

LONGWALL MINE DESIGN FOR CONTROL OF HORIZONTAL STRESS

By Christopher Mark¹ and Thomas P. Mucho¹

ABSTRACT

Horizontal stress is a significant, although often overlooked, factor in ground control in longwall mines. It can be particularly destructive in development and headgate entries, where it can cause persistent compressive-type roof failure called cutter roof, roof guttering, or kink roof. This paper presents the current state of the art in detecting and controlling horizontal stress. The information was collected through detailed site investigations at several eastern U.S. longwall mines, a survey of ground conditions at 50 U.S. longwalls, and an international literature review.

This paper begins with a discussion of the present knowledge of regional in situ stress fields in the United States. A compilation of underground stress measurements from 47 U.S. coal mines is presented. The measurements indicate a persistent trend of high horizontal stresses trending east-northeast to east-west in the Eastern United States. The direction and magnitude of horizontal stress does not appear to be significantly affected by ancient geologic structures in the East, but surface topography may have an important effect. Horizontal stresses

in the Western United States are less consistent in direction and are generally lower relative to the vertical stress. These observations are consistent with the regional stress fields identified by the geophysicists of the World Stress Map Project, who have lately presented convincing evidence that the horizontal stresses observed underground are linked to plate-tectonic processes.

Next, experience with horizontal stress in longwall mines is addressed. The paper focuses on the northern Appalachian region, where the effects of horizontal stress have been most evident. Three case histories are described in detail, and the solutions developed are highlighted. Evidence of horizontal stress observed underground in Illinois, Alabama, and the Western United States is also discussed.

The degree of horizontal stress damage to longwall gate entries appears to vary by region and by roof geology. Laminated shale roofs, particularly in the northern Appalachian Mountains and in Illinois, appear to be at the greatest risk. Some simple, in-mine, stress mapping techniques are described. Control techniques discussed include panel orientation, cut sequencing, softened entries, and roof support.

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INTRODUCTION

Although the role of horizontal stress in ground control has been recognized in U.S. coal mines since at least the early 1970's, its effects and considerations have not been well understood or communicated in many sectors of the mining community. Mines impacted by severe compressive-type roof failure usually become knowledgeable about horizontal stress, but severely affected mines usually have been economically uncompetitive and forced to close. Most of the industry remains unaware, because the effects of horizontal stress may be neither dramatic nor easily differentiated from those of vertical stress. As a result, horizontal stress is seldom a serious consideration in mine design, even when it detrimentally impacts an operation.

The incognizance of the contribution of horizontal stress to opening instability is somewhat perplexing in view of the knowledge that has accumulated about it over the last 20 years. For example, it is widely accepted that the magnitude of the principal horizontal stress, especially at

depths less than 800 m (2,600 ft), is often two to three times that of the vertical stress (22).² Additionally, given the typical rectangular shape of coal mine entries, traditional elastic theory predicts that horizontal stresses would be in close proximity to the immediate roof-and-floor (figure 1).

In longwall mines, the observed effects of horizontal stresses include—

- *Compressive-type roof failures* (commonly called cutter roof, guttering, shear, snap top, pressure cutting, or kink roof). In thinly bedded (laminated) rock, classic cutter roof develops as the progressive layer-by-layer crushing and buckling of individual beds (figure 2).

²Italic numbers in parentheses refer to items in the list of references preceding the appendix of this paper.

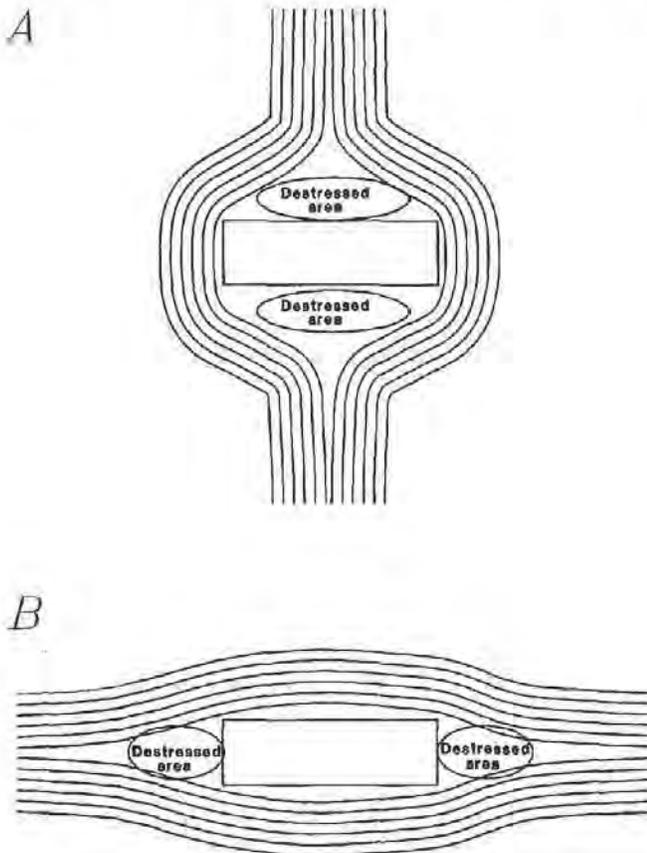


Figure 1.—Conceptualized vertical (A) and horizontal (B) stress distributions around a mine opening.

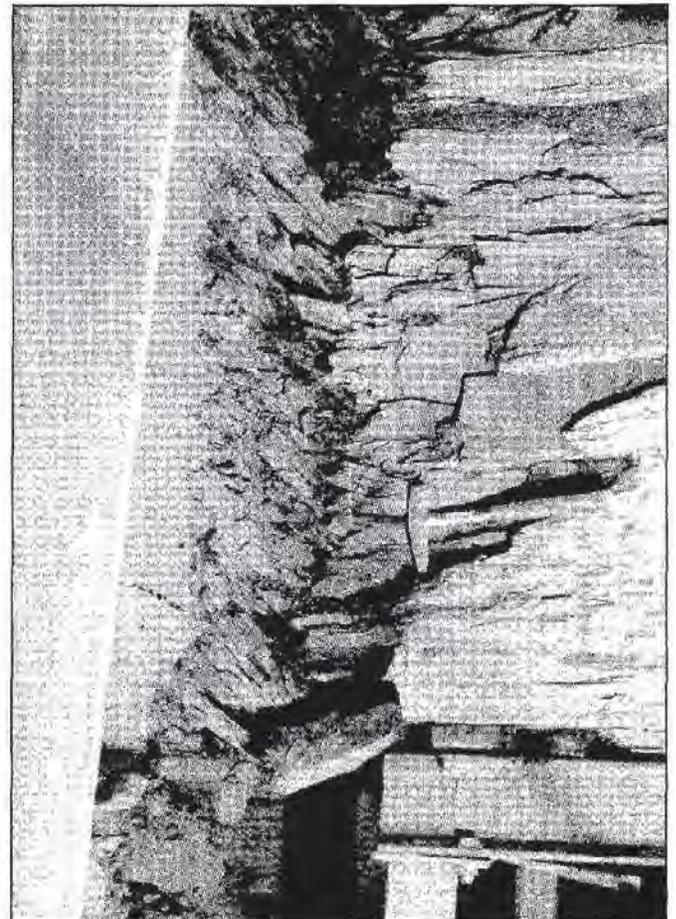


Figure 2.—Cutter roof caused by horizontal stress. (Photo: Frank E. Chase, Pittsburgh Research Center, U.S. Bureau of Mines)

- *Directionality of roof falls.* Many horizontal stress fields are distinctly biaxial, with a maximum horizontal stress (σ_H) much greater than the minimum horizontal stress (σ_h). As a result, entries oriented nearly perpendicular to σ_H suffer much greater damage than those oriented parallel.

- *Headgate failures.* In the absence of horizontal stress, headgates are usually less troublesome than tailgates because they are subjected to lower vertical stresses. When headgates are consistently more troublesome, horizontal stress is the most likely cause. Because horizontal stresses cannot pass through the gob left in the wake of longwall mining, the horizontal stresses are relieved in some areas and concentrated in others. These horizontal stress abutment zones are located where a line drawn parallel to the maximum horizontal stress intersects a corner of the longwall panel without passing through the gob (figure 3).

This paper summarizes the current knowledge regarding (1) in situ horizontal stress fields in U.S. coalfields, (2) the prevalence of gate entry instability that is attributable to horizontal stress, and (3) the effectiveness of available control techniques.

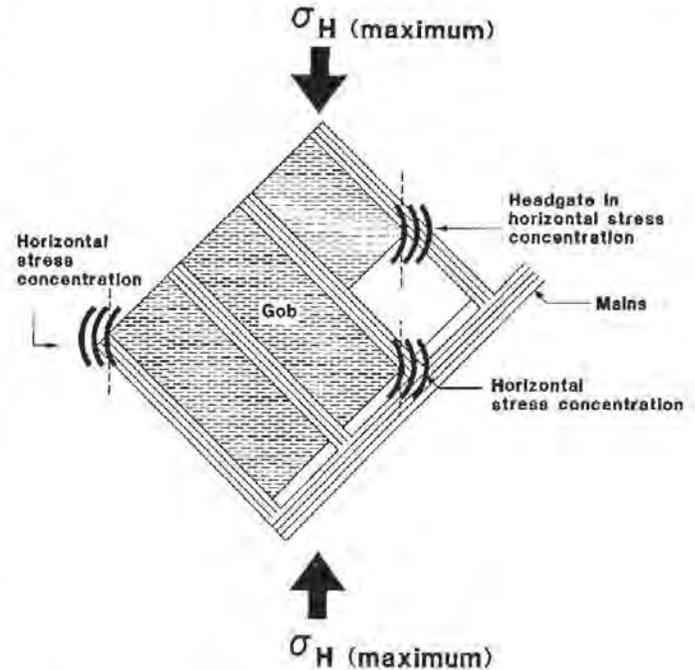


Figure 3.—Horizontal stress concentrations or abutments as a result of retreat mining through the stress field.

HORIZONTAL STRESS FIELDS OF NORTH AMERICA

Evidence that strong horizontal stresses were active in the geologic past is widespread. Mountain chains, thrust faults, and other features are the products of tremendous forces. Present-day earthquakes prove that horizontal stresses are still active. Today, it is widely accepted that horizontal stresses in the Earth's crust are closely linked to the movements and interactions of continental plates. Earlier theories that simply related horizontal stresses to the Poisson's effect have been completely discredited (31).

Recent papers by workers associated with the World Stress Map Project (38, 44-46) have summarized current knowledge about horizontal stress fields in North America. Their more than 400 data points include hydraulic fracturing stress measurements, overcoring stress measurements, borehole "breakouts" or elongations observed in oil and gas drilling, centerline fractures in oriented core, earthquake focal mechanisms, and fault-slip solutions. Some of these measurements were made at depths as great as 20 km (12 mi), but many were in the 450-1,200 m (1,500-4,000 ft) range.

Using these observations, Zoback and Zoback (46) developed the tectonic stress map of the United States shown in figure 4. The stress map divides the continental

United States into eight stress provinces, each defined by reasonably uniform horizontal stress orientations and magnitudes (relative to the vertical overburden stresses). The stress provinces are the result of current plate tectonic activity.

The largest stress province, the Mid-Plate, encompasses most of the eastern two-thirds of North America, including all the major eastern coalfields of the United States and Canada. The Mid-Plate stress province is characterized by horizontal stresses that are very consistently oriented northeast to east-northeast, with some rotation toward east-west in the Illinois Coal Basin. The east-northeast stress orientation coincides with current direction of the North American plate as it is being pushed by the expansion of the mid-Atlantic ridge (46). The Mid-Plate stress regime is called compressional, because the east-northeast horizontal stress is the major principal stress, while the vertical stress is either the minor or the intermediate principal stress.

