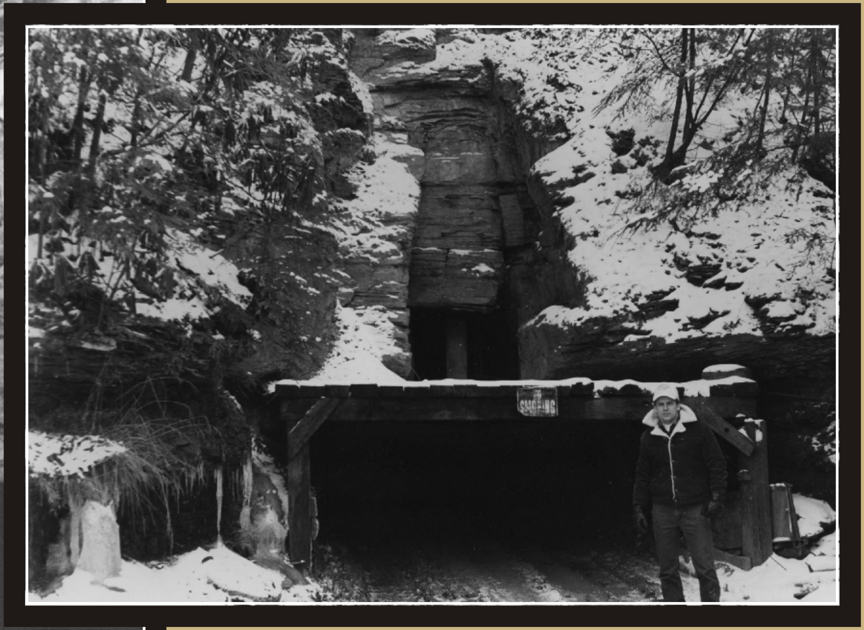
Workplace Safety and Health

IC 9466

INFORMATION CIRCULAR 2003

Geologic Hazards and Roof Stability in Coal Mines



Department of Health and Human Services
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

`**Information Circular 9466**

Geologic Hazards and Roof Stability in Coal Mines

By Gregory M. Molinda

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Public Health Service
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health
Pittsburgh Research Laboratory
Pittsburgh, PA

October 2003

ORDERING INFORMATION

Copies of National Institute for Occupational Safety and Health (NIOSH)
documents and information
about occupational safety and health are available from

NIOSH–Publications Dissemination
4676 Columbia Parkway
Cincinnati, OH 45226-1998

FAX: 513-533-8573
Telephone: 1-800-35-NIOSH
(1-800-356-4674)
E-mail: pubstaft@cdc.gov
Web site: www.cdc.gov/niosh

DHHS (NIOSH) Publication No. 2003-152

CONTENT

Page

ILLUSTRATIONS

ILLUSTRATIONS–Continued

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	km	kilometers
ft^3	cubic foot	mi	miles
gal/min	gallon per minute	min	minutes
in	inch	psi	pound per square inch

GEOLOGIC HAZARDS AND ROOF STABILITY IN COAL MINES

By Gregory M. Molinda[1]

ABSTRACT

The U.S. underground coal miner faces a continuing hazard from the fall of roof. At the root of many injuries and fatalities are weak or defective roof strata. Throughout mining history, millions of miles of entry have provided exposure of every conceivable geologic roof hazard. This report describes the geologic origin, association, and potential danger from the most common hazards. Discussions of weak rock include drawrock, rider coals, head coal, stackrock, and stream valley effects. Discontinuities, or roof defects, are described including, clay veins, slickensides, joints, and paleochannels. A number of examples from U.S. coalfields are used to document geologic structure and associated hazards. Roof fall analysis is a methodology used by NIOSH for hazard recognition and prevention; its application and benefit to the industry are discussed.

---

[1] Research geologist, Pittsburgh Research Laboratory, National Institute for Occupational Safety and Health, Pittsburgh, PA.

BACKGROUND

Although roof and rib fall fatalities in U.S. coal mines have greatly decreased because of technological advances (e.g., roof bolting, canopies, automatic temporary roof supports (ATRS), longwall mining, rib support, and screening), fatalities (figure 1) and injuries (figure 2) continue to plague U.S. undeground coal miners. In 1999, 745 injuries resulted from 2,087 reported roof falls [MSHA 1999]. Many of these fatalities and injuries are due to weak roof strata and unexpected discontinuities in the roof. Within the accident narratives filed by operators to the Mine Safety and Health Administration (MSHA) are numerous references to "slips," "horsebacks," "faults," "coal streaks," "clay veins," "joints," and "rolls".[2] These are all geologic defects or weaknesses in the roof that were not anticipated or adequately supported. The ground control program at the Pittsburgh Research Laboratory for more than 30 years has focused on numerous safety issues. These include roof bolt effectiveness, bump control, strata deformation, subsidence, retreat mining, and horizontal stress. Integral to each one of these topics and many more is geology. Indeed, the behavior of sedimentary sequences to the applied stresses of mining is central to both short- and long-term opening stability. Almost every aspect of the creation of underground excavations will require a description and analysis of the local strata to provide a framework for an engineering solution. This strata description is necessary to explain ground reactions and to attempt to capture the effect of a material variable that can change drastically on a micro and macro scale.

The National Institute for Occupational Safety and Health (NIOSH) has had success in using a rock mass classification called the Coal Mine Roof Rating (CMRR) to evaluate the strength of coal measure roof sequences. A number of successful engineering solutions have been applied to rock mechanics problems using the CMRR. These topics include multiple-seam design guidelines, gateroad design, and selection of tailgate support [Mark et al. 1994]. The CMRR considers discontinuities in the bolted roof sequence and the weakness they impart to the rock mass. With simple field and lab tests, the relative strength of any coal mine roof rock can be determined. The important rock properties include the uniaxial compressive strength (UCS), the effects of moisture deterioration of the rock, and the bedding strength of the core. Researchers have developed other rock mass classifications as well [Bieniawski 1988; Kester and Chugh 1980; Buddery and Oldroyd 1992]. Some systems concentrate on geologic structures and their effect on roof quality [Moebs and Stateham 1985; Milici et al. 1982].

Although this classification approach has proved valuable and has resulted in numerous engineering solutions to ground control problems, much geologic information falls outside the partition of classification. Mining geologists have long known that specific geologic structures can occur either in a systematic or isolated manner and can significantly impact safety and productivity. These structures weaken the roof beam and can cause damage that is not prevented by conventional roof support. In addition, the occurrence of the geologic structures may not be obvious to the untrained observer. For these reasons, NIOSH has undertaken to study and document the nature and occurrence of common geologic structures that may form hazardous roof when exposed. The purpose of this study is to present to the industry real field experiences that have been documented through underground visits and examinations of other exposures, including highwalls. In this way, the NIOSH ground control program addresses regular geology through the CMRR and anomalous geology through individual description.

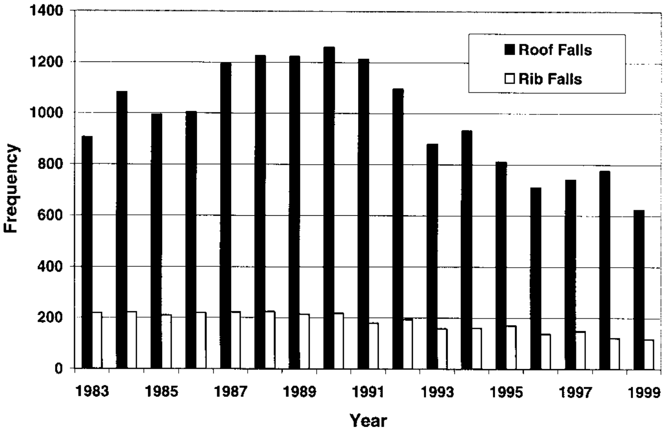


Figure 1.–Injuries caused by the fall of roof and rib in U.S. coal mines, 1983-99.

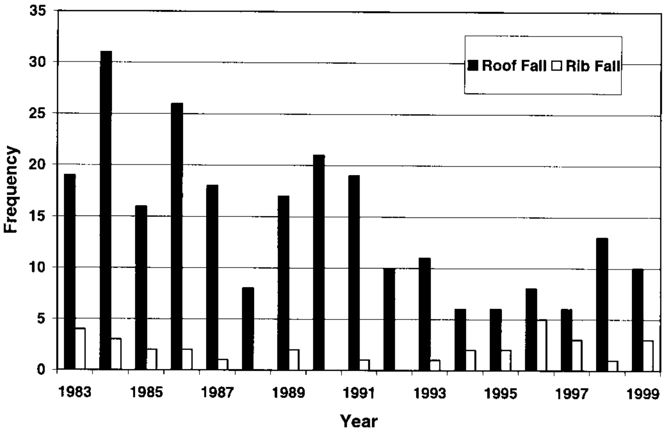


Figure 2.–Fatalities caused by the fall of roof and rib in U.S. coal mines, 1983-99.

Numerous researchers have described the various geologic environments and rock types that form the coal mine roof [Damburger et al. 1980; Ferm 1974; Iannacchione et al. 1981; Ingram and Chase 1987; Milici et al. 1982; Hylbert 1978; Molinda and Ingram 1989; Sames and Moebs 1991; Greb 1991; Nelson 1991]. Geologic models and classifications have been used for the purpose of constructing hazard maps and mine plans. The tracking of hazardous roof layers is

---

[2] Refer to the glossary at the end of this report for definitions.

important, but can be difficult when exploratory drillholes are limited and widely spaced. It is almost impossible to recognize and project geologic defects (clay veins, shears, horsebacks, etc.) in the roof from only exploratory core. Many times recognition and projection of features occurs by close underground observation.

There are three parts to safely mining beneath weak roof: (1) recognizing and understanding the origin, nature, extent, and potential hazard of the geology, (2) predicting/ anaticipating and tracking the feature in the roof, and (3) adequately supporting the roof or avoiding the hazard. This report discusses aspects of all three areas. It also discusses the geologic environment of formation. Some of the more common geologic roof hazards that occur in coal mine roof are presented, but the report is not intended to be an exhaustive reference on all roof hazards.

THE ORIGIN AND HISTORY OF THE COAL SEAM AND OVERLYING ROOF ROCKS

The strength or weakness of coal seam roof rocks can be explained by the depositional environment in which the coal seam was formed and its subsequent burial and tectonic history. James Hutton's *Principle of Uniformitarianism* states that the processes governing the deposition of sediments today can be used to explain the deposition of the rock record of the past. Operators can use the modern-day coastal delta system as a model for coal measure rocks of the past.

Minable coal seams, especially the widespread and continuous coal seams of the Appalachian and Illinois basins, represent unusual geologic conditions not typically found in the geologic record. These coal seams developed from peat swamps that existed, relatively undisturbed, at sea level for several thousands of years. By necessity, the vegetation of the peat swamp required a stable subaerial platform (delta) for this length of time or sea flooding would have terminated the swamp and prevented significant peat formation. Conversely, an emergence of the swamp (by sea level reduction or tectonic uplifting) would have drained the swamp and precipitated its removal by erosion and weathering.

The Mississippi delta system can be used as a model for ancient coal seam deposition in order to envision the formation and preservation of a coal seam. The model also explains some of the disturbances and weakness in coal mine roof rocks. The familiar birdsfoot Mississippi delta complex is a stable structure that is building out into the Gulf of Mexico. It is at this interface where new land is created and swamps are formed. The vegetation on the delta is sustained by influxes of freshwater from the distributary system mixed with seawater. If undisturbed, thick widespread sequences of peat can form (figure 3).

The distributary river system feeding the delta is free, at sea level, to meander about the coastal plane because it is unconfined by valley walls. In addition, lower stream velocities, due to low gradients, also free the stream from channelization. Periodically, the river floods and breaches its banks (crevasse splay). A new river channel and delta complex is established and the previous delta is abandoned (figure 4). This pattern of delta formation and abandonment is repeated countless times in a large delta system (hundreds of square miles in area). In this way, channels are commonly eroded into the peat swamp. Abandoned channels can also fill with sand, silt, and clay, which can disrupt coalbed continuity and become future mining hazards. Channel systems are often "stacked" by overlapping deposits from flooding river systems, causing more roof hazards (figure 5).

Most of the familiar roof rocks of present day coal mines can be explained by this fluvial-deltaic model. As large open-water bays between fingers of the distributary river system become filled with silt from seasonal flooding, they emerge and peat swamps are established. As a crevasse splay floods the peat swamp with silt and clay, the future coal mine roof is formed (siltstones, shales, claystone). If the channel is abandoned, the swamp may drain enough to again establish vegetation using the underlying clay as a seat earth. The result is a rider coalbed with a weak drawrock beneath, again presenting future roof problems.

Thick blanket sandstones, which make excellent roof, may be the result of several different environments. The alluvial plains upstream of the active delta contain more sand, which comes in direct contact with a peat swamp. As rivers meander back and forth over the plane, peat swamps are covered by thick sand blankets, eventually becoming strong, massive sandstone. Another environment is at the distributary mouth where sands are dumped at the end of the river. These sands are then reworked by wave action and spread out as thick beach deposits much like the modern barrier islands of New Jersey. They can overlap adjacent peat swamps and form the future sandstone roof of a coal mine. Limestone roof is more frequent in southeastern Ohio and Illinois mines. These marine deposits are formed offshore of the delta mouth or in marine embayments between delta lobes. Limestone roof is more uniform and laterally consistent because it is formed in quieter offshore waters.

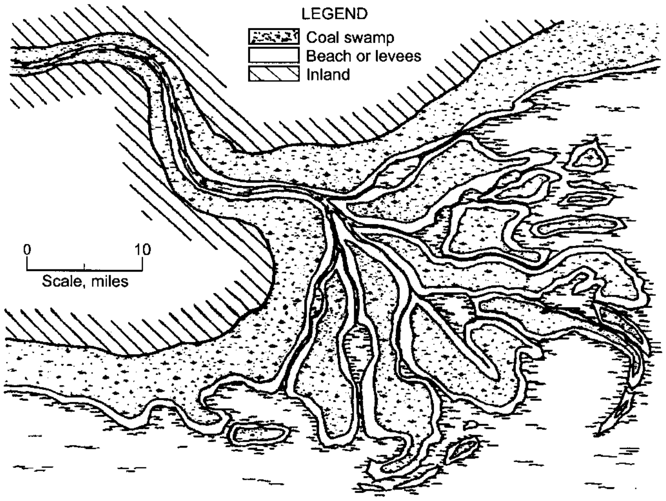


Figure 3.–Deltaic model for the environment of deposition of a coalbed.

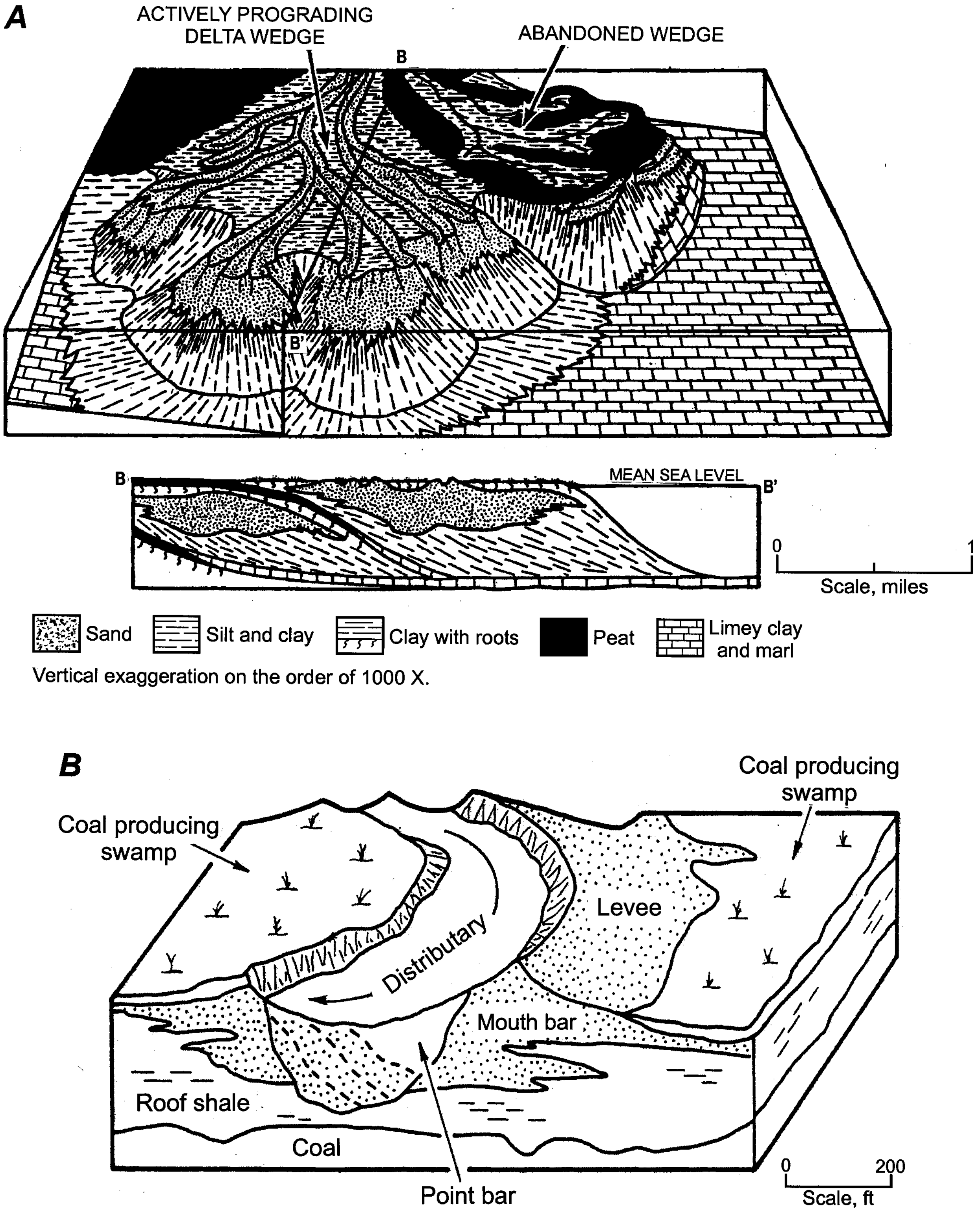


Figure 4.–Coal-forming environment of deposition. ***A*****, Advancing active delta wedge with an adjacent abandoned wedge (modified from Ferm [1974]).** ***B*****, Detailed cross-section of a coal-forming wedge showing a stream channel dissecting a coal-forming sequence.**

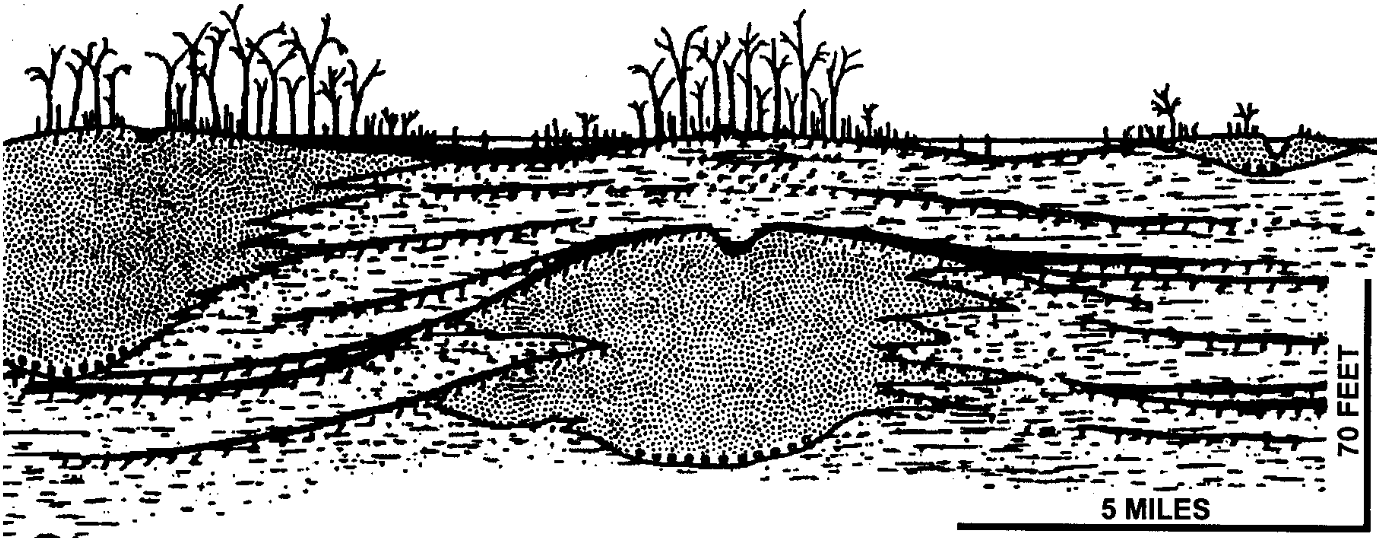


Figure 5.–Stacked paleochannels left from migrating stream channels in a deltaic distributary system. Mining under or near these sand bodies presents a roof fall hazard [Ferm and Cavaroc 1968].

