GATE ROAD DESIGN CONSIDERATIONS FOR MITIGATION OF COAL BUMPS IN WESTERN U.S. LONGWALL OPERATIONS

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ABSTRACT

Longwall mining in the Western United States has long had to contend with the regular occurrence of pillar and panel coal bumps, primarily resulting from deep cover [generally 450+ m (1,500+ ft)], massive sandstone units in the main roof, strong immediate roof and floor strata bounding the coal seam, and the high stress concentrations created along panel peripheries, particularly in multiple-seam workings. To assist mine operators in recognizing bump-prone geologic conditions and, ultimately, in avoiding those entry configurations that further contribute to bump-inducing stress concentrations, this paper summarizes the experience of Western U.S. longwall operations over the past decade. More specifically, this paper highlights those mining conditions that most greatly contribute to bump occurrences, several mining practices that tend to aggravate bump-prone settings, and the problems associated with "critical pillars," the primary contributors to gate road bumps. While U.S. Bureau of Mines research continues to develop proven gate road design technologies, this report serves as a summary of bump control through mine design for Western longwall mines.

INTRODUCTION

Some of the most significant coal-bump problems in U.S. longwall history have been encountered in the Book Cliffs and Wasatch Plateau regions of central Utah, with several fatalities and numerous injuries attributable to this catastrophic failure phenomenon over the past few decades (Koehler, 1994b). Novel gate design approaches and well-planned multiseam mining have largely eliminated the threat of major bumps in the region in more recent years, but with today's higher productivity operations mining seams at even greater depths, the potential for these disastrous events has once again become of serious concern for virtually all of the region's operators. Today, most of the mines in the region are confronted with at least some degree of bump problem, primarily related to mine setting and/or panel design factors. This fact has been all too recently illustrated by the occurrence of serious bump events in longwall *headgates* at two major operations in the region, which is a situation that will continue to plague operators as several mining companies look at moving into areas of the coal district with histories of serious bump problems. This paper presents an overview of the conditions that contribute to bumping in the Wasatch and Book Cliffs Coalfields. It further examines a few of the more major problems with mine design that may aggravate already bump-prone mine settings and emphasizes the severity of bump problems resulting from the misapplication of gate road designs. A very recent example of critical pillar usage at the Sunnyside Coal Co.'s No. 1 Mine, near Sunnyside, UT, is also given.

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GROUND CONDITIONS CONDUCIVE TO BUMPING IN WESTERN LONGWALL MINES

Western longwall operations often contend with a number of mining conditions conducive to the development of serious coal bump problems. Among these conditions are some of the greatest cover depths in the United States [up to 900 m (3,000 ft)], dramatic variations in overburden depths along the length of a panel because of ridge-and-canyon topography, massive sandstone units in the main roof, strong immediate roof and floor strata, strong coal seams with impersistent cleat systems, persistent sand channeling in the immediate roof, and, at some locations, a variety of structural discontinuities such as faults and shear zones. Many mines along the Wasatch Plateau and Book Cliffs escarpments encounter a critical combination of these conditions at some point. Not surprisingly, these conditions have been well cited as the primary contributors to coal bumps in Eastern coalfields (Iannacchione and DeMarco, 1992).

DEEP, VARIABLE COVER

Western coal mines susceptible to bump-prone conditions are generally situated either in the mountainous regions of Colorado or the plateau escarpments of central Utah (figures 1 and 2). As a result, cover depths can be extremely variable over very short distances, commonly exceeding 300 m (1,000 ft) just inby the mine portal. Currently, longwalling in the Wasatch Plateau and Book Cliffs regions is conducted at mining depths ranging from 300 m (1,000 ft) to nearly 900 m (3,000 ft), with average depths of approximately 600 m (2,000 ft). The trend of future mining in this region should involve deeper operations for many years to come.

At most operations, the onset of bump problems has occurred around a depth of 450 m (1,500 ft); however, there are exceptions to this rule of thumb because of panel and/or pillar geometry, number of panels mined, site geology, etc. In some cases, bumps have occurred at depths as shallow as 225 m (750 ft) (Koehler, 1994b). Experience has demonstrated that, in many instances, proper mine design can largely eliminate bumps altogether, as has been the case at several mines operating at depths in excess of 600 m (2,000 ft).

The mountainous topography of central Utah not only engenders coal bumps attributable to great mining depths, but also creates problems along panels where large variations in mining cover occur. For example, a recent study at the Sunnyside operation (described later in this paper) reported cover depths ranging from approximately 840 m (2,800 ft) near the start-up room to 420 m (1,400 ft) at midpanel to 870 m (2,900 ft) near the projected face stopline along approximately 1,500 m (5,000 ft) of panel. This widely varying ridge-and-canyon setting created considerable problems in predicting when and where bump-prone conditions might be encountered, which is a situation common to area mines. In addition, due to inherent spatial variations of sandstone channels and large sandstone units, and their stress-concentrating properties (Maleki, 1988), overall stress distribution near the seam can vary over a short distance, complicating coal bump predictions.

