# AN ANALYSIS OF VIOLENT FAILURE IN U.S. COAL MINES—CASE STUDIES

By H. Maleki[1]

## ABSTRACT

A U.S. Bureau of Mines (USBM) researcher analyzed the causes of violent failure using data from 12 U.S. coal mines as part of the USBM's mission to improve mine safety. It was shown that coal bumps are influenced by stress, stiffness, and yieldability of surrounding rocks, and the dynamic effects associated with failure of surrounding strata. In all bump-prone mines studied, calculated seam stresses exceeded unstable strength levels by at least 20 to 30 pct. In addition, bumps occurred in parts of the mines where there had been rapid stress changes over a short period of time and/or distance. The dynamic effects associated with the failure of surrounding strata triggered bumps in these marginally stable seam structures.

While it was not possible to evaluate the influence of mine stiffness directly, it was shown that coal bumps generally occurred in mines with uniaxial compressive strength and Young's modulus ratios (roof to coal) exceeding 3 to 5. In addition, bump-prone coal exhibited the potential for storing high horizontal stresses. Yielding of the immediate roof and floor reduced horizontal stresses and enhanced gradual failure of coal. A method is proposed to assess coal bumps in which stress analyses, in situ strength data, stiffness and strength ratios of roof to coal, and expected wave magnitude resulting from strata failure and mining experience are incorporated.

## INTRODUCTION

Sudden, violent failures of the rock around mine openings have compromised safety, ventilation, and access to mine workings in both hard-rock and coal mines in many countries, including the United States, Canada, Chile, Poland, Germany, England, France, China, India, and South Africa. Because of the catastrophic nature of these sudden failures, understanding the cause of failure and developing mine design and mitigation techniques for controlling failure have been the objective of many studies. The U.S. Bureau of Mines (USBM) has long been involved in such studies as part of its mission to improve mine safety.

Conditions leading to violent failure are similar in both hard-rock mines and in coal mines; i.e., stresses exceed the strength of the rock mass near the mining excavation or at a geologic discontinuity. In hard-rock mines, both strengths and stresses are higher than those at coal mines and failure is, in general, brittle. In coal mines, violent failure takes place at lower stresses from both brittle and semiductile strata deformation. Failure is generally influenced by local stress concentrations around mining excavations (which are influenced by the strength and stiffness of rocks), and the interaction of mining with regional tectonic structures. Tectonic structures, perhaps, play a bigger role in mining seismicity and rock-burst damage in some U.S. and Canadian hard-rock mines than in coal mines because hard-rock mines are located in proximity to these structures (Williams and others, 1993). Tectonic-related seismic events, however, have not been cataloged in detail for U.S. coal mines because there are no local monitoring systems. Mining-induced stress changes have

[1]Mining engineer, Spokane Research Center, U.S. Bureau of Mines, Spokane, WA.

been reported as triggering movements along faults 2 to 3 km (1 to 2 miles) below U.S. coal mines and have contributed occasionally to tremors having Richter magnitudes of 3.5 (Wong and others, 1989).

There is no consistent terminology for these sudden, violent failures. Hard-rock mines, with extensive seismic monitoring systems, have defined mine tremors better than have coal mines. Table 1 provides some definitions based on experience in hard-rock mines (Chavan and others, 1993); the severity of damage increases with wave amplitude. Ortlepp (1992) and other researchers, however, used peak particle velocity for assessment of damage and for design of support systems using the kinematics of ejected blocks.

**Table 1.—Proposed definitions of seismic events and associated damage**

| Wave amplitude, mm | Definition |
|---|---|
| 15-50 | Minor burst |
| 50-100 | Medium burst |
| Greater than 100 | Major burst |

In view of the lack of a universal definition of coal failures, in this paper, coal bumps are defined as sudden, violent failures that occur near coal mine entries and that are of such a magnitude that they expel large amounts of coal and rock into an excavation, restricting safe and efficient access to the working area. Other terms, such as rock bursts, crump, mountain shot, mountain bump, pillow burst, pressure burst, quake and bounce, and outburst are often used interchangeably in coal mining. Outburst is a term generally defined as a coal bump assisted by gas pressure.

After a review of seismic events and damage in hard-rock mines, the author will attempt to describe simpler causes for coal bumps, excluding the more complex mathematical treatments by authors such as Lippmann (1990) and Kleczek and Zorychta (1993). Then the paper will focus on an analysis of the causes of coal bumps through a brief review of available monitoring data from 12 U.S. coal mines. Five case studies will be examined in more detail to identify specific factors that contributed to the occurrence of bumps or their absence. A preliminary methodology will be proposed for assessing coal bump potential, including the most important factors identified from these case studies.

## CAUSES OF VIOLENT FAILURE

### ROCK BURSTS

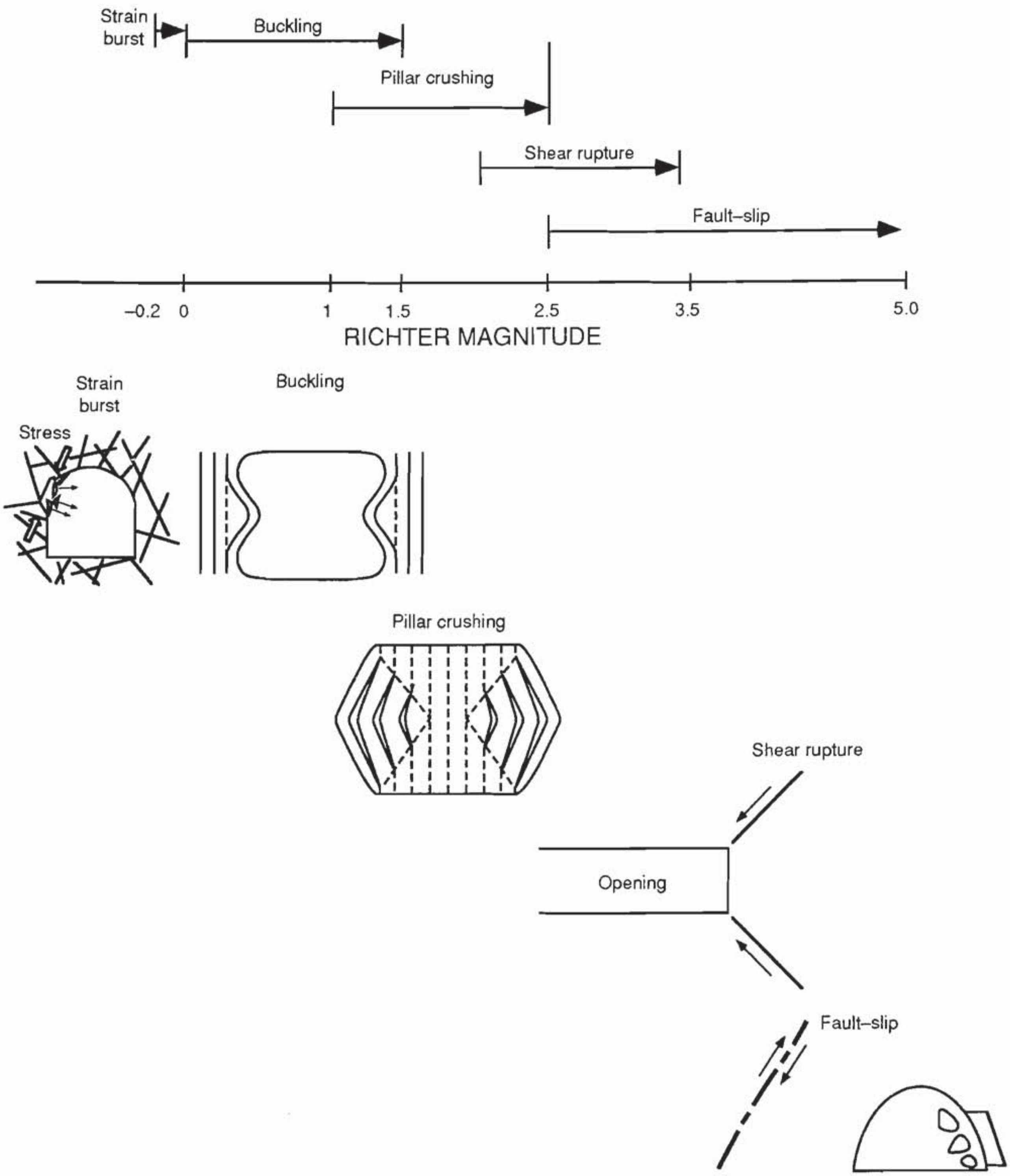
Rock bursts in hard-rock mines have been extensively studied through underground observations, static measurements, and seismic records; these studies revealed a correlation between mining activity and seismic events (Dubinski, 1990). Seismic events are apparently generated as mining activities change the stress field and often result in either rock crushing or movement along geological discontinuities. McGarr (1984) studied these events, proposed formulas for estimating their energy content, and showed that many events did not cause any damage in one property unless the local wave magnitude exceeded 2.5 on the Richter scale. Ryder (1988) proposed the criterion of excess shear stress, which is the difference between the prevailing shear stress prior to slip at a geologic discontinuity minus the dynamic strength of the contact plane, as a means of assessing the potential for slip along a geological discontinuity.

It is important to understand the cause of failure in order to find solutions to failure. Ortlepp (1992) (figure 1) has proposed a simplified concept for defining rock-burst source mechanisms and their relationship with measured wave amplitudes as expressed in Richter magnitudes. The first three categories (strain, buckling, and pillar crushing) are influenced by stress concentrations near entries, while the last two categories (shear rupture and fault slip), which are generally the most violent, represent an ideal situation of shear failure along a plane or a preexisting geologic discontinuity. This simplified relationship (figure 1) is generic, and work by other investigators (Gibowicz, 1990) indicates that large events may not necessarily cause any damage, while small events may cause considerable damage.

Violent ejections of rock fragments and slabs from the surfaces of excavations are termed strain bursting and buckling, respectively. These events are caused by high stress concentrations near mine openings that exceed the strength of the rock. Pillar bursts are larger events resulting from complete failure of pillar(s) where pillar stresses exceed pillar strength. Recent USBM work (White and others, 1995) at the Lucky Friday Mines has identified the influence of preexisting joints on formation of slabs and subsequent ejection of these slabs in the form of buckling and pillar failure (figure 1). Pillar failure may not only affect local conditions, but can also result in a dynamic shock wave that can reach other critically loaded pillars long distances away, triggering spalling and rock bursts at these sites (Pritchard and Hedley, 1993).

Slip along a preexisting fault may result from decreased normal stresses and/or increase of shear stresses caused by nearby mining activities. As faults slip, a large amount of energy is released, and a portion of this energy is transmitted through the rock mass in the form of a seismic

*Figure 1*
**Simplified Relationship Between Wave Magnitude and Rock Burst Source Mechanism.**




**(Modified after Ortlepp, 1992.)**

pulse, which reflects off the walls of an excavation and causes damage. Wave amplitude and frequency influence the type and location of damage to an opening (one rib or both ribs) (Yi and Kaiser, 1993).