GEOLOGIC HAZARDS

Roof deterioration can range from a few inches of scale between bolts to complete failure in the form of a roof fall that could run for hundreds or thousands of feet. MSHA defines a reportable roof fall as any roof failure that (1) causes injury that has reasonable potential to cause death, (2) disrupts regular mining activity for more than an hour, (3) occurs at or above bolt anchorage, (4) impairs ventilation, or (5) impedes passage [30 CFR[3] 75.223]. The goal of primary roof support is to build a stable roof beam or to suspend immediate roof from a competent overlying roof beam between coal pillars. Roof falls can occur when the roof beam is damaged or severed. The geologic hazards that can damage or destroy the roof beam are here grouped into two categories: weak rock and structural discontinuities.

WEAK ROCK

Most of the injuries related to roof falls in U.S. coal mines are due to the fall of small pieces of rock between bolts or from pieces dislodged by the ATRS or the bolting operation itself [Bauer and Dolinar 2000]. These failures are known as "roof skin falls" and are the subject of current NIOSH research. As expected, they occur much more frequently in weak rocks because of weak bedding cohesion and the tendency to weather more easily. Generally, coal measure rocks are weaker than other sedimentary rocks because they have been deposited in shallow near-surface waters and have been subjected to a number of disturbances from rapidly changing environments (peat swamp flooding causing seam splits, channel erosion causing slumping, burrowing, and differential compaction from burial loading) (figure 6). Sediments deposited in quiet waters (lagoons and brackish water interdistributary bays) are clay and mud-rich and have weakly bonded laminations. When overbank floodwaters introduce coarser sediment, the bedding contacts are particularly weak. Within coal measures, the UCS varies greatly from crystallized sandstone (UCS > 20,000 psi) to crumbling clay shales (<300 psi), but most roof rocks are shales, claystones, sandy shales, siltstones, stackrock, or other variations of mudrocks.

The CMRR rates the roof rock from 0 (weak) to 100 (strong) by considering—

- Bedding strength
- An index test for the UCS
- Moisture sensitivity
- The frequency and strength of discontinuities
- A strong bed adjustment

The CMRR is used in this report to indicate the strength of roof sequences.

There are a number of geologic explanations for weak rock in the immediate roof. These include weak, plastic clay compositions; closely spaced laminations; water-sensitive shales; disturbed bedding; and bedding defects like coal stringers, slickensides, and lag deposits. These features are usually depositional and inherent to the rock fabric. They are distinguished from structural discontinuities, which are generally due to erosion, differential compaction, structural faulting/fracturing, and horizontal stress. Weak types of roof strata are explained below.

---

[3] *Code of Federal Regulations*. See CFR in references.

Drawrock

Drawrock is generally defined as soft shale or mudrock that falls soon after mining or is taken down by the miner because it is difficult to support. Geologically, this rock is often a seat earth, underclay, or paleosoil and represents the beginning of another peat swamp established on top of the main coal seam. The rock may be the base of an overlying rider coalbed that was not preserved. The unit rating (UR) of drawrock falls into the 20-35 range (a UR is the strength given to each roof unit in the CMRR calculation) [Molinda and Mark 1996]. In a recent roof bolting survey, 36% of all reporting mines (17 of 47) stated that they mined drawrock from the roof or that drawrock on occasion formed the immediate roof.[4]

Figure 7 is an example of a potentially dangerous drawrock. It is a lag deposit that significantly disrupts the roof in an eastern Ohio mine. Large basal cobbles are intermingled with sand, silt, and clay matrix, forming an immediate roof that is barely self-supporting (UR = 28 (weak)). The rock can be crumbled by hand. Differential compaction has caused slickensides throughout the sequence (up to 4 ft long). This lag is the unsorted product of bed load carried by a fast-moving stream. Here, the lag sequence has damaged the roof over an area of 14 acres and resulted in a roof fall rate of more than 17 falls per 10,000 ft of drivage (high roof fall rates are 2.0 falls per 10,000 ft).

Several mines report using the color of the drawrock as a rule of thumb to indicate its strength. In general, they note that the lighter the shale, the weaker the rock. Although dark color locally can indicate stronger rocks, black shales are often weak on bedding. Usually the drawrock will fall to a more competent unit, which will form a more stable bolted roof beam or anchorage horizon. The difficulty comes when the thickness of the drawrock increases rapidly, resulting in an unacceptable dilution of the coal. When the drawrock reaches 18 in or more, it may become necessary to bolt through the unit and try to support it. This often results in uneven roof where some drawrock has been taken down right next to thick drawrock that has been bolted. The uneven roof decreases the strength of the roof beam by reducing its thickness. The exposed brow also acts as a conduit for moisture. Drawrock is often highly moisture-sensitive and, with time, may result in 6-12 in or more of "chandelier bolts" as the rock "rats out" between the bolts (figure 8*A*). In severe cases of "chandelier bolts" (8-12 in), the roof beam is effectively severed (or at least drastically reduced) and must be rebolted (figure 8*B*). Roof scale can be controlled by steel screen, plastic mesh, or geogrids applied to the roof. One mine in southeastern Ohio reported problems with a weak black shale in the immediate roof spalling out between the shields and in front of the shield tips. This rock is already weak and is additionally fractured when the shields are pressured against it. Large pieces roll off the face, causing an uneven surface for shield setting as well as presenting a hazard to the operators. Another mine reports that tensioned bolts can apply forces large enough to fracture the brittle roof.

Weak drawrock can affect the length of cut taken. Grau and Bauer [1997] report that at one mine where the immediate roof was more stable, more extended cuts were taken on that side of the section than on the side of less stable roof. Remote-control mining machines are damaged from small pieces of drawrock. Drawrock also makes roof bolting more difficult and dangerous due to ragged roof. Weak drawrock is a cause for limiting the length of cut, especially when it is known that bolter delays will prevent quick roof bolting.

Drawrock is more common in fluvial depositional environments. This is the environment more affected by the main stream channel and seasonal flooding. These rapidly changing upper deltaic environments produce high contrasts in rock types: micaceous sandstone on shale, wild coal on silty shale, etc. These contrasts make for weak contacts and weak roof. In marine-dominated roof sequences (Illinois basin), thick shales or limestones make stronger and more persistent roof. Another 59% of reporting mines (22 of 37) in the roof bolting survey also had slaking problems in the immediate roof, which opens the potential for deterioration between bolts.

Roof Bolt Anchorage

In cases where thick drawrock must be bolted up, it is important to try to suspend it from a strong rock unit. The importance of a relatively strong rock member within the bolted interval is known [Molinda and Mark 1994]. It is preferable to support weak roof in suspension rather than try to build a roof beam entirely in weak rock. This may mean longer bolts, and it is essential to locate anchorage either by observation of drill cuttings or by borescope. Although immediate roof that is supported in suspension may only pot out up to the stronger anchorage, roof support that is attempting to build a beam entirely in weak rock has the potential for roof failure above anchorage due to anchor slip and progressively upward delamination and moisture infiltration.

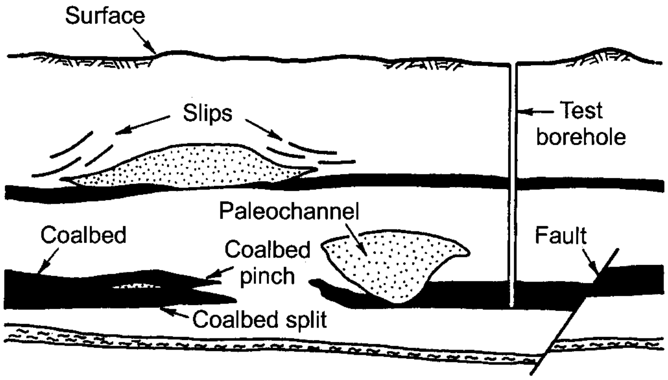


Figure 6.–Potential discontinuities in coal measure rocks caused by changing depositional environments may pose roof fall hazards.

---

[4] Data available on request from G. Molinda.

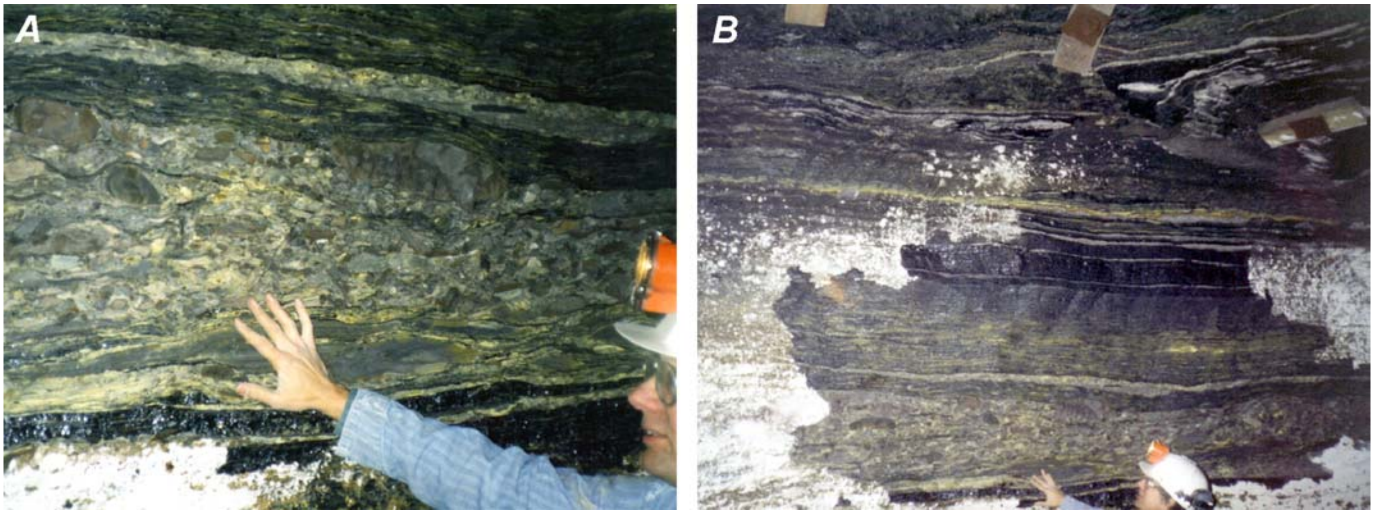


Figure 7.–Wedge-shaped lag deposit forms a weak drawrock in coal mine roof in southeastern Ohio. *A*, Close-up view; *B*, long-range view.

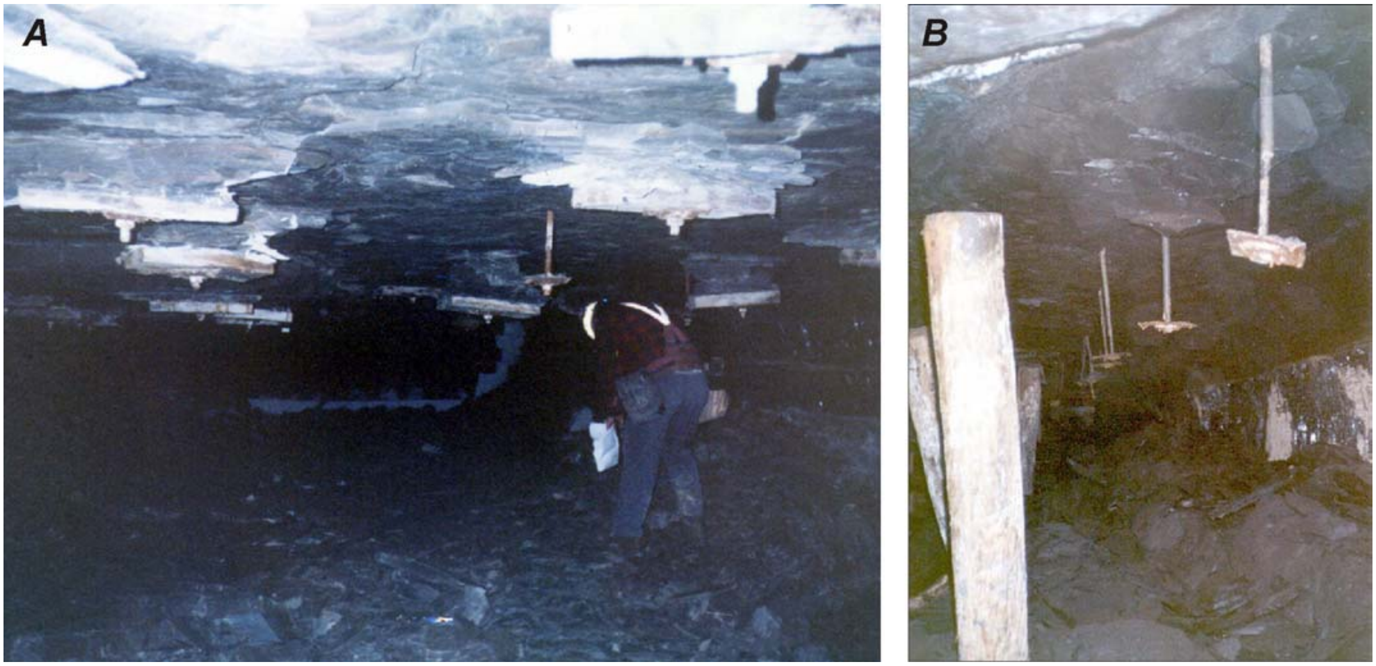


Figure 8.–*A*, Weak drawrock begins to fall out between roof bolts. *B*, Progressive deterioration occurs with time.

Thick drawrock can cause roof bolts to miss their target anchorage. At an Ohio mine, a drawslate with a UR of 17 usually falls out with mining and the roof is formed in the overlying rider coal. Figure 9 shows the roof sequence. The main limestone in the roof was the target anchorage for a 6-ft point-anchored resin-assisted bolt. If this anchorage is achieved, the CMRR = 72 and the roof is effectively supported. If the roof coal or the overlying claystone gets thick, the bolts fall short of the limestone anchorage and the CMRR drops to 30. The loss of the limestone as an anchorage is dramatic to the strength of the bolted roof. For this reason, an 8-ft point-anchored resin-assisted bolt is now used. In addition, if the roof coal thins and falls or is inadvertently cut through, the highly moisture-reactive and slickensided claystone is exposed and pots out. When this occurs, the mine uses metal screen to support the weak, exposed claystone. There are many examples of stable roof when strong rock members are close enough to provide good bolt anchorage. Limestone units, more common in Ohio and the Illinois basin, are generally more uniform and of consistent thickness and location than sandstone bodies. It is always preferable to take down weak rock instead of bolting it, but taking down weak drawrock can present another hazard. With the immediate top down, the drawrock forms the upper rib and sits

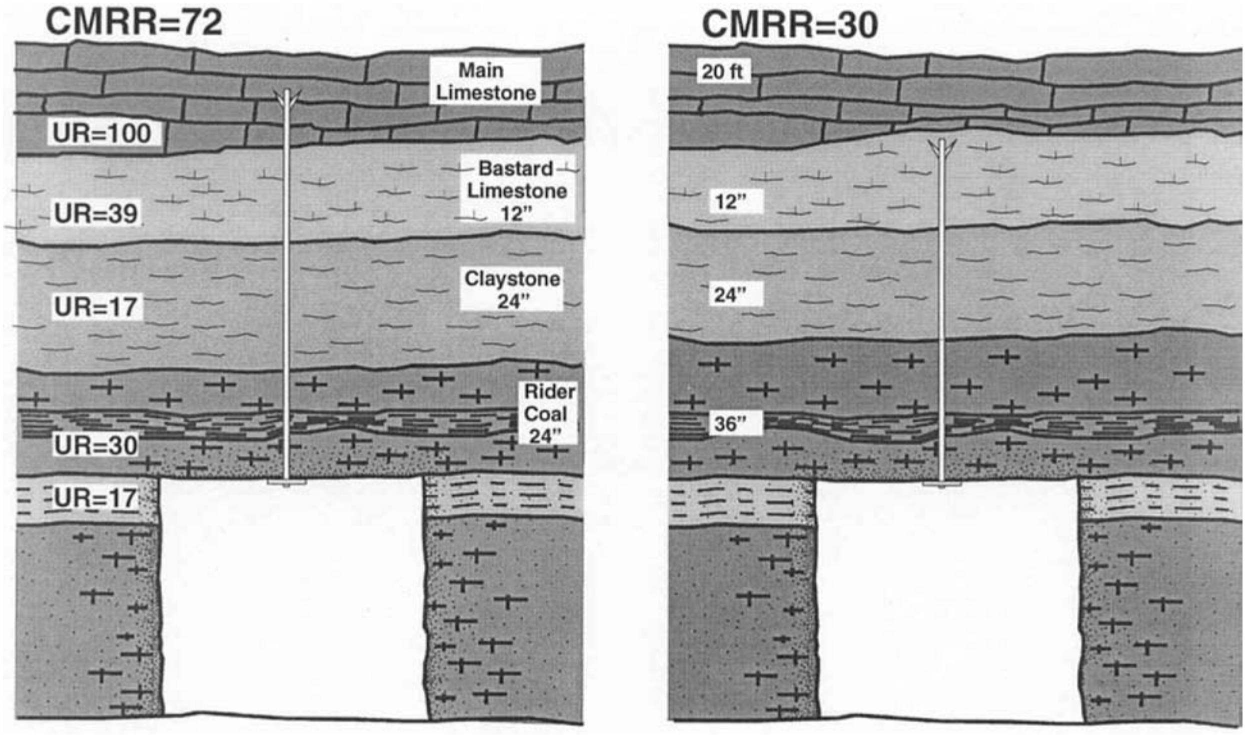


Figure 9.–Head coal in an Ohio mine thickens in the roof, causing roof bolts to miss a strong limestone anchorage, which reduces the CMRR from 72 to 30.

unsupported above the main seam. It is generally highly slickensided, and fatalities have occurred from rib rolls close to the roof.

In rolling sandstone top, it is critical to monitor anchorage height by drilling blind holes every 20 ft. This requirement is written into many roof control plans. In MSHA District 5, test holes are required regardless of strata type [McLoughlin 2001]. One mine in Illinois records the height to a limestone bed on the rib at each intersection. The data are then recorded and plotted on base maps to determine trends.

At a mine in Logan County, WV, the immediate roof contains a brown seat earth with almost no strength (figure 10). This roof member can range from 2 in to 4 ft thick. In this case, bedding has been destroyed by burrowing and differential compaction and the rock fractures in clods. Mostly this drawrock is taken down, but as it thickens locally it must be bolted up. When it is bolted, it tends to fall out between bolts, but the greatest problem is that, commonly, the 6-ft bolt misses a strong anchorage in the overlying sandstone. Unless the bolter can adjust and install longer bolts, the roof beam will be formed in an extremely weak bed.

Figure 10.–As a weak seat earth thickens in a southern West Virginia mine roof, it causes roof bolts to miss anchorage in a strong sandstone.