This problem was also seen at the now-idle Castle Gate No. 3 Mine, where rapid changes in topography made it almost impossible to determine when bumps would occur along the longwall face (figure 3). Face destressing near the tailgate of the 9th East panel (6th panel), a technique that employed a combination of face and tailgate high-pressure hydrofracture holes, was suspended when the longwall came out from under 600 m (2,000 ft) of cover and overburden loads became much lower [depths of 330 m (1,100 ft) to 420 m (1,400 ft) along the face]. The massive Castle Gate sandstone was not present over this portion of the panel and mining proceeded smoothly.

As the face advanced beneath the canyon escarpment once again, stress-relief drilling and hydrofracturing were resumed in an effort to reduce potential face bump conditions; however, the complicated nature of panel loading beneath the edge of the cliffs relegated the success of the destressing program to speculation. The result was that use of these stress-relief techniques was discontinuous and

Figure 1
Ridge-and-Canyon Topography Typical of Book Cliffs and Wasatch Plateau Coalfields.

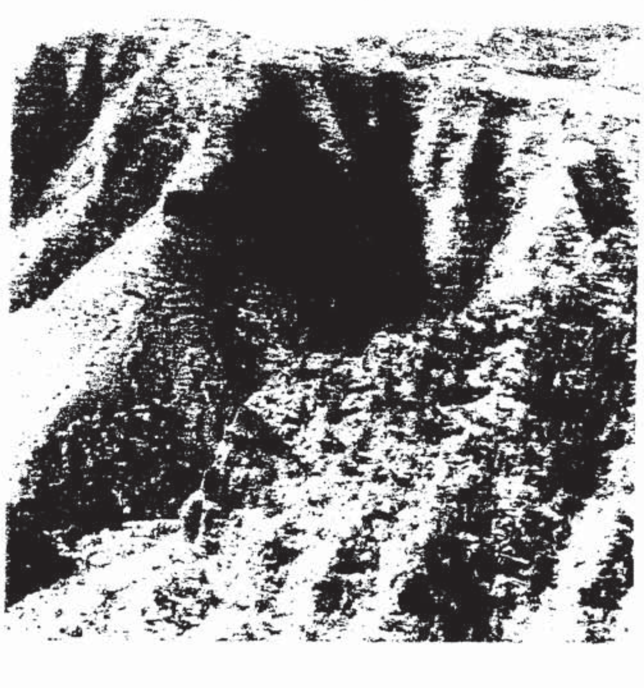


Figure 2
Escarpment of Wasatch Plateau Near Huntington, UT.

erratic until some form of verification was obtained that the drilling was indeed necessary. Such verification came shortly after when a severe face bump stopped mining for several days, indicating the ineffectiveness of the destressing effort. The mine was idled a couple of months later, in April 1989, after the occurrence of several additional bump events (Barron, 1994).

Maleki (1995) has also documented the occurrence of a severe coal bump in an Eastern coalfield due to sudden changes in stress gradient near a ridge providing 660 m (2,200 ft) of mining cover.

MASSIVE SANDSTONE UNITS

One of the leading contributors to coal bumps in the Wasatch-Book Cliffs Coalfields is several massive sandstone units that commonly make up the main mine roof and floor. Among these, in ascending order, are the Starpoint, Spring Canyon (often considered a tongue of the Starpoint), Aberdeen, Kenilworth, Sunnyside, and Castle Gate sandstones (Barron, 1994). Most of these sandstones either bound or are located within the coal-bearing Blackhawk Formation, as shown in figure 4. These sandstones are by no means the only units of strong, competent strata within the Blackhawk; numerous smaller sandstone units and exceptionally strong siltstones make up much of the main roof overburden in the region (figure 5).

The presence of these units contributes to bump-proneness in several ways. Their strength and continuity, particularly in the Castle Gate Sandstone, allow load transfer over the gobs of several panels before they fail and reach a state of maximum subsidence. The result can be, and often is, the transference of considerable abutment loads over relatively large distances. Canyons naturally help to alleviate this problem, but the potential still exists for this excessive load transfer at most of the mines operating along the escarpment front. Case studies have demonstrated good ground conditions typically exist on the first, and possibly the second, panel; however, the third panel tailgate often takes the brunt of the severe abutment loads. Once good caving has been established, these problems generally decline in severity. The use of wider panels has been often recommended to enhance cave conditions (Barron, 1994; Maleki, 1988).

The sudden failure of these massive units is also a contributing factor in the initiation of coal bumps (Maleki, 1995). A recent analysis of a severe coal bump in a Book Cliffs mine has emphasized that the failure of surrounding

Figure 3
Longwall Panel Layouts at Castle Gate No. 3 Mine.