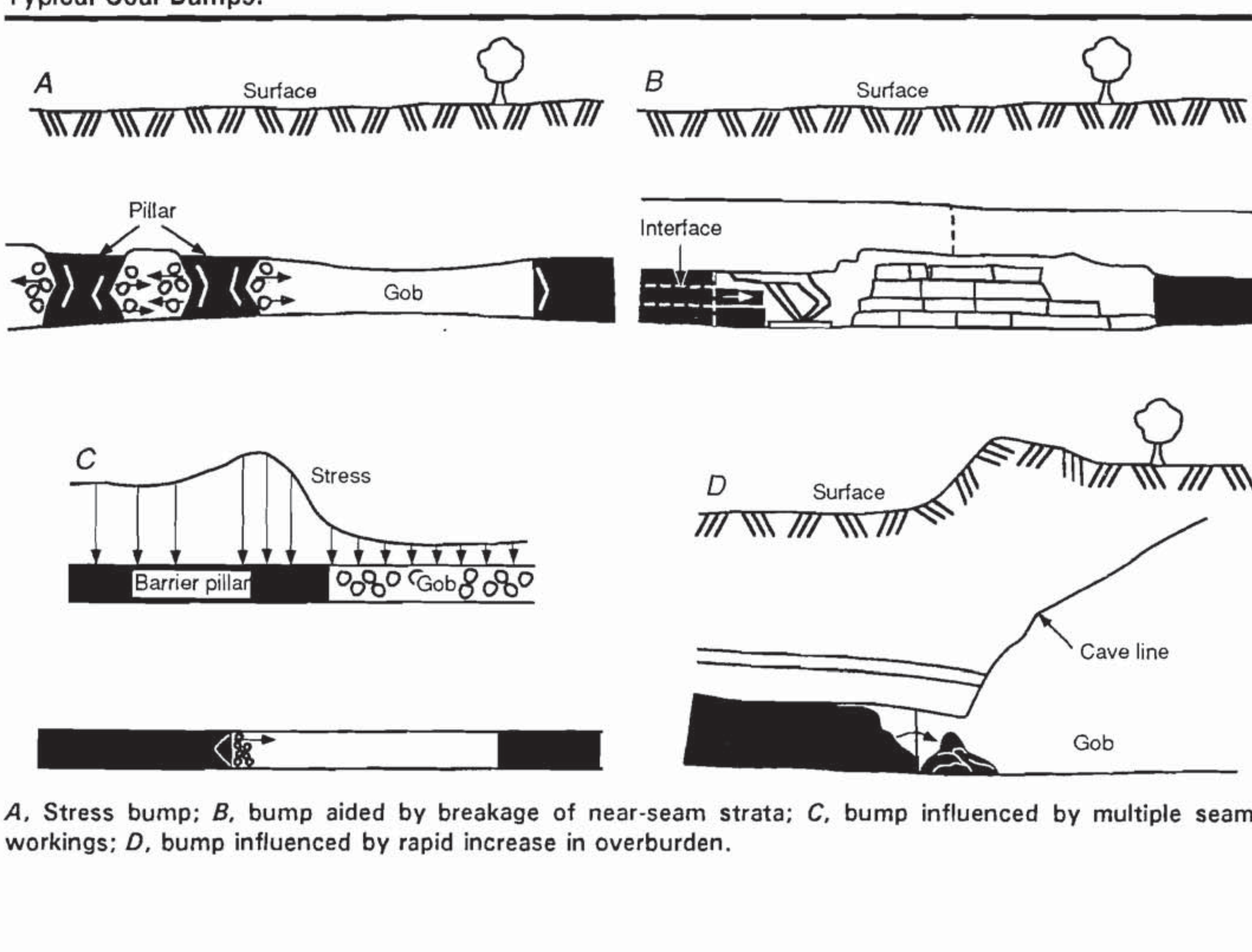
## COAL BUMPS

Rice (1935) categorized coal mine bumps into two general groups: (1) pressure (stress) bumps are influenced by static loading and failure of the seam material (figure 2*A*), and (2) shock (dynamic) bumps are triggered by failure of generally massive strata surrounding a seam (figure 2*B*). In spite of significant research since 1935, researchers have not been able to clearly identify source mechanisms for bumps in U.S. coal mines. To determine source mechanisms, there is a need for three-dimensional, seismic monitoring systems in proximity to underground mines. Also, there are difficulties in obtaining direct stress measurements within coal-measure rocks. Thus a clear understanding of material behavior and stress bumps has not been achieved.

Nonetheless, many laboratory, field, and theoretical investigations have provided some insight into the causes of coal bumps. Laboratory tests have given evidence regarding the influence of confining stresses (Babcock and Bickel, 1984) and postfailure characteristics of coal pillars in producing violent failure. Field studies have emphasized the influence of geology, the presence of stiff or competent noncaving roof and floor strata (Haramy and McDonnell, 1988), and mining layout and excavation sequences that subject coal to rapid stress increases over a short distance (Maleki and others, 1987) (figure 2*C* and 2*D*). Recent theoretical treatments (Lippmann, 1990; Kleczek and Zorychta, 1993) have provided better characterizations of the mechanics of coal bumps.

Some of these investigations into the causes of coal bumps and proposed criteria for assessing coal bump potential are reviewed here. Babcock and Bickel (1984) used a segmented platen and an acrylic sheet (figure 3*A*) to monitor and control confinement at the coal pillar-testing machine contact. The segmented platen constrained the top of the coal sample, while the acrylic sheet expanded laterally at the same rate as the coal. When the vertical stresses on the sample exceeded the unconfined compressive strength of the sample, the stability of the sample depended on the additional strength provided by the

***Figure 2***
**Typical Coal Bumps.**

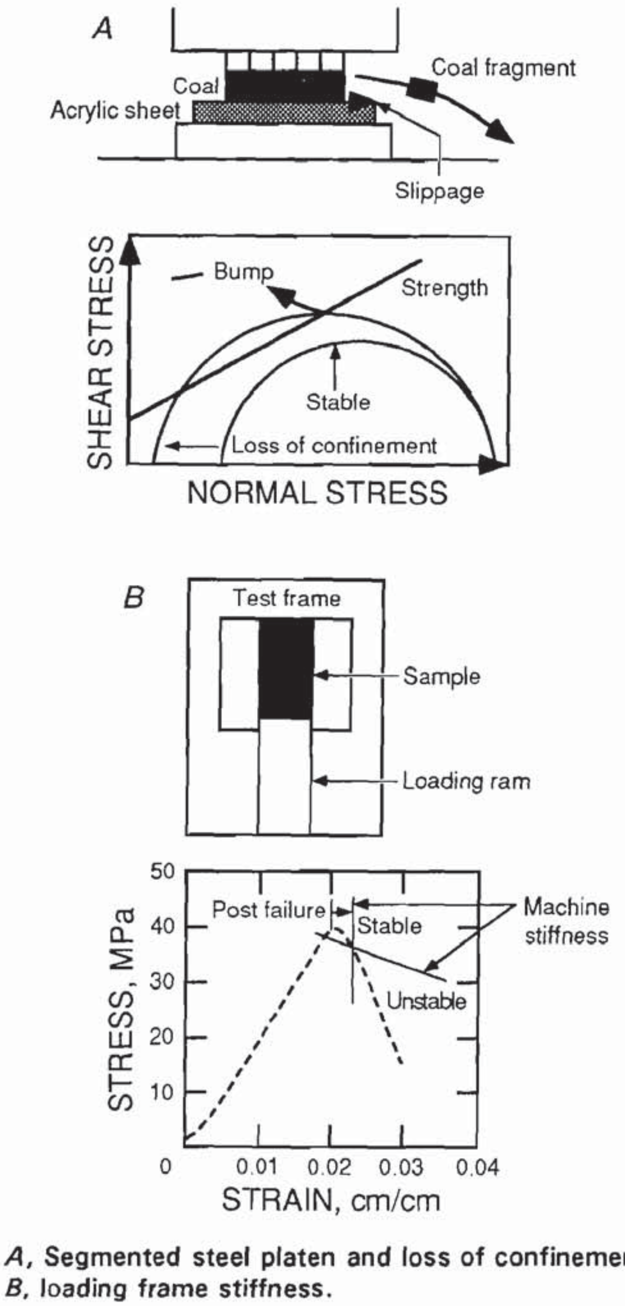



***A*, Stress bump; *B*, bump aided by breakage of near-seam strata; *C*, bump influenced by multiple seam workings; *D*, bump influenced by rapid increase in overburden.**

constraint. When the constraint was lost as a result of slippage (measured at the acrylic sheet contact), the sample failed violently. Figure 3*A* demonstrates this effect using a Mohr-Columb failure criterion; sudden loss of confinement shifts the Mohr circle to the left and results in the failure of the sample coal pillar.

Babcock and Bickel (1984) used sample pillars with a width-to-height ratio of 8.5:1 from 15 mines and 11 seams. They concluded that stress can produce bumps in many coal seams if confinement is suddenly lost because of slippage at the interface. This finding is important because the frictional properties of contact planes at coal-roof-floor or coal-inseam partings are known to be variable (Maleki and others, 1988; Maleki, 1992).

***Figure 3***
**Laboratory Concepts Relating to Stress Bumps.**




***A*, Segmented steel platen and loss of confinement; *B*, loading frame stiffness.**

Cook and Hojem (1966) and Wawersik and Fairhurst (1970) emphasized the importance of testing machine stiffness in obtaining full-load deformation characteristics of coal pillars. A series of stiff testing machines were then introduced that did not store too much energy in the testing frame, driving the sample toward violent failure at peak pillar stresses. Starfield and Wawersik (1972) and Salamon (1970) introduced the concept of local mine stiffness and criteria for distinguishing between stable and unstable pillar failure. They suggested that stable failure occurs when the stiffness of the mine roof and floor exceeds the postfailure slope of coal pillars (figure 3*B*). Unstable failure occurs when local mine stiffness is less steep than the pillar postfailure slope.

Zipf (1992) implemented the local mine stiffness concept in a displacement-discontinuity code and established a linear relationship between local mine stiffness and Young's modulus for roof and floor rocks. Pen and Barron (1994) modified the local mine stiffness concept based on average pillar response and found a better correspondence between location of observed pillar bumps and sudden changes in local mine stiffness. The practical application of these boundary-element methods for coal bump prediction requires input about in situ material properties for coal seams, rock masses, and the gob, as well as caving geometry and the frictional properties of coal and rock at their contacts. Recently, Maleki (1992) produced in situ strength curves for selected U.S. coal seams, identifying stress levels beyond which roof, floor, and pillar stability problems occur. He provided some preliminary guidelines for estimating in situ postfailure behavior of two seams. This development refines the application of the concept of local mine stiffness to actual field conditions.

Numerous field investigators have identified unfavorable geologic and geometric factors that cause localized high stress concentrations on mine structures. Early South African research established a correlation between the rate of energy release and the frequency of rock bursts. To avoid rock-burst damage, it was then proposed to schedule mining activities so that mining could continue under more uniform stress, avoiding large amounts of potential energy release during single mining steps. Figure 4 is a schematic showing the application of this concept to scheduling panel mining sequences. Maleki and others (1987) applied this method to scheduling pillar pulling activities so that a uniform energy release rate was maintained for bump control. They also identified the importance of overall panel and barrier pillar design to avoid mining in areas where stresses had increased rapidly over a short distance. Zipf and Heasley (1990) used this concept to examine different excavation sequences as well.

Campoli and others (1990), and DeMarco and others (1995) have discussed the importance of gate pillar design for coal-bump control. Experience with different gate pillar layouts at the Pocohantas No. 3 Seam indicates that it is important to have a large (stable) abutment pillar to control coal bumps, while DeMarco and others (1995) cataloged the use of yield pillars in several Western U.S. mines for coal-bump control.

Many field studies also have related coal bumps to the presence of competent, stiff, noncaving strata near the seam. Lippmann (1990) suggested that coal bumps occur only when rock in the roof and floor adjacent to the seam are about 10 times stiffer and stronger than the coal. Haramy and McDonnell (1988) used a Schmidt hammer in a rebound test to assess bump-proneness for different coal seams. Noncaving strata are thought to concentrate stress and accumulate large strain energy both in the rock and in the seam. Wu and Karfakis (1994) examined this energy accumulation for different strata and loading conditions in an attempt to identify bump-prone conditions. As strata fail, a portion of this energy is transferred to the coal seam in a dynamic pulse and may trigger slabbing, reduce static friction to sliding friction at geologic interfaces (Lippmann, 1990), and possibly contribute to loss of confinement (Iannachione and Zelanko, 1994). Wu and Karfakis (1994) used a relationship between this energy release and local wave magnitude and proposed that there will be coal-bump damage if wave magnitudes exceed 2.0 on the Richter scale.

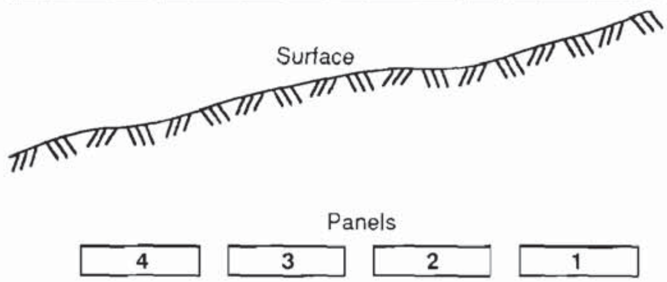
## EVALUATION OF BUMP CRITERIA

Several investigators have proposed specific criteria for assessing bump-prone conditions, but a comprehensive methodology is missing. These criteria use (1) laboratory stiffness and strength of mine roof rock, (2) local mine stiffness, (3) energy release rate, and (4) strain energy accumulation and local wave magnitude. Geotechnical data, numerical models, and in situ pillar strength data from seven bump-prone mines and five mines with nonviolent pillar failure were used to validate the effectiveness of some of the coal-bump prediction criteria (items 1, 2, and 3).