Stackrock

Stackrock is often associated with weak or poor-quality roof, especially when subjected to high horizontal stress. Stackrock is a coalfield name for a sequence of rock composed of interbedded sandstone and shale. The "stack" looks like a tall column of telephone books or newspapers due to its peculiar bedding breakage. It is also referred to as "catalogue rock" or "transition rock." The rock is really a mixture of sandstone and shale in widely varying proportions. It grades into a shale with sandstone streaks as one end member and a sandstone with shale streaks as the other end member (figure 11). Geologically, the stackrock sequence represents alternating periods of high-energy water movement (depositing sandstone) with quiet low-energy standing water (depositing shale). Springtime surges of floodwaters in deltaic rivers may break through natural river levees in a crevasse splay, depositing blankets of sand. Silts and muds are deposited on top of the sand as the surge wanes. Subsequent surges of water through the levee in a subsequent flood deposit more sand and repeat the cycle. As the river meanders across its valley by abandoning its channels, stackrock sequences fan out and overlap vertically. These sequences can be 100 ft or more thick and cover hundreds of square miles (figure 4*B*) [Pettijohn et al. 1973]. Stackrock sequences are flatlying, indicating their discharge into open areas (peat swamps and lakes). At their feather edge, dips are <1°. They often grade laterally into thick sandstone wedges in the direction of the paleochannel. Chances are good that a mine that reports channel sandstones in the roof or eroding the seam will also encounter stackrock at some location on the mine property near the channel. The size of the channel source will determine how far the stackrock wedge will reach (100 ft to several miles).

At first glance it may seem that stackrock would form a stronger beam when reinforced with roof bolts. In structural support, an engineered composite beam is stronger than a beam formed from a single member. The problem with roof bolts is that it is difficult to exert enough compression on the stackrock beam to prevent its laminas from shearing horizontally. Once this delamination occurs, the strength of the beam becomes the strength of the individual laminations. Stackrock can be strong axially (12,000-15,000 psi) depending on the proportion of sandstone in the mix, but is typically weak along bedding. The CMRR of stackrock averaged 40-48 from 90 samples tested. Although average axial strengths ranged from 4,653 to 11,335 psi, average tensile bedding strength ranged only from 1,482 to 2,508 psi in samples with a Ferm number of 322, 323, 332 [Molinda and Mark 1996; Ferm and Smith 1981]. Even small amounts of roof sag can break bedding bonds and begin an unraveling of the sequence. In this situation, quick bolting and an active tensioned system may help reduce sag.

When subjected to horizontal stresses, stackrock makes notoriously bad roof. The sandstone beds can act as stress concentrators and cause tensional delamination with adjacent shale beds as they buckle individually. Weaker shale interbeds may crush and exhibit characteristic "overshoots" or rock "flour." (figure 12). The lower sandstone bed (2-3 in thick) did not shorten and cut because of its higher stiffness. It failed because of stress concentration, falling away to reveal the above shale. The shale above shows feathering and rock floor damage, which is more typical of softer shale. Stress-induced roof falls are often higher and more localized to intersections in stackrock than shale roof. Shale roof cuts and gutters more easily along the rib line because it is less stiff. Falls tend to "run" for long distances depending on the orientation of the entry to the principal stress. Stackrock falls because sandstone interbeds concentrate stress and "bulk," then delaminate vertically until a stable stratum is reached, resulting in a flat-topped fall. In thinly laminated stackrock with a high proportion of shale, it is important to maintain close control on entry width and bolt the roof as soon as possible to prevent initial sag and delamination. In stackrock with a higher percentage of sandstone and thicker shale beds, a staggered-length bolt pattern may prevent accidental anchorage in the weak shale. If roof sag occurs at the weak shale band, the longer staggered bolts will act to suspend the separated roof beam, provided a stiff anchorage is found. In areas of high horizontal stress where bulking and delamination cannot be prevented, cable bolts in intersections will provide a softer support and allow some movement.

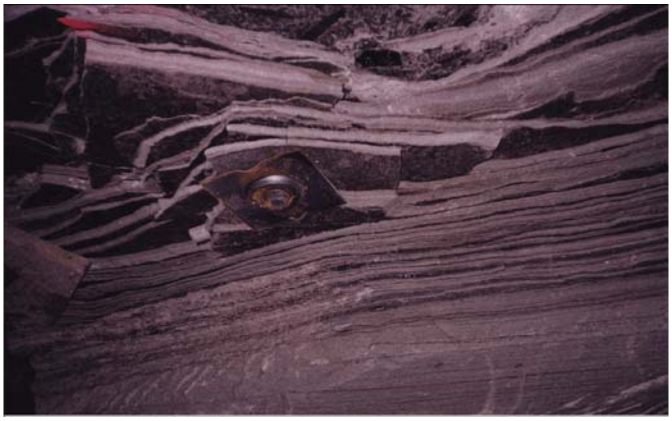


Figure 11.–Stackrock showing weak partings between sandstone and shale beds.

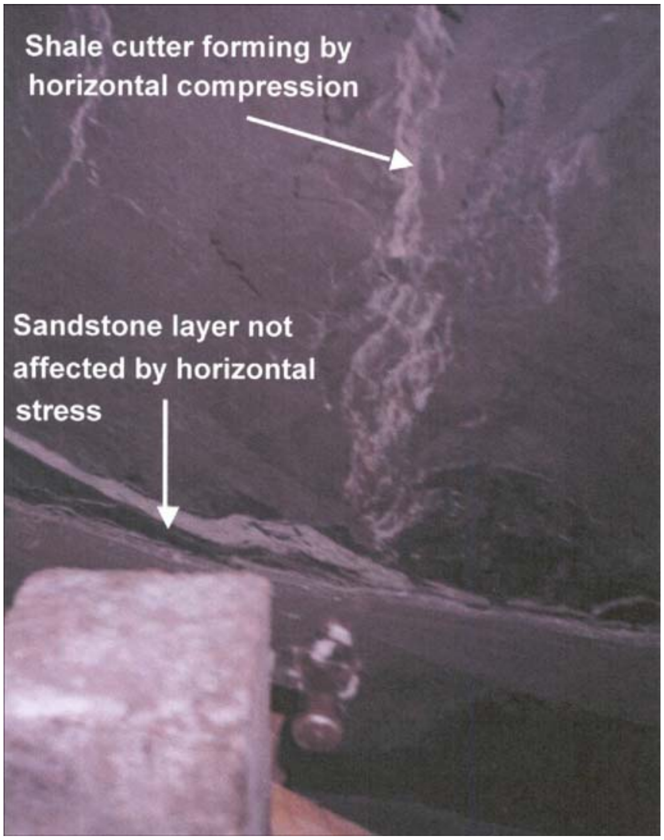


Figure 12.–Cutter forming in shale bed that overlies a thin sandstone (2-3 in) in a stackrock sequence. The lower sandstone acts as a stress concentration and falls away to reveal the shale.

Valley Stress Relief

The effects of mining under valleys are manifested in two ways. First, a valley can act to reorient and concentrate an active regional stress field as the horizontal stress attempts to deflect underneath the valley. This can concentrate stresses at the bottom of a valley and cause roof damage if the mine is close enough to the valley bottom. Van der Merwe [2000] reports the K ratio (ratio of horizontal stress to vertical stress) is much higher at depths <650 ft (up to 5.7), which can occur beneath stream valleys. Secondly, stress relief prior to mining can damage roof rocks as the valley is downcut and confinement removed. The second type is discussed here.

Roof damage due to stress relief under valleys is well documented [Molinda et al. 1992; Fergusen and Hamel 1981; Fergusen 1967; Moebs 1977; Moebs and Stateham 1985]. There is evidence that wide, flat-bottomed valleys have experienced more premining valley floor buckling due to less confinement than V-shaped valleys. (The latter are more likely to have experienced active mining-induced stress and to have cutter damage.) The effects of valley stress relief have been observed at 300 ft of cover and deeper [Fergusen and Hamel 1981] in the form of small overthrust faults, fault gouge, slickensides, and fractured rock. Molinda et al. [1992] found that 52% of all unstable roof areas in five mines occurred beneath valley bottoms. Twenty-four of thirty-one mines (77%) that responded to a survey had roof problems while mining under stream valleys. Problems include cutter roof, swags, fractured roof, large shears, swelling clays, and water inflow. Some operators had roof problems sporadically under valleys; others had problems under every valley.

At a mine in Boone County, WV, a manshaft was being sunk in a deep valley about 800 ft wide. At 43 ft down, a 4-ft-wide natural bedding plane separation was encountered in stackrock. Horizontal drilling showed the opening to extend 8 ft away from the shaft wall. The opening made 80 gal/min of water for 6 days. Blasting to 10 ft below the separation stopped the water inflow. Horizontal movement caused by the transfer of load from the adjacent valley walls (900 ft of relief) seems to have caused the separation even under the confining overburden load. It is impossible to determine the cover at the time of valley stress relief.

Roof damage was documented beneath a side valley at the same mine. Open bedding planes in the stackrock roof were exposed under 160 ft of cover. Roof falls over 100 ft long and 20 ft high were common. Fault gouge 1/8 in thick was present in roof bedding planes, indicating premining failure of the shale members of the stackrock, a result of valley stress relief (figure 13). Roof sag occurred as a result of the removal of the coal support during mining, causing bolts to load and fail. No active stress was observed due to complete valley stress relief.

Head Coal

Head coal is coal that is left in the top part of the minable bench and forms the immediate roof. There are several reasons for leaving head coal. (1) If the seam is too high to mine easily, some coal is left to reduce mining height. (2) Often the upper part of a coal seam is of poor quality due to sulfur or ash content and is left for economic reasons. (3) The most common reason for leaving head coal is to protect a moisture-sensitive mudrock above. Fourteen of thirty-seven mines surveyed (37%) in the aforementioned roof bolt study reported leaving head coal in the immediate roof. The thickness of head coal ranged from 4 to 60 in and averaged about 8 in. Head coal can form an effective barrier to moisture and, because it is generally resistant to moisture effects, will not slake with seasonal variations in intake air. However, because it is also relatively weak (<1,000 psi), it may sag and peel away with time, especially if it has well developed cleat. Typically, "bright coal" (coal with a higher vitrain content) is weaker than dull coal because cleat is better developed in bright coal. Despite low compressive strength, head coal can contribute to the effectiveness of the roof beam. At one Wyoming mine, the gateroads are oriented along strike and the panels pulled downdip. This leaves a wedge of 2-5 ft of head coal across the entry. The head coal is the upper part of the Hanna No. 80 Seam and, although not strong, is significantly stronger (UR = 40) than the overlying carbonaceous mudstone (UR = 27). The carbonaceous mudstone above is thick, and no adequate anchorage is to be found. Where the head coal thickness is <2 ft, roof conditions were noticeably worse [Mark et al. 1994]. This coal forms the strong bed in this roof sequence and significantly increases the CMRR when thick.

At a large mine in western Pennsylvania where head coal has been inadvertently cut down, the roof is significantly slabbier and more uneven. At this mine, some roof falls may be related to areas with no head coal left, although this is difficult to document. At an older mine in Utah, the 24 in of roof coal left is considered the primary support. It is strong enough to be left unsupported and for many years was the only U.S. mine with no artificial roof support requirement.

Difficulties arise in a rolling (or dipping) coal seam when trying to leave a consistent thickness of head coal. Without a consistent marker bed in the seam, it is easy for the continuous mine operator to inadvertently cut out the top coal or leave too much. Either situation is undesirable. If too much top coal is left, bolts may not hit their target anchorage and be ineffective. In one Colorado mine, all of the falls in the mine were in an area of thick head coal (>3 ft) [Mark et al. 1994]. Cutter head-mounted gamma sensors have been used successfully for indicating top coal thickness, but are not common. When leaving head coal, it is important to drill roof test holes every intersection or, more often, to document head coal thickness and keep records.

Rider Coal

In the United States, coal measure rocks are deposited in stable, slowly subsiding, continental basins. This low gradient allows prograding streams in deltaic systems to slowly meander back and forth across the basin surface. As a result, the depositional environments often occur in repeating cycles (cyclothems) as the basin subsides. This is why coalbeds typically occur in stacked sequences (West Virginia has more than 60 minable coal seams [Lotz 1970]). Rider coalbeds are minor coalbeds (6 in to 4 ft thick) that are the result of peat swamps that have been reestablished on top of the main seam. The term "rider coal" is loosely defined and may refer to a coal split at the top of the main seam (figure 14). In the southern Appalachian basin, rider coals are less likely to be preserved than in the northern part of the basin. This is because the southern basin is deeper and subsided faster, resulting in thicker sequences of sandstone being deposited [Ferm 1974]. As a result, minor peat swamps were not preserved and there are fewer rider coals. Shales with a high carbonaceous content or coal streaks are often part of a rider coal roof package. Called "rash", this sequence is generally weak and has a CMRR range of 28-40, depending on the amount of coal or strength of the shale. This roof sequence is characteristic of the Pittsburgh Coalbed, widely known for weak roof.

Rider coals may cause a number of roof control problems. The most significant is a result of the difficulty in tracking their location and thickness. The thickness, location, and spacing of rider coals can be highly variable. In its worst case, the Pittsburgh Coalbed has up to five rider coalbeds in varying thickness and spacing. Rider coals in the bolted interval are a common occurrence depending on geographic location. In 17 of 21 mines surveyed, rider coals were reported within the bolted interval. If roof bolts are systematically anchored in a rider coal, separation and roof fall can occur. Ground penetrating radar has shown promise in mapping rider coals, but regular (every 20 ft) test holes with records are still the most reliable and inexpensive method [Molinda et al. 1996]. An operator's roof support program may revolve entirely around the location and thickness of the rider coal(s). Often a roof bolt operator will carry longer bolts on the machine and will have authorization to install these bolts based on test holes. There are a number of other support options, such as narrow entries, staggered crosscuts, timbers, or beams.

Roof falls often top out in the overlying rider seam (10-30 ft up). This does not necessarily mean that the roof beam first separated at the weak rider. It may only mean that the arching fall found a convenient place to stop at the last weak roof member.

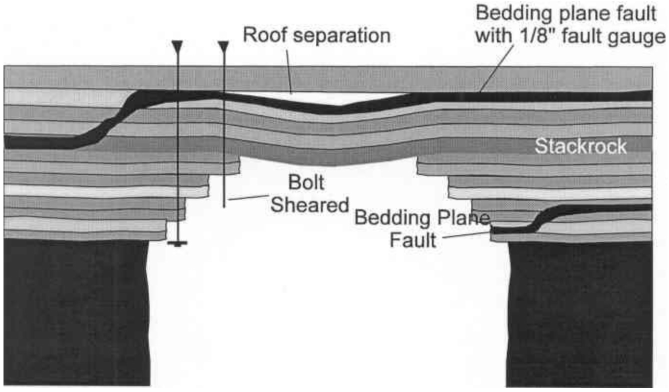


Figure 13.–Bedding plane faulting caused by lateral movement of valley floor members due to valley stress relief.

Figure 14.–Rider coalbeds above the main bench of the Pittsburgh Seam.

DISCONTINUITIES

Coal measure rocks, both weak and strong, can be affected by defects that disrupt the lateral continuity of bedded rocks. These can range from features on a microscopic scale to major faults offsetting beds for miles [Molinda and Ingram 1989]. The size of the features that most often affect coalbeds can be measured from inches to tens of feet. Artificial support of flatlying coal measure rocks relies on the strength properties 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. A roof fall rate for a typical mine is generally 1.0/10,000 ft of drivage or less [Molinda et al. 2000]. This means that 99.5% of the roof in even a mine with poor top has been successfully supported. It is suspected that roof falls in a mine with otherwise solid roof and no abnormal loading are often due to random defects or discontinuities in the roof. Other causes include improperly installed roof support or use of roof support systems inconsistent with the strata.

Most of the structures that occur in coal mine roof were created during deposition and compaction or shortly thereafter. These include paleochannels, clay veins, kettlebottoms, slips, shears, pinchouts, lag deposits, concretions, rolls, or small faults [Moebs and Stateham 1985; Ingram and Chase 1987; Kertis 1985; Chase and Ulery; 1987 Sames and Moebs 1989; Iannacchione et al. 1981]. Other structures are due to tectonic events (folds and faults) [McLoughlin 1986; Molinda and Ingram 1989]. Some, such as joints, are believed to occur both during and long after deposition. In Virginia, many "horsebacks" are formed as a result of drag along bedding plane faults [McLoughlin 2001]. Some of the more common coalbed discontinuities and their effect on roof stability are discussed below.

Clay Veins

Clay veins or clay dikes occur when soft, ductile roof or floor mudrocks are squeezed into tension fractures in the coalbed. They can also be injected parallel to bedding, or they may occur as a combination feature as in a stairstepping pattern (figure 15). Clay veins and their associated mining problems (water and gas barriers, roof damage) have been well documented [Chase and Ulery 1987; Hill 1986]. On a smaller scale, clay veins have squeezed into existing joint systems. The clay-filled tension features can then form the boundaries of roof falls. Clay veins can range in thickness from millimeters to tens of feet, and the dikes can occur from a single one to one every 10 ft or more often. Roof damage can be severe (figures 16-17). Roof rock dissected by clay veins is already failed upon exposure by mining and can fall out before bolting, covering the continuous miner and limiting cuts to only a few feet before cleanup and bolting. When a clay vein cuts through a pillar corner, large rib rolls can occur. When excess horizontal stress is added to a clay vein-broken roof, mining can be a nightmare. Conversely, there is some indication that clay veins can act as shock absorbers for horizontal stress. They can soften roof enough to prevent some massive roof falls that may have occurred in stiffer roof.

Pennsylvania Example

At one Pennsylvania mine with numerous clay veins, horizontal stress produced a number of falls in an area devoid of clay veins (figure 18). This is the only area with significant horizontal stress damage in the mine. It may be that horizontal stress, present throughout the mine, was relieved by roof softening due to clay veins. Figure 19 shows a section of the same mine infested with clay veins. The mapped clay veins represent only a portion of the sinuous and bifurcating structures. Numerous reportable (above anchorage) roof falls and very ratty top result. A number of headings were stopped due to roof damage from clay veins. It is impossible to detect

Figure 15.–Clay vein injected into the coalbed. Note inclusion of "floating" coal pieces.

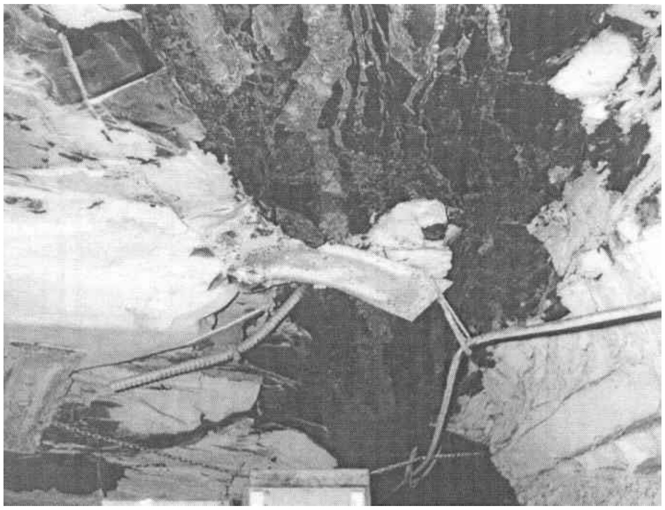


Figure 16.–Roof damage caused by clay veins.

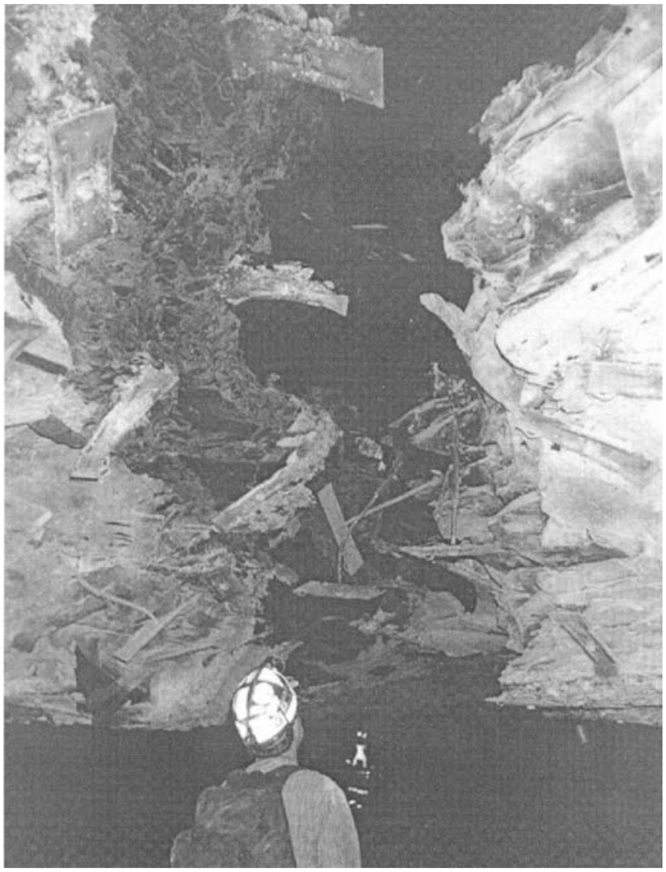


Figure 17.–Roof guttering caused by fall of clay vein.