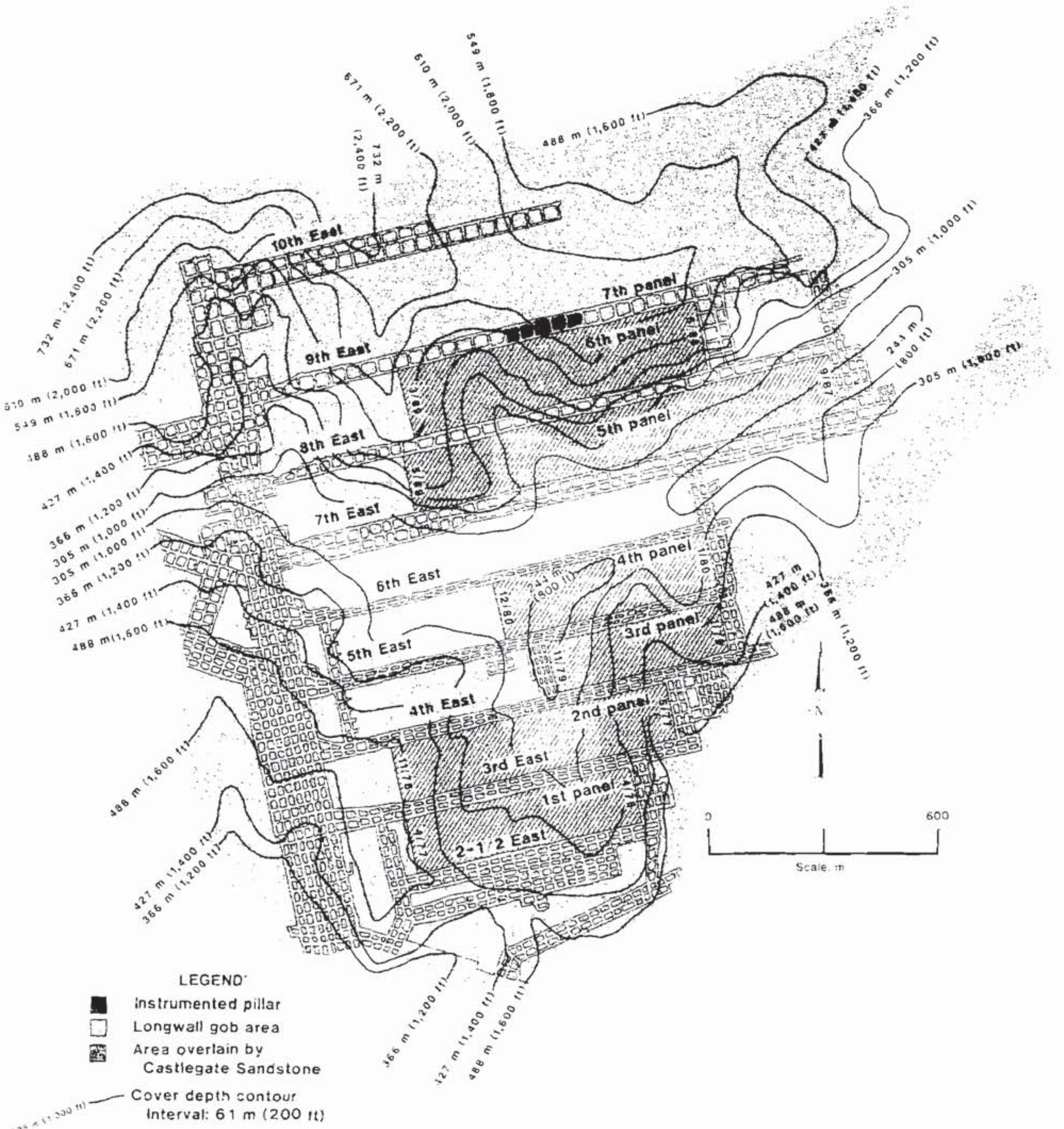


Figure 4
Generalized Stratigraphic Sections, Wasatch Plateau and Book Cliffs Coalfields.