The present-day stress field in eastern North America is significantly different from the ancient stress field responsible for the Appalachian Mountains. In fact, the current stress field is "not noticeably affected by faulting or

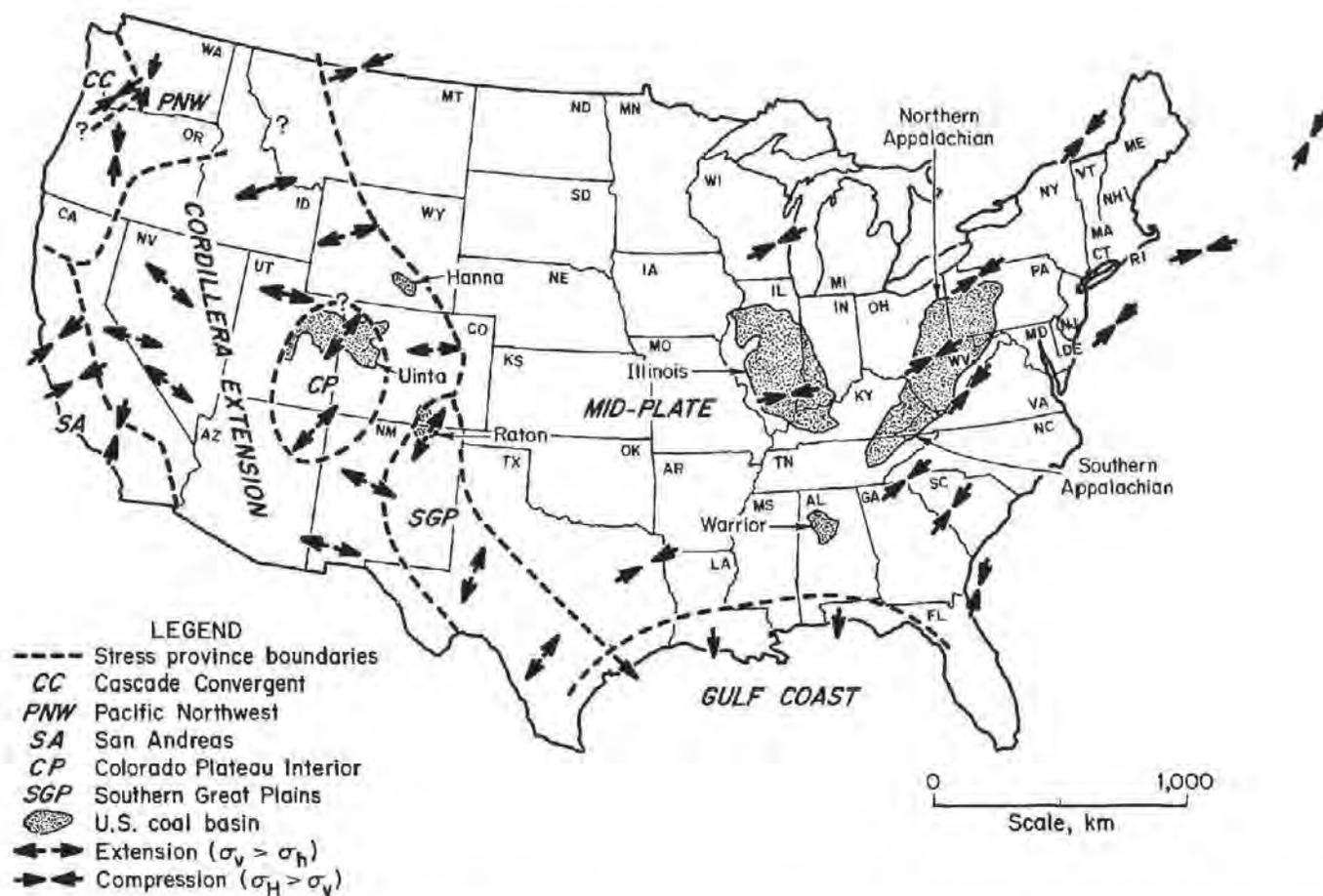


Figure 4.—Eight stress provinces of the continental United States. Arrows indicate the orientation of the maximum horizontal stress. (After Zoback and Zoback (46)).

folding on a regional scale" because of its consistency across several geologic and physiographic provinces (38). The evidence "that residual stresses from past orogenic events do not appear to contribute in any substantial way to the modern stress field" includes the fact that "the modern ENE orientation is maintained in detail in Pennsylvania through a region where the Appalachian orogenic belt makes a 40 degree bend in strike" (45).

In the Western United States, the coalfields lie within three stress provinces: the Colorado Plateau Interior, the Cordillera Extension, and the Southern Great Plains (figure 4). These three stress provinces are called extensional because the vertical stresses equal or exceed

the horizontal. The Western United States is an area of high topography, and it is believed that recent uplift is responsible for the development of the extensional stress regimes (44, 46). The typical major horizontal stress orientations are west-northwest in the Cordillera Extension province and north-northeast in the Colorado Plateau Interior and the Southern Great Plains provinces, but there are wide local variations in direction and magnitude (46). Parts of the eastern Wasatch Plateau-Book Cliffs region are even believed to be characterized by a compressive stress regime, although "the nature of these stresses is not well understood" (44).

STRESS MEASUREMENTS IN U.S. COAL MINES

During the past 20 years, a significant number of stress measurements have been conducted in underground coal mines. The appendix to this paper contains a compilation of measurements from 47 mines taken from more than 20 sources. Measurements from the eastern U.S. coal mines are presented in table A-1 in the appendix to this paper, while those from western U.S. coal mines are presented in table A-2.

MEASUREMENTS IN EASTERN U.S. COAL MINES

Table A-1 in the appendix to this paper presents data on stress measurements obtained from 5 coal mines in the northern Appalachian coalfields, 13 from the southern Appalachians, 8 from the Illinois Coal Basin, and 3 from Alabama. Some very clear patterns emerge from the data. In 69% of the measurements from mines in the Appalachian and Warrior Coal Basins, the orientation of maximum horizontal stress falls between N. 80° E. and N. 50° E. (figure 5). In the Illinois Basin, 75% of the measurements indicated that the stress field is rotated toward east-west by approximately 15°. These measurements confirm that the regional east-northeast stress field in the Mid-Plate

province is predominant in the eastern U.S. coalfields. The correlation between the measurements and the regional stress field is particularly remarkable, considering that the measurements were made by a wide variety of researchers using a vast range of equipment.

Several explanations may be advanced to explain those measurements that do not conform to the general trend. The most important is perhaps surface topography. Numerous studies have shown that the presence of surface stream valleys can concentrate stresses in the underlying ground (21). One recent study (32) found that 52% of unstable roof at eight selected mines occurred beneath the bottommost part of stream valleys. Underground mapping, in situ stress measurements, and numerical modeling all indicated that stream valleys strongly interacted with the in situ stress field, sometimes rotating it or even relieving it through thrust faulting. Mines located above drainage, however, may operate in a largely stress-relieved environment. It seems likely that severe surface topography, such as in the southern Appalachians, may often mask the in situ stress field. Some geologic structures, such as faults, may influence local stress fields, but current research indicates that in the Eastern United States, the

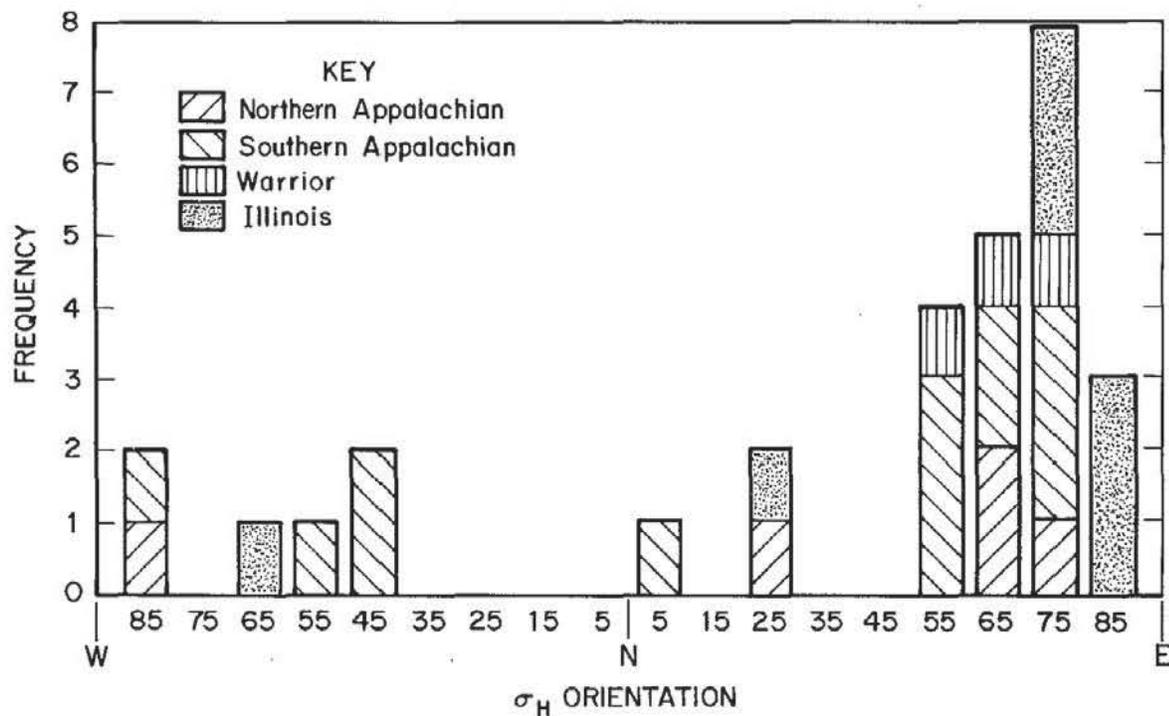


Figure 5.—Orientation of maximum horizontal stress measured in eastern U.S. coal mines.

effect is minimal or nonexistent (24). Lastly, errors in measurement may have contributed some inconsistency to the data.

Figure 6 shows that the horizontal stress exceeded the vertical stress in more than 90% of the observations, most often by a factor of two or more. Again, this conforms to the description of the compressional stress regime in the Mid-Plate stress province. Perhaps surprisingly, the seven highest measurements, all in excess of 21 MPa (3,000 psi), are from southern Appalachian coal mines. The measurements may be somewhat biased by the fact that many of them were conducted in mines that had been experiencing a high incidence of stress-related failures. Some of the measurements indicate that stresses may be relieved when the mine is located above the level of drainage. It also appears that, while the magnitude of the horizontal stress continues to increase with depth, the ratio of the horizontal to vertical stress tends to decrease.

MEASUREMENTS IN WESTERN U.S. COAL MINES

Table A-2 in the appendix to this paper presents data on stress measurements obtained from 8 Utah and 10

Colorado coal mines. In the western U.S. coal mines, the trends in stress field orientation (figure 7) are much less clear than for the eastern U.S. mines. Measurements from Colorado mines appear to be fairly randomly distributed, while those from Utah mines indicate some tendency toward the north-northwest trend predicted for the Colorado Plateau Interior stress province (figure 4). Generally, there appears to be much more variation in stress direction from mine to mine and even within individual mines. It seems likely that faults and other geologic structures may be actively influencing local stress fields to a much greater extent than in the East. Many mines are also located near the boundaries between stress provinces.

The magnitude of the horizontal stresses, relative to the vertical stresses, are lower than in the East. As figure 8 shows, in most cases the horizontal stress is almost equal to the vertical stress. Again, this stress ratio is what is expected in the extensional stress regimes prevalent in the western U.S. stress provinces.