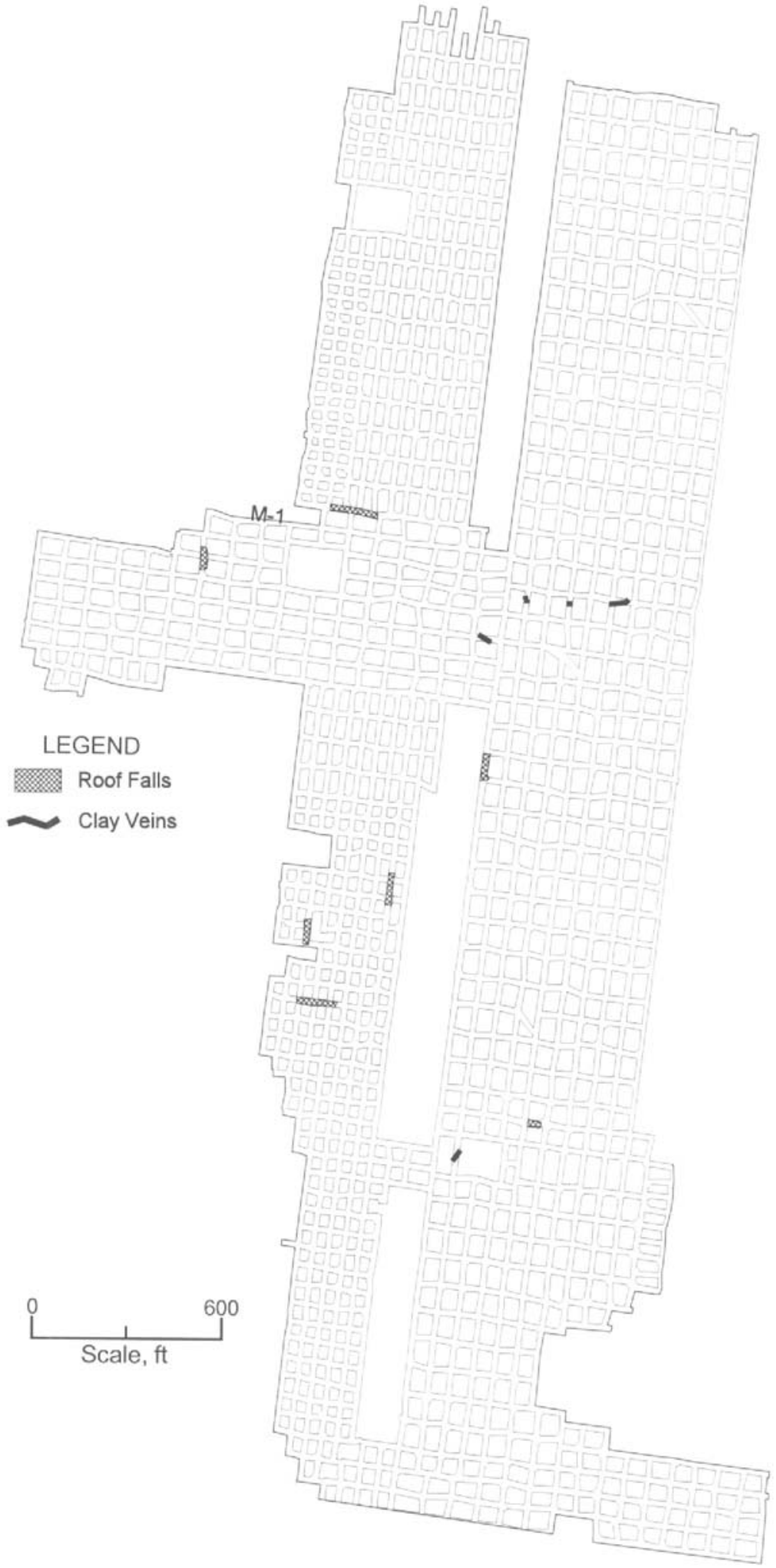


Figure 18.–Western Pennsylvania mine section without clay veins showing roof falls caused by horizontal stress.

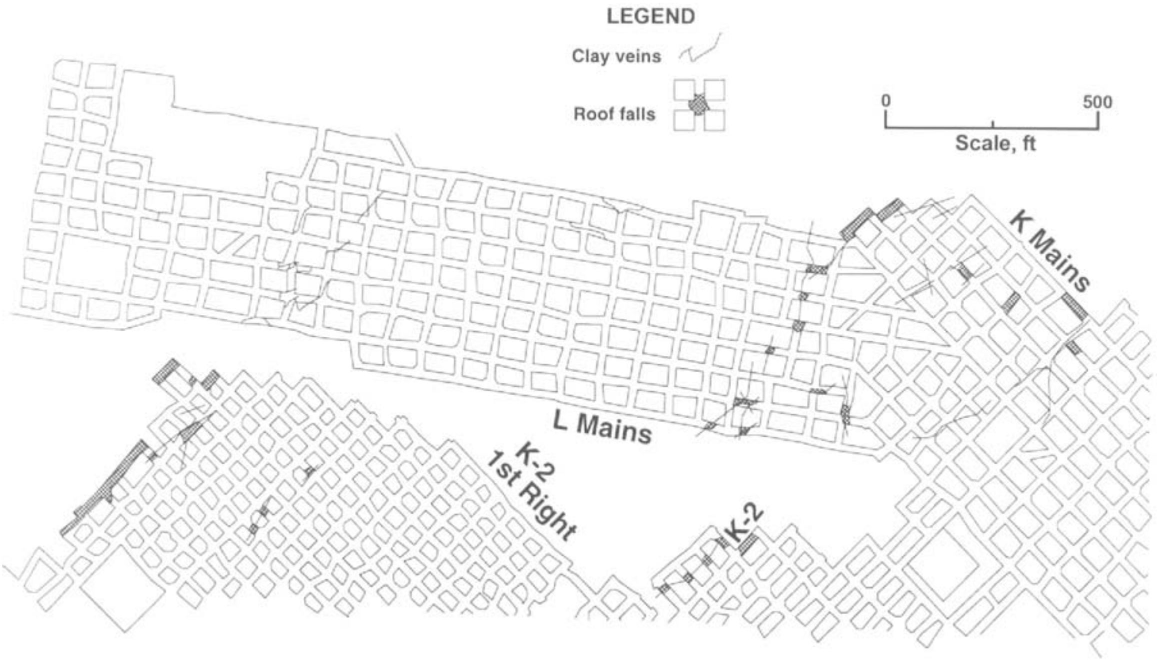


Figure 19.–Western Pennsylvania mine with numerous mapped clay veins. A number of headings were stopped by clay veins and associated roof falls.

clay vein occurrence with exploratory drilling and difficult to anticipate mining into a clay vein on a working section. Although many clay veins seem random, their *trend* can sometimes be projected for hundreds and even thousands of feet, giving early warning before mining interception. In one mine in western Pennsylvania with hundreds of roof falls, 90% of them have been caused by clay veins. The source of clay vein material is the black clay shale roof. This material is weak and moisture-sensitive (CMRR = 36-39). When exposed to water, the soft mud filling swells and bulks the roof shales below, causing bolt failure (figure 20). At the shaft bottom, a number of point-anchored resin-assisted bolts were broken at the coupler. The fall at this area showed at least five stacked clay veins parallel to bedding in 15 ft of exposed roof. The combined load from these bulking clay veins was enough to overload the bolts. The broken bolts could not be explained by excessive dead loads, only by the high pressures exerted by swelling clays (figure 21). If water cannot be excluded from clay vein areas, it may be necessary to accept bulking and roof sag and control the roof in intersections with a softer system using cable bolts or slings.

Clay veins at the western Pennsylvania mine are more prevalent beneath stream valleys. Poor rock quality occurs in the form of horsebacks and large slips. Clay veins may have infiltrated this damaged rock and are aggravated by water inflow. This suggests that the clay veins may have formed after the development of the surface drainage. Mining is very difficult beneath *any* stream valley in this mine.

The mine has attempted to control the clay veins by controlling the intersection spans (figure 22), by only turning crosscuts *toward* the belt and track, and by dropping crosscuts when they would result in wide spans. The mine has also used fully grouted bolts to stop moisture entry, roof bolting is completed as quickly as possible, and mining is avoided under stream valleys if possible.

Central Illinois Example

Clay veins dominate roof stability at another mine in central Illinois. Operators here attribute over 90% of the falls to clay vein disturbances. The roof typically consists of 3-6 ft of weak, black, carbonaceous shale (UR = 32) overlain by 12-18 in of strong limestone (UR = 97) (figure 23). The roof support goal is to anchor the fully grouted bolt at least 1 ft into the limestone in order to form a strong beam and anchorage for shale suspension. The limestone varies in thickness and locally it splits. Figure 24 shows a large section of the mine where limestone thickness has been mapped. Roof falls are also shown. When the limestone is <12 in thick, the roof fall rate increases over 5.5 times (figure 25). Clay veins ranging from 6 in to 6 ft thick occur sporadically about the mine. When these structures penetrate the limestone, a cantilevered beam can occur, resulting in a roof fall.

The mine has a well-developed plan for controlling the roof. Through systematic roof hole monitoring, the thickness of the shale and limestone is painted on the intersection rib. Figure 24 shows the variability of roof geology at this central Illinois mine. This volume of data over such a large area is rare, but illustrates the need for systematic roof geology exploration if roof support selection is tightly linked to geology. A bolt 1 ft longer than the shale thickness is used to obtain 1 ft of anchorage in the limestone (e.g., when there is 5 ft of shale, a 6-ft bolt is used). When limestone is <1 ft

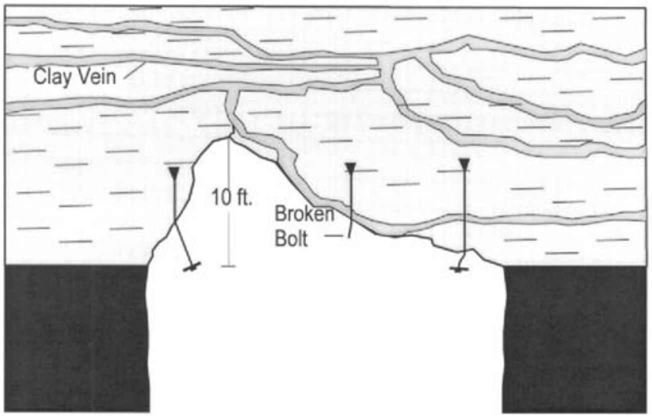


Figure 20.–Stacked clay veins infiltrated along bedding swell when exposed to moisture and cause roof falls by bulking the strata.

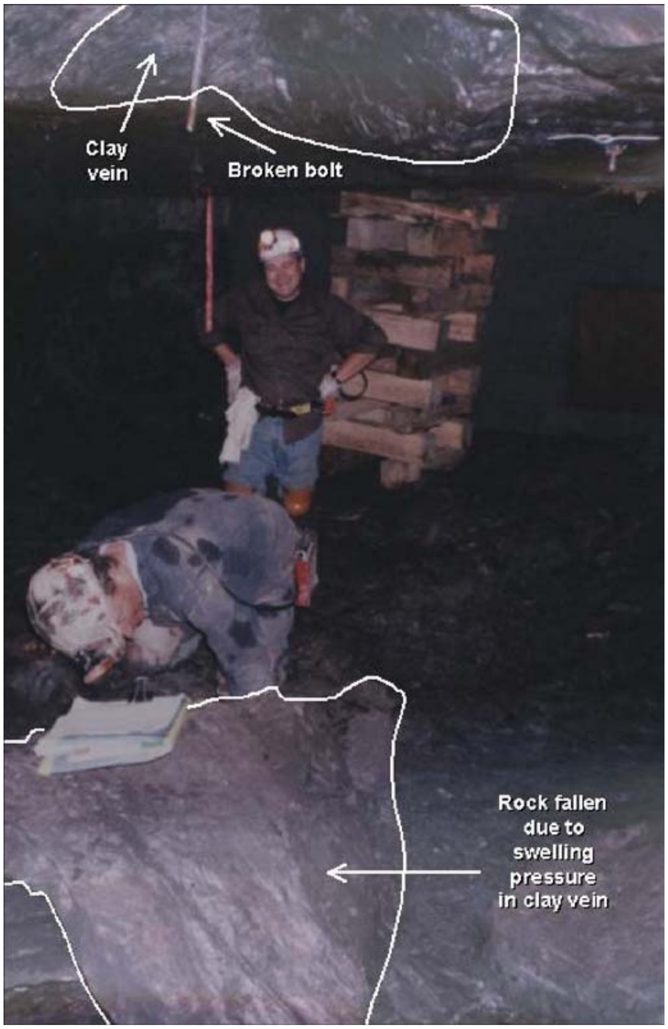


Figure 21.–Rock fall occurred when swelling pressures in a roof clay vein broke a roof bolt.

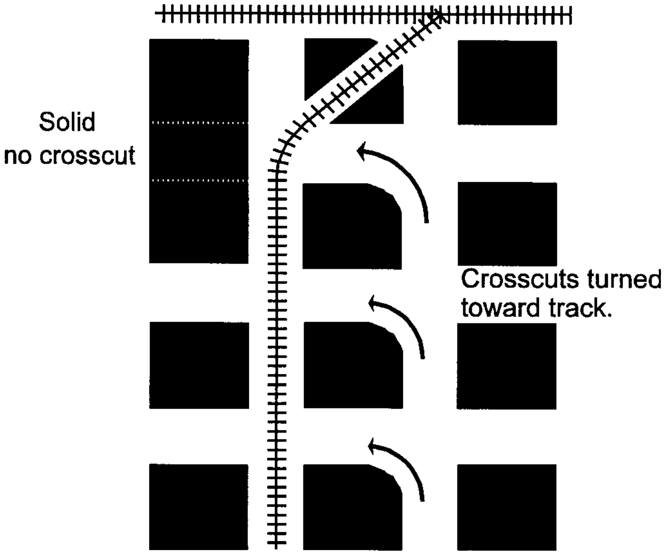


Figure 22.–Intersection spans are controlled by turning crosscuts only one way and dropping a crosscut in an already overspanned track chute.

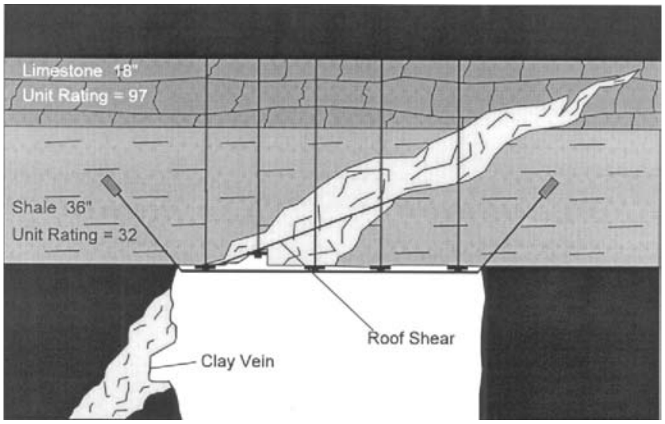


Figure 23.–Clay vein damaging the roof and rib in an Illinois mine.

thick, an 8-ft bolt is used regardless of the shale thickness. When significant clay veins are encountered, a minimum of 6-ft bolts are used and trusses in the intersections. Bolt spacing is reduced and straps are used to support exposed clay veins. The roof bolter has the immediate responsibility to select bolts. This strategy has helped to dramatically reduce roof falls. The mine routinely installs roof sag monitoring devices in intersections and has developed support procedures triggered by preset sag action levels. The operators also have a "roof failure rating system" for alerting the section boss to expected problems. The system incorporates a point-based rating that uses the size and orientation of clay veins, the limestone thickness, and shale damage to evaluate the roof fall hazard.

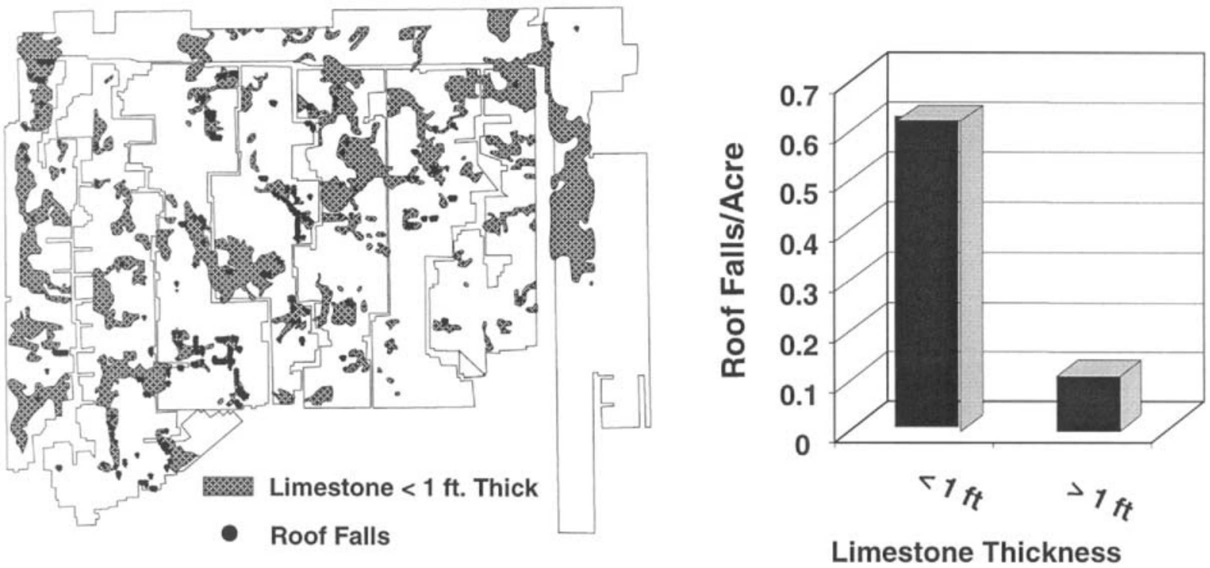


Figure 24.–Roof falls in an Illinois mine are related to areas of limestone in the roof <1 ft thick and the occurrence of clay veins.

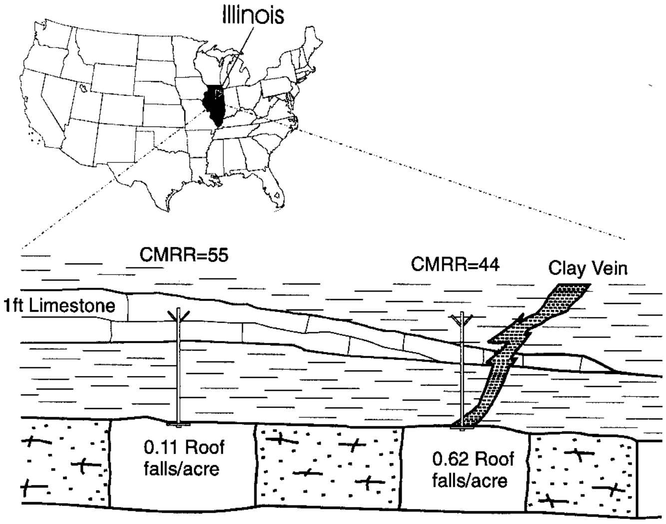


Figure 25.–Roof fall rate increases dramatically with reduced CMRR and clay vein occurrence.

West Virginia Example

Another factor in the stability of clay vein-plagued roof is timing. At a mine in northern West Virginia, 56% (10 out of 18) of the falls in 1 year were caused by clay veins. The average standup time of all falls was 3.9 months (n = 39) (standard deviation = 3.1 months). This may represent the average time it takes the clay filling in the clay veins to swell and bulk the roof enough to cause roof falls. Monitoring of roof sag is an effective way to determine the critical amount of sag necessary for the roof to fail. In this way, the mine can use fall timing to indicate when to install additional support.