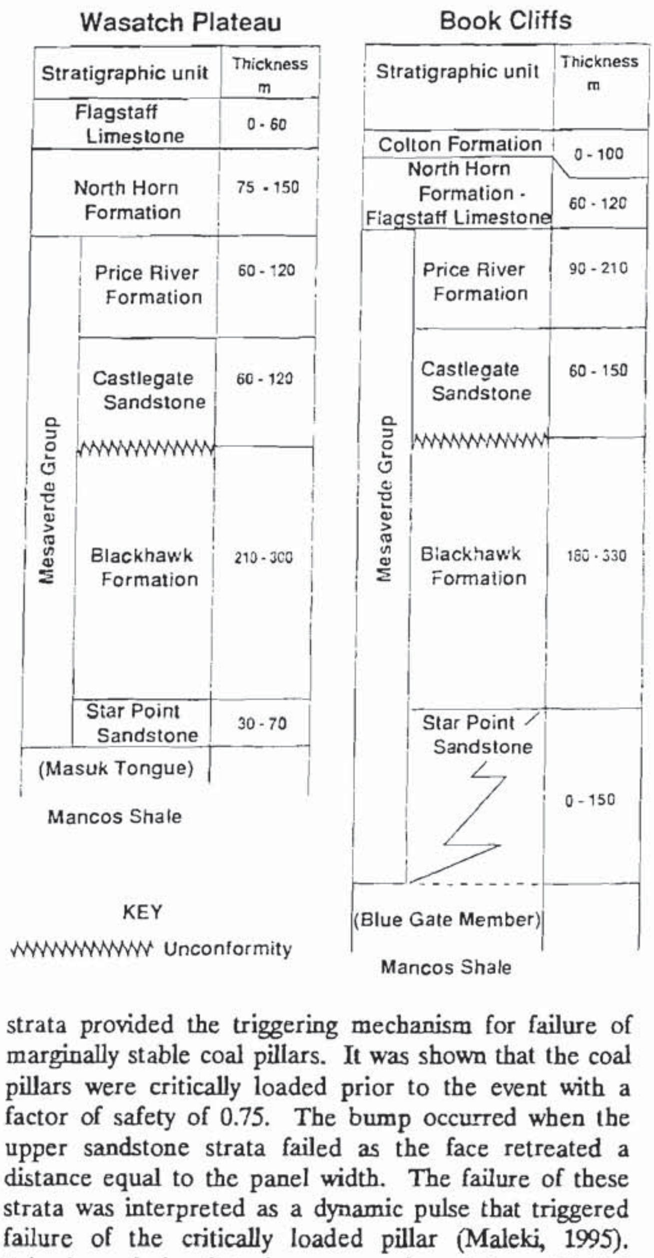


Figure 5
Exposure of Star Point Sandstone at Cottonwood Mine Loading Facility.

Upper portion of unit is below Hiawatha Seam located even with small cubical building above concrete silo. Numerous strong sandstone and siltstone units can be seen to overlie seam workings as well.

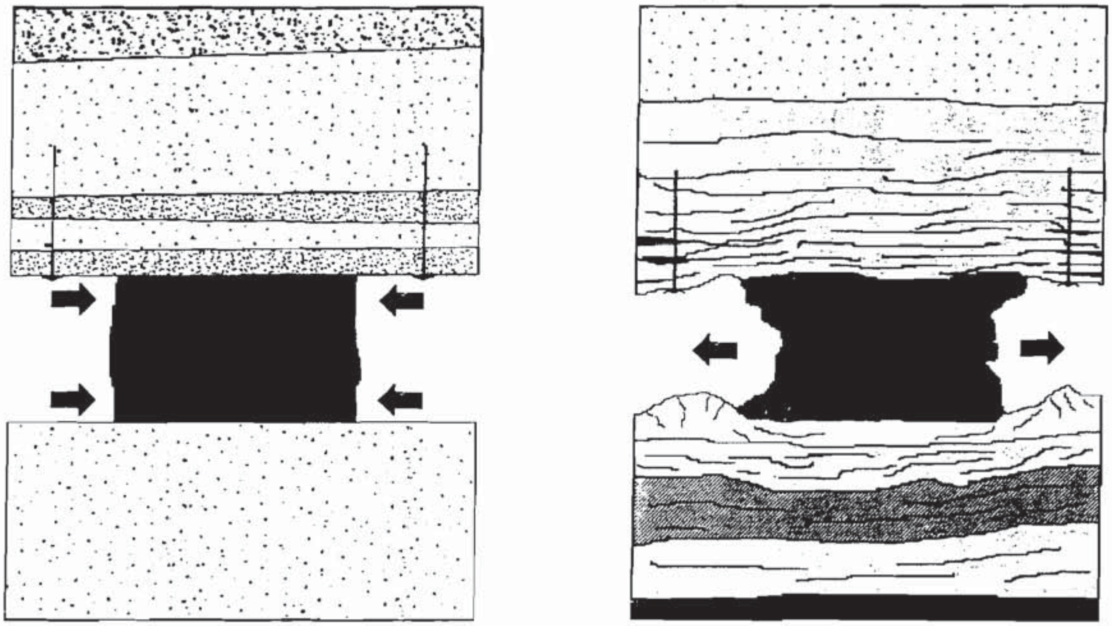
strata provided the triggering mechanism for failure of marginally stable coal pillars. It was shown that the coal pillars were critically loaded prior to the event with a factor of safety of 0.75. The bump occurred when the upper sandstone strata failed as the face retreated a distance equal to the panel width. The failure of these strata was interpreted as a dynamic pulse that triggered failure of the critically loaded pillar (Maleki, 1995). Seismic analysis of strain energy released from this 3.6 Richter-magnitude event also confirmed that a source of energy from the upper strata, in addition to pillar strain energy, was needed to balance energy calculations (Boler, 1994).

STRONG ROOF AND FLOOR STRATA

Strong floor strata immediate to the coal seam and strong roof strata within 9 to 15 m (30 to 50 ft) of the seam have long been recognized as major contributors to coal bumps (Holland and Thomas, 1954; Iannacchione and DeMarco, 1992; Peparakis, 1958). In fact, the confinement offered to the coal seam by these stronger, stiffer strata appears necessary to generate levels of stored energy sufficient to cause bumps within and immediate to the coal seam structure (Babcock, 1984). Conversely, weak roof and floor strata do not allow the accumulation of high loads and excessive strain energy on the coal structure because of stress-dissipating deformation into the mine openings (figure 6). Soft ground conditions may actually help lessen the integrity of the coal seam near the periphery of the entry as the strata migrate into the opening, thereby concentrating the high stresses deeper in the structure where the strength of the confined coal is much greater than the applied load.

Figure 6

Illustration of Pillar Confinement Offered by Strong Roof and Floor Strata (Left) Versus Weak Strata (Right).