Figure 5 shows that using only ratios of roof or floor strength-to-coal strength and Young's modulus to assess bump-proneness, as implied by Lippmann (1990), is inadequate based on uniaxial data from 12 mines. Although most coal bumps have occurred in mines where the Young's modulus ratio (roof- or floor-to-coal) was greater than 8 and the strength ratio (roof- or floor-to-coal) was greater than 4, severe bumps occurred at two room-and-pillar operations where Young's modulus and strength ratios were as low as 5 and 3, respectively. The Young's modulus is shown to be linearly related to roof and floor stiffness (Zipf, 1992) and thus is used in this comparison.

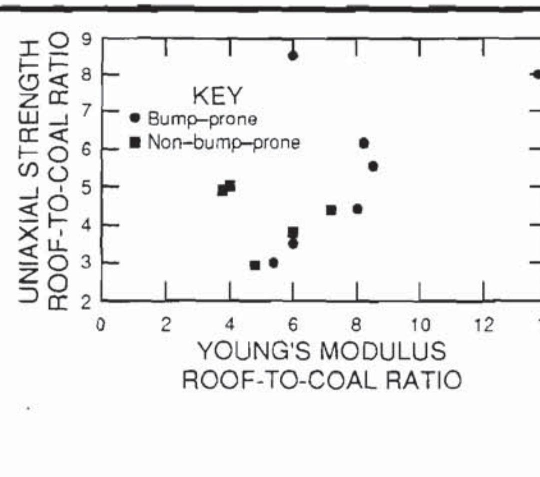
To test the usefulness of the concept of local mine stiffness to the prediction of coal bumps, in situ pillar strength data from two mines showing violent and nonviolent pillar failure were used. The full load deformation of these pillars was characterized through geotechnical monitoring in which in situ pillar behavior for typical U.S. coal seams was identified (Maleki, 1992). Local mine stiffness was estimated using average pillar stiffness (Pen and Barron, 1994) (figure 6). The steeper line indicates slightly higher local mine stiffness for a sandstone roof in a bump-prone mine. Since local mine stiffness was steeper than the slope of pillar postfailure for both mines, pillar failure was predicted to be stable in both mines. Thus, these

***Figure 4***
**Simplified Presentation of Mining Under Uniform Stress.**




**A panel mining sequence as numbered from right to left is advantageous because this sequence subjects each panel to similar levels of stress. Mining from left to right, however, can induce higher stresses on subsequent panels because of variations in cover (see Maleki, 1988).**

***Figure 5***
**Strength Ratio Versus Young's Modulus Ratio for Roof and Coal.**

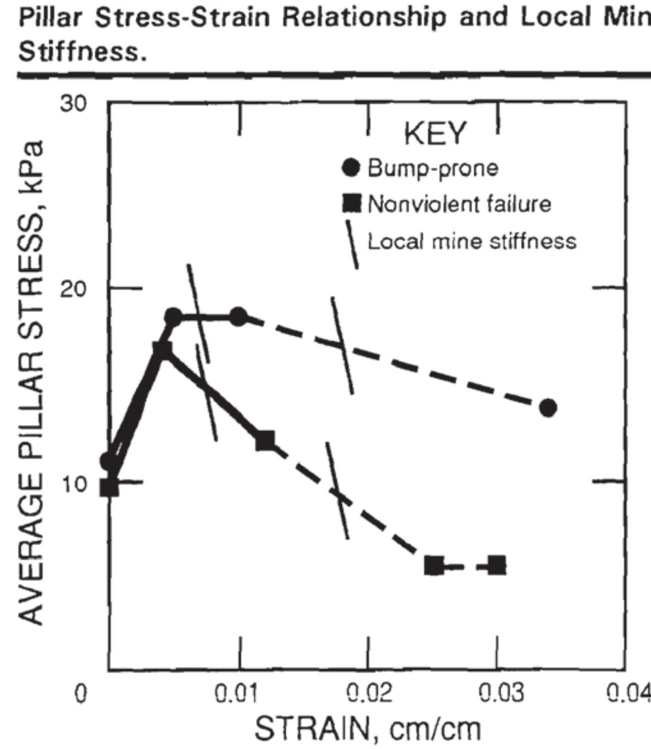


examples show that the local mine stiffness concept cannot consistently be used for predicting violent failures and is possibly more appropriate for distinguishing between stable and unstable "progressive" pillar failure as originally intended by Salamon (1970) and discussed by Zipf (1992). These example calculations are also influenced by (1) limitations of boundary-element methods in modeling the actual three-dimensional nature of coal mine excavations, (2) statistically insufficient data regarding the full load-deformation behavior of pillars across the example mines, (3) lack of scaling laws to adjust Young's modulus for rock masses based on joint spacing and other features, and (4) inadequate representation of local geologic factors, such as interfaces, cleats, and nonlinear deformation of immediate roof and floor strata.

Zipf and Heasley (1990) identified similar problems with the effectiveness of using energy release rate for coal-bump prediction. As shown in figure 5, many coal bumps occur in mines with stiff, competent roof and floor and not in seams surrounded by incompetent rocks, such as shales. Since the energy release rate is inversely proportional to roof and floor Young's modulus, a higher energy release rate and a less stable situation will be projected for mines with shalely roofs (assuming that shales are generally softer than sandstones). This is quite contrary to the experience in U.S. mines where many bumps have occurred when mining under sandstone roof.

In view of a lack of coherent criteria for coal bump occurrence, the author has examined several bump-prone mines. This leads to an additional preliminary methodology for assessing coal bump potential.

*Figure 6*
**Pillar Stress-Strain Relationship and Local Mine Stiffness.**




**Dashed lines indicate estimated behavior.**

## ANALYSIS OF CASE STUDIES

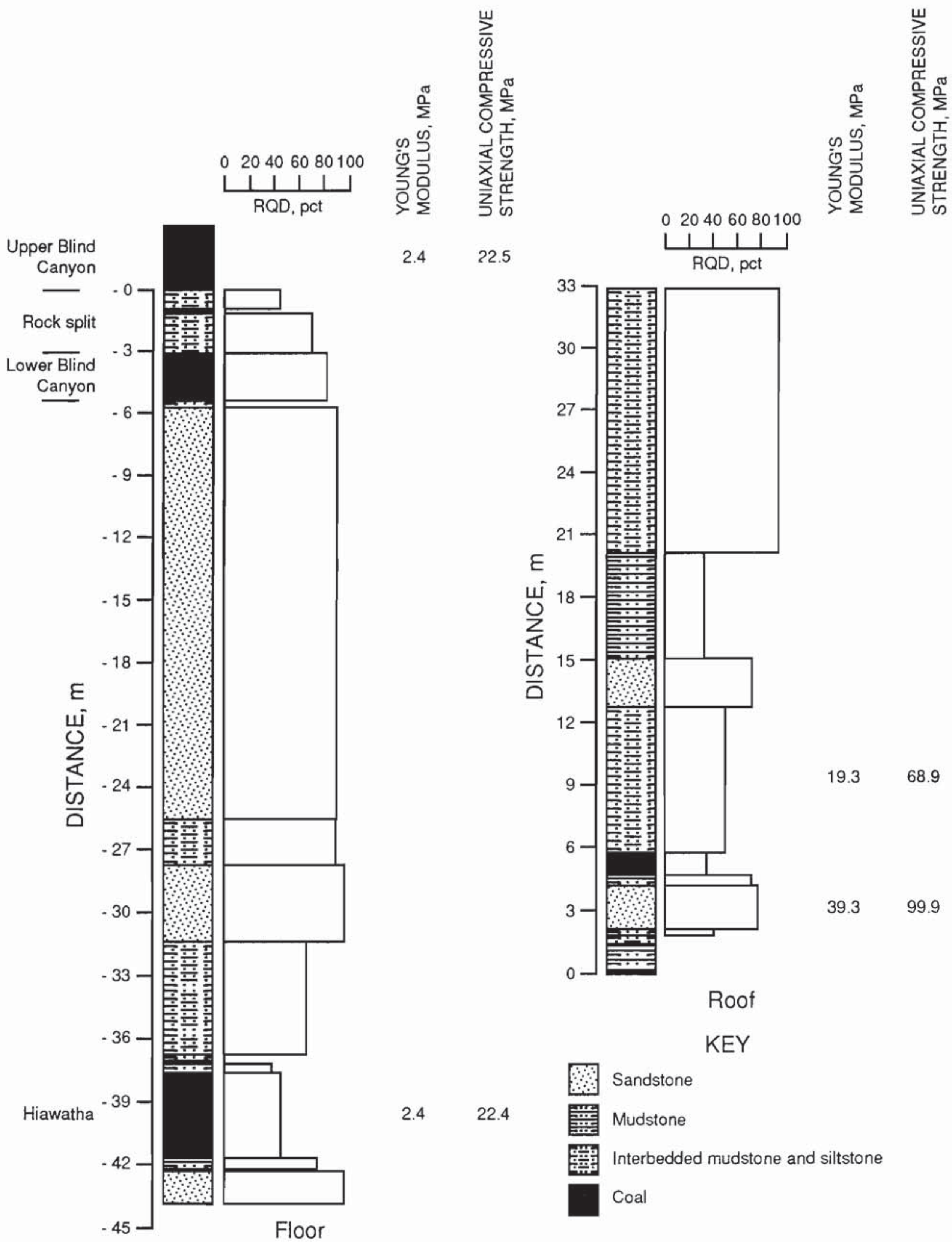
Long-term measurements, underground observations, and numerical modeling results from studies of five coal mines were integrated to investigate the factors that influence violent failure. These mines represent typical conditions in Western and Appalachian coal fields where room-and-pillar and/or longwall methods are used in mining single and multiple seams. Four of the mines have experienced coal bumps. Geotechnical data from one mine with no significant coal bumps are also presented for comparative purposes. At the four bump-prone mines, four factors seem particularly relevant: (1) induced horizontal stresses, (2) rapid changes in stress gradient, (3) upper strata failure, and (4) lack of yielding.

### CASE STUDY 1—INDUCED HORIZONTAL STRESSES

Site 1 is located in the Wasatch Plateau of central Utah in the Hiawatha and upper Blind Canyon coal seams. The immediate roof and floor are similar for both seams and consist of mudstones, siltstones, and sandstones (figure 7). The rock quality designation (RQD) ranges from 50 to 100, uniaxial compressive strength varies from 69 to 100 MPa (10,000 to 14,500 psi), and Young's modulus falls into a range between 19.3 and 39.3 GPa (2.8 and $5.7 \times 10^6$ psi). There are a number of thick-bedded, competent, and stiff units in the roof that resist regular caving and transfer loads to the face during retreat operations. The coal seams have similar laboratory mechanical properties (Maleki and others, 1987), but in situ pillar behavior and frequency of coal bumps are different.

Historically, the mine has experienced severe coal bumps in both the room-and-pillar workings and in the two-seam longwall workings. Geologic and geometric factors influencing major coal bumps in room-and-pillar panels were analyzed by Maleki and others (1987), and the importance of prudent mine layout design in avoiding coal bumps was identified. Two-seam longwall panels were initially associated with coal bumps when mining under remnant barrier pillars of the Blind Canyon Seam. These experiences led to the sole current use of full-extraction longwall mining methods with yielding gate pillars to avoid

*Figure 7*
**Typical Lithology, RQD, and Strength Properties, Site 1.**



load transfer and coal bumps in the Hiawatha Seam. Excluding those bumps related to two-seam mining, the Blind Canyon Seam is known to be more bump prone than the Hiawatha Seam.

A field study was initiated by the mining company to compare the in situ behavior of the 9-m-wide by 25-m-long (30-ft-wide by 80-ft-long) "yielding" pillars in the upper Blind Canyon and Hiawatha gateroads (Maleki and others, 1988). The pillar in the upper Blind Canyon Seam exhibited higher strength and resistance to yielding than the pillar in the Hiawatha Seam. In fact, if not for the yielding of the mine floor, the Blind Canyon pillars could have experienced minor bumps. Mining depth was 610 and 190 m (2,000 and 620 ft) for the test sites in the Blind Canyon and Hiawatha seams, respectively. Premining horizontal stress fields were measured and shown to be small in comparison to the vertical stresses.