Slickensides

Slickensided rock is common to coal mine roof. It is one of the structures that seriously weakens the strength of coal mine roof. In addition, slickensided roof is responsible for large numbers of injuries on the working section due to the fall of small rocks between roof bolts. A slickenside, slip, or shear is actually a failure surface on which there has been lateral movement of shale or other clay-rich rocks (figure 26). Striations often indicate the plane and direction of movement. These structures occur less often as rocks coarsen into sandstones because of the ability of coarser grains to resist shearing. Slickensides occur early in the rock's diagenesis as a result of differential compaction, or later as a result of high confinement and slippage due to local or tectonic faulting. In any case, slickensides are already present in the roof at the time of mining and are not caused by mining-induced stresses.

Because mudrocks are soft and can be compressed and dewatered, differential-compaction slickensides are common to shales. These commonly occur beneath the margin of paleochannels and wherever stiffer rocks abut softer rocks. Slickensides are common in the flatlying immediate shale roof of the Pittsburgh Coalbed. Figure 27 shows how slickensides are formed in a Pittsburgh Seam mine in southwestern Pennsylvania. The Pittsburgh Sandstone commonly occurs as a flatlying, tabular, crevasse splay deposit 0-20 ft up in the roof. It acts as a platen on the weak rash roof package below. As the overburden load was applied, the muds sheared horizontally along bedding and subvertically into random slickensides, millimeters to inches long. This zone, locally called "slickrock," occurs immediately above

Figure 26.–Slickensides on a rock fallen from a coal mine roof.

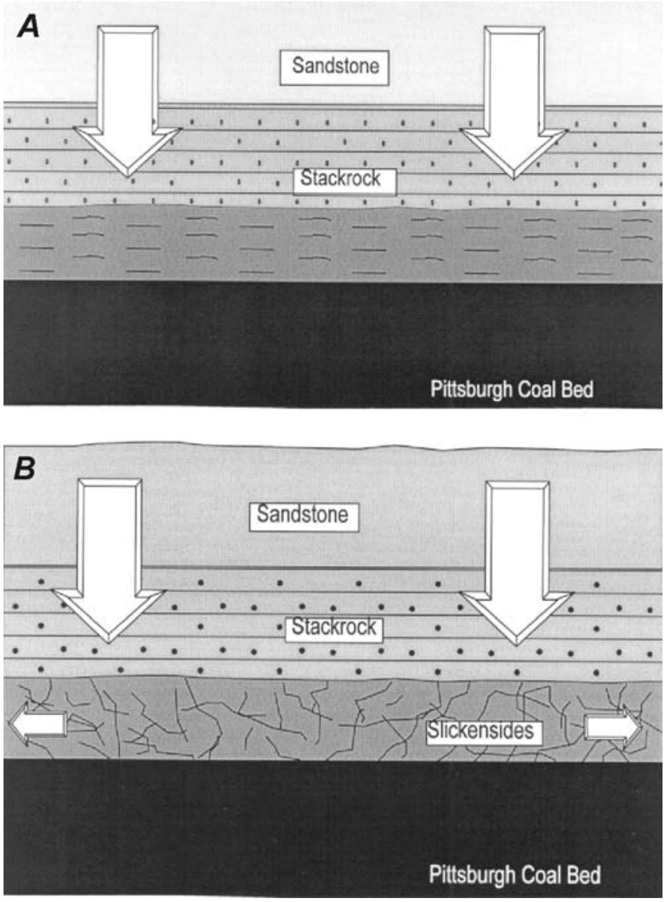


Figure 27.–Slickensides are formed when a massive roof rock (sandstone and stackrock) (*A*) compresses a softer claystone, causing small internal faults (*B*).

the coalbed and is about 4 ft thick. This rock often falls out on mining and, when bolted, sloughs out between bolts with time. These small falls are sometimes named "horsebacks" because of their shape (figure 28). It is essential to bolt this roof with straps or mesh immediately after exposure to reduce roof sag and moisture exposure. With the introduction of the integrated continuous miner and roof bolter, mining has been revolutionized in the Pittsburgh Seam. The notoriously weak Pittsburgh roof can be controlled by narrower entries and immediate roof support.

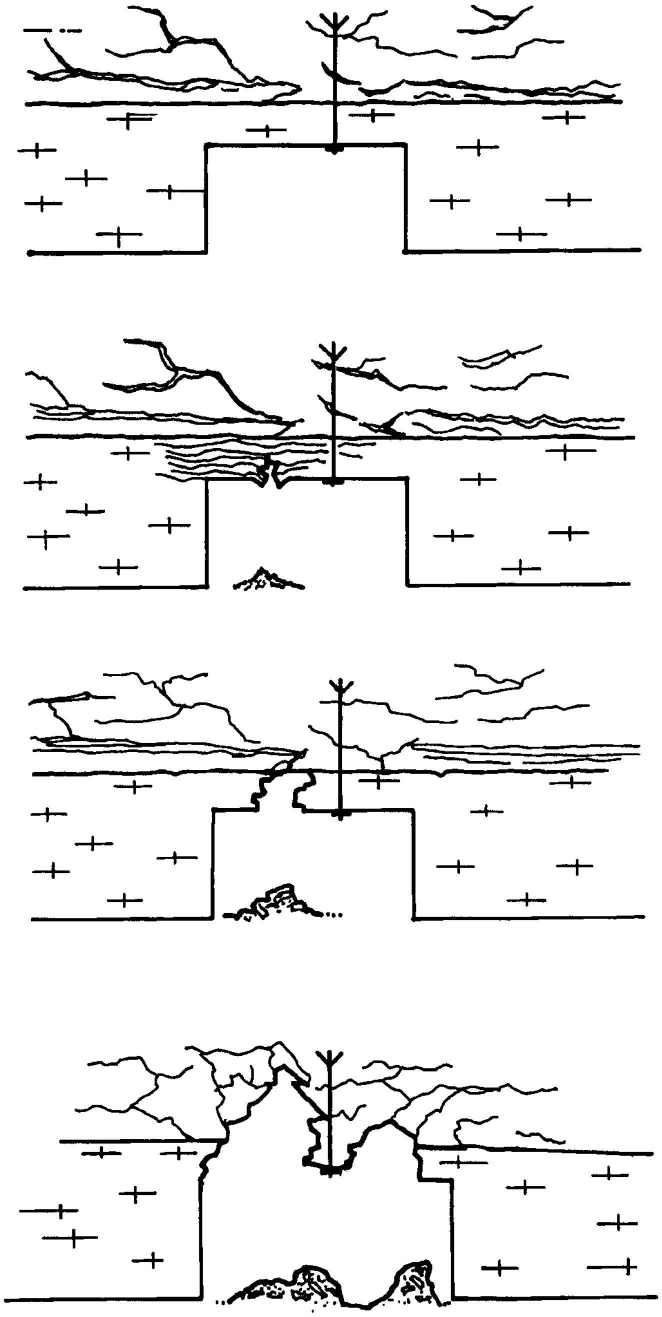


Figure 28.–Progressive failure ("horseback") caused by sagging head coal and exposure of slickensided shale above.

Slickensided black shale or "slickrock" occurs in an Ohio mine with thick limestone in the main roof. The weak black shale below the limestone is highly slickensided due to vertical loading by the limestone "platen." When possible, this rock is taken down, but if it becomes too thick, it must be bolted. Even when bolted, this unit tends to fall out in blocks. It is also a problem because it tends to fall out in front of shield tips on the longwall face.

In a longwall mine in western Maryland, the roof rock appears wet because of its high reflection. On closer inspection, however, the roof is a highly slickensided shale. Its numerous intersecting slickensided planes give the appearance of broken panes of glass. This roof falls out up to 40+ inches immediately after mining. It can only be mined in 5- to 8-ft cuts. Where it does not fall out, it is taken down by the miner. Mining is only possible because metal screen is installed on cycle (figures 29-30). Another problem caused by the removal of 3-4 ft of slickensided roof is unstable high ribs. This brow and rib is controlled by 4-ft angled planks bolted on 6-ft centers. The rib bolts can be retightened with Crosby clamps after sloughage. The mine is testing a new four-head walk-through bolting machine with a rib bolter mounted on the back for quick rib support. These innovations have allowed mining to continue under extremely weak, slickensided rock.

Sandstone Channels

Much has been written about sandstone channels and their adverse effects on the stability of adjacent and underlying coal mine roof [Molinda and Ingram 1988; Ingram and Chase 1987; Kertis 1985; Krausse et al. 1979; Roen and Farrel 1973]. In the fluvial-deltaic distributary environments of deposition typical of coal measure rocks, disruption of the continuity of roof rocks by channel scour and fill is common. Major paleochannel systems, including the Walshville, Anvil Rock, and the Galatia channel, cause roof hazards and mining disruptions in southern Illinois [Krausse et al. 1979]. Figure 31 shows the extent of paleochannels in the Herrin No. 6 Seam in southern Illinois. A major paleochannel system also disrupts the Pittsburgh Seam. These channel disruptions are mostly located by mining. They can extend for hundreds of miles depending on the size of the alluvial valley or delta distributary system. Figure 4 shows an erosional channel in relation to the surrounding depositional environments. A number of adverse features are associated with paleochannel cutouts or depressions of coal seams. Severe disruptions including faulting, crushed rock, slickensides, shears, rolls, water, clay veins, rotated cleat, and slumped structures can occur. Figure 32 shows a cross-section of a paleochannel disruption in a mine in Washington County, PA [Ingram and Chase 1987]. The crushed and faulted zone fell out immediately upon exposure and required significant supplemental support.

Some disruption occurs during the deposition of the peat swamp. As the channel scours the peat, slumping occurs on the cut bank and crossbedding occurs on the point bar side of the channel. Both features can cause hazards in the future roof strata. Slump surfaces become slickensided by loading. The resulting disrupted, rotated blocks fall between bolts. After burial, even more disruption of the paleochannel and surrounding rocks occurs because of differential compaction. The channel fill acts to point load the soft peat, which flows away from the base of the paleochannel. The result is thick coal sequences and highly sheared and friable rocks on the margin of the paleochannel. Figure 33 shows the effect of a paleochannel system on mining in a mine in the Upper Freeport Seam in Preston County, WV. At least seven separate developments were prematurely terminated due to complete seam washout or poor roof quality and difficult mining conditions (rolls and splits).

Figure 29.–Metal screen supporting roof scale formed in highly slickensided shale.

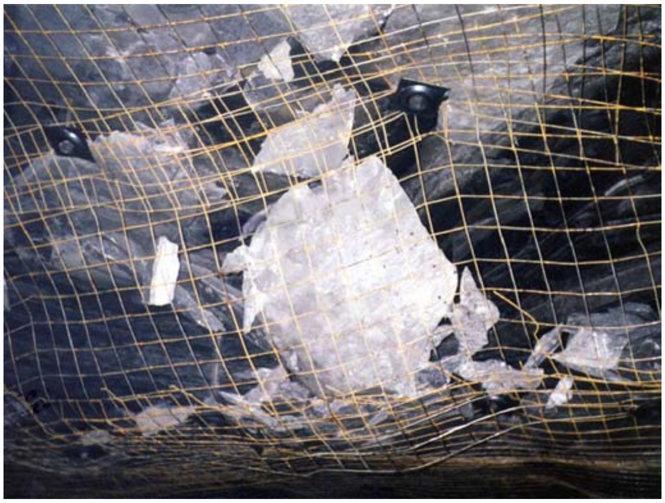


Figure 30.–Roof rock supported by metal screen.

Mapping at one large longwall mine in southwestern Pennsylvania shows numerous roof falls and pots when one paleochannel, from a large ancient river system, came near the roof (figure 34). Weak rock beneath and along the margin of the structure potted out when mining approached too close to the sandstone. Associated hazards included horsebacks, low-angle faults, ragged sandstone, and water dripping. When the paleochannel approaches the mined opening from the roof, less head coal could be left, allowing roof sag and falls up to the bottom of the sandstone.

Joints

Joints are vertical or near vertical fractures in coal mine roof caused by tension. These discontinuities typically form planar surfaces and can extend from 6 inches to tens of feet.

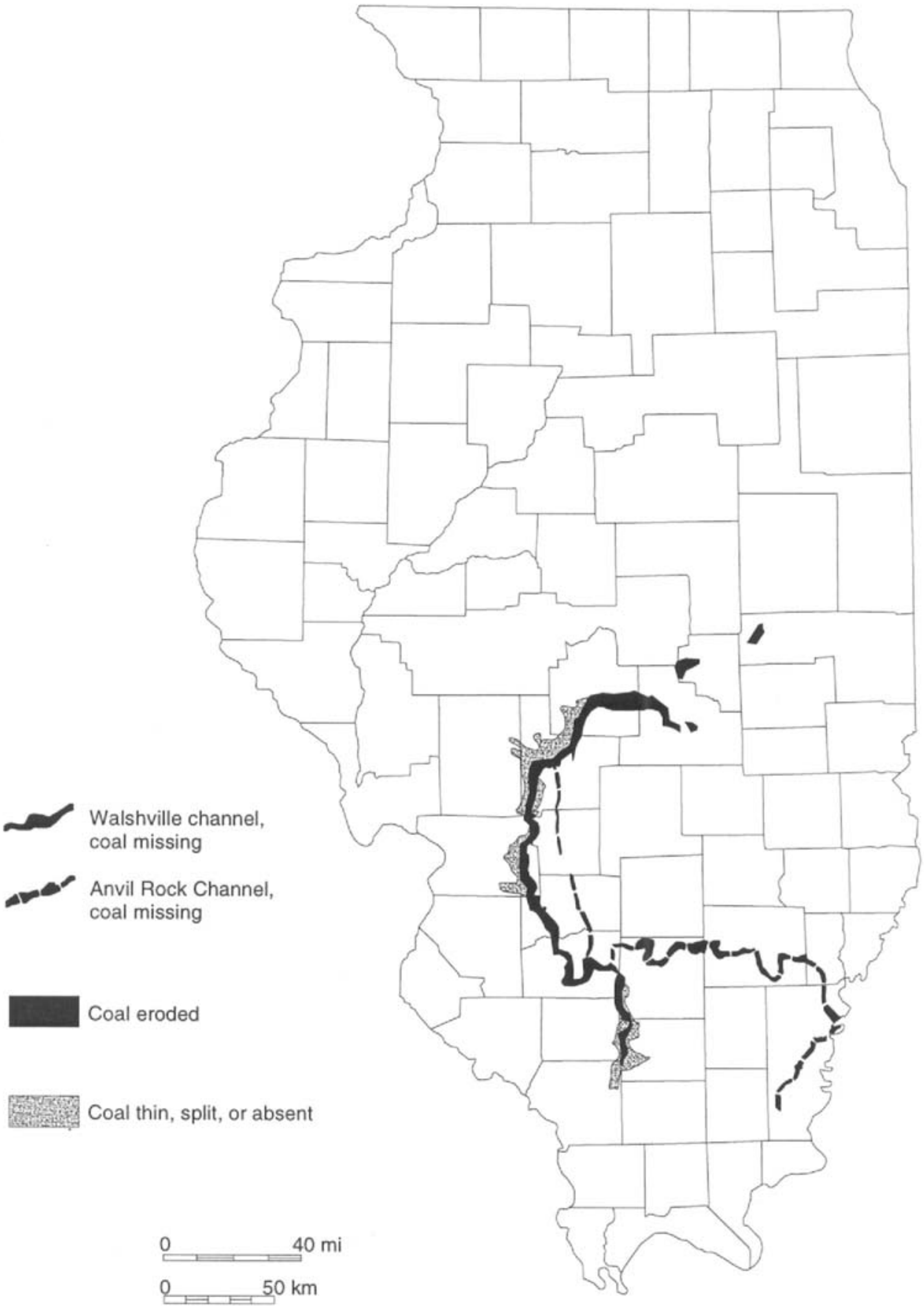


Figure 31.–Illinois coalfields showing system of paleochannels with disruption or erosion of the coalbed [modified from Krausse 1979].

Joints can occur early in a rock's formation because of local warping, or later when large regional forces shape anticlines and synclines. Coal cleat is a type of joint that can be formed relatively shortly after peat burial. Cleat distortion near paleoslumping is evidence of early cleat formation [Ingram and Chase 1987]. Other cleat systems parallel the axes of major folds, indicating their formation by later regional forces [McCulloch et al. 1975].

Rocks have different strengths and respond to tension in different ways. Joints are more closely spaced in mudrocks than in clastic rocks. In a roof sequence, joints may continue only for the thickness of the host strata and abut vertically in the upper or lower strata. This situation in a southwestern Pennsylvania mine resulted in small pieces (2-3 in thick) being isolated in the immediate roof shale, but only extending upward the thickness of the black shale (6 in) (figure 35). Conversely,

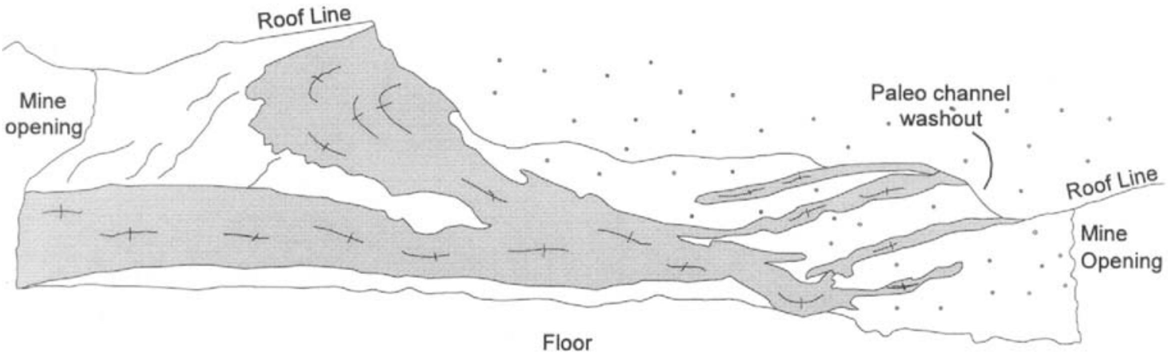


Figure 32.–Erosional paleochannel in a western Pennsylvania mine causing severe coalbed and roof disruption. Slump features along the margin of the channel created poor roof conditions.

Figure 33.–Complete washout of the coal by a paleochannel in a West Virginia mine terminated numerous headings.

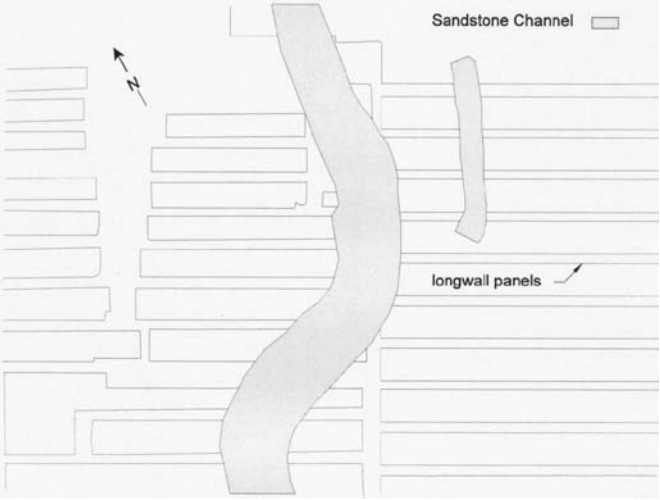


Figure 34.–When a paleochannel approached the roof in a southwestern Pennsylvania longwall mine, roof falls and roof pots were common.

Figure 35.–Systematic jointing in the shale roof of a southwestern Pennsylvania mine continued only about 6 in vertically and terminated against a siltstone.

joints may be persistent, extending through numerous roof strata, effectively severing the roof beam. At one western Pennsylvania mine, joints formed the severed termination of a number of roof falls (figure 36). The fall pictured in the intersection had two turnouts, contributing to its oversized intersection span of 74 ft and likely triggering the fall (figure 37).

Systematic joint sets near outcrop are called hillseams. These are the result of valley stress relief through downcutting and removal of confinement [Sames and Moebs 1989]. As confinement is removed, the valley walls move outward and fracture vertically in tension. The trace of hillseams are often parallel to outcrop, and they can curve around points of land. They can form zones of failed rock of more than 4 ft thick (figures 38-39), allowing surface water to infiltrate and expand weathered zones within the hillseam. Mining near outcrop through hillseams can be extremely hazardous. Most hilltop mines must leave at least 150 ft of barrier between the mine and outcrop. At one mine in western Pennsylvania, a fatality occurred when mining proceeded within 100 ft of the outcrop because of a surveying error. The factors contributing to the death included wet, weathered, clay-filled hillseams and sheared coal ribs.