In the Wasatch-Book Cliffs coal region, the strata immediate to the seam are conducive to bumping in a number of mines. In these mines, the floor is commonly composed of thick sandstones overlain by thin siltstones and mudstones, and, as a result, floor heave is rarely experienced. The intervals of weaker materials separating the sandstones from the overlying seam can vary considerably across a given property, and it is not uncommon to find these massive sandstone units immediately contacting the bottom of the seam. This has been noted by the authors in those operations working in the Sub-3 Seam and the Hiawatha Seam where the Starpoint Sandstone is often found next to the seam.

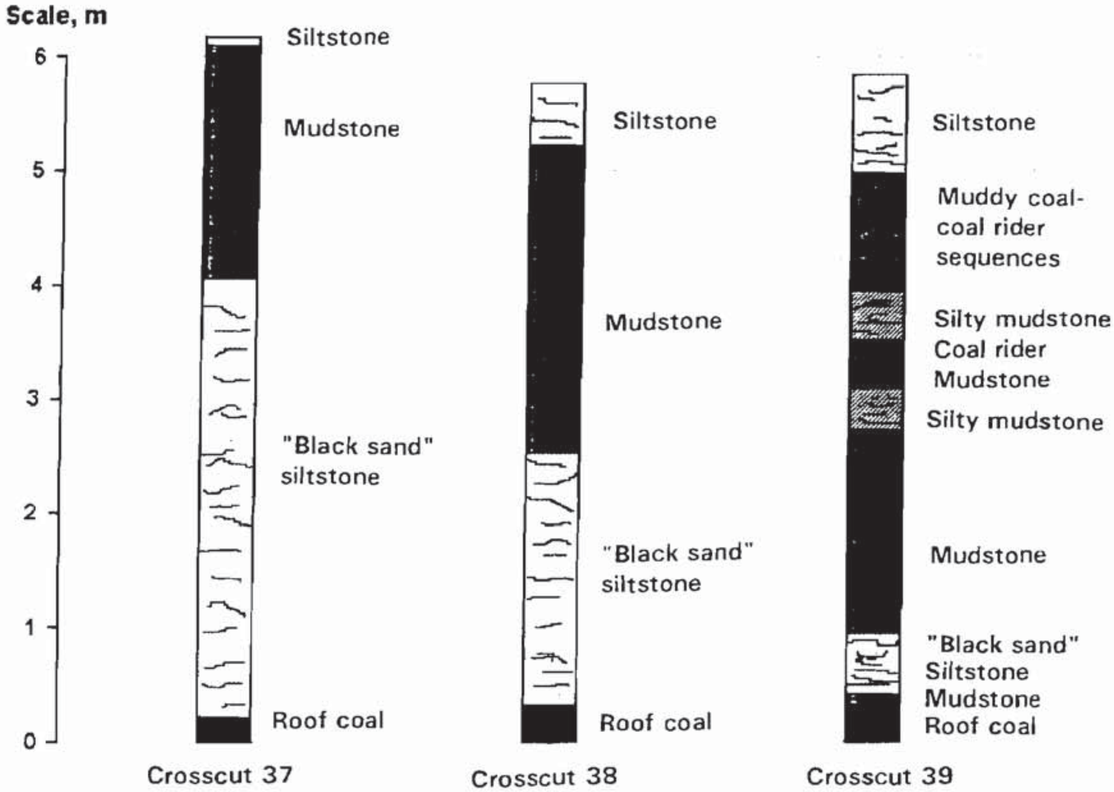
Roof strata at some bump-prone operations are considerably more variable than the floor strata. At these mines, it is not uncommon to find significant changes in the thickness of individual roof units over very short lateral distances, particularly in areas where channel deposits are frequently encountered. This condition was present at the Sunnyside No. 1 Mine, near Sunnyside, UT (figure 7). Clearly, highly variable roof strata create difficult ground control problems with regard to roof support, but these relatively stiff roof members (siltstones and sandstones isolated at various points along the gate road and longwall face) also tend to concentrate bump-initiating stresses. This was certainly the case at Sunnyside and has been the case at many operations where channel features are common.

The primary roof strata encountered in bump-prone operations include massive mudstones, siltstones, fine-grained sandstones, and massive weak sandstones (figure 8). While the mudstones are generally of moderate strength, the lack of bedding structures or slickenside features may provide for good confinement along seam contacts. The strongest units commonly encountered in bump-prone operations are unquestionably dense siltstones and fine-grained sandstones. Whereas the unconfined compressive strength of mudstone may range from 41.4 to 69.0 Mpa (6,000 to 10,000 psi), recent tests on siltstone and fine-grained sandstone from the Sunnyside operation showed strengths ranging from 151.7 to 220.7 MPa (22,000 to 32,000 psi). Such numbers are often found in the mines throughout the region and are considered high even for strong roof conditions.

Barron (1994) describes the geology at four Wasatch-Book Cliffs mining operations that have experienced bumping to different degrees at one time or another. Bumps at two of the operations, the Sunnyside No. 1 Mine and the Castle Gate No. 3 Mine, resulted from the effects of highly variable, yet strong, roof strata. The other two operations, the Wilberg Mine and the Starpoint No. 2 Mine,[3] both experienced bumping related not to average mine roof conditions, but rather to the presence of sandstone channels in the immediate mine roof.

