moisture-sensitive gray shale in a western Kentucky mine.

Spalling failure occurs in most coal basins. Eighteen of 22 mines visited in this study had some roof deterioration due to weak and moisture-sensitive roof rock. This condition is particularly prevalent in the Illinois Basin. Nine of 10 mines visited from the Illinois Basin had some roof damage due to moisture-sensitivity.

Evidence for this spalling type of disaggregating failure between bolts in weak rock can be seen in the rock pile below a roof fall. It is not uncommon to see small pieces of rock (8-15 inches across) which are piled up almost as though dumped from a truck (Figure 23). It is unlikely that the rock was broken this way from the impact of hitting the ground. Instead, the whole rock mass probably became fragmented between bolts and unraveled intermittently as small pieces. In very weak rock, spalling between bolts is common (Figure 24). In such potted roof, the rock mass was not even coherent enough to load the bolts and pull them from their anchorage. In fact, it is unlikely that these roof bolts ever saw any significant loads. As the rock unraveled, sometimes to the point that the plate is left with no rock contact, the reinforcing value of the roof bolts is reduced. A roof bolt plate that spins indicates no plate load and re-support may be necessary. Roof marked by chandelier bolts (hanging roof bolts or roof bolts that have columns of rock isolated around them) is often described as both "undersupported" and "unsupported", depending on the depth of "chandeliering" (Fig. 18).

The use of full column resin bolts is particularly important in very weak rock. The rock-resin interface facilitates load transfer to the bolt and resists vertical bed separation. In addition, full column grouting helps to resist bedding shear, which is the beginning of roof sag and unraveling.

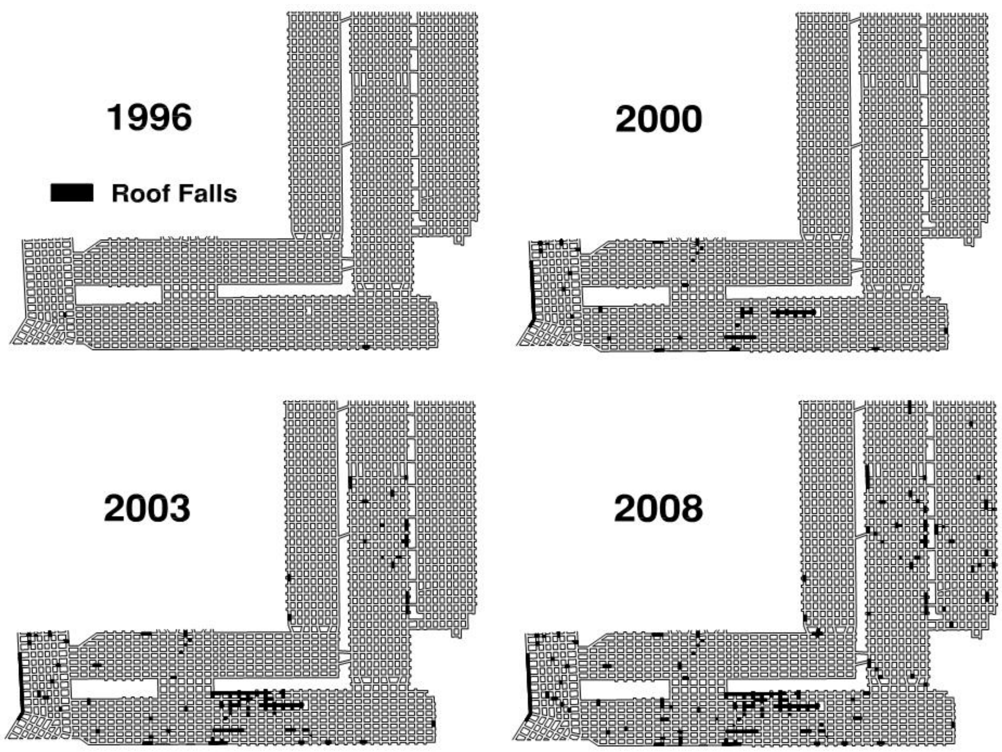

Figure 26: Time-dependent roof deterioration in an Illinois basin coal mine.

A common roof sequence in the No. 5 and 6 seams in the Illinois basin has an immediate black shale (12-24 in) overlain by thick gray shale. This roof can experience failure by mechanical disintegration of the black shale exposing the overlying moisture-sensitive gray shale. The black shale, while not moisture-sensitive, is often well-jointed. With time (3-5 years), the joints loosen and the black shale spalls away, exposing the highly moisture-sensitive gray shale. This rock weathers quickly, leaving chandelier bolts and roof potting progressing towards roof fall. (Figure 25). This process was observed at a mine in western Ky. The roof consisted of 12 in of black shale overlain by 20-30 ft of gray shale. The Coal Mine Roof Rating ranges from 39 (dry roof) to 36 (Ground water exposed). Immersion testing in water indicated moderate-severe moisture-sensitivity of the overlying gray shale. Roof falls in older workings were extending and increasing in numbers, indicating a time-dependence related to continued roof deterioration (Fig. 26). Since the damage also extended well into the mine, it seemed likely that the deterioration was only partially caused by weathering due to mine ventilation humidity, and partly from progressive mechanical failure along bedding. Torque-tension bolts are used in the primary pattern. These bolts are not fully grouted. In weak rock that spalls and fails around bolts, tension may be quickly lost as rock moves along bedding defects. It may be important to install a roof bolt with a full column of resin in order to maintain rock contact and resistance.