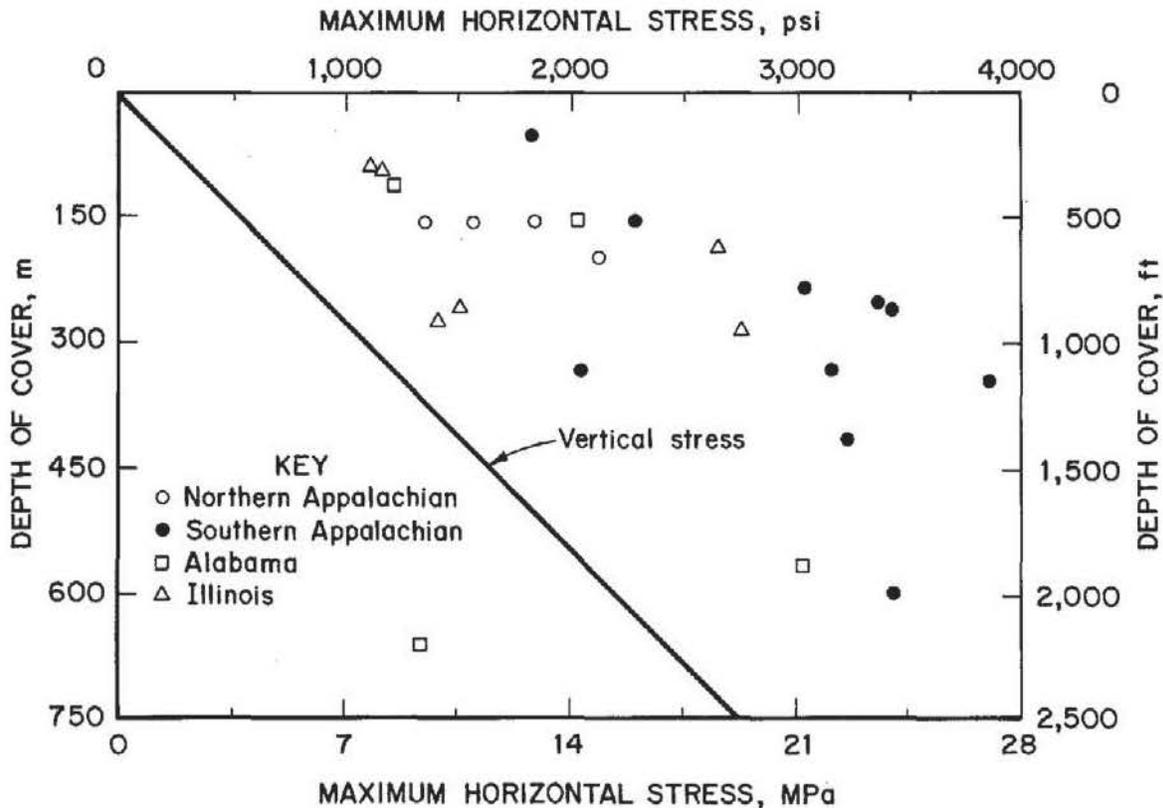


Figure 6.—Relationship of σ_H to depth in eastern U.S. coal mines. Vertical stress (σ_v) shown as .025 MPa/m (1.1 psi/ft).

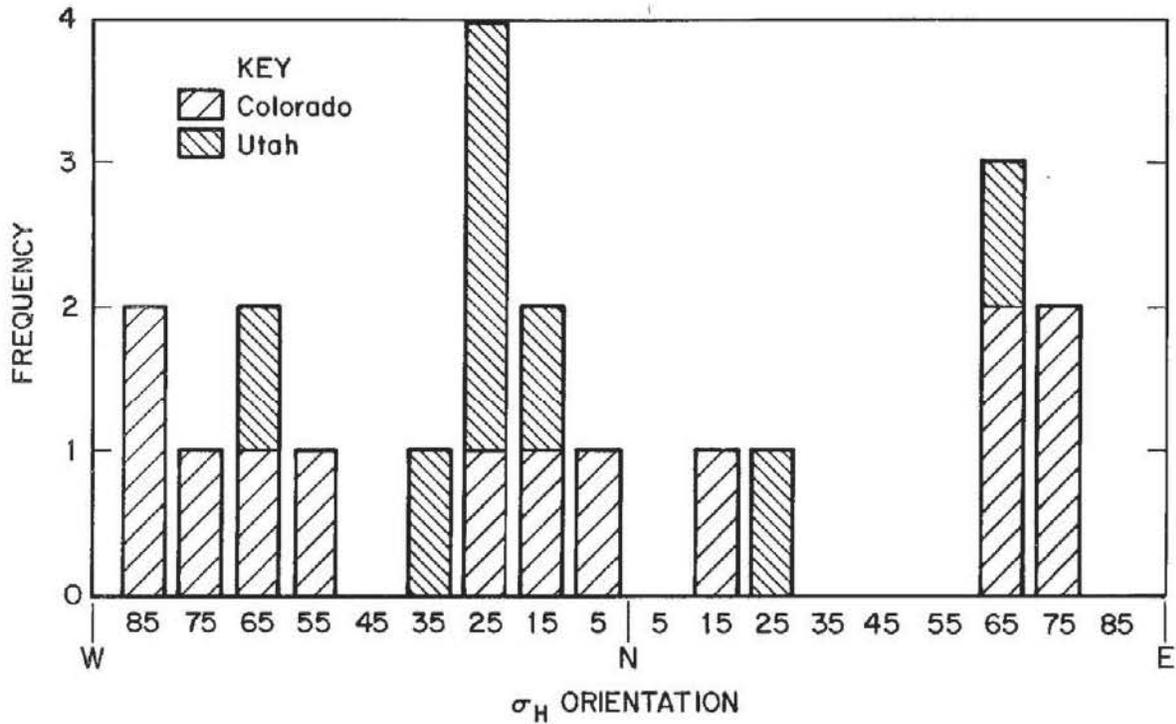


Figure 7.—Orientation of the maximum horizontal stress measured in western U.S. coal mines.

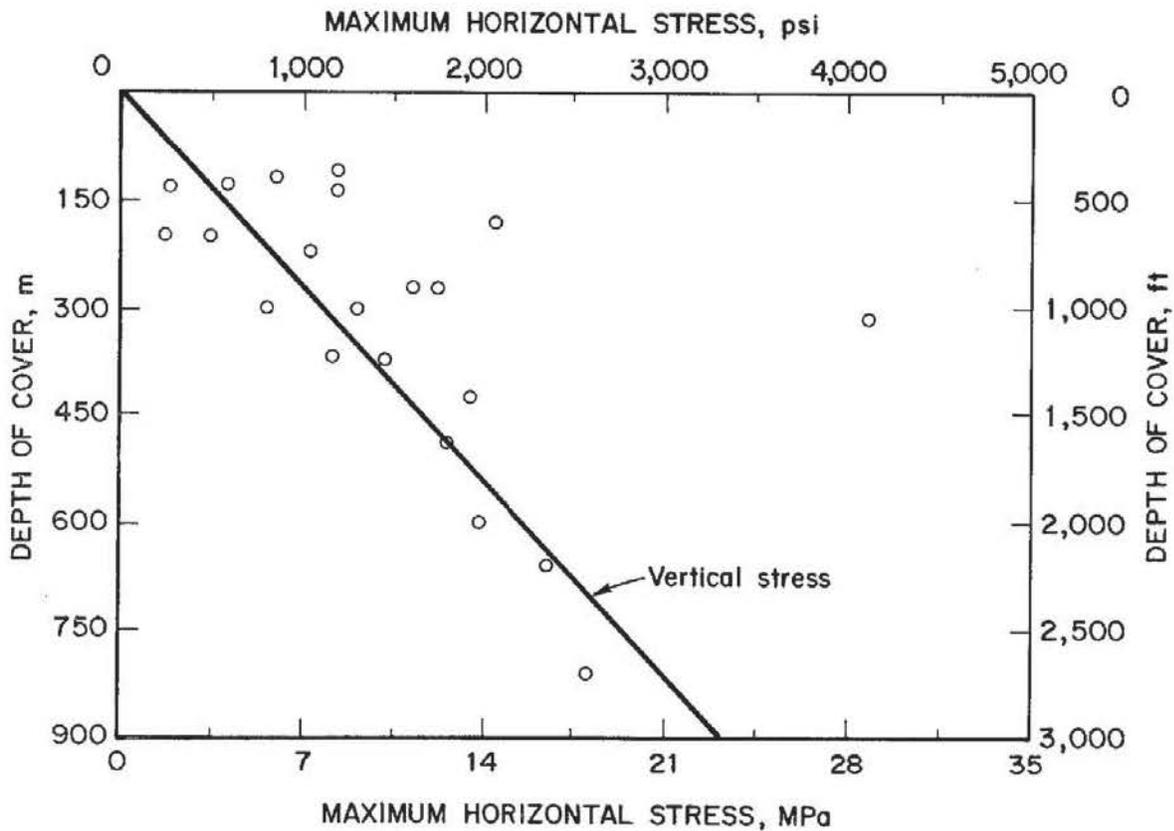


Figure 8.—Relationship of σ_H to depth in western U.S. coal mines. Vertical stress (σ_v) shown as .025 MPa/m (1.1 psi/ft).

LONGWALL MINES AND HORIZONTAL STRESSES

In situ horizontal stresses have been observed to adversely affect longwall mines throughout the world, and they certainly are not new to U.S. coal mines. As early as 1948, Roley (40) described a phenomenon he called pressure cutting in the Illinois mines. During the 1970's and 1980's, U.S. Bureau of Mines (USBM) research shed considerable light on the origin and control of cutter roof (7, 20, 26). Many of the control technologies now used in Australia and the United Kingdom—including stress mapping, entry orientation, sacrificial entries, and high-strength roof bolts—were pioneered in the United States.

PITTSBURGH COAL SEAM

The Pittsburgh Coal Seam is the most extensively longwalled coalbed in the United States, as well as the most recognized in terms of horizontal stress. Even before the advent of longwall mines, miners had noticed that cutter roof and snap top seemed to occur preferentially in north-south headings. A classic study by Dahl and Parsons in 1972 (14) determined that horizontal stress was responsible for these and other directional phenomena, including floor heave, rib spalling, and the formation of tensile cracks.

Based on their prelongwall mining history and some early poor experiences, most mines in the Pittsburgh Coal Seam have oriented their longwall panels nearly east-west. At the 8 Pittsburgh Seam longwall mines composing this study, a total of 157 longwall panels have been extracted during the past 20 years. Of these, 58% were oriented between east-west and N. 70° W. (figure 9). No serious problems attributable to horizontal stress were reported to have occurred on any of these panels, except in crosscuts. Another 29% of the panels had been oriented between N. 70° W. and N. 60° W., with some of these experiencing headgate instability, which will be described in detail later. Only 2 of the 157 panels had been oriented north-south. Both of these experienced conditions so poor that the panels were abandoned before they were completed. Most observers seem to agree that, in general, mine roof falls are much less common now than 20 years ago, particularly in north-south headings. This improvement is often attributed to better roof bolts, which have progressed from mechanical anchors, through fully grouted resin, to the resin-anchored tension bolts used today in most Pittsburgh Seam longwall mines.

Many of the mine officials noted, however, that crosscuts still tended to be troublesome on longwalls and that

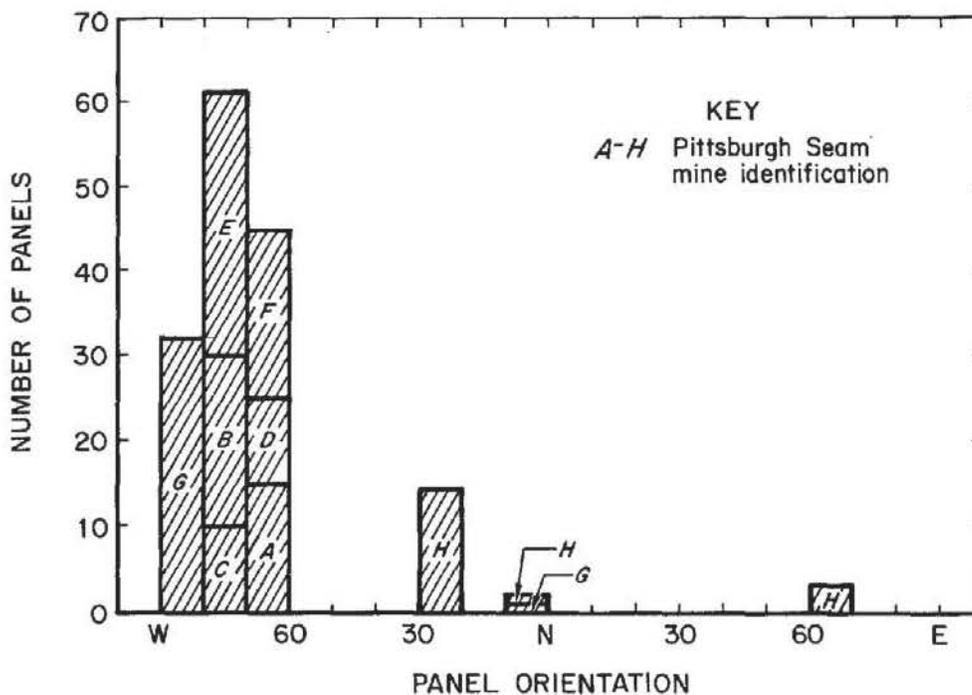


Figure 9.—Orientations of longwall panels in the Pittsburgh Coal Seam.

they usually added extra support in them. At least one mine has experimented with crosscuts oriented at N. 40° E., N. 10° E., and N. 20° W. No significant differences in performance were apparent, although theory predicts that N. 40° E. would be the best for the presumed east-northeast stress field.