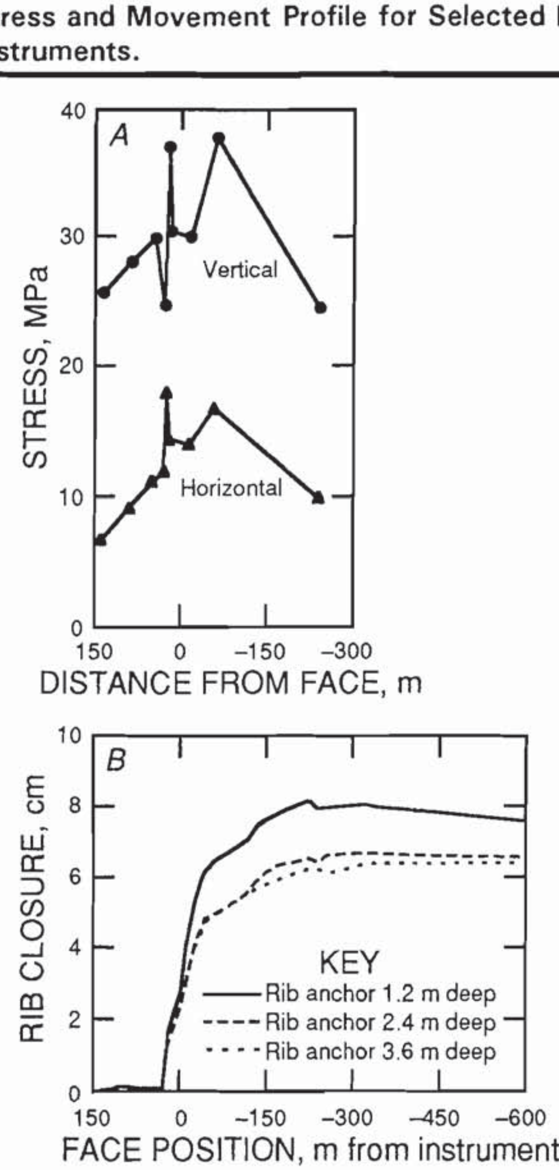
Pillar strength was measured as 27 MPa (4,000 psi) in the Blind Canyon Seam; this in situ strength was higher than the uniaxial compressive strength of coal [22 MPa (3,200 psi)], indicating pillar strengthening because of the confining horizontal stresses. Figure 8*A* demonstrates the buildup of horizontal stresses within the pillars as vertical stresses increased during the retreat of the longwall face toward the instruments (Poisson's ratio effect). In this figure, vertical and horizontal stresses are calculated on the basis of borehole pressure cell data oriented both horizontally and vertically and the procedures developed by Babcock (1986).

The confining horizontal stresses generally increased until the face passed the instruments by about 20 m (65 ft). Vertical stresses dropped, but quickly rebounded; at this time, there were numerous bounces (shocks) in the area that were possibly related to failure of the surrounding strata. Nevertheless, the confining stresses were significantly high in the pillar, helping to maintain gradual pillar unloading until the face passed the instruments at a distance of 250 m (800 ft).

Figure 8*B* illustrates pillar dilation history, confirming development of yield zones within the pillar as the face approached the instruments; pillar dilation was calculated by placing several anchors within the pillar and measuring the changes in the distance between these anchors and a reference point on the opposite side (solid block).

Roof-floor convergence measurements (Maleki and others, 1988) had a similar trend as shown in figure 8*B*; convergence increased significantly in the entries as the face approached the instrumented pillar. A total convergence of 0.5 m (1.6 ft) was measured; floor heave accounted for 97 pct of the total movement. Because the maximum deformation always occurred in the floor, it was inferred that the failure process was initiated in the mine floor as a result of pillar penetration. Failure and yielding of floor material were associated with rock dilation toward the entries; this reduced horizontal confining stresses gradually at the base and within the pillar, contributing to nonviolent failure (Maleki and others, 1993).

***Figure 8***
**Stress and Movement Profile for Selected Pillar Instruments.**




***A*, Calculated stresses from several pressure cells; *B*, pillar dilation history.**

This case study is important because (1) it provides field evidence of buildup and loss of horizontal stresses in a pillar that reached the postfailure loading stage in a rather stable manner in spite of the presence of thick-bedded competent roof beams and (2) the gradual yielding of the immediate floor was an important natural barrier, reducing the potential for violent failure. Yielding of the floor material directly below the pillar was associated with rock dilation and a reduction in horizontal stresses.

## CASE STUDY 2—RAPID CHANGES IN STRESS

This site is located in southeastern Kentucky. Room-and-pillar mining with occasional pillar pulling has been used in the overlying seam while longwall mining has been practiced in the lower seam, some 36 m (120 ft) below. The topography of the surface is rugged and mountainous.

The lower seam consists of four distinct coal beds, designated 180, 182, 184, and 186, separated with partings or splays (figure 9). The thickness and frictional properties of the splays vary over the deposit, influencing pillar behavior (Maleki, 1992). In a portion of the reserve, the splays change laterally into a sandstone channel approximately 7.6 m (25 ft) thick. With the exception of one coal bump thought to be related to sudden changes in topographic relief, coal bumps all have occurred within the zone of influence of this channel system and/or at locations influenced by the overlying room-and-pillar geometry.

The immediate roof generally consists of a series of shales, sandstones, and siltstones. The immediate floor consists of a meter of shale underlain by sandstone. As shown in figure 9, most roof and floor rocks are strong, stiff, and contain nonpersistent joints. The sandstone channel is not stronger than other roof strata, but it is more massive and lacks the bedding planes that enhance caving.

Coal bumps have generally caused displacement of large amounts of coal into openings, damaging equipment and occasionally injuring personnel; the bumps are believed to have been influenced by in-seam partings and seam-rock interfaces, as "red dust" has been consistently observed at these contact planes, indicating movement. These bumps have registered up to 3.8 on the Richter scale and have occurred either in the tailgate or at the face near the tailgate.

Among all events, there are two coal bumps that can be related to mining in areas where stresses and/or strength changed rapidly over a short distance and time. The first event registered 3.8 on the Richter scale and was associated with failure of an abutment pillar and a solid coal block at the tailgate position. The geology in this area was rather uniform, and thick sandstone channels were absent, but mining height was locally greater, which reduced pillar strength. In addition, mining had approached a topographic high where cover reached 670 m (2,200 ft). The 46- by 46-m (150- by 150-ft) abutment pillar was reported to have bumped, scattering coal around.[2]

As cover increases, abutment loads, which are transferred to the gate pillars, increase at a significant rate. [Mark (1990) assumes an increase proportional to the square of cover.] A rapid change in cover thickness thus increases stresses over a short distance and contributes to sudden failure of the abutment pillar. Preliminary elastic analyses have indicated that abutment pillar loads exceeded strength levels that caused stability problems (Maleki, 1992) by at least 30 pct during tailgate loading. Another local factor contributing to reduced pillar stability was an increase in mining height as a result of thinning of the partings at this location; pillar strength is inversely related to the mining height.

Figure 10 is a schematic that presents the two-seam mining geometry that contributed to the second coal bump. This bump occurred at the face during tailgate loading (second panel mining); a 7.5-m (25-ft) thick sandstone channel was present in this roof, but the topography was uniform [cover 610 m (2,000 ft)]. During the retreat of longwall 1, abutment stresses were transferred to the sides of the panel; these stresses caused crushing of the pillars in the upper seam (A, B) and transferred stresses farther toward panel 2. Because of caving in panel 1 and the proximity of the abutment loads in the upper seam, these stresses could not be fully redistributed over the gate pillars and were concentrated along the face of panel 2. In other words, pillar crushing in the upper seam made the gate pillar system in the lower seam very ineffective in limiting load transfer toward panel 2. Upon the retreat of panel 2, additional forward abutment stresses were transferred to the face area. Crushing in the C and D pillars in the upper seam further increased stress over a short time within the abutment zone and contributed to the face bumps.

In summary, this case study identified both two-seam and topographical geometries that locally increased stress over both short distances and periods of time and contributed to the violent failure of marginally stable gate pillars and/or longwall faces. In addition, a reduction in pillar strength because of variations in local geology further reduced pillar stability, which increased the potential for coal bumps. It is not always required to have a noncaving immediate roof and floor to generate coal bumps.

## CASE STUDY 3—UPPER STRATA FAILURE

The mine studied for case 3 is located within the Book Cliffs Coal Field east of Price, UT; this field lies on the gentle northeastern flank of the San Rafael Swell. Continuous miner equipment has traditionally been used to mine coal from the Rock Canyon and Sunnyside seams.

In this area, coal-measure rocks are generally strong, stiff, and contain one to three sets of joints (figure 11). There are two regionally massive sandstones (upper and lower Sunnyside tongues) above the Rock Canyon Seam; these sandstones are approximately 12 m (40 ft) thick, have a uniaxial compressive strength of 103 MPa (15,000 psi), and an RQD of 100 pct. The Castle Gate Sandstone lies 110 m (330 ft) above the coal beds and is 60 to 90 m (200 to 300 ft) thick.

[2]Personal communication from J. Holloe, manager of Geology and Exploration, 1994.

*Figure 9*
**Typical Core Hole Lithology, Uniaxial Compressive Strength, and Elastic Properties, Case Study 2.**