Figure 27: Roof screen holding a large amount of broken rock.

At the same mine, timbers were installed at the entrance to crosscuts for support. Where the roof was heavy and sagging, and floor heave also occurred, the timbers would punch through the black shale. This exposed the gray shale to deterioration, leading to progressive roof falls. This mechanism may explain the time-dependent roof failure. As a result, the mine replaced the timbers with 9 ft point-anchored bolts (7/8 in diameter).

MINE D – A CASE STUDY OF SPALLING ROOF

An underground mine in the Illinois Basin is mining in the No. 6 seam. The roof is composed of Energy shale which has two facies:

1. 0-6 ft of laminated shale

2. ≥6 ft of gray shale.

Both of the rock types are extremely weak (breakable by hand) and moisture-sensitive (complete disintegration within one hour of water immersion). There is a weak-moderate horizontal stress field, oriented E-W, attacking the roof. Roof falls are oriented N-S. The biaxial stress field is not overwhelming but strong enough to cut the weak roof shale (UCS = 1,200 psi). A small stress cutter develops on the ribline in entries oriented N-S and again on the box cut in the entry center. Once these cutters open up the roof, infiltrating moisture begins to deteriorate the roof. Weathering begins to occur within one month of roof exposure and is worst nearest the intake shaft and intake entries. Roof screens bag and are holding a large amount of broken rock (Fig. 27). Without the screen, much of the roof would likely be on the floor.

At the study mine roof deterioration and falls are time-dependant and much more frequent in the older workings (Fig. 28). More than 90% of the falls occur 2 or more years after mining. Roof falls are directly related to deterioration of rock between bolts. Roof and rib damage due to weathering steadily decreases when travelling away from the shaft from older workings into newer workings. Roof falls typically begin to occur 4-7 yrs after mining after rib guttering has severed the roof beam. In places where there is humidity roof conditions are extremely poor.

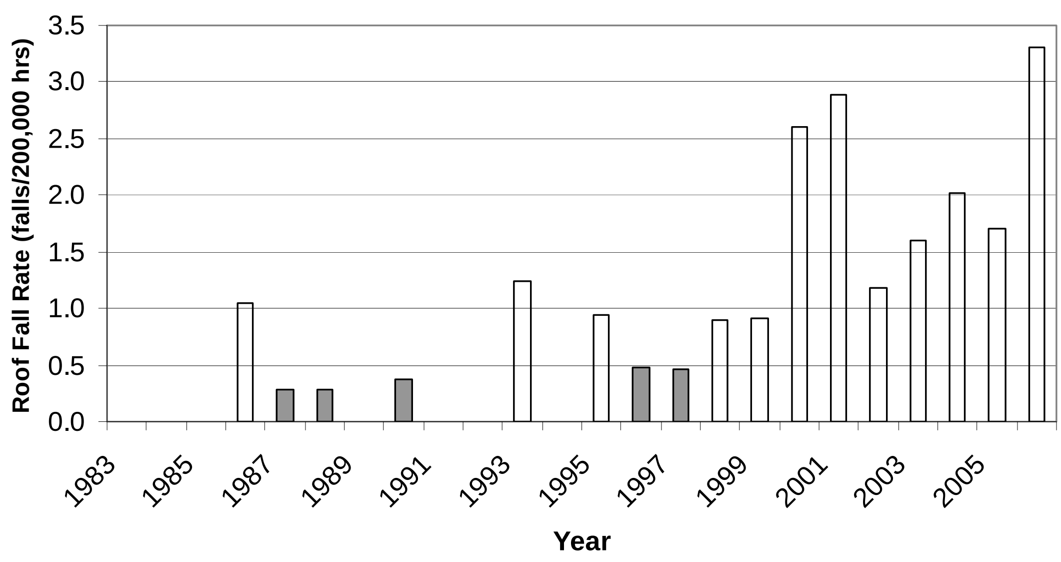

Figure 28: Reportable roof falls increase with time and roof deterioration at an Illinois mine.

Such extreme weakness and moisture-sensitivity forced the mine to reduce entry width to 16 ft, and use a dense 6 bolts per row roof pattern to cut down the spacing between roof bolts. Each row consists of four, 9 ft, point anchored, resin-assisted bolts, with two 4 ft “cutter” bolts angled over the rib to support the corner. The entire roof was screened with welded steel wire. Even though the roof is essentially rubbleized, the roof screen, supported by the dense roof bolt pattern, is effectively controlling it (Fig. 29).

In the highly fractured roof, installed bolt tension can quickly dissipate. When the roof screen loads from spalling rock, it effectively transfers load to the roof bolts and makes them again active.

The effectiveness of the roof screen in preventing roof falls can be demonstrated by contrasting the screened area with one that was not been screened. This area is four years old. Extreme deterioration around roof bolts leading to roof falls has occurred. Rock piles on the floor from roof deterioration are 4-5 ft high. The adjacent workings were fully screened after mining, and, even though these screened workings are over 14 yrs old, the entry is intact. Figure 30 shows the contact between screened and unscreened areas. The area that is not screened is impassible. The screened area, even though the roof is extremely broken, is still intact. The adjacent belt entry was screened and stands perfectly in contrast to the unscreened entry. The roof screen provides the confinement between bolts to arrest upward unraveling and transfer rock load to the roof bolts.