[3]Private communication from J. M. Mercier, supervisory geologist, Cyprus Plateau Mining Corp., Starpoint No. 2 Mine, Price, UT.

Figure 7
Roof Logs From Sunnyside No. 1 Mine.



Logs illustrate widely varying nature of roof lithologies encountered in many Wasatch Plateau-Book Cliffs Coalfield mines.

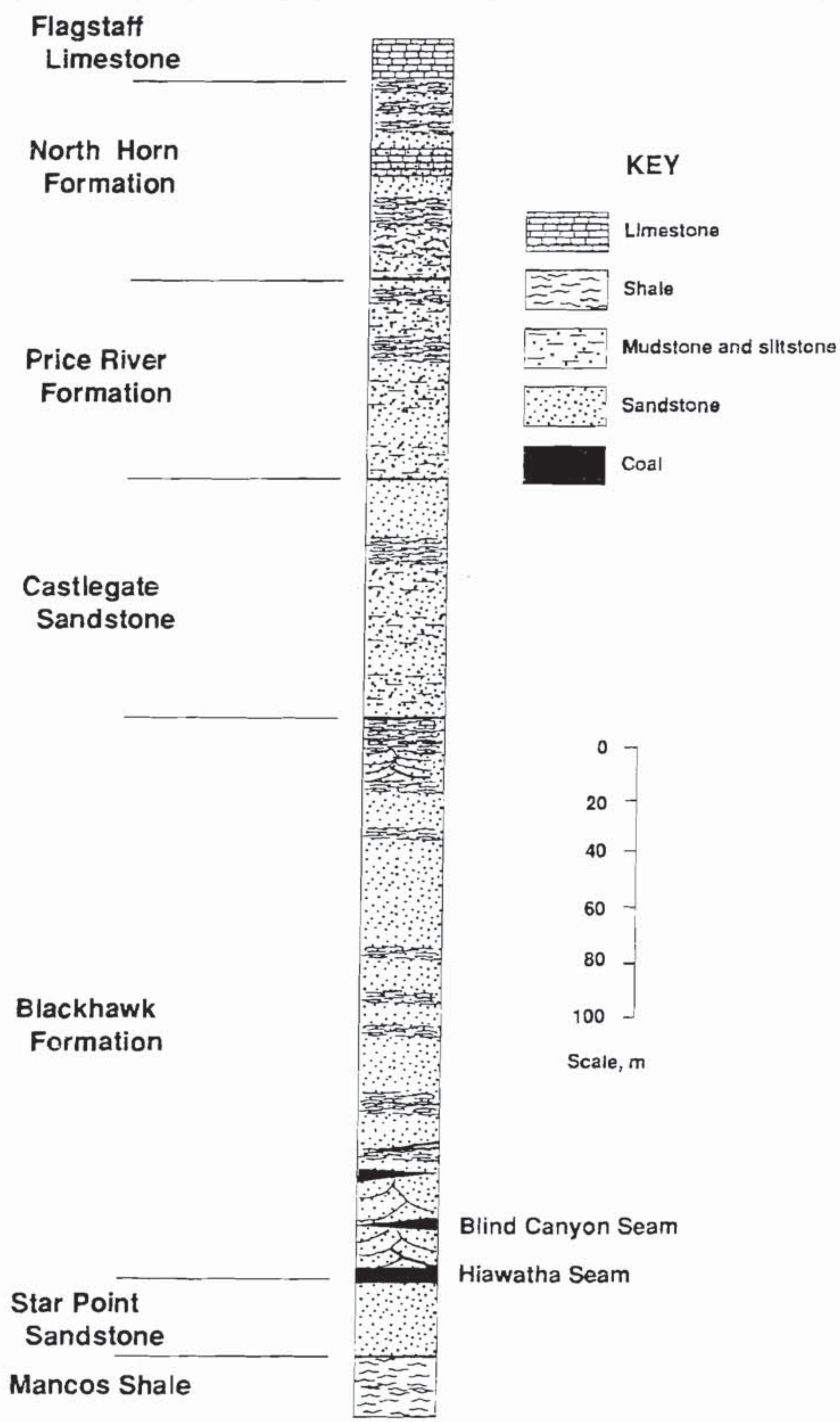
SANDSTONE CHANNELS IN IMMEDIATE ROOF

Considering the combination of massive, weak roof members and extremely strong units distributed in a discontinuous manner along the length of the gate entries (figure 7), it becomes clear why it is difficult to pinpoint likely areas of bumping in most of the region's operations.

An exception to this problem involves the occurrence of sandstone channels in the immediate roof. Sandstone channels are stress-concentrating structures that are directly related to bumping along longwall panels nationwide. These features are common to the region's mines (Barron, 1994) and are seen both as deep channel cuts of limited lateral extent (less than a hundred meters across) that may or may not scour the seam and broad washes that may extend for several hundred meters laterally along the entry system within the bolted horizon of the roof. The unconfined compressive strengths of these units can vary considerably, but they are generally lower than the unconfined compressive strengths of the siltstone and fine-grained sandstone units described above. The massive nature of many of these units (or lack of bedding and joint structures) appears to be the major factor affecting bump initiation immediate to these features. That is to say, the *rock mass* strength of the entire channel deposit is of more concern than the absolute intact unit rock strength of the sandstone comprising the channel. Many of these units do possess considerable structure in the form of distinct bedding and/or regular jointing (Maleki, 1988), but it is not uncommon to find the channels as large, relatively solid structural units.