Surface stream valleys were correlated with entry stability problems at three of the mines, all in southwestern Pennsylvania. Both east-west and north-south streams were implicated, but the problems appeared to be focused in the north-south headings.

One of the three mines had conducted a program of stress mapping using empty roof bolt holes. Horizontal stress can cause the mine roof to slip along bedding planes, and the movements are observed as offsets in the holes (figure 10). The direction of maximum offset should correspond to the direction of the maximum horizontal stress, while the magnitude of the offsets may be indicative of stress intensity (37). It was found that the great majority of the offsets occurred beneath stream valleys and that their orientation ranged between N. 85° E. and N. 80° W. regardless of entry direction.³

At the time of the study, only one of the Pittsburgh Seam operations, designated "Mine D", was experiencing serious ground control problems that could be attributed to horizontal stress. In a single year, 10 roof falls had occurred in headgate entries at this mine. Although the mine reported that cutter roof had never been a problem in development headings, the unique pattern and directionality of the headgate instability leaves little doubt that horizontal stress is responsible.

At Mine D, panels have been extracted in both directions back to a set of mains oriented approximately N. 25° E. (figure 11). The headgate problems have all occurred in the "X-Panels," while some "Y-Panels" have experienced problems in the tailgates. The difference in behavior can be explained by a horizontal stress abutment. As figure 11 shows, the horizontal stress abutment moves with the headgate corner on the X-Panels, while the headgates on the Y side remain in the stress shadow provided by the gob.

A detailed look at the behavior of an X-Panel headgate provides further evidence of a horizontal stress abutment (figure 12). As the longwall mines by a crosscut, the

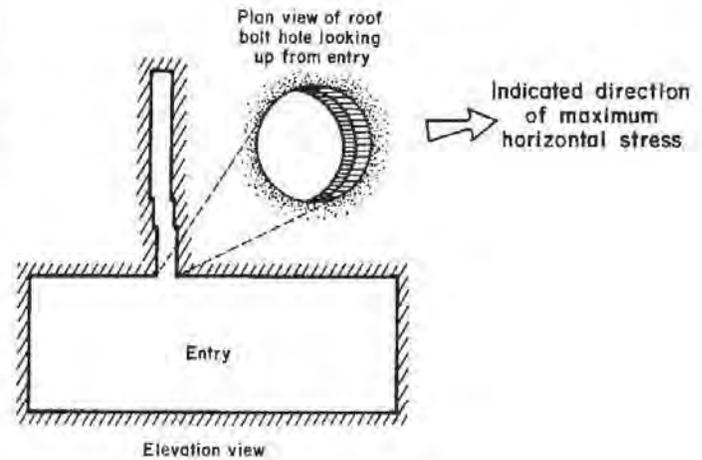


Figure 10.—Empty roof bolt holes used to determine stress orientation (after Parker (37)).

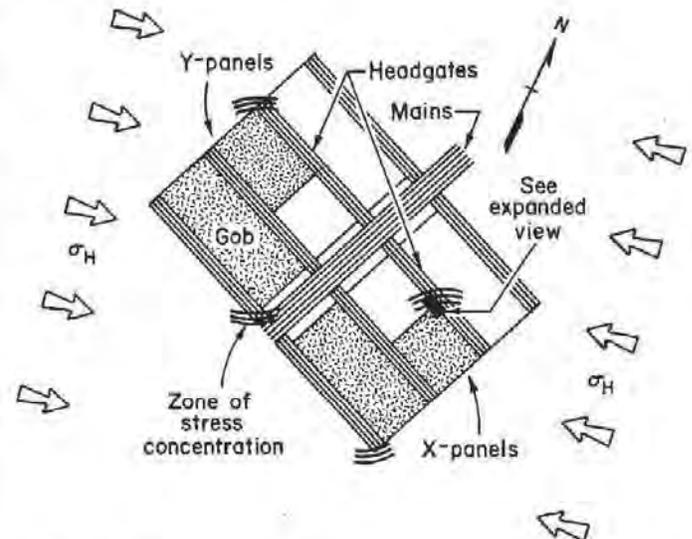


Figure 11.—Horizontal stress concentrations around longwalls at Pittsburgh Seam Mine "D". Expanded view is shown in figure 12.

crosscut roof usually collapses and mining proceeds smoothly for the next 15-18 m (50-60 ft) of longwall face advance. As the longwall subsequently begins to move beyond the stress shadow provided by the crosscut, a cutter begins to develop in the headgate roof along the pillar side. The cutter continues to worsen until the face passes the intersection and the crosscut fails. The entire cycle then repeats.

³Mouyard, D. P. Effect of Stress and Geologic Structure on Underground Coal Mines. Unpublished M.Sc. Thesis, WV Univ., Morgantown, WV, 121 pp.

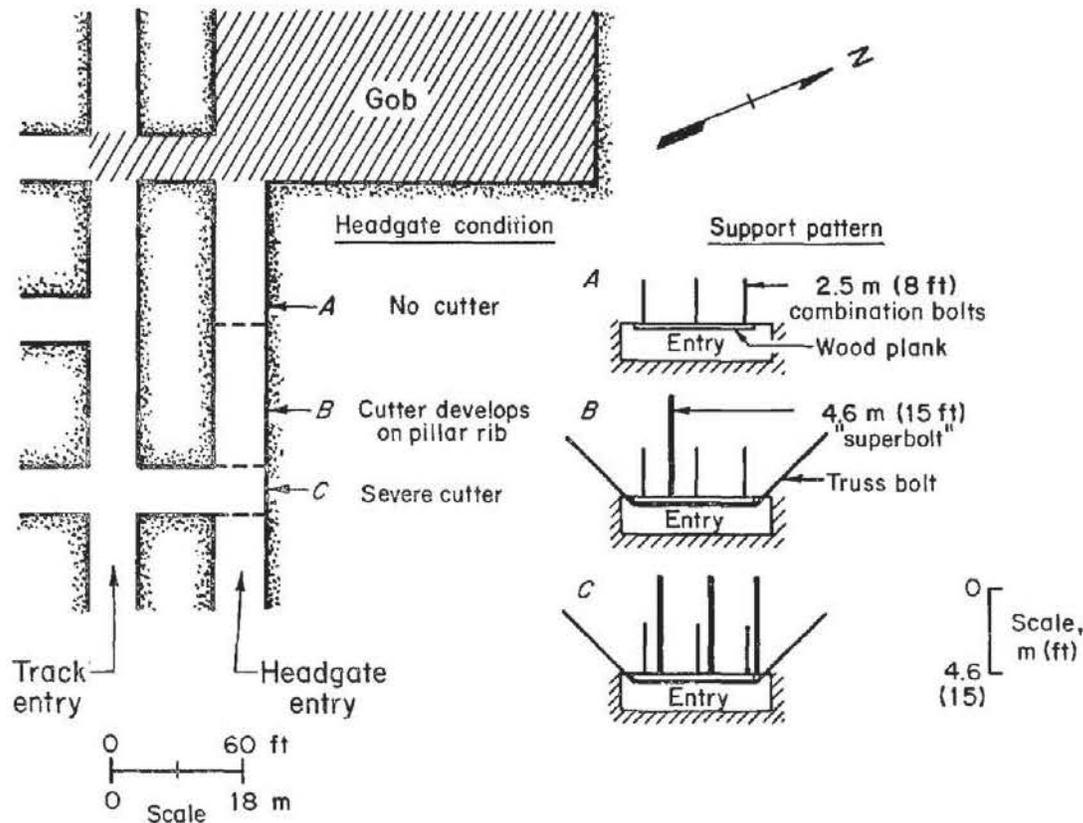


Figure 12.—Sequence of entry failure during longwall face advance at Pittsburgh Seam Mine "D".

Secondary roof bolting has brought the horizontal stress problem under control at Mine D, although at some expense. The primary roof support consists of three, 2.5-m (8-ft) long resin-anchor tension bolts and wood planks on 1.5-m (5-ft) centers. As shown in figure 12, this is all the support necessary in the areas just outby the crosscuts. Starting about halfway between breakthroughs, a heavy-duty truss bolt and a 25-mm (1-in) diameter, 4.6-m (15-ft) long "superbolt" are added between each row of primary support. Finally, in the intersection itself, a truss bolt and three superbolts are installed for each row of bolts.

It is obvious to question why Mine D is unique among the Pittsburgh Seam mines in experiencing horizontal stress problems. Several nearby mines have extracted panels at similar, or even less favorable, orientations and several have employed the same extraction sequence as the X-Panels. One possible explanation is that the magnitude of the horizontal stresses is greater at Mine D or that the stress field there is rotated slightly counterclockwise.

Another more likely explanation is geology. In the study, stratigraphic columns were constructed from observations of roof falls at all eight longwall mines (A through H) in the Pittsburgh Coal Seam (figure 13). At the other mines, the immediate roof consisted primarily of drawrock, a rider coal, and/or rash (interbedded shales and coals). At Mine D, both the drawrock and the rider were very thin, and the roof above appeared to consist entirely of finely laminated shale. Laminated shale may be particularly prone to horizontal stress failure because the many closely spaced, smooth, low-cohesion bedding planes greatly reduce rock strength horizontally.

OTHER NORTHERN APPALACHIAN LONGWALL MINES

Mines in the Pittsburgh Coal Seam are not the only northern Appalachian longwall mines affected by horizontal stress. The study found that two operations in the

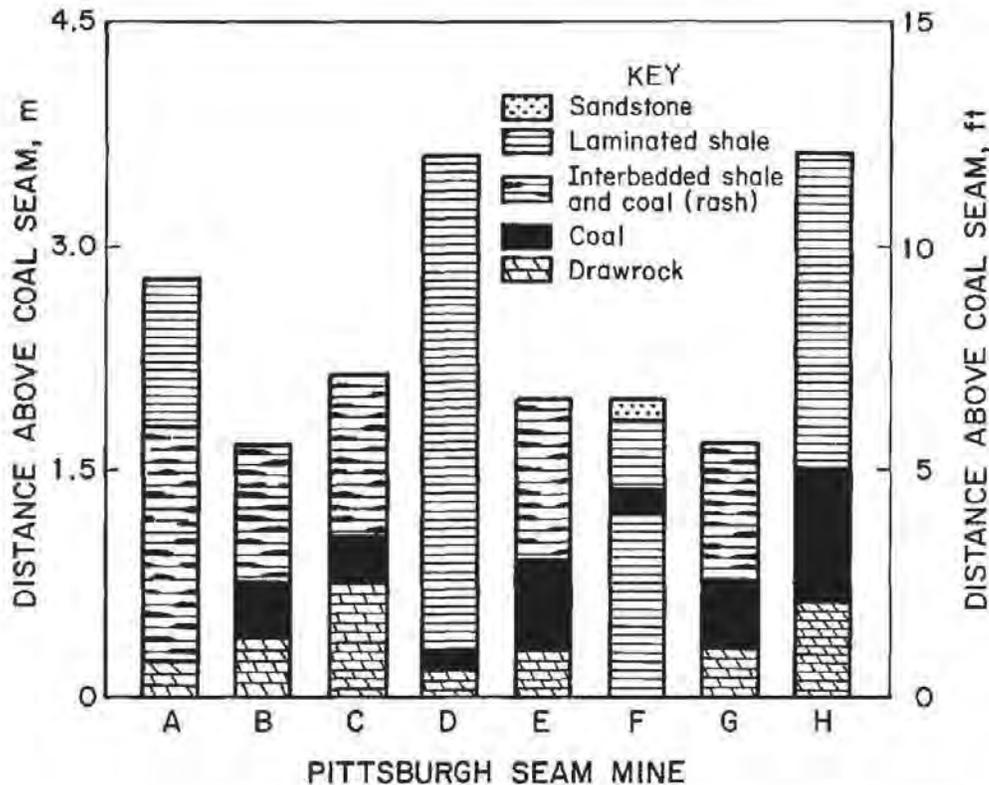


Figure 13.—Roof lithology observed at eight longwall mines in the Pittsburgh Coal Seam.

Freeport Coal Seam—one in Pennsylvania and one in Maryland—displayed indications of horizontal stress. Other examples from the Freeport Seam in Ohio and Pennsylvania can be found in the literature (7, 27). However, the two best documented case histories of horizontal stresses in longwalls are from mines working the Lower Kittanning Coal Seam.