Figure 29: The rubbleized roof is effectively controlled by roof screen.

Figure 30: The screened entry is stable and the floor is clear. The unscreened entry is impassable.

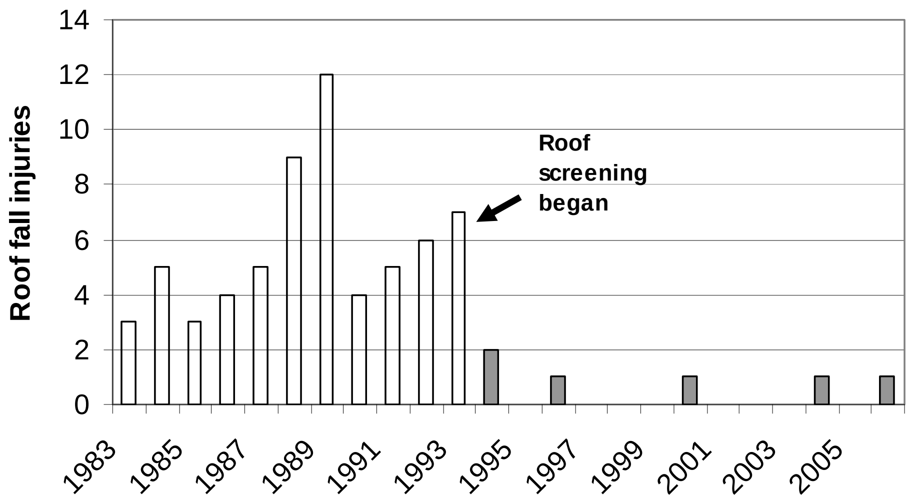

Figure 31: Roof fall injuries dropped dramatically with the use of roof screen at an Illinois coal mine.

The roof fall rate was calculated for those areas where roof screen was installed, and compared against those areas with no roof screen. The roof fall rate was 10.1 falls/10,000 ft of drivage for unscreened areas and was reduced to 2.5 roof falls/10,000 ft of drivage for areas with full screen. Roof fall injuries also decreased dramatically in the screened areas (Fig. 31).

In the initial screen installation at the mine, the roof screen extends only to within 18 in of the rib line. The unscreened corner allowed severe guttering to progress high up into the roof beam (Fig. 23). The problems were worst where the entry had been inadvertently cut wide, leaving unscreened roof in the corner. With time the corner guttering developed into roof falls even in screened entries. To control the guttering and brow development, the later steel screen installations were extended halfway down the rib (Fig. 32). Experience showed that corner guttering could even be arrested after it began. The mine used a special tool to push screen up into gutters to allow fallen rock piling up on the screen to confine the gutter (Fig. 33). After full roof and rib screening was introduced, roof falls were essentially eliminated.

Figure 32: Rib and corner screening controls rib line guttering.

Figure 33: Screening of rib gutters can stop further deterioration.

In such extreme roof deterioration, reduced entry width, high density bolting patterns, and full surface control have allowed mining to continue. The use of head coal to protect the reactive shale has also been effective. The mine has also been successful when using a spray-on sealant in a limited area of the belt.

Sandstone Bodies in the Roof

The effect of sandstone-filled channels on coal mine roof is well documented [Molinda 2003; Ingram and Molinda 1990; Ingram and Chase 1987; Kertis 1985; McCabe and Pascoe 1978; McCulloch et al. 1975]. Of the 22 mines in the database, 18 report that sandstone in the roof impacts roof stability. There are 4 main ways that sandstone can affect the roof.

- The sandstone is within roof bolt reach and provides a stable and competent roof.
- The sandstone margin is slickensided and disturbed, and causes poor roof conditions.
- The sandstone is a groundwater aquifer which introduces water that infiltrates into the moisture sensitive, slickensided shales below, weakening the rock and causing roof falls.
- Stackrock can form on the margins of sandstone channels and horizontal stress can concentrate in this rock, damaging the roof.

A number of mines in the Illinois Basin track the location of sandstone bodies in the roof in both the #5 and #6 seams. When a sandstone body gets within approximately 15-20 ft of the coal seam, roof conditions often deteriorate. The frequency of slickensides and horsebacks associated with differential compaction increases beneath the sandstone bodies. Water inflows also increase, especially from longer, ungrouted cable bolt holes.

When the sandstone body is within reach of the roof bolts, the roof can be supported in suspension. Perhaps the most straightforward roof support method is suspension of an underlying rock mass from an adequate anchor rock. If a substantial anchorage can be achieved, then the required roof bolt capacity can be determined from a simple dead load calculation. Where this anchorage can not be achieved, separation at the contact can occur and result in roof fall (Fig. 34). Again, this type of roof support relies on the competence of the suspended rock mass and its' ability to stay intact. In the Illinois Basin, when marine roof conditions prevail, limestone can also provide a significant anchorage horizon.