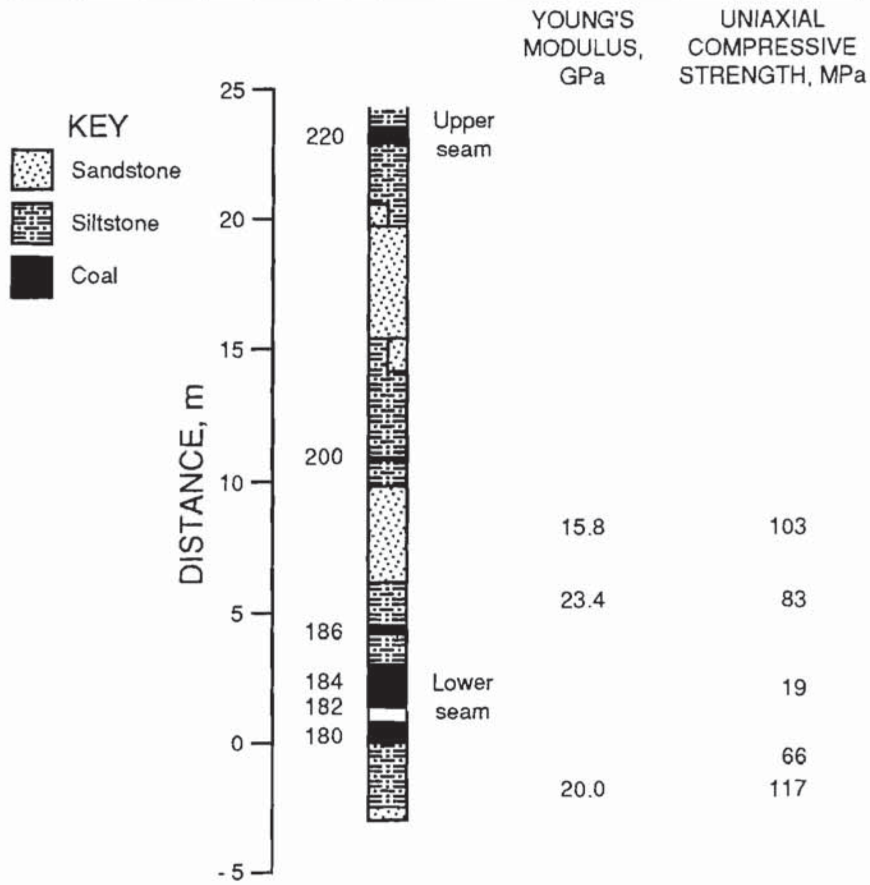



*Figure 10*
**Load Transfer for Two-Seam Mining Geometry.**

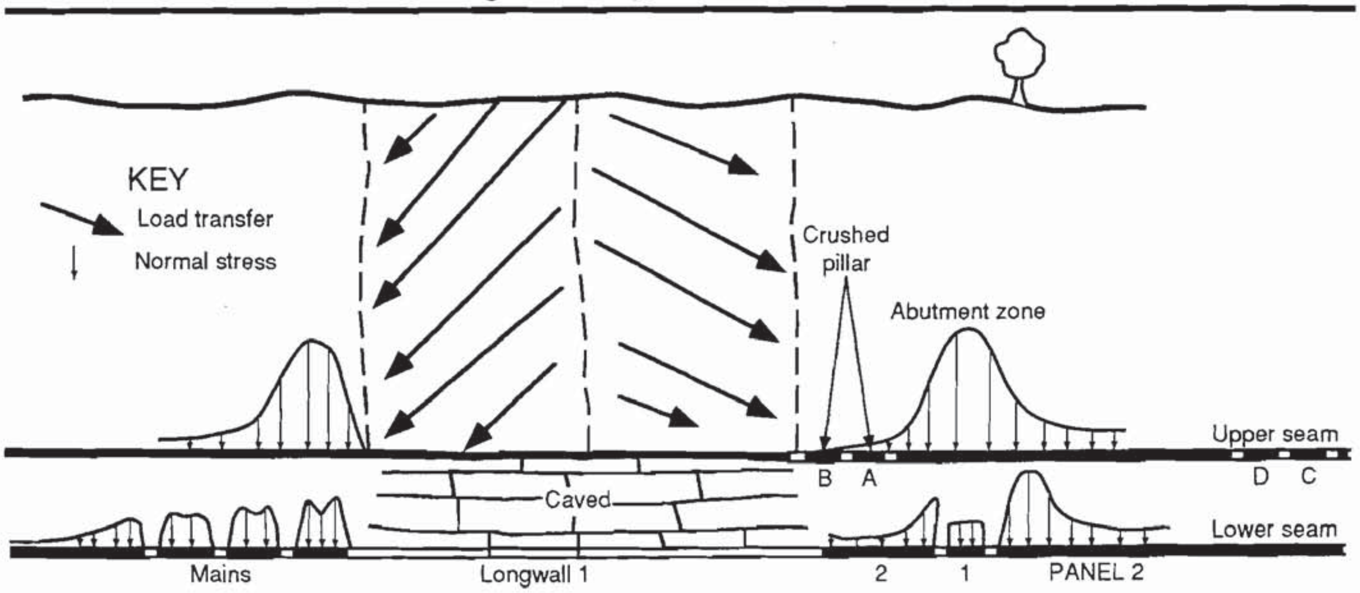
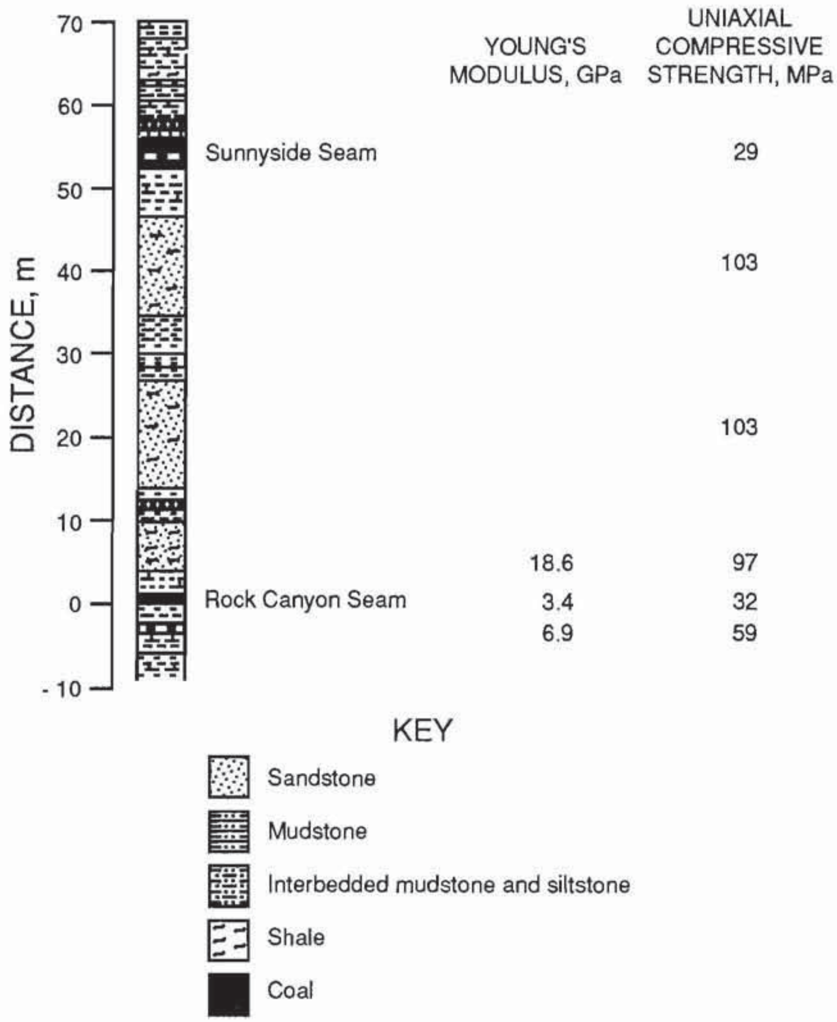


*Figure 11*
**Typical Cross Section Lithology, Strength, and Modulus Log, Case Study 3.**




Recently, several coal bumps, one a 3.6-Richter-magnitude bump, occurred in an area of the Rock Canyon Seam, where cover ranged between 460 and 610 m (1,500 to 2,000 ft) thick (figure 12). These bumps took place where 18-$m^2$ (60-$ft^2$) pillars and 6-m (20-ft) spans were being used. The time lag between panel development and pillar pulling was maximum (5 years) for panel A and minimum (1 year) for panels C and D. Underground observations indicated that the immediate roof (including the lower Sunnyside tongue) caved favorably in these sections.[3]

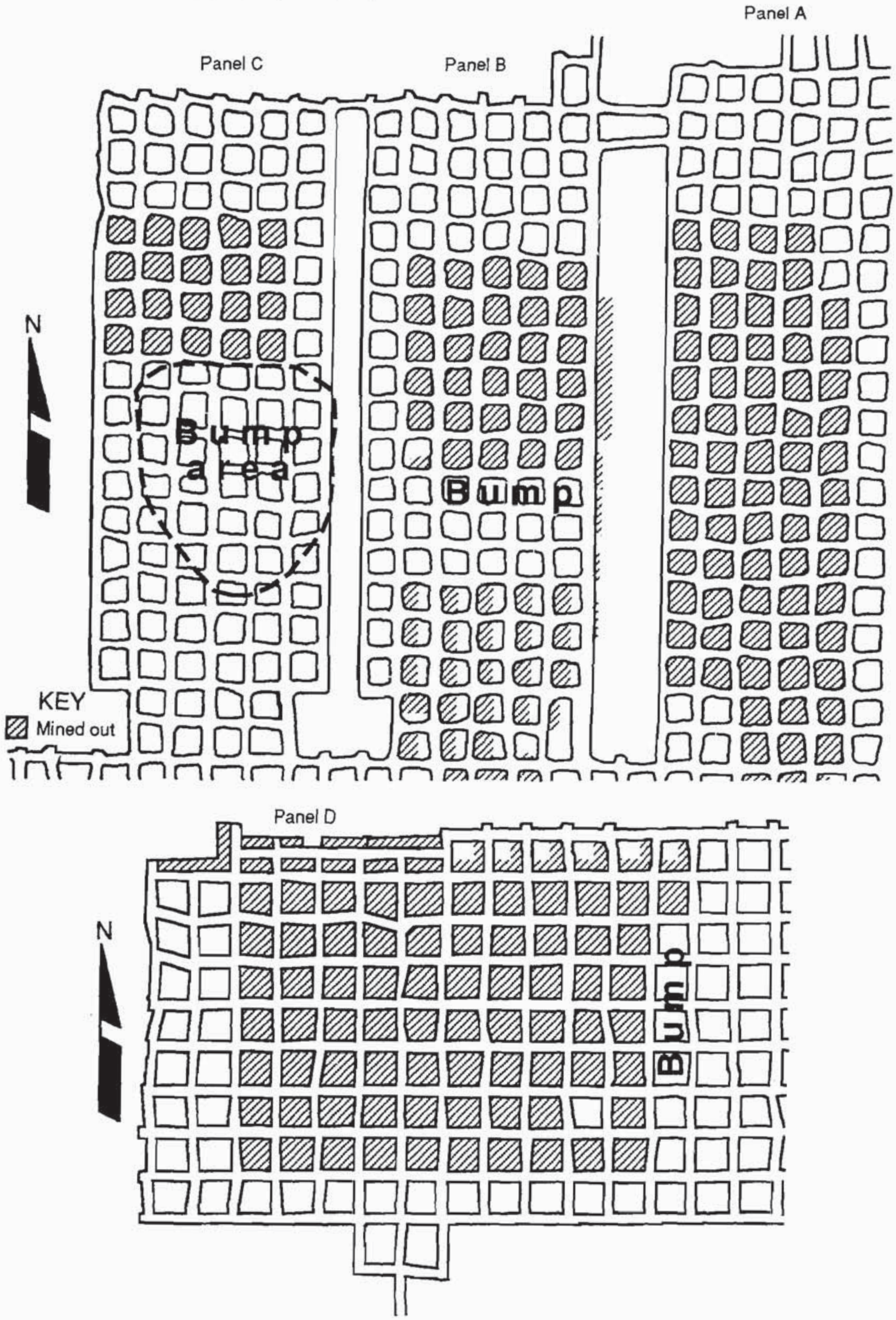
Following are some geometric and mining factors that contributed to bumping in panels B, C, and D (figure 12).

[3]Personal communication from D. Spillman, mining engineer, 1994.

Calculated elastic pillar stresses for these panel geometries were similar, exceeding the strength levels that were shown to cause roof, floor, and pillar stability problems (Maleki, 1992) by a minimum of 25 pct. Other factors contributing to such high pillar stresses were panel width and barrier pillar width, discussed elsewhere (Maleki and others, 1987; Zipf, 1993).

Many coal bumps occurred as the retreat line reached a distance equal to panel width (a square extraction). The cyclic nature of loading related to caving of upper strata that is associated with these square geometries has been identified by Maleki (1981) using direct pressure measurements in the gob (Maleki and others, 1984). The failure of upper strata was interpreted as a dynamic pulse that

*Figure 12*
**Panel Geometry and Bump Locations.**



triggered violent failure of critically loaded pillars at the face.

Considering the size of the extracted areas and depth of cover, and using numerical models of caving progress (Maleki, 1981), it is suspected that the coal bumps in the B, C, and D panels were triggered by failure in the upper Sunnyside and Castle Gate sandstones, respectively. Seismic analysis of strain energy release for panel C[3] also pointed out that an additional source of energy beyond pillar strain energy was needed to balance the energy calculations; two possibilities were identified as supplying this additional energy, both relating to movement and collapse of roof strata.

In summary, this case study provides evidence of coal bumps triggered by failure of upper strata as much as 100 m (300 ft) above the coal seam. Coal pillars were critically loaded prior to caving by thick cover and panel geometries.

## CASE STUDY 4—LACK OF YIELDING

This case study is similar to case study 1, except that there was no yielding in the mine floor, and thus coal bumps occurred frequently regardless of which alternative gate pillar layout was used. Yielding of the floor materials was associated with rock dilation, which reduced horizontal stresses in the pillar and enhanced gradual pillar failure.

The mine is located near Helper, UT. The longwall mining method has been used for the extraction of the D and Sub-3 seams (figure 13), which are some 130 m (430 ft) apart (Barron and others, 1994). Mining in the D Seam has been associated with the least number of coal bumps, while severe coal bumps in the Sub-3 coal seam have frequently interrupted mining.

The Sub-3 coal seam rests directly on the Star Point Sandstone, a thick, competent stratigraphic unit common in many mines in Utah. The seam contains a hard siltstone parting at midheight and two sets of cleats. The immediate roof is generally a thinly laminated siltstone underlain by 15 cm (6 in) of carbonaceous shale and intersected by sandstone channels (Bunnel and Taylor, 1986). Laboratory tests of mechanical properties of the immediate [6 m (19 ft)] roof and floor indicate that the materials are generally strong and stiff. No faults are present in the mining block and horizontal stress approximates vertical premining stress (Barron and others, 1994).