The first of these is Kitt Energy Corp.'s Kitt No. 1 Mine, which opened near Philippi, Barbour County, WV, in the late 1970's. Kitt struggled over the years with severe cutter roof and was finally closed in 1987 because a cost-effective solution was not found. The mine has since reopened, but under new owners and without the longwall.

Kitt may be an example of a mine where even the minor horizontal stress exceeds the strength of the roof rock parallel to bedding. The immediate roof over much of Kitt consisted of a highly laminated shale. Several researchers noted that, although the compressive strength of the shale perpendicular to bedding approached 110 MPa (15,000 psi), it was difficult to test because the shale specimens broke so easily along laminations (30). Other areas

where the roof was a channel sandstone tended to be free of cutters, although roof falls occurred where a cross-bedded sandstone was underlain by less than 1 m (3 ft) of gray shale (23).

The mine was designed with entries oriented N. 50° E. and N. 40° W., but running roof falls were common in both orientations. Overcore measurements conducted at Kitt indicated that the maximum horizontal stress was approximately 18 MPa (2,600 psi) oriented N. 66° E. (1). Iannacchione and others (23) mapped more than 10 km (6 mi) of roof cutters at Kitt and determined that their most common orientation when they occurred away from the rib roof interface was N. 10° E-N. 10° W, indicating a stress field oriented approximately east-west.

The most direct effect of the cutter roof was to slow down development of new longwall panels to unacceptable rates. The roof in the gate entries was often badly damaged by cutters during development, and longwall stresses often caused the roof to collapse. One longwall panel was terminated early owing to roof falls in the head-gate in a horizontal stress abutment zone.

Numerous techniques were employed at Kitt to reduce the incidence of roof falls. Mechanical bolts of varying lengths quickly gave way to fully grouted resin bolts, often supplemented by truss bolts. The truss bolts did not seem to prevent cutter roof from occurring, but they were usually able to prevent the broken rock from falling. Mine officials also believed that the several different coal pillar designs that were employed had little observable effect.

The only technique that appeared to be fully successful was the sacrificial entry. During the development of one set of gate roads, severe cutter falls developed all along the length of the belt entry. When a new belt entry was driven parallel to the first in the stress shadow of the cave, conditions were excellent. The decision was then made to use the sacrificial entry in an experimental gate road development concept.

The last longwall mined at Kitt was developed with an arched center entry driven 4.6 m (15 ft) high by a U.K. roadheading machine. This entry, driven some 20 m (60 ft) in advance of the outside headings, was supported with unblocked yieldable steel arches so that the mine roof could collapse an additional 3 m (10 ft) to a total height of 8 m (25 ft). A series of stress measurements was conducted to determine the extent of the stress relief generated by the arched entry (4). It was found that the zone of stress relief extended at least 25 m (80 ft) from the arched entry (figure 14). Two independent researchers later attempted to reproduce these results using numerical models. Both found that slippage along horizontal bedding planes was necessary to explain the extent of the stress relief (4-5).

In an attempt to determine the degree to which horizontal stresses were concentrated by longwall panel extraction, vibrating wire stressmeters were installed in the roof of a crosscut adjacent to a headgate entry (30). Figure 15 shows the results from two stressmeters installed within 2 m (6 ft) of the roofline, one of which was oriented parallel to the crosscut and the other perpendicular. The measurements indicated that horizontal stress increased by as much as 7 MPa (1,000 psi) as the face advanced into the intersection. The additional horizontal stress induced the formation of a roof cutter, which in a matter of hours caused the roof in the crosscut to collapse.

Conditions in the headgate protected by the stress-relief entry were excellent and represented the best ever observed at Kitt. The panel also broke all the mine's previous longwall production records. Unfortunately, the expense of the arched entry proved too great to continue on a routine basis.

Another well-documented case history of horizontal stress is BethEnergy Mines, Inc.'s Cambria Slope Mine No. 33 near Ebensburg, Cambria County, PA. Cambria Slope first adopted the longwall technique in the early 1960's, largely in response to difficulties in controlling cutter roof falls (16). While conditions improved somewhat in the intervening years, recent development down the flank of a syncline toward deeper cover has led to the reemergence of the cutter roof problem.

The predominant shale roof rock at Cambria Slope, like that found at Kitt No. 1 Mine, is quite strong perpendicular to bedding. Again, researchers report that "obtaining and preparing test specimens was difficult because of the

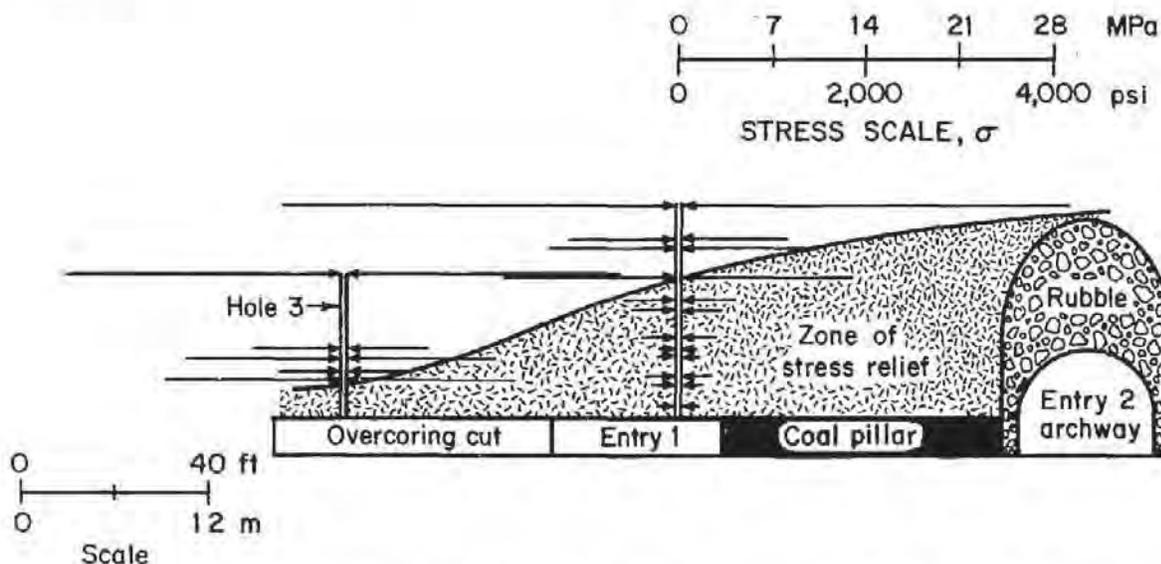


Figure 14.—Measurements of stress relief provided by the arched entry at Kitt No. 1 Mine (after Aggson and Mouyard (4)).

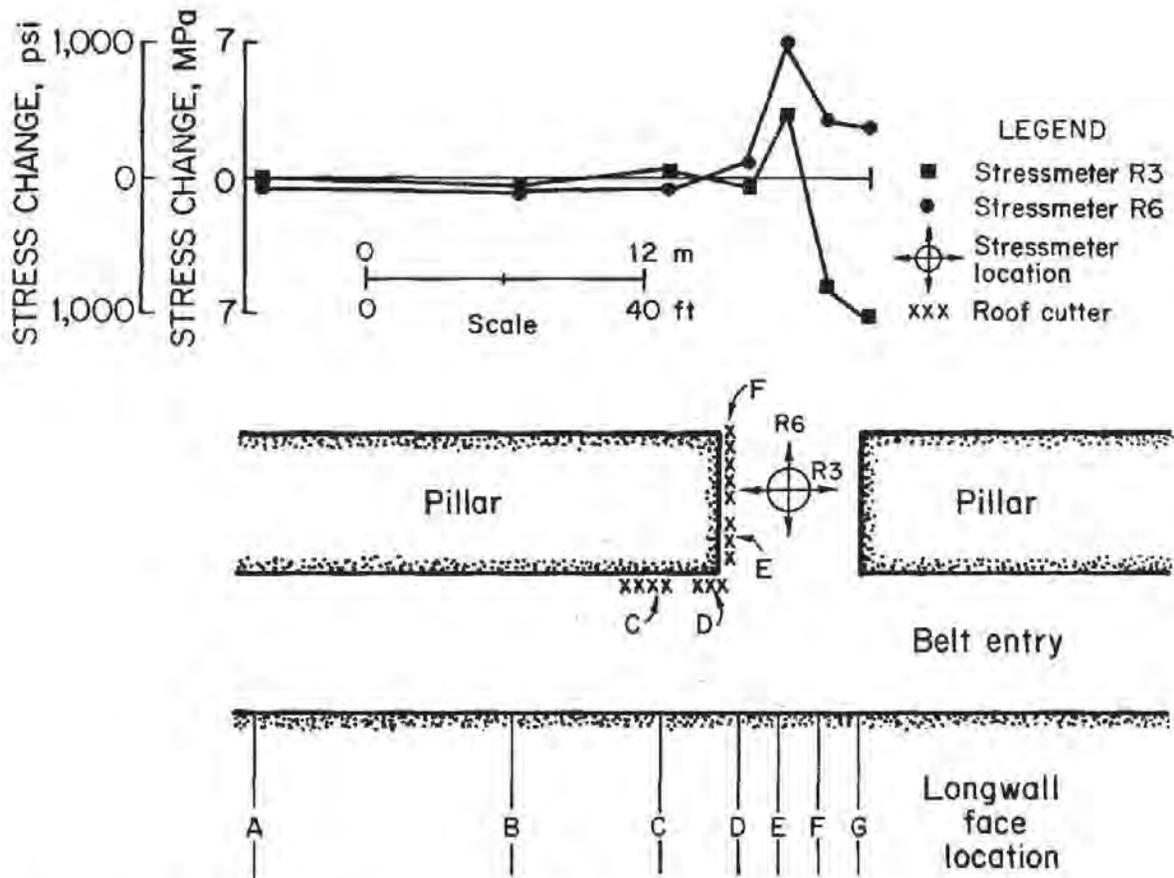


Figure 15.—Measurements of the horizontal stress abutment at Kitt No. 1 Mine near Phillippl, Barbour County, WV.

thinly laminated nature of the roof and the weak bonding of these laminations" (25). Roof falls are most common in the gate entries oriented N. 30° E., but also occur in the submain headings.

Primary support for development entries consists of 1.8-m (6-ft) fully grouted resin bolts on 1.5-m (5-ft) centers. In a typical three-entry gate, only the "uphill," or future, headgate entry has been subject to severe cutting. Additional support consisting of steel rails supported by four yielding steel posts has been necessary to carry the broken roof rock. Often, 8 mm (3 in) of downward displacement is recorded on the posts. Apparently, the stress relief provided by this heading is effective in allowing the other two headings to be developed with primary support only. Installing the rails and posts is expensive in terms of material cost, labor, and slowed development rates. Two of the posts also must be removed during longwall retreat to allow the stageloader to pass.

The first part of the solution was to remove the problem from the headgate to the less sensitive center entry. By advancing the center entry 35 to 45 m (120 to 150 ft) ahead, it became the first to contact the stress field (figure 16). The future headgate and tailgate entries were

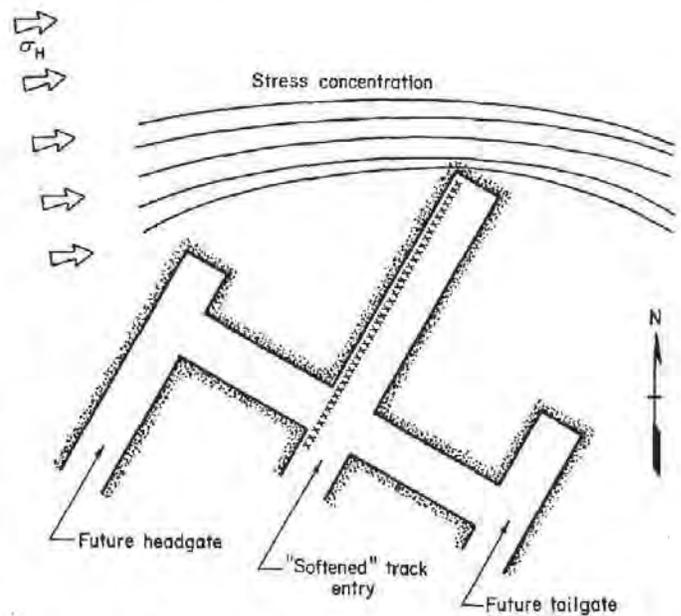


Figure 16.—Softened entry development at Cambria Slope Mine No. 33 near Ebensburg, Cambria County, PA.

stress-relieved. The second problem was to provide more economical support for the softened center heading. Experimentation with different bolting patterns led to a support plan in which the rail and two of the posts were replaced by a truss bolt, two additional resin bolts, and two superbolts. It was found that the superbolts were too stiff, and more reliance had shifted to trusses. It has also proved difficult in practice to keep the center heading sufficiently in advance of the other two.