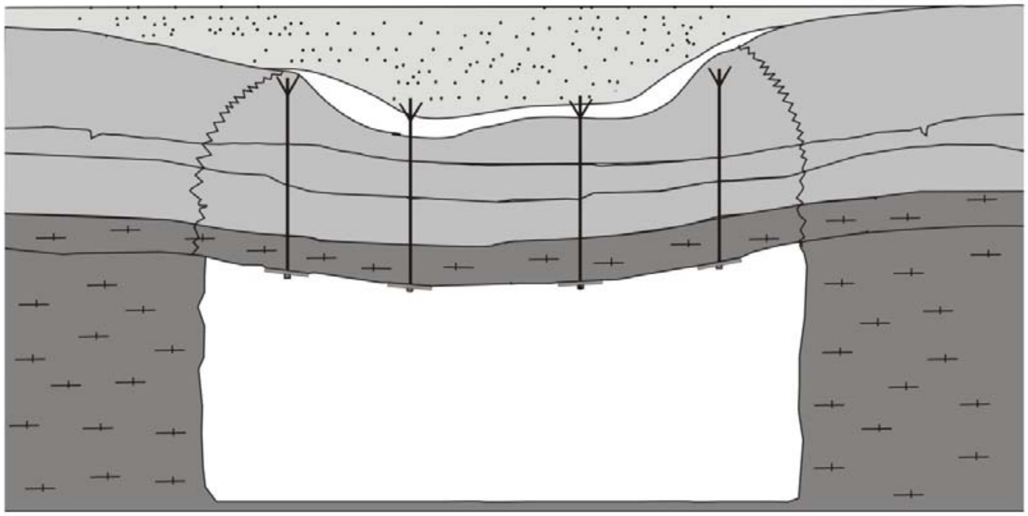

Figure 34: Failure to reach a stable anchorage with roof bolts can result in a roof fall.

Many of the roof sequences in the Illinois Basin were formed when marine waters inundated coal swamps. In non-marine conditions, sandstone channels locally come down within reach of roof bolts to make good bolt anchorage. This situation is often short-lived as the sandstone channels may continue and cut out the coal bed completely. The margins of sandstone channel cutouts can be extremely hazardous because of sharp angular contacts and soft sediment disruptions. A Pittsburgh seam mine in WVa. had good roof when the sandstone layer laid directly on the coal seam. On the margins of this channel sandstone, slickensided "soapstone", and disrupted rider seams fell out on mining and formed a lumpy, uneven roof (Fig. 35). As a result the mine had numerous roof falls and rock fall injuries from rock falling between roof bolts. Longer roof bolts and cable bolts were required to reach the sandstone anchorage.

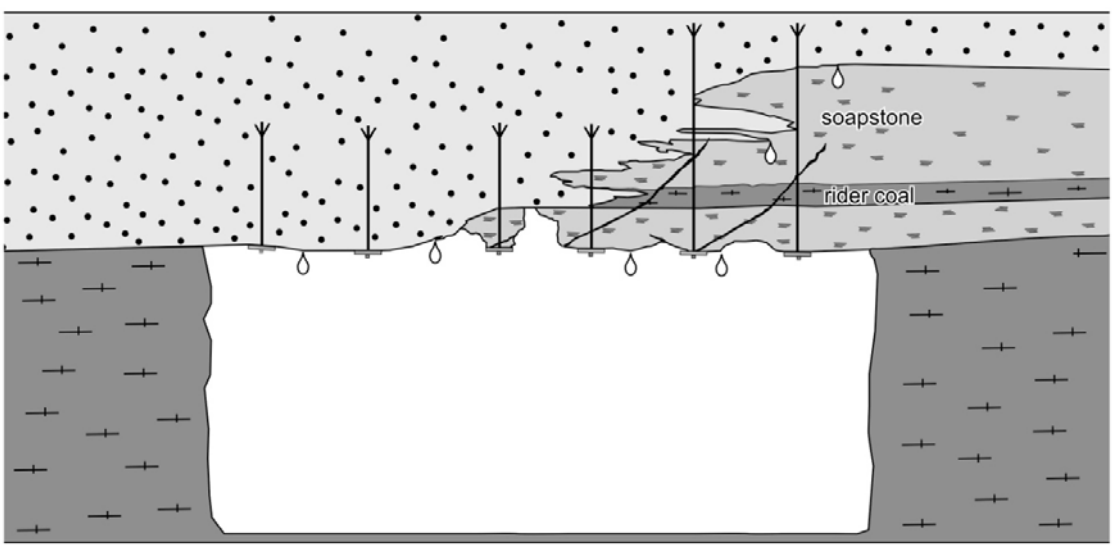

Figure 35: Hazardous roof conditions occur on the margins of a sandstone channel at a West Virginia mine.

Cable bolts can be relied upon, through suspension, to transfer the load of the intact beam to a point in the roof far removed from rock unraveling. Again, it is important to take into consideration the competency of the rock mass in the design of cable bolts. A rock load height calculation is only one factor in the design. While a single massive cable bolt may have the same capacity as four smaller roof bolts, it is not correct to assume it has the same reinforcing value. A denser cable bolt pattern may be necessary to distribute the load and preserve the roof beam.