Longwall mining in the sub-3 Seam was conducted in areas with 300 to 610 m (1,000 to 2,000 ft) of cover and a high topographic relief. Both two- and three-gate entry systems using pillars 9, 15, 26, and 38 m (30, 50, 85, and 120 ft) in width were used to mitigate tailgate and face bump problems. None of these gate pillar layouts proved to be effective in controlling coal bumps as the second panel retreated.

Borehole pressure cell data indicated buildup of high horizontal stresses within the coal pillars, as illustrated in figure 14*B*. In this case, the pillars were 36 by 36 m (120 by 120 ft), a geometry that concentrated high stresses, particularly near the gob line (figure 14*A*). Coal bumps, however, persisted in this mine, irrespective of the gate pillar layout; nonyielding of the seam and floor contributed to the buildup of high stresses and sudden release of strain energy in the form of coal bumps.

## CASE STUDY 5—NO BUMPS

The mine is located on the east margin of the Wasatch Plateau in Utah. The longwall mining method has been used to extract two-seam reserves within the Wattis and Third-Bed seams, which are 11 to 17 m (35 to 55 ft) apart. The cover varies over the longwall area from 300 to 350 m (1,000 to 1,160 ft). Cover materials are persistently jointed by three to four sets of joints. Horizontal stresses are directional and less than vertical stresses.

Figure 15 presents the lithology, RQD, and mechanical properties for the roof, floor, and Wattis Seam. This coal seam has a well-developed cleat system. The immediate roof and floor exhibit large strength variations but are generally weak. Sandstone channels have frequently replaced the siltstones in the mine roof. These channels are, however, well jointed and have caving characteristics similar to the siltstones and shales (Maleki, 1988).

During development and retreat of a 7-longwall block, no significant coal bumps occurred at this site. Underground measurements revealed that the 9- by 24-m (30- by 80-ft) gate pillars experienced rib yielding during development mining, transferring stresses to the pillar core. The pillar core lost confinement and crushed nonviolently as the face approached the instrumented site; this was shown by the vertical and horizontal borehole pressure cells positioned toward the middle of the pillar (figure 16).

In comparison to case study 1, pillar confining stresses were much less, pillar strength was significantly lower (38 pct), and the postfailure slope was higher for the gate pillars. The cleated nature of the coal, the yielding of the immediate floor, and the sharp contact between the roof

[3]Boler, F. M., S. Billington, and R. K. Zipf. Estimates of Radiated Energy and Strain Energy Release for a Magnitude 3.6 Coal Mine Event. Paper presented at the 1994 Seismological Society of America meeting, Apr. 4-7, 1994.

*Figure 13*
**Stratigraphic Column, Case Study 4.**

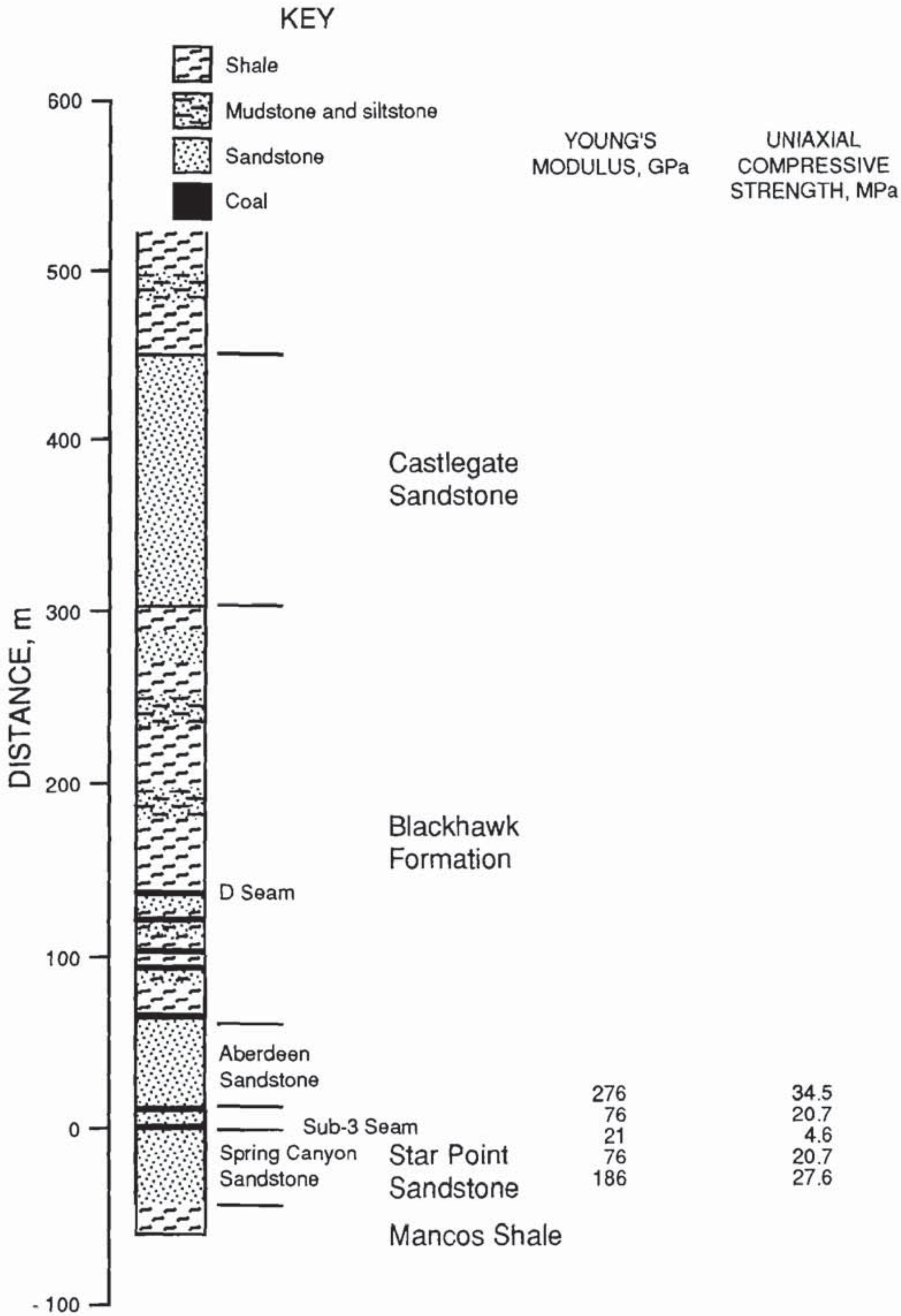
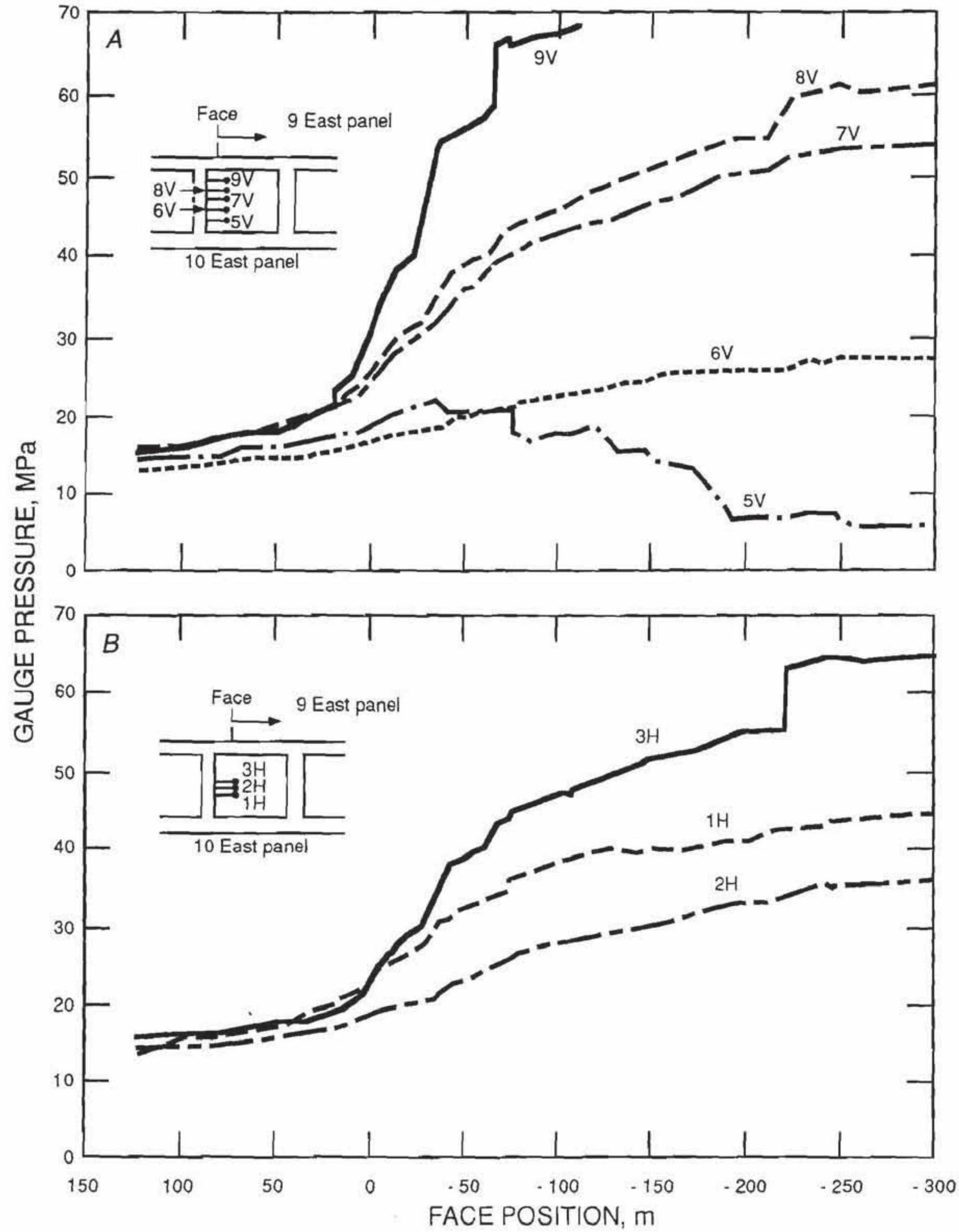
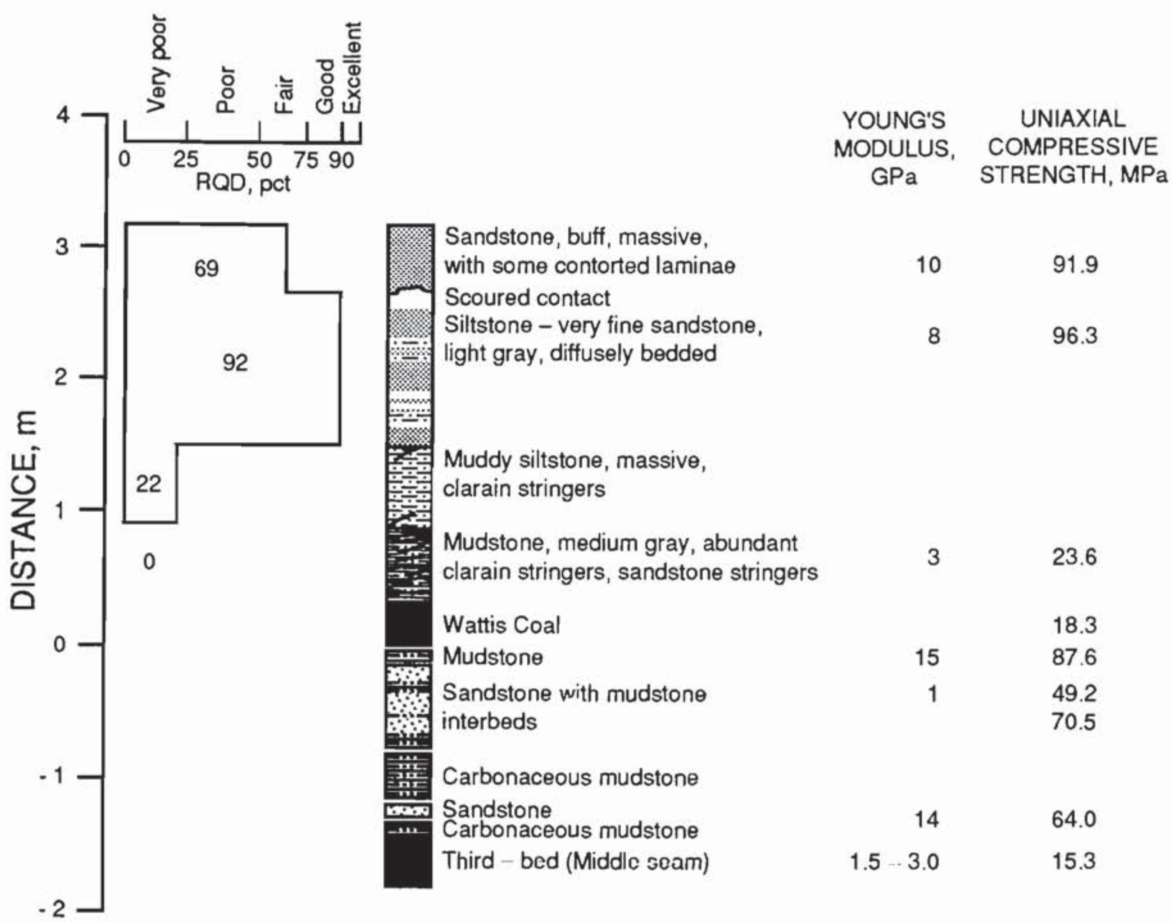


*Figure 14*
**Borehole Pressure Cell Pressure Changes Versus Face Position, Case Study 4.**




*A*, **Vertical cells;** ***B*, horizontal cells.**

*Figure 15*
**Typical Near-Seam Rock Structure and Strength Properties, Case Study 5.**



and the coal promoted gradual loss of confinement and nonviolent pillar behavior. Maleki (1988) and DeMarco and others (1995) have cataloged the benefits of such yield pillar systems for control of coal bumps.