Cambria Slope also has extensive experience with sacrificial entries. Early observations indicated that entries developed within 90 m (300 ft) of a gob line could be advanced with little difficulty. Caving chambers were later employed, but the technique proved difficult.

ILLINOIS COAL BASIN

In the Illinois Coal Basin, the occurrence of directional roof falls and kink roof have been observed for decades (40). Horizontal stress has been acknowledged as the cause, however, for only about the last 10 years. Research conducted at a room-and-pillar operation—Inland Steel's No. 2 Mine (10, 19)—appears to have been responsible in large part for the shift in thinking. The roof at Inland No. 2 was described as "highly laminated, with bedding planes [12-37 mm] 0.5-1.5 in apart" (11), and for some years the mine led the State of Illinois in total mine roof falls. Through trial and error, some measure of ground control was achieved at Inland No. 2 with high-strength, resin-assisted mechanical bolts. The bolts were installed in a pattern that placed longer bolts near the ribs to suspend the beam created by the center bolts. Entry reorientation to 45° off north-south also proved to be helpful. Some new stress mapping techniques were also proposed, including mapping of striations within roof crush zones and evaluating the appearance of intersection falls (11).

Inland No. 2 worked the Springfield (No. 5) Coal Seam, but until recently all of the longwall mines in Illinois have been in the Herrin (No. 6) Coal Seam. The early longwall mines tended to be oriented north-south, and the difference in gate entry conditions between those and others oriented east-west was noted early on. It was also observed, however, that east-west panels were more difficult to cut. As longwall shearing machines became more powerful, cuttability became less of a concern. Nearly all of the panels have been oriented east-west since the mid-1980's. Measures have also been taken to upgrade the roof bolts. Today, resin-assisted mechanical anchors installed with high torques have largely replaced fully grouted resin bolts. It should also be noted that the most troublesome shale roof above the Herrin Seam, the Energy shale, contains many natural discontinuities, but is not noticeably laminated.

SOUTHERN APPALACHIAN COALFIELDS

With few exceptions, longwall mines in the southern Appalachian and Warrior Coalfields have given little notice to horizontal stress. The study found that among the 13 southern Appalachian mines surveyed, panel orientations were evenly distributed across all points of the compass (figure 17). The depth of cover in the southern Appalachians can exceed 600 m (2,000 ft), and the stability problems associated with excessive vertical loading may be overshadowing the effects of horizontal stress. Horizontal stress effects may also be reduced because the roof rock quality is generally higher, and the regional stress field may be extensively reoriented by the rugged surface topography.

High horizontal stresses have been measured in the Beckley and Sewickley Coal Seams near Beckley, WV (1). No longwall mines are currently active in either of these seams, but at least one of the longwalls formerly operating there suffered from severe cutter roof in north-south longwall development headings (41). Other nearby room-and-pillar operations experienced excessive floor heave caused by horizontal stress (3). Of the study mines, two located in south-central West Virginia reported cutter roof beneath surface stream valleys. Some indications of horizontal stress were also observed in several longwall mines near the Virginia-Kentucky border, but the degree to which they influenced stability remained unclear.

WARRIOR COAL BASIN

In Alabama, most longwall mines have been oriented north-south. Coal pillar design for tailgate protection has been the greatest concern at these operations, but recently it has become evident that some of the tailgate difficulties may in fact be related to horizontal stress. Cutters along the panel rib have been a common problem in north-south tailgates, and it has sometimes been necessary to install a second pattern of bolts, biased toward the panel side, as supplemental support before the panels are extracted.

The USBM conducted a geotechnical survey in one Alabama mine and found that roof guttering occurred in nearly 70% of leading entries driven north-south. In contrast, only about 20% of east-west entries or lagging north-south entries experienced guttering. The location of the guttering also depended on the direction of drivage and the location of the box cut (figure 18). It appears that the box cuts contact the horizontal stress field first, damaging the mine roof but providing stress relief for the lagging entries. Tailgate conditions might be improved by adjusting the cut sequence during development.

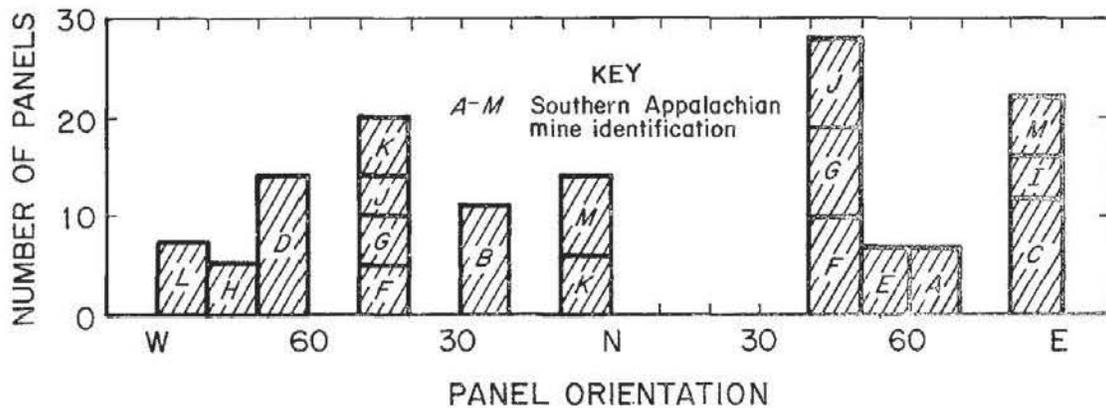


Figure 17.—Orientation of longwall panels at 13 southern Appalachian longwall mines.

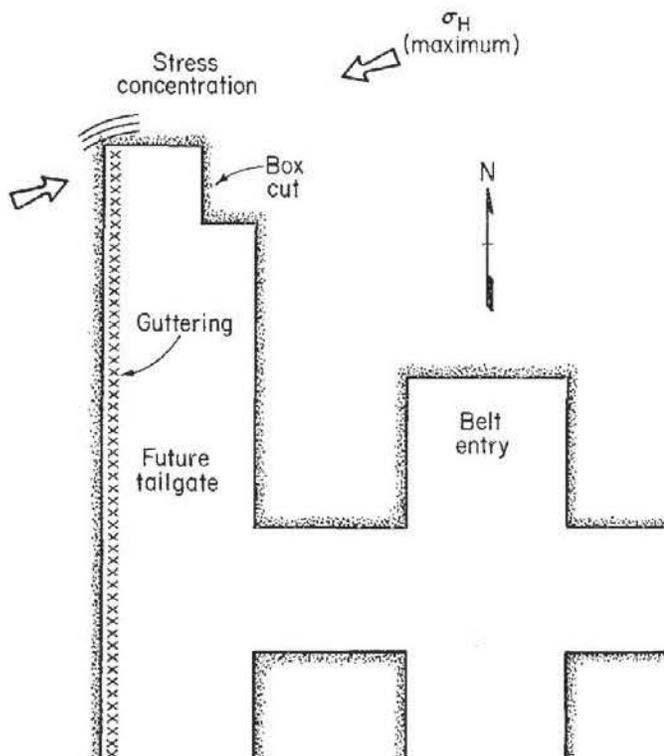


Figure 18.—Development of cutter roof during longwall development in Alabama.

WESTERN U.S. COALFIELDS

Horizontal stress has received relatively little attention in the western U.S. coalfields. Few effects of horizontal stress have been observed at most western U.S. longwall mines probably owing to the relatively low stress levels and the generally strong roof conditions. Horizontal stress

cannot be entirely ignored in this region, however. Very troublesome horizontal stress concentrations have developed in the headgate entries at two longwall mines near Scofield, UT, and Rangely, CO. The Utah longwall now uses 3-m (10-ft) long, 25-mm (1-in) diameter bolts to support its headgate. The Colorado longwall relies on trusses and cable slings to back up its primary support. The major horizontal stress is oriented approximately east-west at both mines, indicating that they may be located just outside the boundary of the north-northwest-trending Colorado Plateau Interior stress province.

FOREIGN LONGWALL MINES

In situ horizontal stresses have been observed to adversely affect longwall mines throughout the world. Since the late 1970's, Australian ground control researchers have been actively developing technology for detecting and controlling horizontal stress. Their approach has gained wide acceptance in the United Kingdom, where the trends toward retreat faces, roof bolting, and in-seam drivage of development headings have required fresh approaches to ground control. Today, in some areas of the U.K. coalfields, mine designs must be approved by a strata control engineer based on consideration of the in situ stress field (39).

Australian longwall mines typically operate at depths of 350-400 m (1,200-2,000 ft). The horizontal stresses measured there are typically 1.5 to four times the vertical stresses. The region is still experiencing active tectonism. As a result, the stresses observed in mines are often influenced by local structural features, and there is little evidence of a regional stress field. The horizontal stresses are most destructive when the mine roof is laminate rock, consisting of finely interbedded sequences of mudstone,

shale, siltstone, and sandstone (18). Massive sandstone roof is reported to be impervious to the effects of horizontal stress.

Horizontal stresses are most disruptive in Australia during development work. Detailed underground surveys, supported by numerical modeling, have shown that the degree of damage is determined largely by the angle between the maximum horizontal stress and the entry. As shown in figure 19, conditions at two mines were found to be better when the angle was less than 30° and worse when the angle was greater than 60°. Australian strata control engineers, therefore, place great emphasis on determining the stress field orientation throughout the mine by stress mapping (34).

Perhaps the most significant contributions of Australian research relate to the use of roof bolts for controlling failures induced by horizontal stress. Detailed studies of mine roof behavior and bolt performance indicated that high-strength bolts encapsulated in high-strength resin grouts can be quite effective. Bolt length and pattern are optimized based on field measurements of bolt load and roof movement. For cases in which roof support by bolting alone does not appear feasible, the Australians have developed cable bolting technology as an alternative to standing support (17).

Stress control techniques that attempt to modify the stress fields around the mine openings are also employed in Australia. The first of these techniques is entry orientation. Wherever possible, longwall panels are laid out parallel with the maximum stress to minimize the

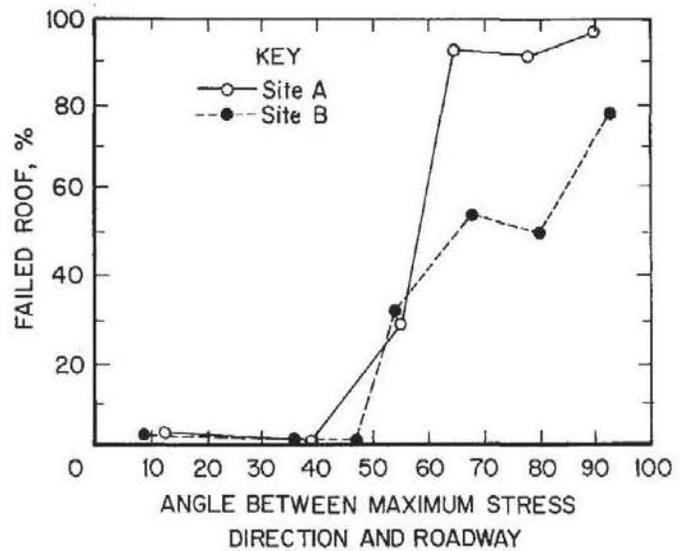


Figure 19.—Relationship between mine roof conditions and angle of roadway to the principal horizontal stress (after Nicholls and Stone (34)).

length of drivage in unfavorable directions. It has also been found that once an entry fails, regardless of whether it fully caves, the stress shadow can provide improved ground conditions in parallel headings driven as far as 30-40 m (100-125 ft) away. This principle has been used to optimize drivage sequences for longwall setup rooms and multientry gate systems.