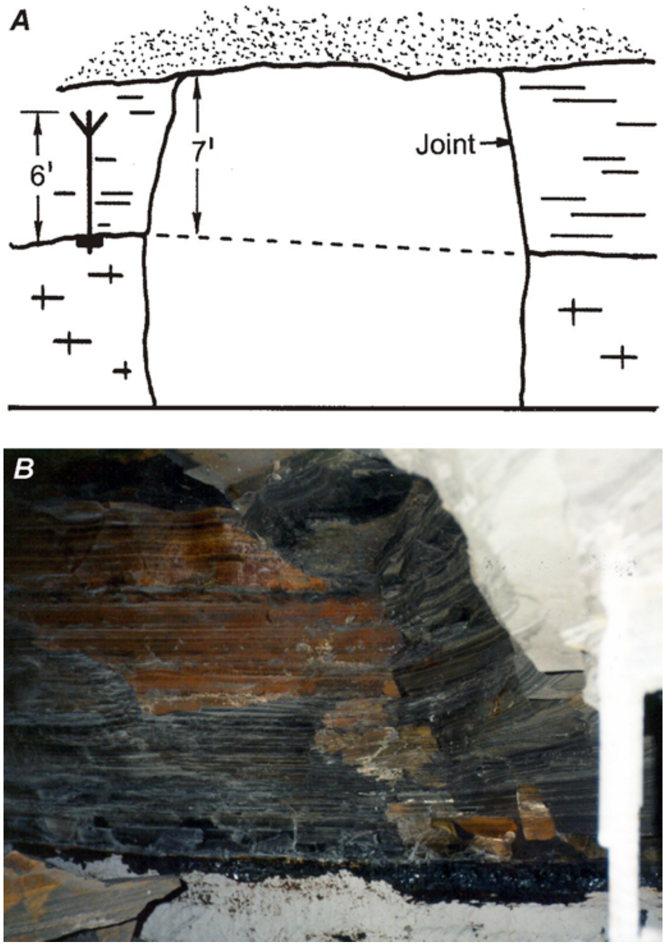


Figure 36.–Roof fall terminating against a large joint face. *A*, Diagram; *B*, photograph.

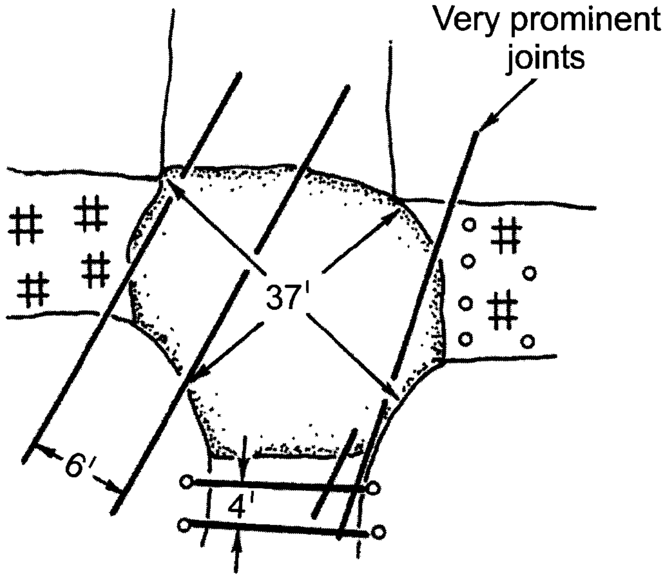


Figure 37.–Roof fall caused by large joints spaced 6-10 ft and overspanned intersection.

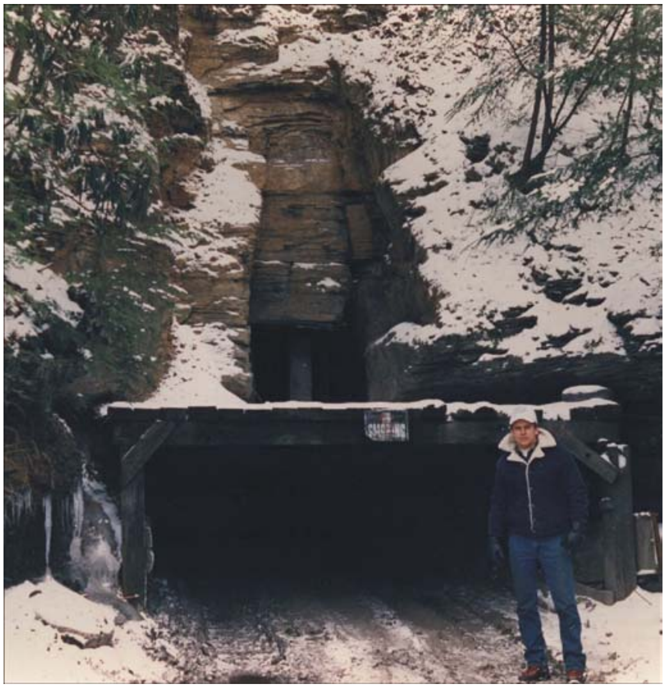


Figure 38.–Hillseam near mine portal presents a roof hazard.

Figure 39.–A hillseam is a zone of numerous extensional fractures.

ROOF FALL ANALYSIS

One of the most important diagnostic tools for evaluating roof failure is the systematic analysis of the roof fall itself [Ferm et al. 1978; Moebs and Stateham 1985]. Often only a cursory investigation of the roof fall is made. This reveals little to prevent or avoid similar falls. A review of roof fall accident reports filed by operators to MSHA often lists "roof slips" or "cracks" in the roof as the cause. Most likely the reason for this lack of information is the observer is untrained in what to look for and how to document it.

The roof fall analysis should focus on two areas. First, the accurate mapping of roof falls is not only an MSHA requirement, but can reveal important trends that can only be seen on a large map scale. Figure 40 shows that the failure of roof in different parts of one mine and between several mines in different seams were related to two thrust faults [Molinda and Ingram 1988]. Without mapped data showing the roof failures were spatially related, their common source might be obscured. Figure 41 shows linear, oriented roof falls that are the result of a high east-west horizontal stress in an Illinois mine. At a map scale of 1 in = 400 ft, the direction of the most entry damage (north-south) becomes obvious.

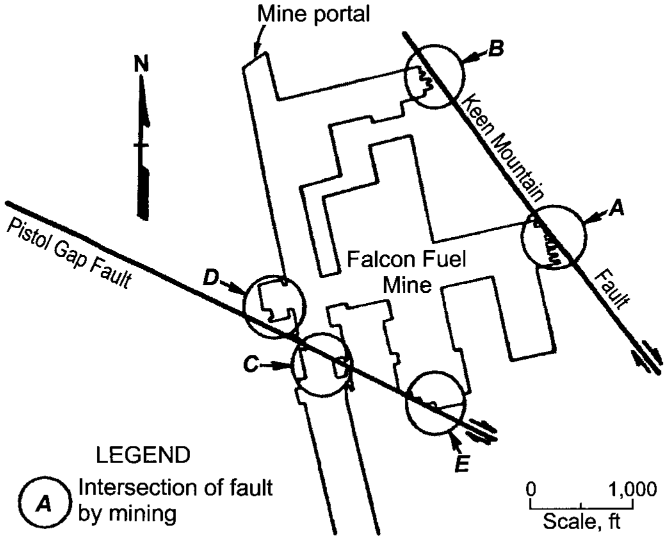


Figure 40.–High-angle thrust faults cause poor roof conditions in a southwestern Virginia mine.

Secondly, the investigation of the individual falls should be systematic and capture information that can be used to determine the performance of the support, the strength of the roof, and the immediate cause of the fall and to identify any extenuating circumstances at the site.

Obviously, a cleaned-up fall provides the best access for investigation, but information can also be gained (from a safe distance) at falls that will not be loaded out. Sometimes the cause of a fall can be immediately determined. Crosscutting defects in the roof are often the cause of destroyed roof beams. If a large slip or fault is cutting through an intersection, the smooth failure plane may be obvious. The plane may be obscured, but fault gouge (thin layer of clay) present on the plane may provide a clue. The fact that the roof stayed up long enough to be bolted shows that it was at least temporarily self-supporting or that bolts were installed to bridge the slip. In this case there may be a time-dependency factor to the fall. The standup time of each fall should also be documented.

Large slips often occur in swarms and may be mapped in adjacent entries. If a slip is present in the fall, it should be mapped out of the fall to determine its orientation and the stability of adjacent entries. At one mine in Virginia, large slips in the roof related to regional structure were regularly spaced at about 300 ft. The crosscut was turned at the same orientation as the slip plane. When the crosscut coincided with the slip plane, roof falls occurred (figure 42).

It is important to make a sketch of the exposed lithology, along with a description and measured or estimated thicknesses. A handheld spotlight will greatly aid in the observation. Weak rock units (rider coals, underclays, coal streaks, ironstone lenses, etc.) may have inadvertently become anchorage zones, and their location could explain the fall. Note should be made of the presence and location of water entering the roof fall cavity. The relationship of the water to moisture-sensitive members should be noted. The CMRR should also be calculated from the roof fall exposure. This is usually the best exposure of the roof strata.

Figure 43 is an example of a roof fall report from a mine in southeastern Ohio. Other data sheets developed by NIOSH are available that include additional relevant information (figure 44). The sheet provides a space for the plan view, as well as a lithologic cross section. The plan view shape of the fall can indicate an orientation. Oriented falls can indicate horizontal stress influence. Cutter roof and roof damage adjacent to the fall can be sketched here. The cross-sectional shape of the fall (stairstepped, flat-topped, arched, or cone-shaped) may highlight the various units of the bolted interval.

An assessment of the performance of the primary roof support must be made at the scene of a roof fall. Broken roof bolts are a sign of exceptional loading. If bolts have loaded and failed, they may be under capacity. Bent plates and popped bolt heads may also be signs of excessive stress. If bolts have not taken load, then the problem may be failure of key blocks, which allows rocks that are bounded by slips to fall between bolts, thus severing the beam (figure 45). Bolts that have not loaded may also indicate that the beam is isolated by sag above the bolt horizon, causing tensional breaks on the beam. Finally, another cause of roof failure without bolt loading may be slip due to faulty anchorage.

Horizontal stress damage to a roof sequence has received a lot of attention in the last 10 years. Previously thought to be roughly one-third of the vertical stress, horizontal stress is now believed to be regularly much higher and to be responsible for many more roof falls. An assessment of the contribution of horizontal stress to the fall should be made.

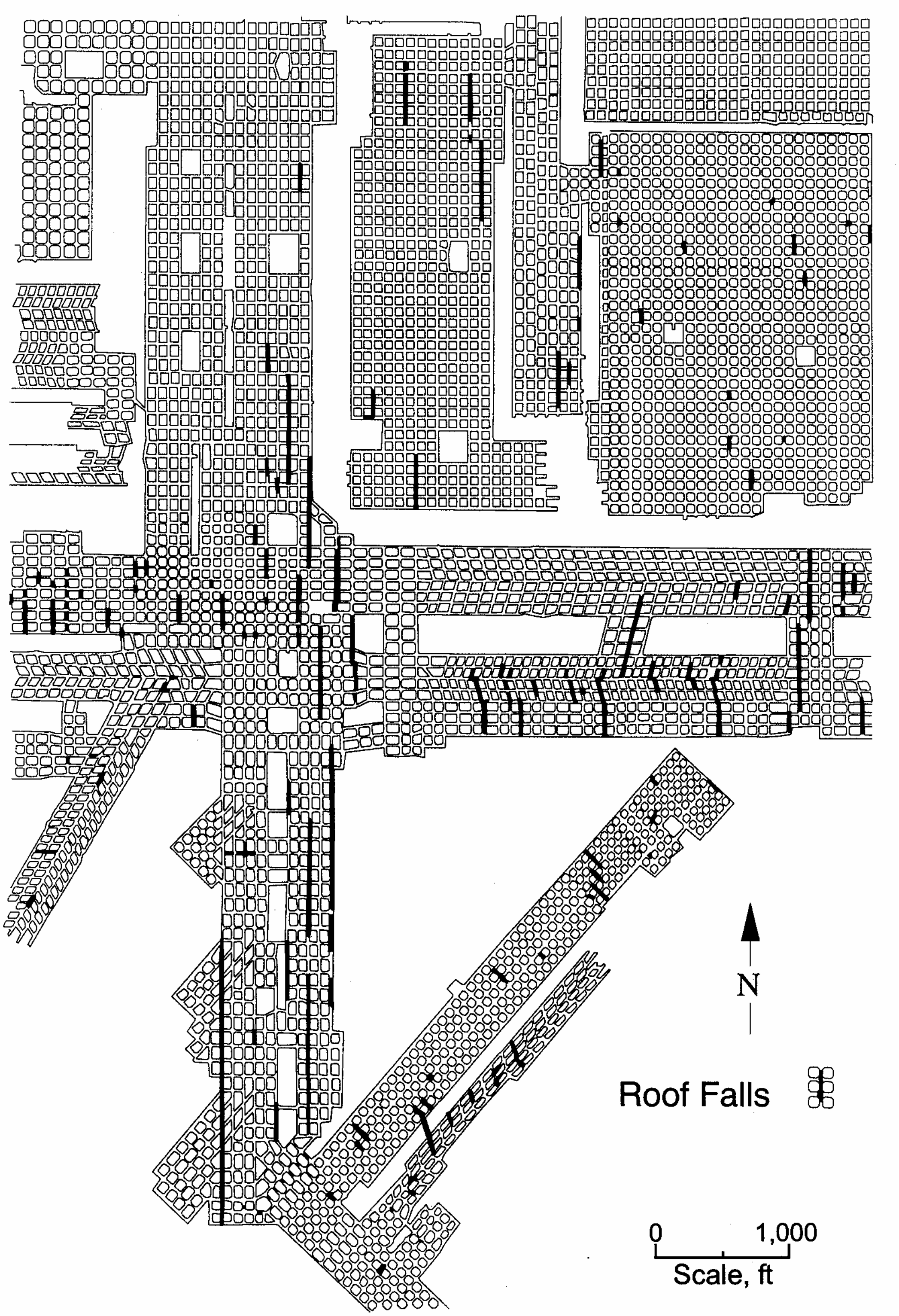


Figure 41.–High horizontal stress oriented east-west causes extensive north-south roof falls in an Illinois mine.

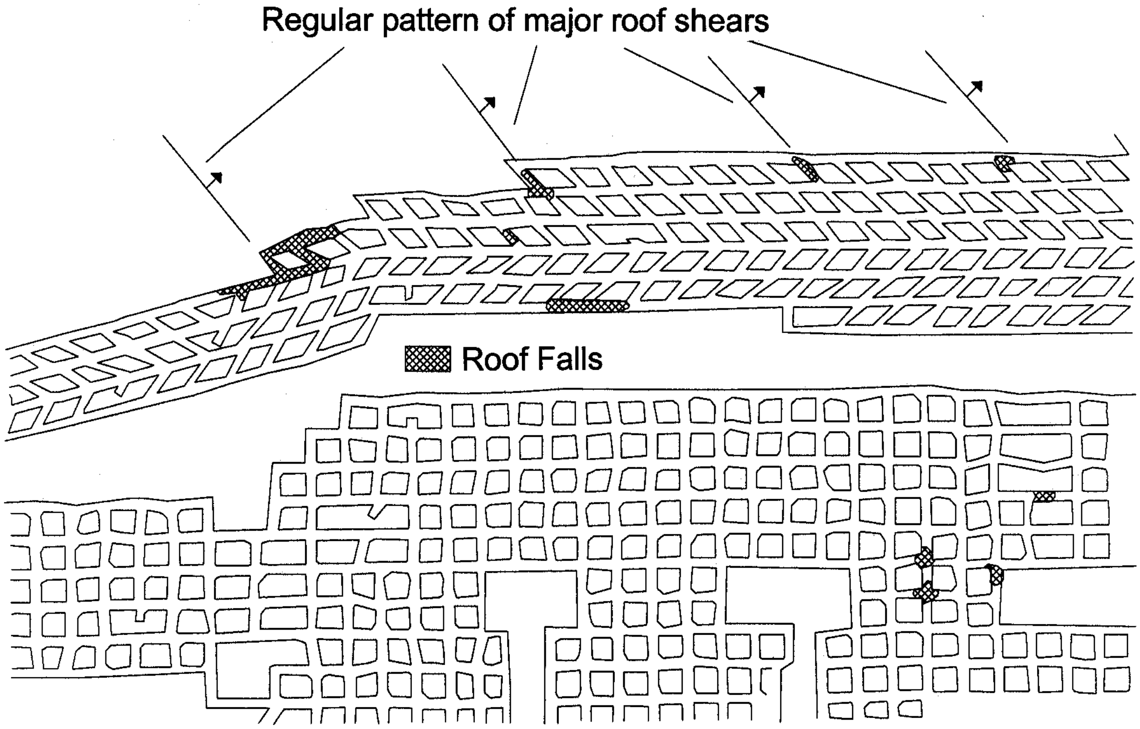


Figure 42.–Regular roof shears in a southwestern Virginia mine cause roof falls when crosscuts are aligned parallel to them.

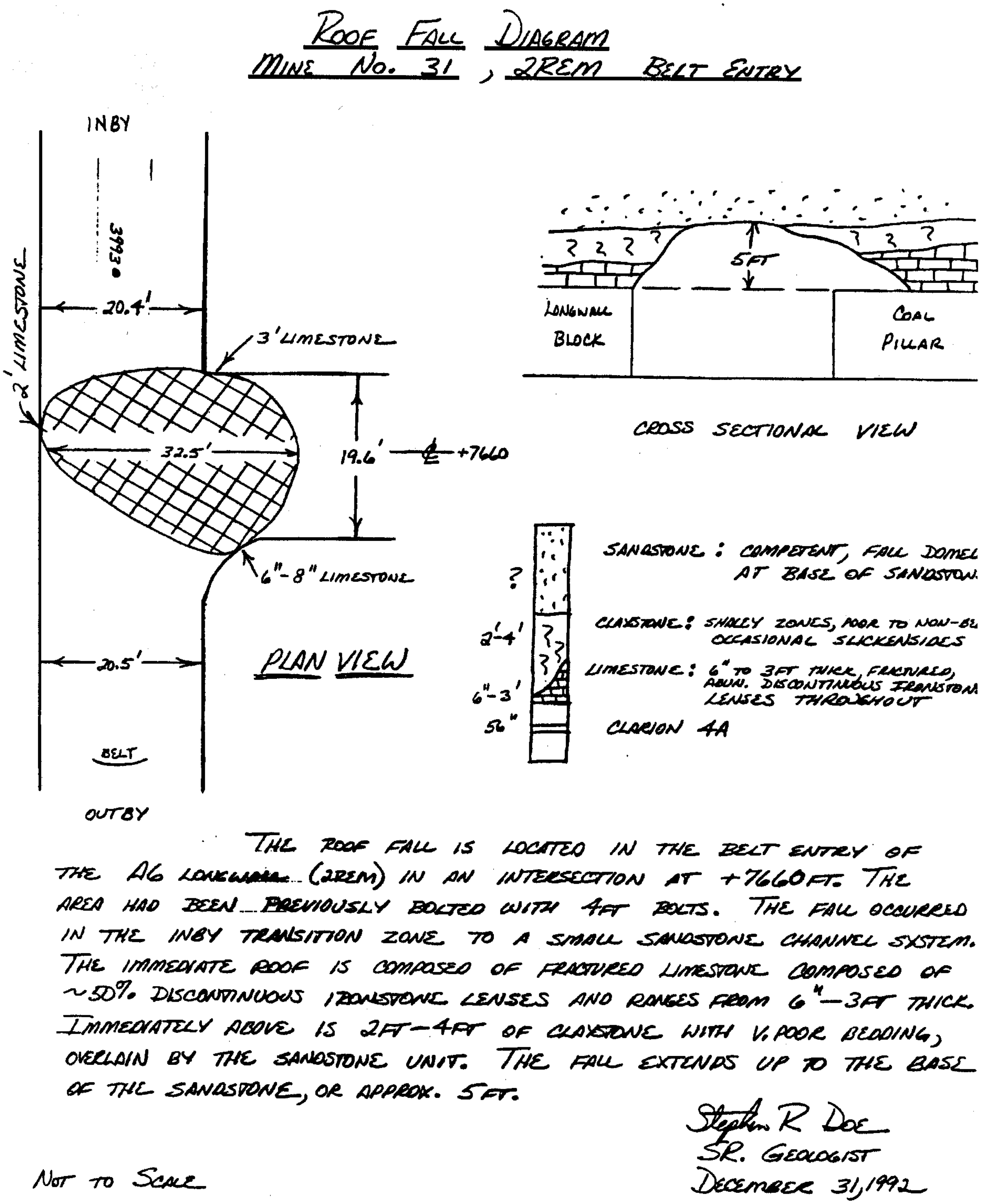
Indicators of horizontal stress are many. These include cutters or guttering, roof "stitching" or rock flour, long running falls, "snap top," oriented roof falls, and offset bolt holes [Mucho and Mark 1994; Ingram and Molinda 1988]. Shortening of the roof due to horizontal stress may also cause roof blocks to fall between bolts. Stiff roof members, like the sandstone interbeds in a stackrock, can concentrate stresses and, by bending, they can delaminate and fail underlying layers in tension.