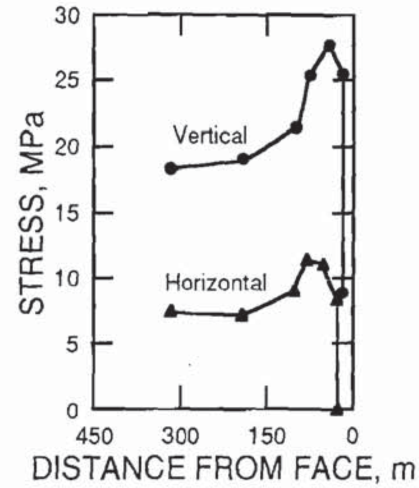
In summary, pillar behavior in this mine is controlled by structural features consisting of cleats and sharp contact planes, as well as yielding floor strata. These factors reduced pillar strength and strain energy accumulation, leading to nonviolent failure. The well-jointed nature of the mine roof enhanced regular caving and noncyclic pillar loading.

### SUMMARY

All case studies indicated that the calculated elastic pillar stresses exceeded by 20 to 30 pct the strength levels associated with roof, floor, and pillar stability problems (Maleki 1992). In addition, mining took place in areas where there was a rapid change in stress over a short distance and/or time, variations in topography, and pillar failure in an adjacent seam. Thus, a first step in minimizing coal bump potential is through development of mine layout and extraction sequences that would minimize activity in areas with high stress gradients.

Analysis of data from both bump-prone and nonbump-prone mines indicates that, in general, coal bump potential increases as the uniaxial compressive strength and Young's modulus ratios exceed 3 to 5. The role of mine stiffness could not be validated directly through the use of local stiffness in determining coal bump potential because there is not enough data regarding postfailure behavior of coal seams and the mechanical properties of large-scale rock masses.

***Figure 16***
**Calculated Stresses From Two Pressure Cells.**




Striking differences in coal behavior exist in neighboring bump-prone and nonbump-prone mines, even when both mines have similar laboratory-determined mechanical properties. In bump-prone mines, high horizontal stresses formed within the coal and eventually dissipated while the immediate floor yielded. In the nonbump-prone mine, horizontal stress buildup was moderate and loss of stress occurred over a short time but in a very stable manner. The strength and behavior of this structurally controlled coal seam was influenced by persistent cleats, sharp contact between the roof and the seam, and the presence of readily yielding floor material. Yielding in the roof or floor was associated with dilation and a reduction in horizontal stresses, enhancing gradual pillar failure.

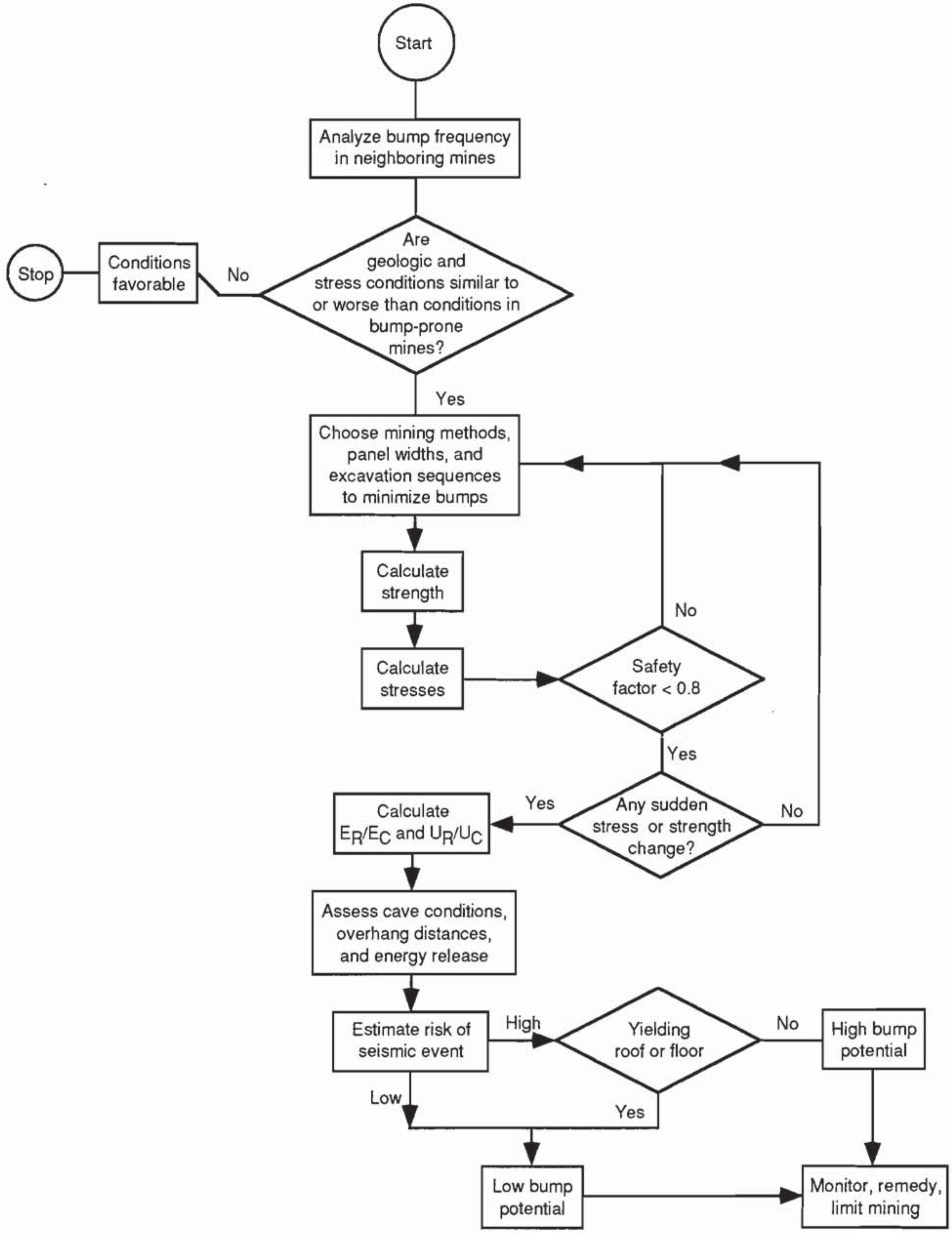
## COAL BUMP ASSESSMENT METHODOLOGY

Through analyses of case studies and an evaluation of existing criteria, it is apparent that violent failures are influenced by the state of stress, stiffness of surrounding strata, dynamic effects associated with failure of surrounding strata, and near-seam depositional and structural features. It is apparent that existing criteria are generally too simplistic and address only either static or dynamic effects. A methodology is proposed here as a tool for assessing coal bump potential; this approach is useful during preliminary mine design to determine the potential for coal bump problems at an early stage in mine planning. If calculations reveal a high potential for coal bumps, additional geotechnical data may need to be collected during development of the property to increase confidence in predictions. Such calculations may include in situ strength of the coal seam, Young's modulus and uniaxial compressive strength ratios (roof- and/or floor-to-coal), beam thickness, overhang distances in the gob, and other factors.

This approach (figure 17) is initiated by thoroughly examining experience in mines with the same or other seams with similar geologic, strength, and loading conditions. If conditions are similar to the bump-prone seams, then additional considerations are highly recommended.

The first step in minimizing coal bump potential is through development of mine layout and extraction sequences that minimize activities in areas with high stress gradients. Specific designs may be evaluated by calculating the average strength and stress and ensuring that the ratio of the two (factor of safety) is greater than 1. Excluding yield pillar applications, all analyzed coal bumps occurred

*Figure 17*
**Flow Chart for Assessing Coal Bump Potential.**




**$E_R/E_C$ = Young's modulus. $U_R/U_C$ = Uniaxial compressive strength ratio.**

when the stresses exceeded the strength levels associated with stability problems by a minimum of 20 pct (factor of safety 0.8).

Additional considerations should be given to any sudden changes in stresses caused by variations in topography and multiple-seam geometries. Localized changes in strength resulting from variations in geology and/or mining height should also be considered.

The Young's modulus ratio $E_R/E_C$ (roof to coal) and uniaxial compressive strength ratio ($U_R/U_C$) should be calculated if safety factors are unfavorable. Modulus and strength ratios exceeding 5 to 3, respectively, and the absence of joints favor formation of large overhangs in the gob. Failure of these strata releases strain energy and contributes to coal bump incidence by providing a triggering mechanism for these marginally stable structures.

The damage potential of the seismic event may be estimated on the basis of expected local wave magnitude resulting from failure of surrounding strata. In general, wave magnitudes exceeding 2.5 on the Richter scale have been associated with high risks of damage.

Experience, numerical modeling, and engineering judgment may be used to assess the extent of yielding in mine roofs and floors; such controlled yielding may help reduce horizontal stresses and lead to less violent failures. Lack of yielding within the roof, coal, and seam promotes high bump potential where there is a high risk of a seismic event and a low factor of safety.

Mining conditions that are calculated to create a bump potential need special considerations to avoid production delays, damage to equipment, and danger to miners. Mining under such conditions should be conducted in conjunction with geotechnical monitoring and should be flexible in terms of remedial actions, including leaving blocks of coal in place. Seismic monitoring, tomographic surveys, and face support (shield) pressure recording can aid in detecting those anomalous geologic and stress conditions that contribute to coal bumps.

## CONCLUSIONS

Geotechnical data, mining experience, and long-term underground observations were analyzed in an effort to better understand causes of violent failure in U.S. coal mines. It was shown that coal bumps are influenced by the interaction of geologic and stress conditions that govern postfailure behavior of coal-measure rocks. Case studies provided new insight into buildup and loss of horizontal stresses, geometric factors that cause zones with high stress gradients, contrasts in stiffness and the mechanical properties of rock and seam, and failure of upper strata.

Because geotechnical factors that influence coal bumps are multiple, existing criteria are inadequate to assess coal bumps. A preliminary methodology was developed based on experience in U.S. mines for assessing bump potential. In this approach, mining experience, stiffness and strength ratios, safety factors in coal structures, yieldability of roof and floor, sudden changes in stress gradient, and failure of roof strata are taken into consideration to assess coal bump potential.

## REFERENCES

Babcock, C. O. Equation for the Analysis of Borehole Pressure Cell Data. Paper in Rock Mechanics: Key to Energy Production. 27th U.S. Symposium on Rock Mechanics (Univ. of AL, Tuscaloosa, AL, June 23-25, 1986). Soc. Min. Eng., 1986, pp. 233-240.