CONTROL OF HORIZONTAL STRESSES

The first step to controlling horizontal stress is to determine its presence and direction. Many of the control techniques require a fairly precise determination of the principal stress direction. The regional stress fields delineated in this paper, particularly the east-northeast stress field in the eastern U.S. coalfields, provide a good starting point. More precise definitions of local stress direction are usually best obtained from stress mapping.

STRESS MAPPING

Horizontal stress manifests itself in a variety of features that can be observed underground (figure 20). Stress mapping is simple and inexpensive, yet can apply to a large

area while detecting local changes in orientation due to topography or other effects. While it does not provide the magnitude of the stresses, it can indicate the relative magnitude, especially as related to the strength of the surrounding rock. In situ stress measurements by overcoring can provide more precise information on stress magnitude and orientation, but they are expensive, time-consuming, difficult, and possibly limited in their area of influence.

Table 1 describes the features that should be mapped and the information they provide regarding the horizontal stress field. The USBM is currently refining the stress mapping technique.

Table 1.—Stress mapping features

Feature	Observation noted	Relationship to σ_H
Cutter or kink roof	Location in entry, especially tendency through intersections.	Location in entry gives indication of angle of mining to stress field. In intersections, cutters are aligned with σ_h .
Tensile fractures	Direction	Parallel with σ_H .
Roof potting	Direction of major and minor axes . .	Major axis is parallel with σ_h .
Roof bolt hole offsets	Direction of roof movement	Roof layers move in direction of σ_H .
Shear planes and rock flour	Direction	Planes and rock flour lines are parallel with σ_h .
Striations on roof rock	Direction	Striations are parallel to σ_H .
Roof falls	Location, shape, and appearance . . .	Location gives clues as to the general directionality of the stress field. High angular shape usually indicates horizontal stress with stepped shear failures usually predominate on one side.

σ_H = Maximum horizontal stress.

σ_h = Minimum horizontal stress.

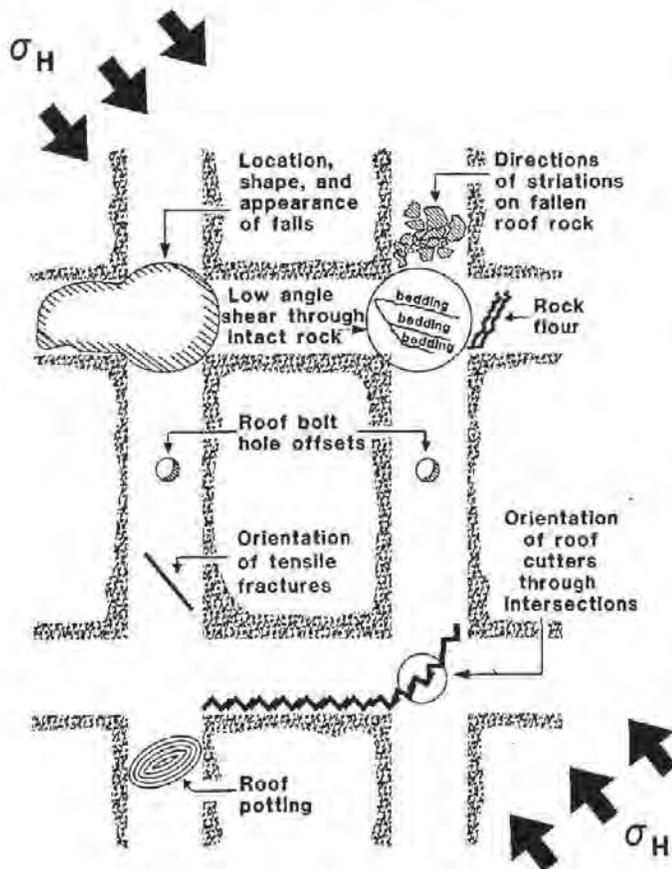


Figure 20.—Summary of underground stress mapping techniques.

The following principles are fundamental to the interpretation of stress mapping results and to the development of many stress control strategies:

1. Less ground damage occurs the more closely the direction of drivage is aligned with the major principal horizontal stress direction.
2. When horizontal stress damage is immediate (occurring with or within hours of initial mining), the leading entry (the first to encounter the stress field) will suffer the most damage.
3. Once ground is damaged by horizontal stress, it will stress-relieve adjacent ground, minimizing or eliminating damage to openings driven within the stress shadow. Gob areas will also create stress shadows.
4. Mining activity also creates areas of stress concentration. These occur where a line drawn parallel to the major horizontal stress contacts the edge of the entry or gob area and are typically zones of maximum roof damage.
5. Where permitted to do so, such as crossing intersections and across openings, major failure features, such as cutters and bottom heave, will try to align themselves with the minimum principal stress. Roof potting and shear failures will try to do this at all times.

PANEL ORIENTATION AND RETREAT DIRECTION/SEQUENCING

Proper mine design is a basic control strategy where horizontal stress is a problem. If possible, longwall mines should be oriented so that the gate entries closely parallel

the maximum horizontal stress. This orientation should provide the best development conditions for the gate roads. If crosscut damage creates problems, angling them in a more favorable direction toward the maximum horizontal stress is often a viable option during longwall development. Additionally, longwall panels create areas of horizontal stress concentration as they retreat into the stress field, as shown in figure 3. These concentrations will fall on either the headgate or tailgate side of a longwall panel and can result in consistent, occasional, or periodic ground control problems in these areas. Aligning the panels with the maximum principal stress will minimize these concentrations.

If mine design dictates that longwall panels must intersect the stress field at an angle exceeding 20° to 30° , their mining sequence should be such that the headgate corner remains within the stress shadow provided by the gob (figure 21). Panels may also be sequenced to locate stress concentrations in noncritical areas.

STRESS SHADOWING AND SACRIFICIAL ENTRIES

Several control techniques employ stress shadowing principles. For example, the least critical entry can be driven into the stress field first, suffer the damage, and provide stress relief for neighboring entries (figure 22). In this softened entry technique, care must be taken to design the mining cycle so that the lead entry always remains in the lead. Otherwise, the protected entries tend to be brought up too rapidly because conditions in the softened lead entry are usually painfully slow and difficult. The width of the coal pillar between the lead entry and the protected entry is also important. Underground measurements have shown that the degree of stress relief decreases with the distance from the softened heading. The extent of the stress shadow is also a function of the height of damage (or softening) in the sacrificial entry, with a higher damaged zone creating a longer shadow. Additionally, the problem of providing effective, rapid, and relatively inexpensive support for a softened entry has not been completely solved. Lastly, if the method is to work consistently, the mine roof in the softened heading must fail as soon as it is exposed. If the failure is delayed, it can eventually develop in one of the "protected" headings instead.

Another variation of this method is to totally sacrifice an entry by installing only enough support to permit initial development, then encouraging failure by driving wider openings, partial pillaring, removing support, etc. Once the sacrificial entry has failed, an adjacent replacement entry can be driven. Good ground conditions can be expected in openings driven near the failed entries. Sacrificial entries may not be routinely practical, but they may

have application for shadowing longwall setup and/or bleeder entries when those critical entries must be driven in an unfavorable direction.

MINE ROOF SUPPORT

Roof bolts and other supports have been effective in many instances for horizontal stress control. In the United States, best results have been achieved with high-strength, high-installed-torque, resin-anchored tensionable bolts. The goals of these developments have been to increase support anchorage, increase capacity, and increase installed bolt tension. Additionally, where normal bolt density does not provide sufficient reinforcement to prohibit immediate roof failure, U.S. mine operators usually first opt for longer supports. It may also be desirable to bias the bolts toward the rib where the most roof damage is occurring or to use longer bolts that will anchor outside the cutter zone near the ribs. When these measures do not provide entirely satisfactory results, yielding types of support, such as

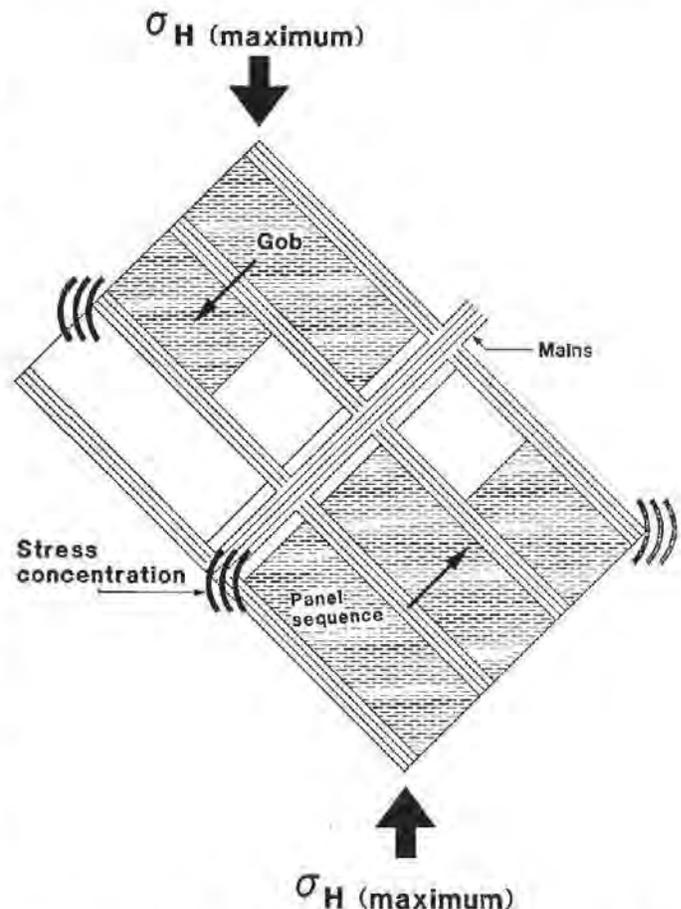


Figure 21.—Use of panel sequencing to stress-relieve headgate entries.

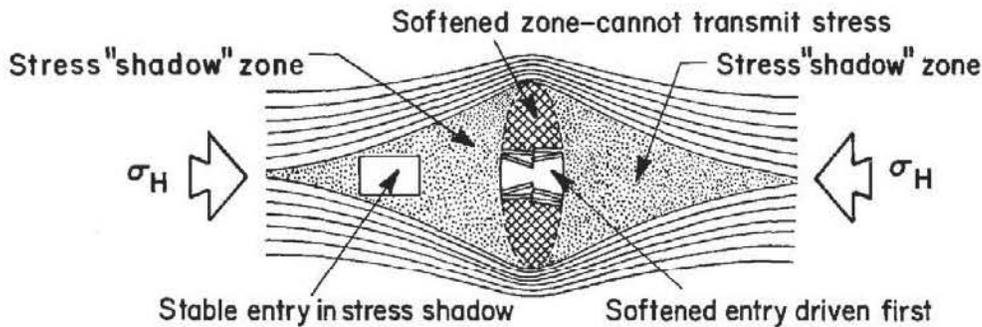


Figure 22.—Development of a stable entry in the stress shadow of a sacrificial entry.

trusses, slings, and standing passive supports, are usually used to contain the failed, very immediate mine roof and use it to provide confinement to the higher strata to prevent total roof collapse.

In Australia and the United Kingdom, where many of the ground control problems are related to horizontal stress, the development of roof support theory and hardware has been aimed at this particular problem. In these countries, the goal is to support the mine roof as quickly as possible with sufficient reinforcement to prohibit strata separation along bedding and interfaces, subsequent deformation, and eventual failure of the laminated roof. As a result, their mining and roof support systems are designed to install fully grouted, tensioned, high-capacity supports as close to the face as possible. As conditions become more difficult to control, these supports are installed in increasing density, often with as many as seven or eight bolts per row. To facilitate better load transfer of

the strains of the rock to the support, better support anchorage through reduced hole annulus and stiffer resin is emphasized. The rationale is that fully grouted supports will best resist any lateral movement and high-installed bolt tensions will provide reinforcement to the weak bedding and interface planes of the strata. Fully grouted, torque-tension rebars like those used in the United Kingdom and Australia have not found wide acceptance in the United States.

The USBM is currently investigating a variety of mine roof support systems in different geologic and stress environments. Measurements of roof deformations and bolt loading are being integrated with observations of mine roof quality to help identify the most significant factors affecting roof support performance. The ultimate goal is to develop support selection recommendations for horizontal stress control.