Both channel types have contributed to coal bumps in U.S. mines. Narrower channels tend to concentrate loads along the tailgate, which creates the potential for isolated bumping problems within tailgate pillars and along the tailgate portion of the panel face (DeMarco, 1988). Unless these features are clearly identified during gate development, either by direct observation or by logs of roof conditions obtained during bolting, bumps related to these channel features will occur without apparent reason. To forestall such problems in mines where numerous, narrow channel deposits are present, it is a requirement that channel locations and distributions be mapped accurately. Only in this way can changes in gate support design and/or destressing be effectively employed.

Figure 8
Typical Stratigraphic Section for Hiawatha/Blind Canyon Seams.



Broad channel features are common in Wasatch Plateau operations and, because they are easier to identify underground, afford a certain degree of predictability where bump-prone conditions are concerned. As with the less-easily located and identified narrow channel deposits, the primary concern appears to be excessive loading along the tailgate. Stresses about gate peripheries are generally better distributed by broad deposits, yet the magnitudes of stress along tailgate panel abutments are higher than those recorded under normal mining conditions. These higher loads can be dealt with most effectively through proper gate design, employing either full-yielding pillar or abutment-yield pillar entry systems. Gate designs that inadequately minimize stress concentrations along the tailgate entry and face areas will require extensive panel destressing in the tailgate immediate to overlying channel sandstones (DeMarco, 1994).

STRONG COAL SEAMS

While it has been shown that most U.S. coals can be made to bump under the right combination of confinement and loading conditions (Babcock, 1984), it is worthwhile to discuss seam characteristics in some Western operations that appear to influence bumps. The two most prominent contributors are (1) impersistent cleating and (2) the presence of strong rock splits in the mid-to-upper portion of the seam. While it is not necessary for these conditions to be present for bumps to occur, they have been linked to some of the worst bump conditions documented in Western mining.

During a USBM study at the Castle Gate No. 3 Mine (Barron, 1994), numerous bumps occurred on the longwall face and within the tailgate pillars that eventually led to the closure of this operation. In addition to very strong roof and floor conditions, strong seam conditions were observed. Cleating in the coal was difficult to discern and did not appear to contribute significantly to rib-side yielding along the gate entries during panel mining (figure 9). A hard siltstone parting at approximately midseam height was also present throughout the mine. The confinement effects of the stiffer roof and floor strata, coupled with the seam-strengthening effects of the parting, assisted in generating extremely high loads immediate to pillar and panel riblines. This was seen very clearly in pressure cell load data. Forward abutment loads peaked within 0.3 m (1 ft) of the faceline, and pillar yield zones were limited in depth, often within 1 to 1.5 m (3 to 5 ft) of the rib. As a result, the coal was incapable of supporting these high loads and severe bumping occurred, particularly along the tailgate (figure 10).

Similar conditions have been experienced at the Sunnyside mining complex over the past 30 years of longwalling (Koehler, 1994). A recent USBM study on gate road pillar sizes at this mine showed that large abutment pillars exhibited high loads close to the ribline during mining of the first panel and just prior to bumping. While the Lower Sunnyside Seam does yield fairly readily, a strong parting in the upper portion of the seam appears to strengthen the composite coal-parting material. Stress-detection drilling indicated that high loads in these pillars were concentrated between 1 to 3 m (3 to 9 ft) from the ribline, although experience suggests a much deeper yield zone should exist at the nearly 900 m (3,000 ft) of cover to which these pillars were subjected. As a consequence of the high loads, many of the oversized yield pillars (critical pillars) bumped violently with passage of the first face.

Again, it must be noted that numerous cases of bumping have occurred in the Wasatch-Book Cliffs coal regions where these seam conditions did not exist. However, it appears that enough bumps have taken place in strong, structureless coal seams and rock splits to warrant their being considered where bump potential is a concern.