Babcock, C. O., and D. L. Bickel. Constraint — The Missing Variable in the Coal Burst Problem. Paper in Rock Mechanics in Productivity and Protection. Proceedings, 25th Symposium on Rock Mechanics, ed. by C. H. Dowding and M. M. Singh (Northwestern Univ., Evanston, IL, June 25-27, 1984). Soc. Min. Eng., 1984, pp. 639-647.

Barron, L. R., M. J. DeMarco, and R. O. Kneisky. Longwall Gateroad Stability in Four Deep Western U.S. Mines. USBM RI 9406, 1994, 84 pp.

Bunnel, M. D., and T. W. Taylor. Roof Lithology and Coal Seam Characteristics of the No. 3 Mine, Carbon County, Utah. Paper in Contributions to Economic Geology in Utah. Spec. Study 69, UT Geol. and Miner. Surv., 1986, pp. 1-29.

Campoli, A. A., T. M. Barton, F. C. Van Dyke, and M. Gauna. Mitigating Destructive Longwall Bumps Through Conventional Gate Entry Design. USBM RI 9325, 1990, 38 pp.

Chavan, A. S., N. M. Raju, and S. B. Srivastra. Rock Burst Prediction — An Empirical Approach. Paper in Rockbursts and Seismicity in Mines. Proceedings of the 3rd International Symposium on Rockbursts and Seismicity in Mines, ed. by R. P. Young (Kingston, ON, Aug. 16-18, 1993). Balkema, 1993, pp. 163-168.

Cook, N. G. W., and J. P. M. Hojem. A Rigid 50-Ton Compression and Tension Testing Machine. J. S. Afr. Inst. Mech. Eng., v. 1, 1966, pp. 89-92.

DeMarco, M. J., J. B. Koehler, and H. Maleki. Panel and Gateroad Design Considerations for the Mitigation of Coal Bumps in Western U.S. Longwall Operations. Paper in Proceedings: Mechanics and Mitigation of Violent Failure in Coal and Hard-Rock Mines. USBM Spec. Publ. 01-95, 1995, pp. 141-165.

Dubinski, J. Characteristics of Seismicity Induced by Mining Operations in the Upper Silesian Coal Field. Paper in Proceedings of the 18th Czechoslovakia-Poland Conference on Geophysics. 1990, v. 83. pp. 115-127.

Gibowicz, S. J. Keynote Lecture: The Mechanism of Seismic Events Induced by Mining. Paper in Rockbursts and Seismicity in Mines, Proceedings of the 2nd International Symposium on Rockbursts and Seismicity in Mines, ed. by C. Fairhurst (Univ. of MN, Minneapolis, MN, June 8-10, 1988). Balkema, 1990, pp. 3-27.

Haramy, K. H., and J. P. McDonnell. Causes and Control of Coal Mine Bumps. USBM RI 9225, 1988, 35 pp.

Iannachione, T., and J. C. Zelanko. Pillar Mechanics of Coal Mine Bursts: A Control—Strategy. Paper in Proceedings of the 16th World Mining Congress, (Sofia, Bulgaria, Sept. 12-16, 1994). Bulgarian Nat. Organ. Comm., v. 5, 1994, pp. 15-23.

Kleczek, Z., and A. Zorychta. Coal Bumps Induced by Mining Tremors. Paper in Rockbursts and Seismicity in Mines 93. Proceedings of the 3rd International Symposium on Rockbursts and Seismicity in Mines, ed. by R. P. Young (Kingston, ON, Aug. 16-18, 1993). Balkema, 1993, pp. 87-90.

Lippmann, H. Mechanical Considerations of Bumps in Coal Mines: Keynote Lecture. Paper in Rockbursts and Seismicity in Mines, Proceedings of the 2nd International Symposium on Rockbursts and Seismicity in Mines, ed. by C. Fairhurst (Univ. of MN, Minneapolis, MN, June 8-10, 1988). Balkema, 1990, pp. 279-284.

Maleki, H. Coal Mine Ground Control. Ph.D. thesis, CO Sch. Mines, Golden, CO, 1981, 432 pp.

Maleki, H. Ground Response to Longwall Mining. CO Sch. Mines Q., v. 83, No. 3, 1988, 52 pp.

Maleki, H. In Situ Pillar Strength and Failure Mechanisms for U.S. Coal Seams. Paper in Proceedings of the Workshop on Coal Pillar Mechanics and Design, comp. by A. T. Iannacchione, C. Mark, R. C. Repsher, R. J. Tuchman, and C. C. Jones (Santa Fe, NM, June 7, 1992). USBM IC 9315, 1992, pp. 73-77.

Maleki, H., J. R. Aggson, F. Miller, and J. F. T. Agapito. Mine Design Layout for Coal Bump Control. Paper in 6th International Conference on Ground Control in Mining: Proceedings, ed. by S. S. Peng (WV Univ., Morgantown, WV, June 9-11, 1987). Dept. of Min. Eng., WV Univ., Morgantown, WV, 1987, pp. 32-46.

Maleki, H., W. Hustrulid, and D. Johnson. Pressure Measurements in the Gob. Paper in Rock Mechanics in Productivity and Protection. Proceedings, 25th Symposium on Rock Mechanics, ed. by C. H. Dowding and M. M. Singh (Northwestern Univ., Evanston, IL, June 25-27, 1984). Soc. Min. Eng., 1984, pp. 533-545.

Maleki, H., Y. Jung, and K. Hollberg. Case Study of Monitoring Changes in Roof Stability. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., v. 30, No. 7, 1993, pp. 1395-1401.

Maleki, H., M. Moon, and J. F. T. Agapito. In Situ Pillar Strength Determination for Two-Entry Longwall Gates. Paper in 7th International Conference on Ground Control in Mining: Proceedings, ed. by S. S. Peng (WV Univ., Morgantown, WV, Aug. 3-5, 1988). Dept. of Min. Eng., WV Univ., Morgantown, WV, 1988, pp. 10-19.

Mark, C. Pillar Design Methods for Longwall Mining. USBM IC 9247, 1990, 52 pp.

McGarr, A. Some Applications of Seismic Source Mechanism Studies to Assessing Underground Hazard. Paper in Rockbursts and Seismicity in Mines, ed. by N. C. Gay and E. H. Wainwright (Proc. of Symp. on Seismicity in Mines, Johannesburg, S. Afr., 1982). S. Afr. Inst. Min. Metall., Symp. Series 6, 1984, pp. 199-208.

Ortlepp, W. D. The Design of Support for the Containment of Rockburst Damage in Tunnels—An Engineering Approach: Invited Lecture. Paper in Rock Support in Mining and Underground Construction. Proceedings of the International Symposium on Rock Support, ed. by P. K. Kaiser and D. R. McCreath (Sudbury, ON, June 16-19, 1992). Balkema, 1992, pp. 593-609.

Pen, Y., and K. Barron. The Role of Local Mine Stiffness in Pillar Bump Prediction. Paper in Rock Mechanics Models and Measurements Challenges from the Industry. Proceedings of the 1st North American Rock Mechanics Symposium, ed. by P. P. Nelson and S. E. Laubach (Univ. of TX at Austin, TX, June 1-3, 1994). Balkema, 1994, pp. 1017-1024.

Pritchard, C. J., and D. G. F. Hedley. Progressive Pillar Failure and Rockbursting at Denison Mine. Paper in Rockbursts and Seismicity in Mines 93. Proceedings of the 3rd International Symposium on Rockbursts and Seismicity in Mines, ed. by R. P. Young (Kingston, ON, Aug. 16-18, 1993). Balkema, 1993, pp. 111-116.

Rice, G. S. Bumps in Coal Mines of the Cumberland Field, Kentucky and Virginia—Causes and Remedy. USBM RI 3267, 1935, 36 pp.

Ryder, J. A. Excess Shear Stress in the Assessment of Geologically Hazardous Situations. J. S. Afr. Inst. Min. Metall., v. 88, 1988, pp. 27-39.

Salamon, M. D. G. Stability, Instability, and Design of Pillar Workings. Int. J. Rock Mech. Min. Sci., v. 7, No. 6, 1970, pp. 613-631.

Starfield, A. M., and W. R. Wawersik. Pillars as Structural Components in Room-and-Pillar Mine Design. Paper in Basic and Applied Rock Mechanics. Proceedings, 10th Symposium on Rock Mechanics, ed. by K. E. Gray (Univ. TX at Austin, May 20-22, 1968). Soc. Min. Eng., 1972, pp. 793-809.

Wawersik, W. R., and C. Fairhurst. A Study of Brittle Rock Fracture in Laboratory Compression Experiments. Int. J. Rock Mech. Min. Sci., v. 7, No. 5, 1970, pp. 561-575.

White, B. G., J. K. Whyatt, and D. F. Scott. Geologic Factors in Rock Bursts in the Coeur d'Alene Mining District: Structure. Paper in Proceedings: Mechanics and Mitigation of Violent Failure in Coal and Hard-Rock Mines. USBM Spec. Publ. 01-95, 1995, pp. 243-264.

Williams, T. J., J. M. Girard, and C. J. Wideman. Investigation of a 3.5 $M_L$ Rockburst. Paper in Rockbursts and Seismicity in Mines 93. Proceedings of the 3rd International Symposium on Rockbursts and Seismicity in Mines, ed. by R. P. Young (Kingston, ON, Aug. 16-18, 1993). Balkema, 1993, pp. 267-271.

Wong, I. G., J. R. Humphrey, J. A. Adams, and W. J. Silva. Observations of Mine Seismicity in the Eastern Wasatch Plateau, Utah, U.S.A.: A Possible Case of Implosional Failure. PAGEOPH, v. 129, 1989, pp. 369-405.

Wu, X., and M. G. Karfakis. An Analysis of Strain Energy Accumulation Around Longwall Panels Under Strong Roofs. Paper in Proceedings, 5th Conference on Ground Control for Midwestern U.S. Coal Mines, ed. by Y. P. Chugh and G. A. Beasley (Collinsville, IL, June 1994). 1994, pp. 230-253.

Yi, X., and P. K. Kaiser. Mechanisms of Rockmass Failure and Prevention Strategies in Rockburst Conditions. Paper in Rockbursts and Seismicity in Mines. Proceedings of the 3rd International Symposium on Rockbursts and Seismicity in Mines, ed. by R. P. Young (Kingston, ON, Aug. 16-18, 1993). Balkema, 1993, pp. 141-148.

Zipf, R. K., Jr. Analysis of Stable and Unstable Pillar Failure Using Local Mine Stiffness Method. Paper in Proceedings of the Workshop on Coal Pillar Mechanics and Design, comp. by A. T. Iannacchione, C. Mark, R. C. Repsher, R. J. Tuchman, and C. C. Jones (Santa Fe, NM, June 7, 1992). USBM IC 9315, 1992, pp. 128-143.

Zipf, R. K., Jr. Stress Analysis in Coal Mines With MULSIM/NL. Paper in Proceedings of the 89th Meeting of the Rocky Mountain Coal Mining Institute (Beaver Creek, CO, 1993). Rocky Mt. Coal Min. Instit., Lakewood, CO, 1993, pp. 38-43.

Zipf, R. K., Jr., and K. A. Heasley. Decreasing Coal Bump Risk Through Optimal Cut Sequencing With a Non-Linear Boundary Element Program. Paper in Rock Mechanics Contributions and Challenges: Proceedings of the 31st U.S. Symposium, ed. by W. A. Hustrulid and G. A. Johnson (CO Sch. of Mines, Golden, CO, June 18-20, 1990). Balkema, 1990, pp. 947-954.

Special Publication 01-95

# Proceedings: Mechanics and Mitigation of Violent Failure in Coal and Hard-Rock Mines

Edited by Hamid Maleki, Priscilla F. Wopat, Richard C. Repsher,
and Robert J. Tuchman

UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES
Rhea L. Graham, Director

**Library of Congress Cataloging in Publication Data:**

**Maleki, Hamid N.**

Proceedings : mechanics and mitigation of violet failure in coal and hard-rock mines / edited by Hamid Maleki ... [et al.].

p. cm. — (USBM special publication; 01-95)

Includes bibliographical references.

Supt. of Docs. no.:I 29.151 : 01-95.

1. Rock bursts—Congresses. 2. Mine roof control—Congresses. 3. Coal mines and mining—Safety measures—Congresses. 4. Mines and mineral resources—Safety measures—Congresses. I. Title. II. Series: Special publication (United States. Bureau of Mines); SP 01-95.

TN317.M35 1995 622'.28—dc20 95-7138 CIP