CONCLUSIONS

It appears certain that a horizontal stress field trending east-northeast persists throughout the eastern U.S. coalfields. Measurements indicate that the magnitude of maximum horizontal stress typically exceeds the vertical stress by a factor of two or more. Questions remain regarding the effect of surface topography on stress magnitude and direction. Horizontal stresses in the Western United States are generally lower, but less predictable.

The effects of horizontal stresses have also been observed in longwall mines throughout the United States. Although the greatest stresses have been measured in the southern Appalachian coalfields, the most severely affected mines have usually been in the northern Appalachians and in Illinois. The intensity of horizontal stress damage, however, varies considerably from mine to mine. It appears that the most severely affected mines usually

have a highly laminated shale immediate roof. The weakly bonded bedding planes within this type of rock may make it more susceptible to failure when loaded parallel to bedding. Other weak rock types may also be troublesome when subjected to high horizontal stress, but apparently to a lesser extent. Strong roof, such as massive sandstone, does not seem to be affected.

Although the United States has pioneered many of the techniques for identifying and controlling horizontal stress, awareness of the problem remains low. Proper design for horizontal stresses, based on site-specific mapping of the in situ stress field, could significantly improve day-to-day ground control at many longwall installations. Perhaps more importantly, it could forestall major ground control failures that might otherwise occur unexpectedly.

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APPENDIX—STRESS MEASUREMENTS IN U.S. COAL MINES

This appendix contains tables presenting a compilation of measurements from 47 U.S. coal mines gleaned from more than 20 published sources. Measurements from the eastern U.S. coal mines are presented in table A-1, while those from western U.S. coal mines are presented in table A-2. Nearly all of the measurements were conducted using overcoring techniques. The most popular instrument, used in 80% of the measurements, is the USBM borehole deformation gauge (BDG). The BDG is a mechanical device normally installed in a vertical borehole to measure the stresses in the horizontal plane (σ). Other devices listed in the tables essentially allow strain gauges to be glued to the rock. Some of these, such as the South African CSIR Triaxial Cell and the more recent Australian CSIRO Hi Cell, can measure three-dimensional stress in a single hole.

Wherever possible, the minewide values of the maximum horizontal stress, its orientation, and the ratio of the maximum to minimum horizontal stress are the values given in the referenced publications shown in the tables. In some instances, data from two or more holes at the same mine were available. Where the results from the separate holes were consistent with each other, the values

presented in the tables are averages. In nearly every case, the orientation varied by less than 20° from hole to hole, and the magnitude of the maximum horizontal stress varied by less than 7 MPa (1,000 psi). At five mines (four of which were located in the West), results from separate boreholes were not consistent with each other; these are therefore presented individually. In other cases, the source provided only individual test results. In such instances, values for the hole were calculated as the average of the individual measurements. In some holes, the measured stresses rotated and became more consistent farther up the hole. Here, it was assumed that the lower measurements were influenced by the presence of the mine opening, and these measurements were eliminated from the average.

Because of the difficulties associated with conducting stress measurements, the measurements presented in the following tables are probably of varying quality. In general, the most reliable measurements of far-field stresses are those based on more and deeper tests and on more holes. The experience of the team that performed the tests also plays a significant function, because the techniques are difficult to master.

Table A-1.—Stress measurements from Illinois, Alabama, and northern and southern Appalachian coal mines

Location and mine (or coal seam)	Reference No.	Stress measurement technique ¹	Depth of cover		Maximum test dis- tance into borehole		Number of holes/tests	σ_H maximum horizontal stress		σ_H/σ_h	Orientation of σ_H	σ_H/σ_v^2
			m	ft	m	ft		MPa	psi			
Eastern Kentucky:												
Hendrix 22	42	BDG	152	500	³ 7.1	23	1/3	15.6	2,257	1.25	N. 66° E.	4.1
Leeco 22	42	NA	NA	NA	7.7	25	1/6	5.1	741	1.48	N. 14° E.	NA
(Coalburg Seam) ⁴	43	TRX	91	300	4.9	16	1/7	0.8	122	3.39	(⁵)	0.4
Do. ⁴	43	TRX	91	300	5.2	17	1/7	1.0	142	2.68	N. 75° E.	0.4
(Warfield Seam)	43	TRX	NA	NA	4.3	14	1/4	4.2	613	^{5,6} 87.57	N. 80° W.	NA
Western Kentucky:												
Camp No. 2	42	BDG	91	300	7.1	23	1/4	7.9	1,145	1.10	N. 85° E.	3.5
Southern West Virginia:												
Beckley No. 1 ⁷	2	BDG	335	1,100	4.6	15	2/8	21.6	3,127	1.79	N. 72° E.	2.6
Beckley No. 2 ⁷	2	BDG	335	1,100	4.0	13	2/NA	14.0	2,026	1.36	N. 49° W.	1.9
Bonny	2	BDG	347	1,140	7.4	24	2/7	26.3	3,815	1.23	N. 57° E.	2.5
Maple Meadows	2	BDG	262	860	7.7	25	5/19	23.3	3,380	1.37	N. 68° E.	3.6
Beckley Mining Co.	2	BDG	253	830	8.0	26	4/22	23.0	3,339	1.33	N. 59° E.	3.7
Olga	35	BDG	419	1,375	4.0	13	3/11	22.1	3,200	1.39	N. 60° E.	2.1
Mine 132	32	BDG	233	765	7.4	24	2/10	20.7	3,000	1.25	N. 47° W.	3.6
Do.	32	BDG	49	160	7.4	24	2/6	12.4	1,800	2.57	N. 59° W.	10.2
Northern West Virginia:												
Kitt No. 1 ⁸	4, 8	BDG	183	600	³ 4.6	15	3/15	18.1	2,624	1.57	N. 66° E.	4.0
Humphrey No. 7	14	HF	^c 198	^c 650	30.0	100	NA	14.5	2,100	2.33	N. 84° W.	2.9
(Upper Freeport Seam)	42	TRX	152	500	³ 4.6	15	1/4	⁹ 10.6	1,544	¹⁰ 1.98	N. 80° E. ⁹	2.8
Virginia:												
(Pocahontas No. 3 Seam)	13	BDG	610	2,000	NA	NA	1/NA	23.4	3,400	2.14	N. 76° E.	1.5
Southwestern Pennsylvania:												
BethEnergy	NA	DST	^c 152	^c 500	9.2	30	3/NA	9.2	1,337	1.27	N. 32° E.	2.4
Ohio:												
Nelms No. 2	27	DST	152	500	1.5	5	1/3	12.5	1,811	4.12	N. 69° E.	3.3
Alabama:												
North River	8, 15	BDG	152	500	3.7	12	1/5	13.9	2,013	10.48	N. 60° E.	3.7
Jim Walter Resources No. 5	36	BDG	671	2,200	4.6	15	NA	9.1	1,323	1.40	N. 78° E.	0.5
Jim Walter Resources No. 7	NA	HI	580	1,875	5.0	16	2/8	21.0	3,010	NA	N. 71° E.	1.5
Illinois:												
NA	33	NA	NA	NA	NA	NA	NA	NA	NA	NA	N. 67° W.	NA
NA	33	NA	NA	NA	NA	NA	NA	22.0	3,191	2.29	N. 76° E.	NA
Wabash	24	BDG	274	900	4.9	16	3/15	9.7	1,400	1.75	N. 83° E.	1.4
Galatia	24	BDG	259	850	4.3	14	3/16	10.3	1,500	3.00	N. 78° E.	1.6
Inland No. 2	10	VWS	283	930	NA	NA	NA	18.8	2,721	3.16	N. 87° E.	2.7
Peabody No. 10	19	BDG	110	360	1.2	4	1/9	8.3	1,207	1.76	N. 73° E.	3.0
Elkhart	8	BDG	84	275	NA	NA	NA	7.6	1,097	1.71	N. 37° E.	3.6

Do. Same as above. NA Not available. ^cEstimated.

¹BDG = USBM borehole deformation gauge; TRX = CSIR Triaxial Cell; HF = Hydrofracture; DST = CSIR Doorstopper; HI = CSIRO Hi Cell; VWS = Vibrating Wire Stressmeter.

² σ_v calculated as .025 MPa/m (1.1 psi/ft) of depth.

³Lowest holes apparently influenced by entry, not included in calculation.

⁴Above drainage, near strip pit.

⁵Highly variable.

⁶Minus signifies tension.

⁷Second hole tested 3 years after first.

⁸Two studies, 7 years apart.

⁹Maximum stress nearest horizontal.

¹⁰Minimum principal stress nearest horizontal.

Table A-2.—Stress measurements from western U.S. coal mines
(Stress measurement technique in all cores was USBM borehole deformation gauge)

Location and mine (or coal seam)	Reference No.	Depth of cover		Maximum test dis- tance into borehole		Number of holes/tests	σ_H maximum horizontal stress		σ_H/σ_h	Orientation of σ_H	σ_H/σ_v^1
		m	ft	m	ft		MPa	psi			
Utah:											
Sunnyside	8, 15	323	1,060	NA	NA	NA	28.3	4,107	1.25	N. 31° W.	3.5
Utah Fuel	12	^c 274	^c 900	6.2	20	3/NA	^{2,3} 11.0	1,593	⁴ 2.41	N. 60° W. ²	1.3
Do.	12	^c 274	^c 900	6.2	20	3/NA	^{2,3} 11.9	1,724	⁴ 3.42	N. 30° E. ²	1.6
(Upper Hiawatha Seam) ...	28	NA	NA	NA	NA	NA	NA	NA	2.00	N. 16° W.	1.0
Emery No. 50	8	137	450	NA	NA	NA	8.1	1,177	4.07	N. 22° W.	2.4
Sufco No. 1	8	305	1,000	NA	NA	NA	8.8	1,282	1.55	N. 16° W.	1.2
King No. 4	8	372	1,220	NA	NA	NA	7.9	1,145	2.04	N. 20° E.	0.9
Castle Gate No. 3	6, 8	670	2,200	NA	NA	NA	⁵ 16.1	2,329	1.19	N. 29° W.	1.0
Colorado:											
Orchard Valley	8	107	350	NA	NA	NA	8.0	1,165	4.27	N. 69° E.	3.0
Do.	8	495	1,625	NA	NA	NA	12.2	1,768	2.89	N. 83° W.	1.0
Coal Basin No. 5	8	305	1,000	NA	NA	NA	5.4	779	1.38	N. 52° W.	0.7
Dutch Creek No. 1	8	823	2,700	NA	NA	NA	17.6	2,554	3.11	N. 29° W.	0.9
Bear Mine	8	381	1,250	NA	NA	NA	9.8	1,419	4.26	N. 69° E.	1.0
Eagle No. 5	9	201	660	4.6	15	1/5	1.6	235	1.27	N. 12° E.	0.4
Do.	9	201	660	4.0	13	2/9	⁶ 3.2	470	2.83	N. 78° E.	0.6
Apex No. 2	9	128	420	3.4	11	1/5	3.9	567	1.15	N. 86° W.	1.2
Do.	9	128	420	3.7	12	1/4	⁶ 1.8	257	1.21	N. 19° W.	0.6
Foidel Creek	9	118	387	4.9	16	2/11	⁷ 5.7	830	1.58	N. 71° W.	2.1
Rienau No. 2	9	224	735	5.2	17	1/5	7.1	1,024	1.71	N. 67° W.	0.7
Deserado	8	184	605	NA	NA	NA	14.1	2,044	1.37	N. 77° E.	3.1
Southfield	29	430	1,410	NA	NA	NA	13.1	1,903	1.47	N. 7° W.	1.2

Do. Same as above. NA Not available. ^cEstimated.

¹ σ_v calculated as .025 MPa/m (1.1 psi/ft) of depth.

²Maximum principal stress nearest horizontal.

³Three-dimensional stress measured in coal.

⁴Minimum principal stress nearest horizontal.

⁵One hole each in roof-and-floor.

⁶Measured in floor.

⁷Two sites.

Special Publication 01-94

New Technology for Longwall Ground Control

Proceedings: U.S. Bureau of Mines Technology Transfer Seminar

Compiled by Christopher Mark, Robert J. Tuchman,
Richard C. Repsher, and Catherine L. Simon



UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES

Cover Photograph: The U.S. Bureau of Mines has developed highly practical technologies for maintaining effective ground control in the hazardous tailgate entries of longwall mining systems, which will significantly improve the safety of the Nation's underground mineworkers. (Photo: Alan A. Campoli, Pittsburgh Research Center, U.S. Bureau of Mines)