MINE E – A CASE STUDY OF SANDSTONE IN THE ROOF

A mine working the #5 seam in the Illinois Basin had 39 reportable roof falls in less than 15 months of operation. The roof consists of 6-24 inches of black shale overlain by 0-20 feet of weak, poorly bedded, moisture-sensitive gray shale. Overlying the gray shale is a massive sandstone layer 30-40 ft thick. Fifteen of 39 roof falls had sandstone exposed in the fall or water associated with sandstone. Slips, often occurring beneath or adjacent to the sandstone, were observed in 21 falls. The water associated with the sandstone may compromise the roof in several ways:

- water swells the gray shale and causes roof bulking and damage.
- water pressure damages the weakened gray shale.
- water causes chemical weathering of the shale and reduces its strength.

Falls occur several weeks to months after mining with very few falls occurring on the working section. This time-dependency may be an indication of the progressive roof damage from water inflow. The mine operators' measurement indicated that all of the falls took place where the sandstone was less than 18 ft above the coal seam. The roof fall rate where the sandstone is less than 15 feet over the coal seam is 6 times greater than the rate when the sandstone is more than 15 ft above the coal seam.

The roof falls average 8-12 ft high and usually extend to a flat top at the sandstone boundary. The gray shale below the sandstone is extremely moisture-sensitive. When exposed to formation water it swells and dislodges slickensided roof blocks. When downward pressure is put on the highly-jointed black shale it is easily fractured and falls. Once the black shale confinement is removed, the overlying gray shales are exposed to mine air humidity and quickly deteriorate, spalling progressively upward.

In weak roof, intersections are vulnerable because of their greater spans. The rock load that must be carried in suspension by the supports is proportional to the cube of the intersection span [Molinda et al. 1998]. Minimizing the intersection span, often accomplished by reducing the number of turnouts, can therefore significantly reduce the support requirements.

Due to the soft and moisture-reactive roof rock, secondary support including posts, trusses, cable bolts, and Propsetters are routinely installed in high value entries and intersections**.** When the sandstone is located near the coal seam, cable bolts can be sized to anchor into the massive sandstone.

Test holes every intersection provide data to effectively track the sandstone body. Surface drill data is not dense enough to provide the detail to track rapid changes in sandstone height. One issue is the introduction of water to the roof sequence through long test holes. On the other hand, even when the sandstone body is 15-20 ft above the roof, the water will find its way into the roof sequence even without a test hole. The test hole may actually provide a conduit for relieving water pressure and draining the roof.

At this mine the correlation of roof falls to sandstone proximity is so well-established that the roof control plan calls for 10 ft cables as a supplemental support wherever the sandstone is within 15 ft of the coal seam. Additionally, when water is encountered dripping into the roof, indicating close proximity of the sandstone layer to the roof, supplemental support is automatically installed.

MINE F – A CASE STUDY OF SANDSTONE IN THE ROOF

A room and pillar mine in Ohio is mining the middle Kittanning seam with a mining height of 55-60 in. The roof geology consists of massive sandstone (50-75 ft thick) which alternately lays directly on the coal and rises up into the roof above roof bolt anchorage (Fig. 36). The surface of the sandstone unit weathers to a fine powder, but the rock itself makes a solid roof. When the sandstone rises into the roof it is underlain by weak, moisture-sensitive clay shale. The shale is 0-8 ft thick and begins to weather when the roof is only 6 months old, deteriorating to splintery fragments. Roof samples of the shale were tested for moisture-sensitivity and averaged 71% out of a possible 100% (very moisture-sensitive) [Molinda and Klemetti 2008; Unrug 1997]. The shale is bisected locally by kettlebottoms and numerous slips and small faults. No significant horizontal stress damage occurs.

Figure 36: Sandstone layer is the roof bolt anchorage when close to the coalbed.

Locally, when the slips are more frequent, the roof shale falls out on mining up to the sandstone, creating a lumpy, uneven roof line. Mining is slowed considerably due to cleanup and additional roof support. When the shale stays intact, the roof support is designed to suspend the shale from the strong sandstone using 6 ft torque-tensioned bolts with 2 ft of fast set resin and 4 ft of slow set resin. The 2 ft resin anchor achieves significant anchorage in the sandstone and the tension puts a clamping force on the slips. The mine has had no roof falls since tensioned bolts were substituted for untensioned bolts.

When 8 ft test holes do not encounter sandstone, 10 ft cable bolts are installed in the mains and intersections to reach the sandstone and suspend the shale. With time, considerable weathering has caused deterioration of the weak shale. Steel screen is used in the mains travelway, intake, and return to accept the load of weathered rock between roof bolts. Steel screen provided a significant benefit in maintaining the intake entry roof compared to roof in unscreened entries [Klemetti *et al.* 2009].

Roof Sag

The stackrock failure model described previously is a delamination of bedding driven by horizontal stress. Separation of roof rock can also be driven by gravity. In thick shale sequences with no stiff sandstone interbeds and weak bedding cohesion, layers can sag under the force of gravity. In order for sag to occur, bedding contacts must be broken in shear or tension. As this softened zone deflects, significant bed separation can occur (Fig. 37). If the separation occurs in or above the bolt anchor zone, roof fall can occur. As the beam deflects, crushing develops on the roof-rib abutment causing cutter roof. Tension cracks can also develop in the entry center (Fig. 38, 39). In order to prevent this deflection and reinforce the roof beam, it may be necessary to install a stiffer primary support. Stiffness can be increased by using a larger diameter bolt with full column resin grouting. Stiffness can also be increased by adding additional bolts to the pattern and increasing the density of the support by reducing the row spacing.