Defective bolts may be the cause of more roof falls than is widely believed. Although sometimes hard to document, it is worth the effort to examine roof bolts in roof fall debris. Poor roof bolt installation can result from a number of practices [Mazzoni 1996]. “Glove-fingered” bolts occur when the bolt spins within the resin cartridge, failing to break the bag and preventing resin contact with the wall of the roof bolt hole (figure 46). At one mine in southern Illinois, nearly all of the bolts observed (n = 10) in several roof falls were "glove-fingered." "Glove-fingered" bolts can be eliminated by reducing the resin annulus and spinning the bolt as it is inserted. This can be done by drilling a smaller diameter hole or installing a larger bolt in the hole. One support manufacturer has developed a rebar that has a serrated surface, which ensures complete resin tube penetration during initial inserts of bolt in hole. If mechanically anchored bolts are undertensioned, roof failure can result. If the same bolts are overtensioned and high-strength bolts are used, crushing of the rock could occur, resulting in lost tension. Bolt corrosion should also be documented. This can be identified by rust-through, but also by a characteristic coning of the corroded end. This is a result of progressive corrosion.

The intersection span (sum of the diagonals) should always be recorded. A previous study showed that over 70% of roof falls occurred in intersections [Molinda et al. 1998]. In addition, the spans of intersections around the fall (n = 8-10 intersections) should be recorded to determine if a systematic overspan contributed to the roof fall. At a mine in southwestern Pennsylvania, the roof fall rate for the 20-ft-wide belt entry was six times the fall rate for the other 16-ft-wide entries. Figure 47 shows the method for measuring an intersection span. Diagonals were taken from the midpoint on the pillar corner between the spalled rib and the original cutpoint of the corner.

TIMING OF ROOF FALLS

Unplanned roof falls are always a potential hazard. Falls that happen on the working section expose more miners to injury and death than those in outby areas. Weak roof that falls immediately upon mining is troublesome, but can be cleaned up and bolted. Falls that occur several crosscuts back from the face are more dangerous.



ROOF FALL DIAGRAM
MINE NO. 31, 2REM BELT ENTRY

SANDSTONE: COMPETENT, FALL DOMEL AT BASE OF SANDSTON

CLAYSTONE: SHALEY ZONES, POOR TO NON-BE OCCASIONAL SLICKENSIDES

LIMESTONE: 6" TO 3FT THICK, FRACTURED, ABUN. DISCONTINUOUS IRONSTON LENSES THROUGHOUT

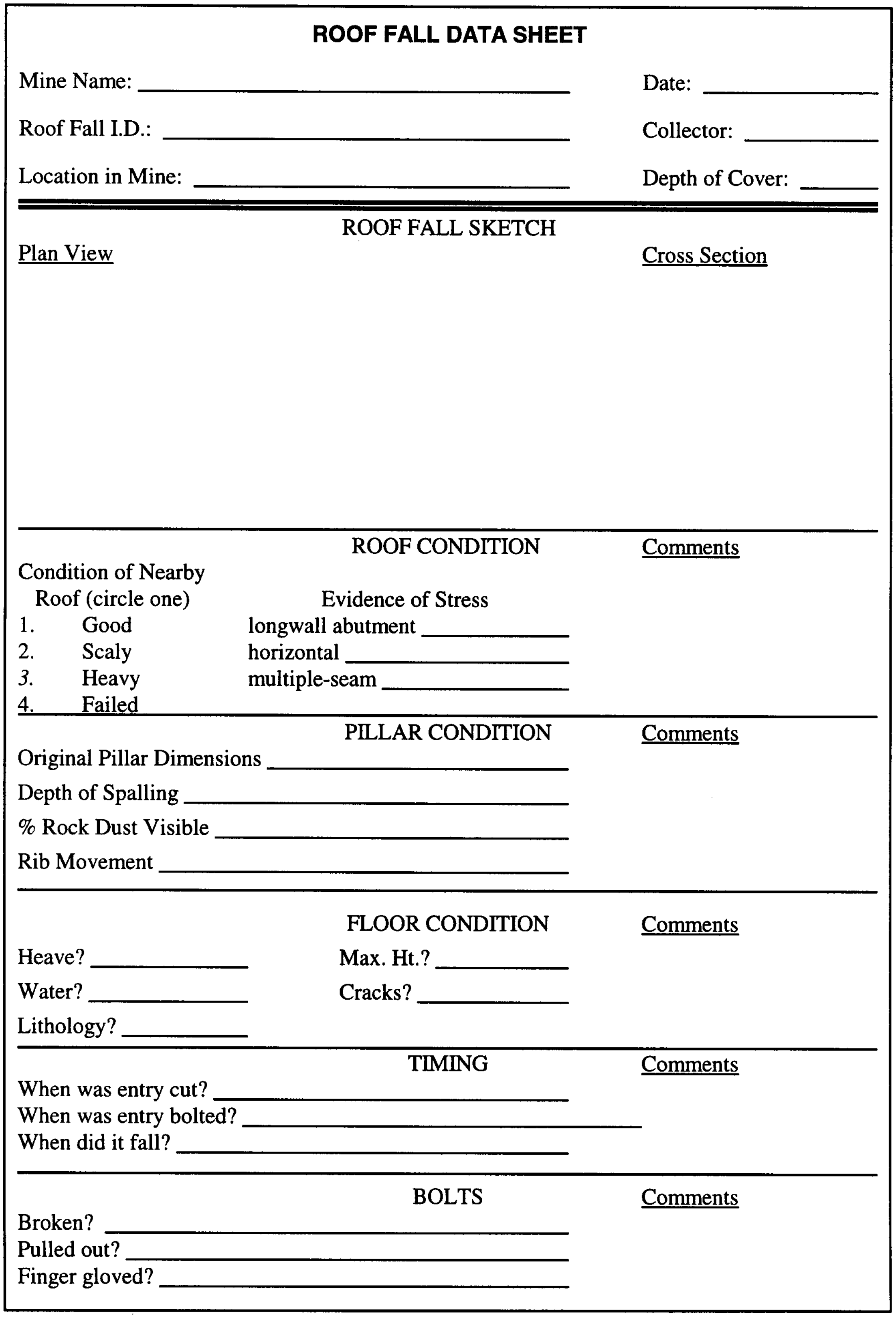
CLARION 4A

THE ROOF FALL IS LOCATED IN THE BELT ENTRY OF THE A6 LONGWALL (2REM) IN AN INTERSECTION AT +7660 FT. THE AREA HAD BEEN PREVIOUSLY BOLTED WITH 4FT BOLTS. THE FALL OCCURRED IN THE INBY TRANSITION ZONE TO A SMALL SANDSTONE CHANNEL SYSTEM. THE IMMEDIATE ROOF IS COMPOSED OF FRACTURED LIMESTONE COMPOSED OF ~50% DISCONTINUOUS IRONSTONE LENSES AND RANGES FROM 6"—3FT THICK. IMMEDIATELY ABOVE IS 2FT—4FT OF CLAYSTONE WITH V. POOR BEDDING, OVERLAIN BY THE SANDSTONE UNIT. THE FALL EXTENDS UP TO THE BASE OF THE SANDSTONE, OR APPROX. 5FT.

Stephen R Doe
SR. GEOLOGIST
DECEMBER 31, 1992

NOT TO SCALE

Figure 43.–Roof fall report by a geologist at an Ohio mine.



ROOF FALL DATA SHEET

Mine Name: ____________________ Date: __________

Roof Fall I.D.: ____________________ Collector: __________

Location in Mine: ____________________ Depth of Cover: ______

ROOF FALL SKETCH

Plan View

Cross Section

ROOF CONDITION

Comments

Condition of Nearby Roof (circle one)

1. Good
2. Scaly
3. Heavy
4. Failed

Evidence of Stress

longwall abutment __________

horizontal __________

multiple-seam __________

PILLAR CONDITION

Comments

Original Pillar Dimensions __________

Depth of Spalling __________

% Rock Dust Visible __________

Rib Movement __________

FLOOR CONDITION

Comments

Heave? __________

Water? __________

Lithology? __________

Max. Ht.? __________

Cracks? __________

TIMING

Comments

When was entry cut? __________

When was entry bolted? __________

When did it fall? __________

BOLTS

Comments

Broken? __________

Pulled out? __________

Finger gloved? __________

Figure 44.–Roof fall data sheet developed by NIOSH.

Figure 45.–Roof fall caused by broken rock falling between bolts.

Figure 46.–Two views of "glove-fingered" bolts that provide little mechanical interlock to support strata.

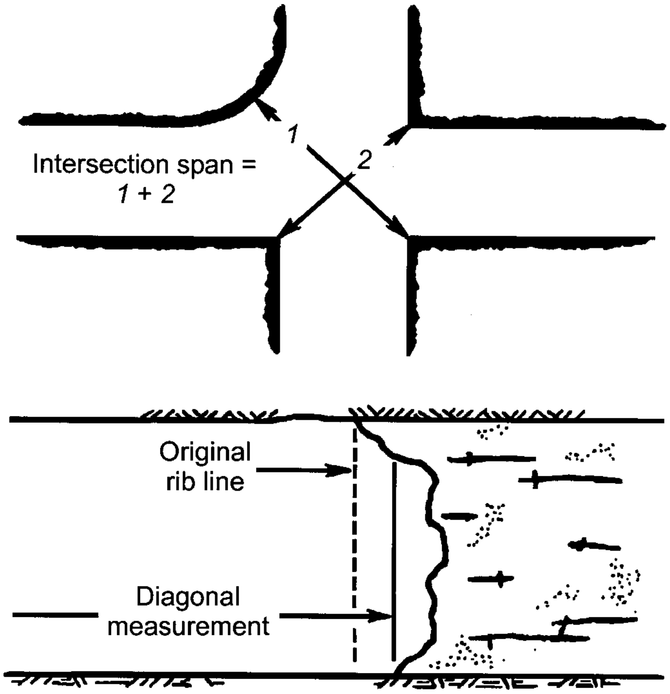


Figure 47.–Method for measuring intersection diagonals.

At one western Kentucky mine over a 3-year period, only 12% of 161 total falls occurred inby the feeder breaker, but 46% of the falls occurred within 1 month of development when mine workers are still frequently exposed (figure 48). This mine had more than 100 reported roof falls in 1996, the highest in the country. The roof lithology of this mine consists of a siltstone (UR = 32) 0-8 ft up in the roof with a 3-in-thick, highly reactive mudband 15-18 in up in the roof. In numerous falls, it seems that swelling of this member as well as the siltstone itself may be responsible. The siltstone "rats" out around the bolts because of pressure from the mudband, which causes "chandelier" bolts and much debris in the intakes. In addition, the use of wooden half headers as plates on some bolts has caused the loss of applied tension to the torque tension bolts used in the mine. Sixty-four percent of bolts tested, using wood headers, showed torque bleedoff (some of these bolts were as close as one to two breaks from the face). Only 28% of bolts with steel plates showed torque bleedoff. One possible solution to such conditions is the use of a fully grouted torque tension bolt with a steel plate to help prevent swelling and roof ratting. Another might be to leave 6-8 in of head coal. By doing this, the mine may be able to help seal the reactive zone in the roof.

The source of roof failure may sometimes be revealed in a distribution of roof fall standup time. At a mine near Hanna, WY, 21 out of 28 documented roof falls occurred more than 18 months after entry development. The average standup time was 4.1 years. At this mine, 2-5 ft of head coal was typically left to protect an extremely weak carbonaceous mudstone roof. If the head coal that was left was thinner (in the 6-12 in range), then it tended to sag and separate with time, exposing the moisture-sensitive mudstone and causing a roof fall.

At one Illinois mine, most falls occur shortly after mining (figure 49), but a significant number occur many months or even years after development (average standup time is 34.8 months). In this mine the roof shale (Dykersburg Shale) is moisture-reactive. Although many falls occur within 1-2 months of development because of high horizontal stress, which is characteristic of the Illinois basin, moisture slaking continues, causing roof falls long after development.

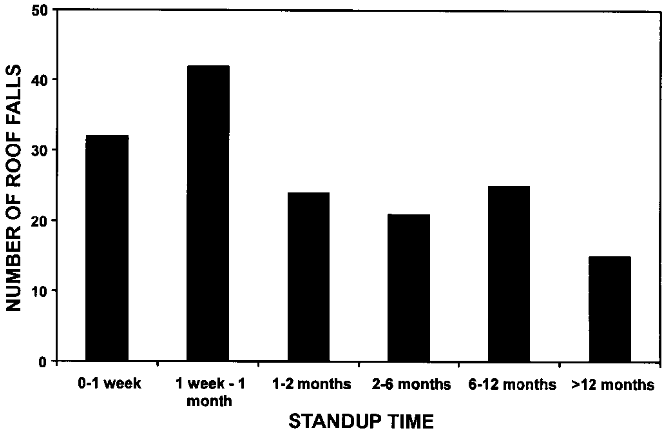


Figure 48.–Standup time for roof falls at a western Kentucky mine.

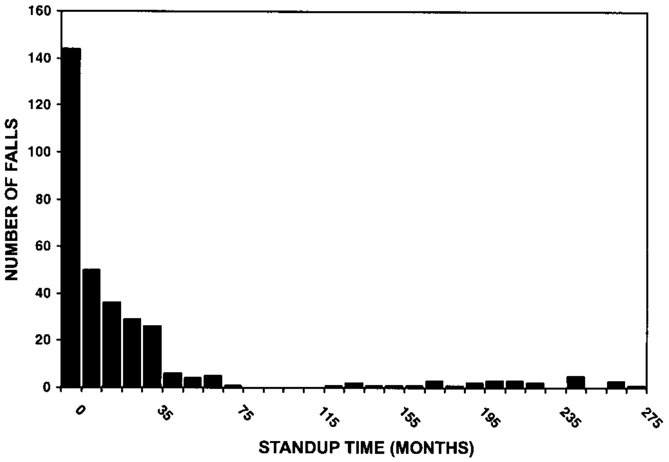


Figure 49.–Standup time for roof falls at an Illinois mine.

CASE STUDY

A roof fall analysis was done at a mine in southwestern Pennsylvania in the Pittsburgh Coalbed. Figure 50 shows the southern part of the mine with roof falls and CMRR values. The mine had a total of 207 roof falls, 108 of which were formally reported to MSHA. Following is a summary of roof fall characteristics from roof fall reports.

(1) Average height of falls: 8.1 ft (figure 51).

(2) Average height of falls over bolt anchorage: 2.5 ft (figure 52).

The average height of the falls gives insight into the extent and nature of the damage. Inordinately high roof falls (20-30 ft) indicate that high horizontal stresses are acting on the roof and bulking the roof strata, resulting in a high roof fall.

(3) Location of falls: Eight-six percent of all falls were in intersections or in both intersections and entries (figure 53).

The location of the falls is important to the resulting control. If falls are predominantly in intersections, there are several possible solutions:

(a) Intersections are overspanned. Reduce the span by minimizing turnouts in critical belts or travelways.

(b) Increase the support, including longer bolts, cable bolts, or standing support for pillar corners.

(c) Reduce the number of intersections by staggering crosscuts.

(4) Average volume of falls: 6,258 ft^3.

This value is important for estimating cleanup costs.

The performances of various roof bolts used were analyzed for a relationship with roof falls. The following is a distribution of roof falls by roof bolt type.

Roof bolt type	Falls
5-ft resin	152
6-ft point-anchored resin-assisted	25
8-ft point-anchored resin-assisted	1
8-ft conventional	16
Mixed pattern	13

The number of roof falls normalized to feet of drivage per bolt type gives a more representative look at the relationship between roof falls and roof bolts (figure 54). The two bolt categories with the highest roof fall rate are the mixed pattern and the 8-ft conventional bolt. The mixed pattern (5-ft resin bolt with 8-ft point-anchored resin-assisted bolt) roof fall rate can be explained by the fact that this combination of bolts was used only in areas of poor roof. The mine had a significantly higher roof fall rate using the 8-ft conventional bolt early in its life and quickly discontinued its use. Also statistically significant was the markedly *lower* roof fall rate realized by using the 8-ft point-anchored resin-assisted bolt. This apparent improvement in roof control with the 8-ft point-anchored resin-assisted bolt may be due to its greater length, higher load-bearing capacity, tensioned roof support mechanism, or some combination of effects. The analysis also shows that there is no significant improvement in the fall rate with the 6-ft point-anchored resin-assisted bolt.

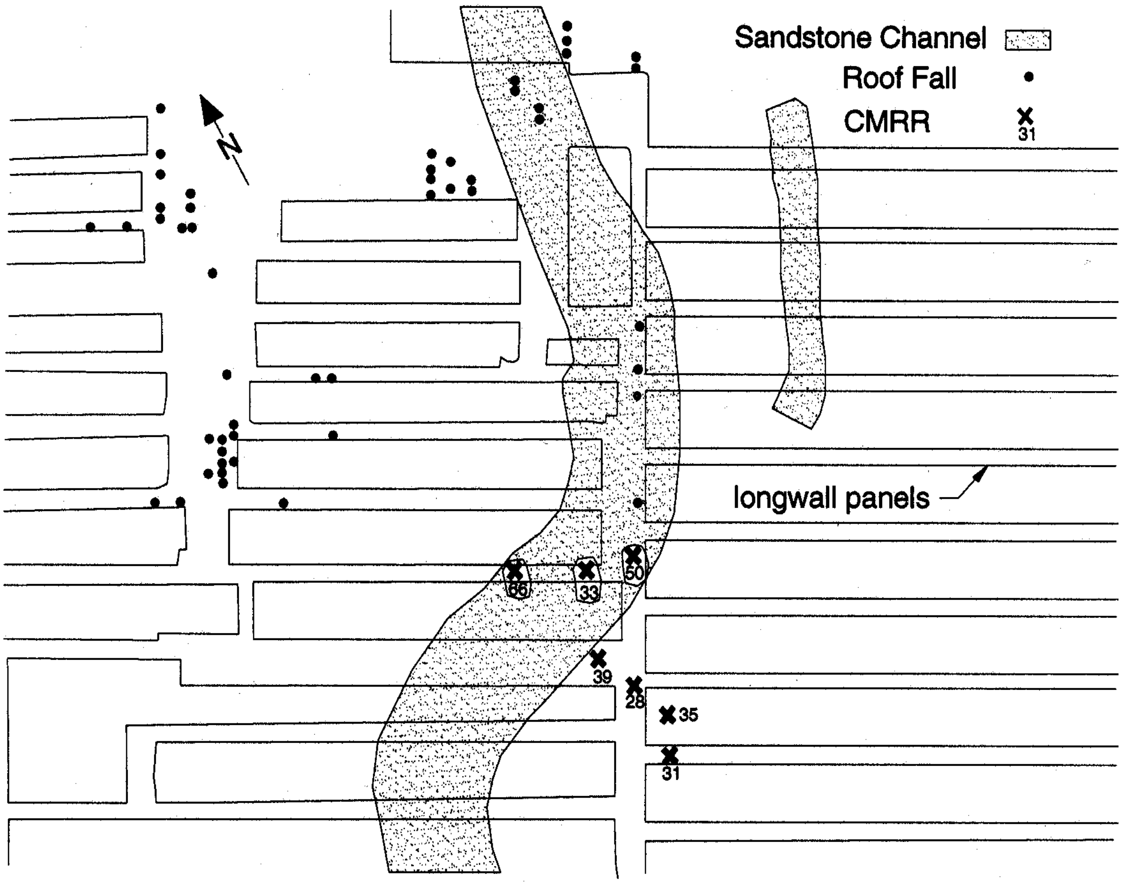


Figure 50.–A portion of a southwestern Pennsylvania longwall mine showing roof falls, sandstone channels, and CMRR.