Figure 37: Bed separation in weak shale.

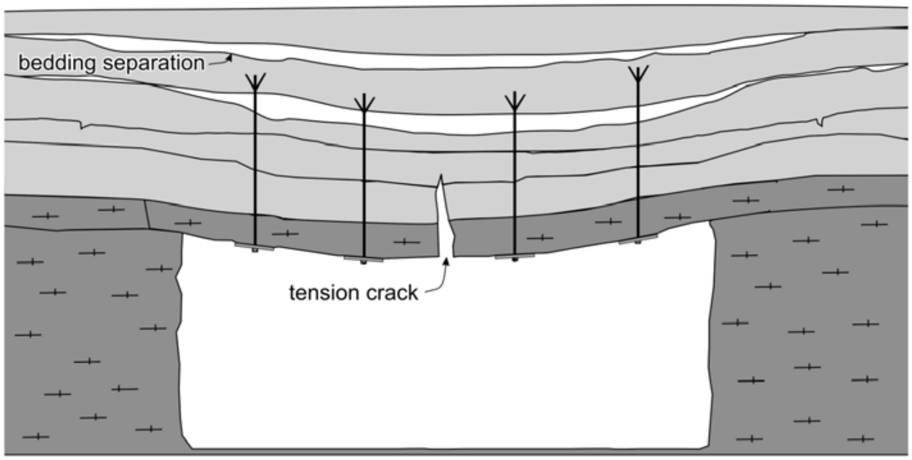

Figure 38: Tension cracks in the entry center develop as roof sags.

MINE G – A CASE STUDY OF ROOF SAG

A number of the roof failure types previously described affect the roof of the study site. The roof sequence at a study mine consists of 2-3 ft of roof coal overlain by a weak, highly slickensided, moisture-sensitive claystone. The claystone has coal streaks and large shears (extending 3-5 ft into the roof). The claystone is extremely moisture-sensitive and turned to mud shortly after immersion into water. Sandstone channels are locally found in the roof sequence over the coal seam, and large shears occur beneath the sandstone causing poor roof conditions. Water is also found in proximity to the sandstone causing swelling and degradation of the claystone. All roof falls have shown roof shears and slips, and it is thought that the density of the shears increases locally leading to roof falls. Horizontal stress damage is minimal.

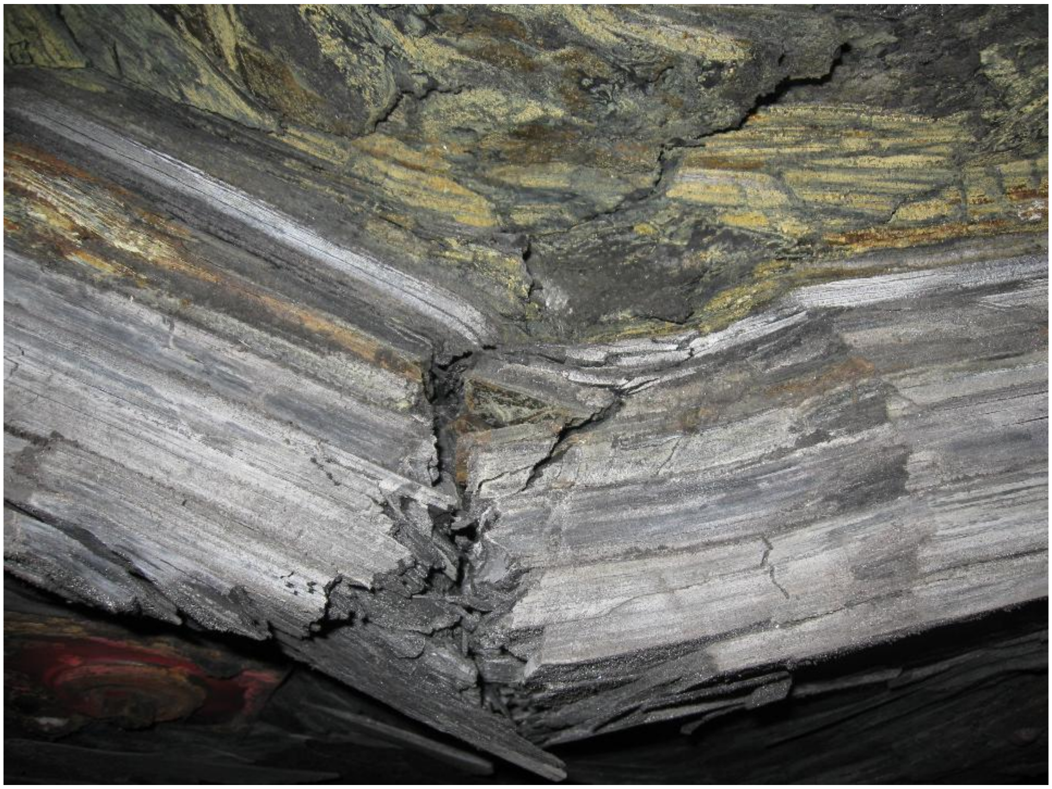

Figure 39: Tension crack develop in entry center as roof sags.

Figure 40: Tension crack in the entry center.

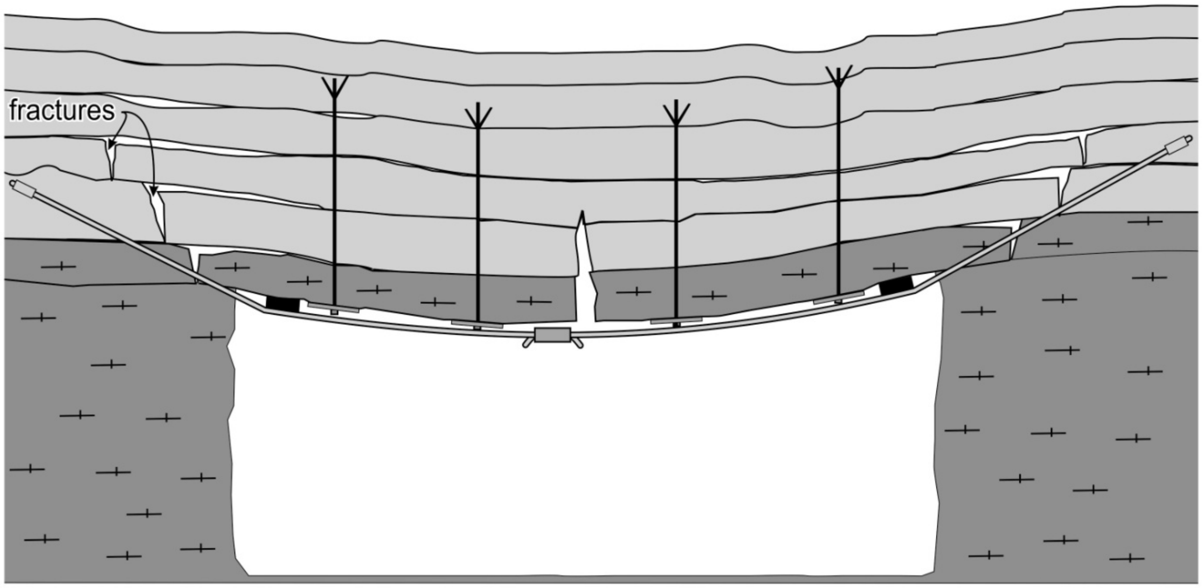

Figure 41: Stairstepping tension fractures begin at the rib abutment and extends over the pillar.

Figure 42: Stairstepping fractures extend over the pillar.

The roof coal has a Unit Rating of 36 and the overlying claystone has a Unit Rating of 32 for an overall ground water-adjusted Coal Mine Roof Rating of 30. The swelling claystone causes significant loading on the roof coal and causes damage to the roof when the roof coal is thinner than 2 ft. A large tension crack, often (3-4 in wide), can open in the entry center as the roof sags (Fig. 40). The roof beam also fails in tension and stair stepping tension fractures occur out and over the rib (Fig. 41). A similar failure was observed at another mine (Fig. 42).

The roof support system is overall very strong consisting of six 7/8 in diameter, 7ft long fully-grouted bolts per row. Secondary support consists of a single row or double row of trusses between bolt rows. The trusses are designed to achieve solid anchorage away from the stair stepping fractures when drilled at a shallow angle over the rib. Post-grouted cable bolts up to 35 ft long with steel mats are used in high value locations or under adverse conditions. The entire roof is covered with welded steel wire screen. As the head coal fractures and sags (over 12 in) when loaded from above by the swelling claystone, the load is transferred to the cable bolts and the trusses. The key component of the system is the roof screen, which confines the soft roof rock between bolts and transfers the load to the cables and trusses. Without this confinement the brittle coal would fracture and fall away leaving no bearing surface for the trusses, bolt plates, and mats.

The amount of roof sag can be extreme and solutions were sought to reduce the sag. One problem is poor roof bolt anchorage in the weak claystone. Short encapsulation pull tests (SEPT) tests were conducted to determine the roof horizon with the best “Grip Factor” [Pile et al. 2003]. The testing was successful in determining the optimum anchorage horizon and thus provides a basis for selecting roof bolt length. Other solutions included a novel hole rifleing bit, and using a larger diameter roof bolt hole to increase the rock resin surface area to prevent anchor pullout. Timely roof bolt installation is also important. If excessive roof sag and separation is allowed before bolting, resin squeezes into bedding cracks and prevents full grouting of the bolt due to resin loss at the collar. Post grouting of cable bolts also helps increase the stiffness of the support to reduce sag. The use of miner-bolter machines may help to reduce this delay in roof bolting.

SUMMARY

A high number of injuries and roof falls occur in weak rock sequences. In 2007 inherently weak and moisture-sensitive rock, coupled with high stresses, lead to 1568 unplanned roof falls and 443 rock fall injuries [MSHA 2007]. Most roof falls and injuries occur in supported ground, indicating that conventional roof support systems in these conditions may be inadequate. Recognition of failure mechanisms is important in designing mining sequences and support systems to safely mine the coal. NIOSH has conducted a study of coal mines with weak roof rock and detailed their geotechnical experiences in order to provide a basis for understanding coal mine roof hazards. Six common roof fall types have been described along with field examples of each. The roof geology, including defects, rock properties, and stress conditions have been described. In addition, roof support and control measures are included to evaluate both success and failure in these difficult ground conditions.