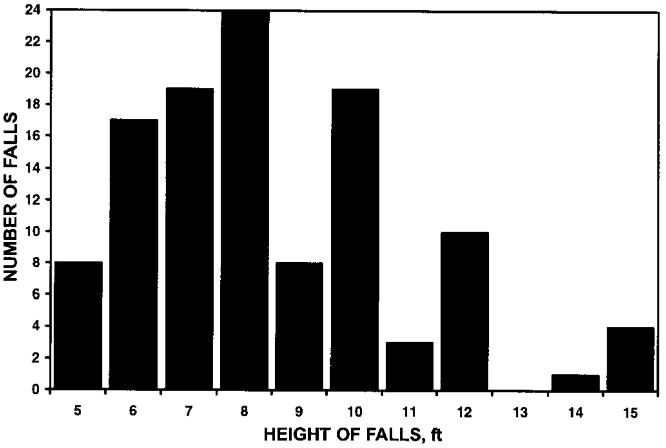


Figure 51.–Height of roof falls at a southwestern Pennsylvania mine.

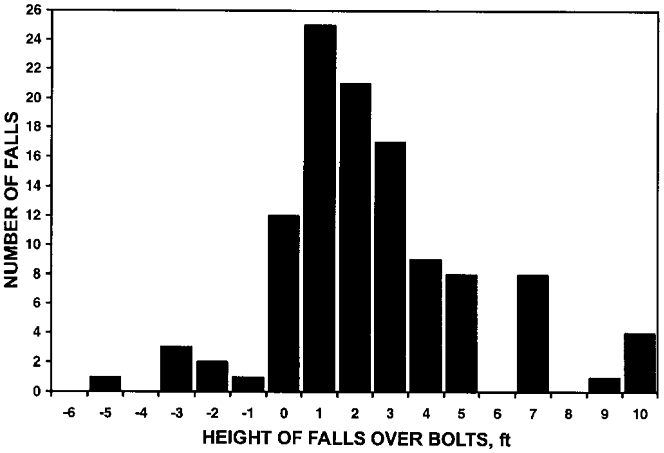


Figure 52.–Height of roof falls over bolts at a southwestern Pennsylvania mine.

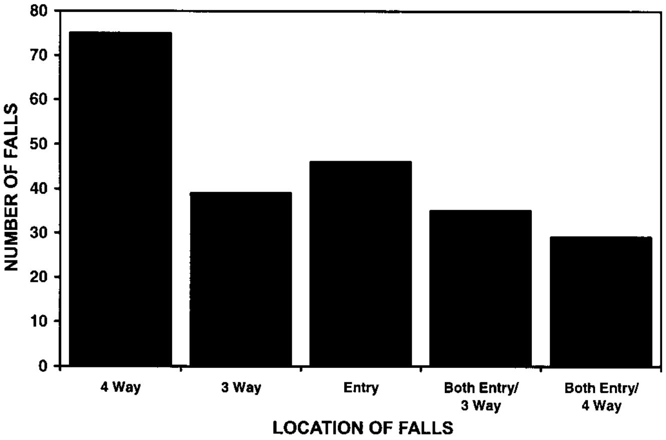


Figure 53.–Location of roof falls at a southwestern Pennsylvania mine.

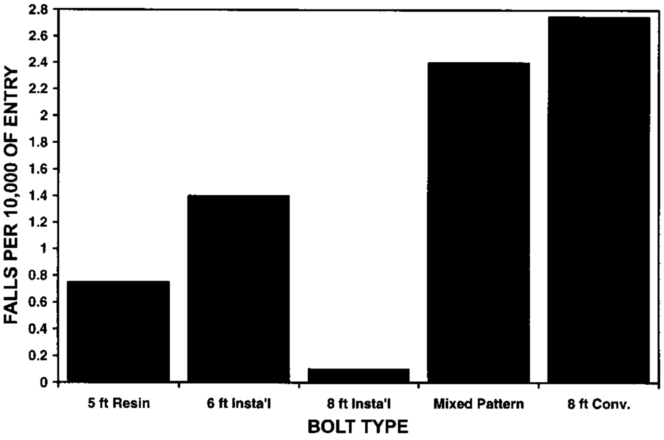


Figure 54.–Roof falls versus roof bolt type at a southwestern Pennsylvania mine.

SUMMARY

The safety of underground coal miners is of great concern to NIOSH. One of the most hazardous areas of mining remains the instability of exposed roof. During 1983-2000, 245 coal miners were killed by roof falls. In addition, an average of 980 injuries per year were attributed to roof falls during the same period. Unlike construction materials for which there are known strengths and other physical properties, roof geology, and thus rock stability, is highly variable. Current roof exploration methods reveal little about the strength of the roof in advance of mining. Therefore, engineers and operations personnel must be able to recognize and support weak rock as they advance. Toward the goal of recognition and projection of weak and defective roof, it is important that strata control personnel understand the origin, nature, extent, and potential hazard of "bad geology." From numerous field investigations, NIOSH has compiled field examples of weak and hazardous roof. Geologic hazards are grouped into two categories: weak rock and discontinuities. The depositional and structural origin, associations, and mining implications for drawrock, stackrock, rider coal, and head coal have been discussed, along with field examples of associated hazards. The roof lithologies are often available in advance in the form of roof bolt hole logs. The systematic collection and analysis of the information may provide advance warning of weak roof rock.

Discontinuities, or defects in the roof, are the most dangerous geologic structures found in coal mine roof. Unseen breaks in otherwise solid roof may provide little warning of impending failure. Clay veins, slickensides, sandstone channels, and joints are the most common of such discontinuities. It is a rare coal mine that has never experienced some type of geologic roof disturbances. An understanding of the origin and occurrence of these features will greatly aid in their tracking and prediction. Support measures can be applied more appropriately if the roof damage and resulting loads are better understood.

Much benefit can be realized from careful and systematic roof fall analysis. Roof falls are the best exposures of roof, especially weak and defective roof. Uncovering the cause of roof falls can reveal trends, including regular shear patterns, weak bolt anchorages, damage from horizontal stress, bolt failures or poor bolt installations, overspanned intersections, and water swelling in clay fault gouge. A CMRR should be determined for each roof exposure and can be plotted against roof fall rate to indicate the threshold of weak roof for that mine. The mapping of falls can reveal their correlation with paleochannels, multiple-seam mining, or stream valleys. The tracking of standup times of roof falls can help identify the personnel most at risk, as well as provide early warning for remedial support application. A roof bolt performance using the roof fall rate as the outcome variable, roof bolting can be optimized based on real mine experiences.

Often a roof fall seems to defy explanation. However, with careful examination and a historical record of the geology of the mine roof, the cause of the fall may be determined. An understanding of coal mine roof geology can only lead to an increased awareness of the hazards facing the coal miner.

REFERENCES

Bauer ER, Dolinar DR [2000]. Skin failure of roof and rib and support techniques in underground coal mines. In: Mark C, Dolinar DR, Tuchman RJ, Barczak TM, Signer SP, Wopat PF, eds. Proceedings: New Technology for Coal Mine Roof Support. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2000-151, IC 9453, pp. 99-109.

Bieniawski ZT [1988]. Rock mass classification as a design aid in tunnelling. Tunnels and Tunnelling *July*:19-23.

Buddery PS, Oldroyd DC [1992]. Development of a roof and floor classification applicable to collieries. In: Proceedings of the Eurock '92 Conference. London: Thomas Telford, pp. 197-202.

CFR. Code of Federal regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

Chase FE, Ulery JP [1987]. Clay veins: their occurrence, characteristics, and support. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 9060. NTIS No. PB 87-204517.

Damberger HH, Nelson WJ, Krausse HF [1980]. Effect of geology on roof stability in room-and-pillar mines in the Herrin (No. 6) Coal of Illinois. In: Proceedings of the First Conference on Ground Control Problems in the Illinois Coal Basin. Carbondale, IL: Southern Illinois University, pp. 14-32.

Fergusen HF [1967]. Valley stress release in the Allegheny plateau. Bull Assoc Eng Geol *4*(1):63-71.

Fergusen HF, Hamel JV [1981]. Valley stress relief in flatlying sedimentary rocks. In: Proceedings of the International Symposium on Weak Rock (Tokyo, Japan, Sept. 21-24), pp. 1235-1241.

Ferm JC [1974]. Carboniferous environmental models in eastern United States and their significance. In: Briggs G, ed. Carboniferous of the southeastern United States. Geological Society of America Special Paper 148, pp. 79-95.

Ferm JC, Cavaroc VV Jr. [1968]. A nonmarine sedimentary model for the Allegheny rocks of West Virginia. In: Klein GD, ed. Late Paleozoic and Mesozoic continental sedimentation, northeastern North America. Geological Society of America Special Paper 106, pp. 1-19.

Ferm JC, Smith GC [1981]. A guide to cored rocks in the Pittsburgh basin. U.S. Bureau of Mines contract No. J0188115. Library of Congress No. 81-51290.

Ferm JC, Melton RA, Cummins GD, Mathew D, McKenna L, Muir C, et al. [1978]. A study of roof falls in underground mines on the Pocahontas #3 Seam, southern West Virginia and southwestern Virginia. University of South Carolina. U.S. Bureau of Mines contract No. H0230028. NTIS No. PB 80-158983.

Grau RH, Bauer ER [1997]. Ground control worker safety during extended-cut mining. In: Peng SS, ed. Proceedings of the 16th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 283-288.

Greb SF [1991]. Roof falls and hazard prediction in eastern Kentucky coal mines. In: Peters DC, ed. Geology in coal resource utilization. Fairfax, VA: American Association of Petroleum Geologists, pp. 245-262.

Hill JL III [1986]. Cutter roof failure: an overview of the causes and methods for control. Spokane, WA: U.S. Department of the Interior, Bureau of Mines, IC 9094. NTIS No. PB 87-116976.

Hylbert DK [1978]. The classification, evaluation, and projection of coal mine roof rocks. Min Eng *30*(12):1667-1676.

Iannacchione AT, Ulery JP, Hyman DM, Chase FE [1981]. Geologic factors in predicting coal mine roof rock stability in the upper Kittanning coalbed, Somerset County, Pa. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 8575. NTIS No. PB 82-145376.

Ingram DK, Chase FE [1987]. Effects of ancient stream channel deposits on mine roof stability: a case study. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 9092.

Ingram DK, Molinda GM [1988]. Relationship between horizontal stresses and geologic anomalies in two coal mines in southern Illinois. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 9189. NTIS No. PB 90-268814.

Kertis CA [1985]. Reducing hazards in underground coal mines through the recognition and delineation of coalbed discontinuities caused by ancient channel processes. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 8987. NTIS No. PB 86-156205.

Kester WM, Chugh YP [1980]. Premining investigations and their use in planning ground control in the Illinois coal basin. In: Proceedings of the First Conference on Ground Control Problems in the Illinois Coal Basin. Carbondale, IL: Southern Illinois University, pp. 33-43.

Krausse H-F, Damberger HH, Nelson WJ, Hunt SR, Ledvina CT, Treworgy CG, et al. [1979]. Roof strata of the Herrin (No. 6) coal member in mines of Illinois—their geology and stability: summary report. Champaign, IL: Illinois State Geological Survey, Illinois Minerals Notes 72.

Lotz CW [1970]. Probable original mineable extent of the bituminous coal seams in West Virginia. Morgantown, WV: West Virginia Geological and Economic Survey.

Mark C, Molinda GM, Schissler AP [1994]. Evaluating roof control in underground coal mines with the coal mine roof rating. In: Peng SS, ed. Proceedings of the 13th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 252-260.

Mazzoni RA [1996]. A trouble-shooting guide for roof support systems. Pittsburgh, PA: U.S. Department of Labor, Mine Safety and Health Administration, Informational Report 1237.

McCulloch CM, Diamond WP, Bench BM, Deul M [1975]. Selected geologic factors affecting mining of the Pittsburgh coalbed. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 8093. NTIS No. PB 249 851.

McLoughlin TF [1986]. Explanation of the regional tectonic map of the southwestern coalfield of Virginia. U.S. Department of Labor, Mine Safety and Health Administration, Informational Report 1177.

McLoughlin TF [2001]. Telephone conversation between G. M. Molinda, Pittsburgh Research Laboratory, and T. F. McLoughlin, U.S. Department of Labor, Mine Safety and Health Administration, District 5, Roof Control Department, Norton, VA.

Milici RC, Gathright, TM, Miller BW, Gwin MR [1982]. Geologic factors related to coal mine roof falls in Wise County, Virginia. Appalachian Regional Commission, contract No. CO-7232-80-I-302-0206.

Moebs NN [1977]. Roof rock structures and related roof support problems in the Pittsburgh Coalbed of southwestern Pennsylvania. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 8230. NTIS No. PB 267 922.

Moebs NN, Stateham RM [1985]. The diagnosis and reduction of mine roof failure. Coal Min *22*(2):52-55.

Molinda GM, Ingram DK [1988]. Case evaluation of a surface seismic reflection technique for delineating coalbed discontinuities. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 9147. NTIS No. PB 88-229885.

Molinda GM, Ingram DK [1989]. Effects of structural faults on ground control in selected coal mines in southwestern Virginia. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 9289. NTIS No. 90-196809.

Molinda GM, Mark C [1994]. Coal mine roof rating (CMRR): a practical rock mass classification for coal mines. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, IC 9387. NTIS No. PB 94-160041.

Molinda GM, Mark C [1996]. Rating the strength of coal mine roof rocks. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, IC 9444. NTIS No. PB 96-155072.

Molinda GM, Heasley KA, Oyler DC, Jones JR [1992]. Effects of horizontal stress related to stream valleys on the stability of coal mine openings. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 9413.

Molinda GM, Monaghan WD, Mowrey GL, Persetic GF [1996]. Using ground penetrating radar for roof hazard detection in underground mines. Pittsburgh, PA: U.S. Department of Energy, RI 9625. NTIS No. PB 96-188123.

Molinda GM, Mark C, Bauer ER, Babich DR, Pappas DM [1998]. Factors influencing intersection stability in U.S. coal mines. In: Peng SS, ed. Proceedings of the 17th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 267-275.

Molinda GM, Mark C, Dolinar DR [2000]. Assessing coal mine roof stability through roof fall analysis. In: Mark C, Dolinar DR, Tuchman RJ, Barczak TM, Signer SP, Wopat PF, eds. Proceedings: New Technology for

Coal Mine Roof Support. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2000-151, IC 9453, pp. 53-71.

MSHA [1999]. Quarterly employment and coal production, accidents/injuries/illnesses reported to MSHA under 30 CFR 50. Denver, CO: U.S. Department of Labor, Mine Safety and Health Administration, Office of Injury and Employment Information.

Mucho TP, Mark C [1994]. Determining horizontal stress direction using the stress mapping technique. In: Peng SS, ed. Proceedings of the 13th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 277-289.

Nelson WJ [1991]. Faults and their effect on coal mining in Illinois. Champaign, IL: Illinois State Geological Survey, Circular 523, pp. 1-40.

Pettijohn FJ, Potter PE, Siever R [1973]. Sand and sandstone. New York: Springer-Verlag, pp. 453-466.

Roen JB, Farrel DE [1973]. Structure contour map of the Pittsburgh Coalbed, southwestern Pennsylvania and northern West Virginia. U.S. Department of the Interior, U.S. Geological Survey open-file map.

Sames GP, Moebs NN [1989]. Hillseam geology and roof instability near outcrop in eastern Kentucky drift mines. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 9267. NTIS No. PB 90-157439.

Sames GP, Moebs NN [1991]. Geologic diagnosis for reducing coal mine roof failure. In: Peters DC, ed. Geology and coal resource utilization. Fairfax, VA: American Association of Petroleum Geologists, pp. 203-223.

Van der Merwe NJ [2000]. Horizontal stress: the root of all evil? In: Peng SS, ed. Proceedings of the 19th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 129-136.

APPENDIX.—GLOSSARY OF TERMS

Chandelier bolts.—When moisture-sensitive shales fall between roof bolts, leaving 2 in to 2 ft of exposed roof bolt.

Clay vein.—A body of soft or somewhat indurated clay that can either cut through or follow bedding in the coal seam. The clay is usually injected into the cleat or coal fractures from the clay forming the roof or, less frequently, the floor. Clay veins range from inches to many feet in lateral extent.

Cleat.—A vertical or rotated systematic joint set found in coal seams formed by tension during compaction or during large-scale structural movement.

Coal streak.—Small piece of coal (2-10 in) found in a matrix of shale in the roof. The coal streak may be formed in place or washed in as a result of flooding.

Cutter.—A linear fracture in the roof that usually occurs along the roof and rib contact caused by compression due to horizontal stress or roof sag.

Decollement.—Small faults or folds occurring in roof rocks and caused by the sliding of overlying or underlying strata along bedding.

Drawrock.—A soft shale or claystone, about 2 in to 4 ft thick, above the coal that falls with the coal or shortly after mining.

Fault.—A failure surface along which there has been movement. Movement can be the result of sediment compaction during burial or larger scale strata movement due to major regional stresses. Often used to describe any interruption in the lateral continuity of the coal seam.

Gutter.—A cavity formed by the fall of roof rock crushed out by a cutter.

Hillseam.—A systematic joint or joint set formed by extensional movement of rock toward a stream valley. Sets can range from 2 in to 10 ft wide and can crosscut the coal seam or can be confined only to the roof strata.

Horseback.—A mass of rock found in the roof with a smooth surface and resembling a horse's back. A ridgelike body that is the result of erosion and filling with sediment. Also, the slickensided cavity in the roof of a rock mass that has fallen out of the roof.

Joints.—A system of fracture surfaces that cut perpendicular or subperpendicular to bedding and along which there has been no movement. Usually found in the roof, but can include cleat in the coal seam.

Pot.—A fall of roof, not reaching to the roof bolt anchorage, that can range from 2 in to 5 ft up into the roof.

Rash.—A sequence of rock consisting of carbonaceous shale, dirty coal, thin riders, and coal streaks found above a coal seam.

Rider coalbed.—A thin (2 in to 4 ft), minor coalbed that occurs above the main coal seam and results from the reestablishment of coal swamps on top of the flooded main seam. Several rider coalbeds can be present above the main seam.

Rolls.—A local thickening of the roof, floor, or interior parting strata causing thinning of the coal seam. This could be due to a washout or coal split. The term is also used to refer to a localized uplift or downdrop of a coal seam.

Scale.—Small slabs or pieces of roof rock that are left as the coal is removed, or formed by separation and sagging of bedding in roof rock.

Seat earth.—A bed representing an ancient soil, usually containing abundant rootlets, under the coal seam.

Shear.—A fault surface in roof, coal, or floor.

Shear bodies.—Large roof features (feet to tens of feet) that are isolated cylindrical bodies formed by slippage in the roof.

Slaking.—The disintegration of clay-rich rocks due to flaking and swelling when exposed to moisture.

Slickensides.—A polished, or sometimes striated surface found in a coal mine roof produced by rubbing during faulting or compaction.

Slip.—Small fault characterized by slickensides and a glassy, glazed appearance. Usually found in the roof or interseam binder and due to soft sediment deformation, such as slumping and compaction with burial. Can range from inches to 10 ft.

Snap top.—Roof rock that, when subjected to compressional loading, works and fails audibly by making a snapping sound.

Stackrock.—A sequence of roof rock consisting of alternating shale and sandstone layers that resembles a stack of newspapers or books.

Stitching.—A zigzag fracture in the roof due to compression and shortening of the roof beam that resembles cloth stitching.

Swag.—A depression in the roof or floor caused by a roll in the coal seam.

Wild coal.—Thin rider coal above the main seam.

Delivering on the Nation's Promise:
Safety and health at work for all people
Through research and prevention

For information about occupational safety and health topics contact NIOSH at:

1-800-35-NIOSH (1-800-356-4674)
Fax: 513-533-8573
E-mail: pubstaft@cdc.gov
www.cdc.gov/niosh

SAFER • HEALTHIER • PEOPLE™

DHHS (NIOSH) Publication No. 2003-152