Recognition of geologic structures and their behavior under stress is an important first step in safe roof support practice. A thorough examination of roof falls will often reveal the contributing factors to the fall. Once an understanding of these factors has been achieved, designing the appropriate roof support becomes easier.

The transition between normal roof conditions and “adverse” roof is often subtle. In very weak roof rock sequences, the rock is often closer to “adverse” most of the time. For this reason, in difficult conditions, many mines use regular, systematic secondary support in high value roadways, including travel, belt, and escapeways. This support is often concentrated in intersections and can be installed on cycle or later when time permits. The support depends on the local conditions but may include a denser pattern of roof bolts, cable bolts, trusses, timbers, straps, or steel screen. Surface control has proven effective, and sometimes indispensible, in maintaining safe working places and travelways. Rock fall injuries and roof falls in supported ground indicate the need for improved roof support. Understanding roof failure mechanisms can help in designing roof support for weak ground conditions.

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Table 1: Geotechnical information from study mines.

Mine ID	State	Coalbed	Cover (ft)	Longwall/R&P	Roof geology	CMRR	CMRR (groundwater adjusted)	Roof defects	Moisture-sensitivity	Water problems	Draw-rock	Sandstone in roof	Horizontal stress damage
A	IN	Danville No. 7	200-300	R&P	Stackrock	38	38	Coal streaks, coal splits, slickensides	Yes	No	Yes	No	Moderate
					Green fireclay	33	24						
B	WY	D-41	250-900	Longwall	Weak claystone	45	36	Kettlebottoms	Yes	Yes	Head coal	Yes	Minor
C	WV	Pittsburgh	100-500	R&P	Roof rash, coal riders, soapstone, claystone	40	33	Slickensides	Yes	Yes	No	Yes	No
D	OH	Middle Kitt.	50-300	R&P	Shale overlain by sandstone	60	57	Slips, kettlebottoms	Yes	No	No	Yes	No
E	KY	No. 9	<600	R&P	Black shale overlain by gray shale	39	26	Siderite nods, faults	Yes	No	No	No	Severe
F	KY	No. 9	475	R&P	Black shale overlain by gray shale, "slips"	38	26	Fossils, siderite nodules	Yes	Yes	No	Yes	Minor
G	IN	No. 5	160-330	R&P	Thick Dyersburg shale (greenish-gray)	39 est.	26 est.	Siderite nodules, slickensides, shears	No	Yes	Yes	Yes	Moderate
					Black shale/limestone	83 est.	83 est.						
					Stackrock	38 est.	38 est.						
H	KY	No. 9	200-300	R&P	Black shale/gray shale	46	29	Mudstone, sag	Yes	Yes	No	Yes	Moderate
I	KY	No. 9	200-300	R&P	Black shale/gray shale	43	33	Slickensides, shears	Yes	Yes	Yes	Yes	No
J	WV	No. 2 Gas		R&P	Black fireclay/brown fireclay	46	37	Coal streaks/fossils	Yes	Yes	Yes	No	Moderate
K	IN	No. 6	110-220	R&P	Black shale/Brereton	84	86	Joints	No	No	No	No	No
					Stackrock	38 est.	38 est.						
L	IL	No. 6	300-600	Longwall	Energy shale, lam shale, gray shale	32	23	Weak rock, slicknsides	Yes	Yes	No	No	Moderate
M	MD	Upper Freeport	180-380	Longwall	Laminated gray shale/sandstone	62	57	Slickensides, clay veins	No	No	No	Yes	No
N	WV	Sewickley	0-600	R&P	Black shale	42	38	Jointing, siderite nodules	No	Yes	Yes	Yes	Minor
					Stackrock	61	59						
					Sandstone/gray shale	48	40						
O	IL	No. 6	600	Longwall	Black shale/limestone	83 est.	83 est.	Joints, siderite nodules, slickensides, faults	Yes	No	No	Yes	No
					Energy shale	36	29						
P	OH	Upper Freeport	400-500	R&P	Stackrock	38 est.	38 est.	Stream valley defects	No	No	No	Yes	Moderate
Q	OH	Mahoning		R&P	Black shale/gray shale	47	41	Slickensides, sandstone channels	Yes	No	No	Yes	Moderate
R	OH	Mahoning		R&P	Black shale/gray shale	47	41	Slickensides, sandstone channels	Yes	No	No	Yes	No
S	IN	No. 5	250-300	R&P	Gray shale/limestone	42	34	Siderite nodules, jointed	Yes	No	No	No	No
T	IL	No 6	200	R&P	Energy Shale	35 est.	25 est.	Varve, sandstone	Yes	Yes	Yes	Yes	Severe
U	NM	No. 8	100-600	Longwall	Roof coal\weak claystone	31	25	Slips, shears	Yes	Yes	No	Yes	No
V	KY	No. 9	350	R&P	Black shale/gray shale	50	43	Joints, siderite nodules	Yes	Yes	Yes	Yes	Moderate