FAULTS AND SHEAR ZONE STRUCTURES

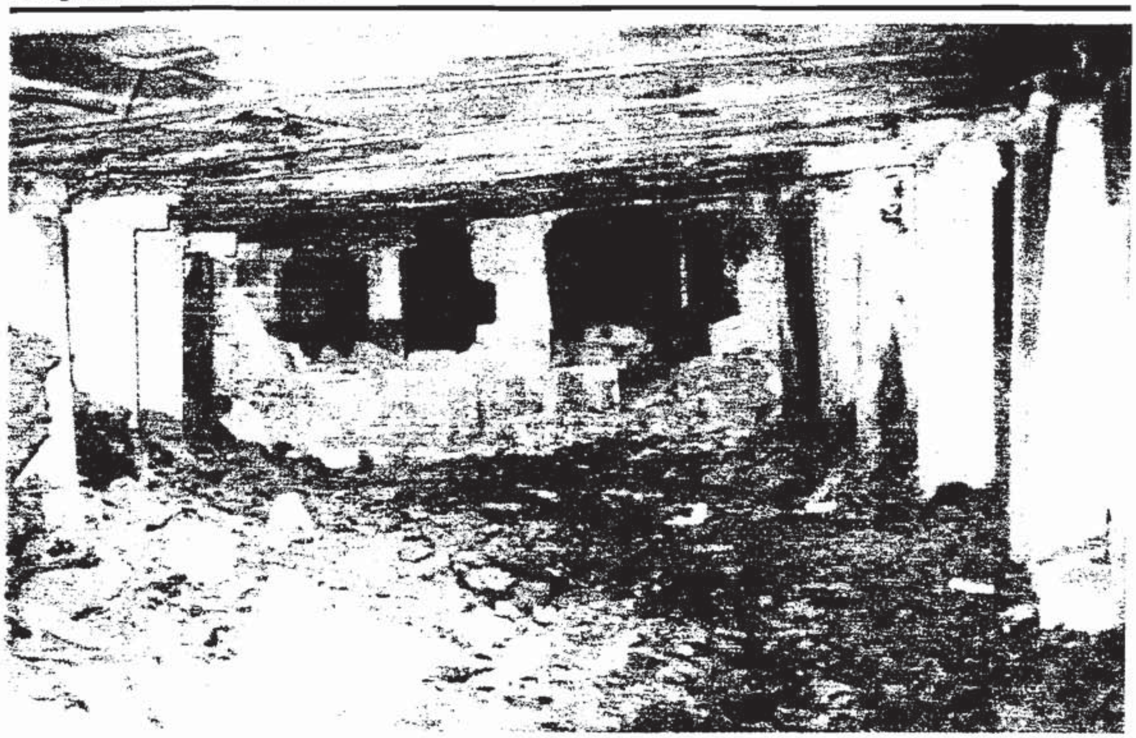
Investigations of fault and shear zone structures in the central Utah coalfields point to two basic concerns: (1) the effect of significant changes in the stress field in the vicinity of these discontinuities and (2) the loading potential of isolated blocks of strata above the seam. Whether stick-slip movement along fault structures is responsible for dynamic load changes has yet to be more thoroughly determined (Boler, 1994), but changes in loading conditions have been noted as major contributors to bumping when mining approaches a discontinuity (Iannacchione and DeMarco, 1992; Peparakis, 1958). Maleki (1981) has also documented large increases in vertical loading dependent upon fault orientation to retreat mining layouts, furthering this assertion.

A bump resulting from an isolated block of roof strata coming to bear on a section of the gate road pillars was recently seen at an operation along the Wasatch escarpment. This operation utilizes a two-entry yield-pillar system at cover depths averaging around 450 m (1,500 ft). Once pillar yielding began following development, it became apparent that a four-pillar-long section of the gate road was not being subjected to appreciable loading, because the yield pillars showed no sign of rib failure. In fact, long after the other gate pillars had shown considerable rib yielding, this section continued to look as though it had only recently been developed. It was soon discovered that the section was bounded by diverging, high-angle shear zones running through the roof, seam, and floor, with observed offsets of 0.3 to 0.75 m (1 to 2.5 ft). During mining of the first panel, the panel abutment was mined out from under the overlying isolated wedge of roof rock between the shear zones, and the subsequent immediate weighting of the pillars resulted in severe bumping adjacent to the face stage loader and belt structure. This block of rock effectively bridged the gate entry until first panel mining allowed the full weight of the block to bear upon the unyielded gate pillars.

Figure 9
Intake Entry of 9th East Gate Road, Sub-3 Seam, Castle Gate No. 3 Mine.

Note typical lack of rib failure. Cover depth is 600 m (2,000 ft). This entry stood open for several years prior to longwalling.

Figure 10
Tailgate Pillar Bump in 8th East Gate Road, Castle Gate No. 3 Mine.



MINING PRACTICES THAT AGGRAVATE DIFFICULT GROUND CONDITIONS

To mitigate the frequency of gate road pillar bumps, over the years mine operators in the Wasatch-Book Cliffs Coalfields have implemented the use of two-entry, yielding-pillar gate road configurations. This approach attempts to soften the ground around the gate system, thereby diverting bump-inducing stresses to deep within the confines of the adjacent panel abutment. In general, the approach has been very successful when employed correctly. Problems arise, however, where pillar sizes are such that inadequate yielding occurs. These improperly sized pillars are termed "critical pillars," and their use can result in the most extreme bump hazard possible.

This section describes the critical-pillar concept and discusses the historical misapplication of these structures in Western mining operations. Also discussed are applications of abutment-yield pillar gate configurations and some considerations for using two rather than three entries.

CRITICAL-PILLAR GATE ROAD SYSTEMS

Where the use of pillars with width-to-height ratios greater than 4 to 5 is concerned, the concept of the *critical pillar* has often governed the performance experienced in *deep* Western coal mines (DeMarco, 1994). A critical pillar can most simply be defined as one that is too large to yield either nonviolently or before the roof and floor sustain permanent damage, and yet is too small to support full longwall abutment loads. The relationship between critical-pillar designs and yield and abutment pillar designs is presented in figure 11. The horizontal axis represents the minimum performance standard separating stable from unstable gate road configurations. A pillar design whose performance falls above the horizontal axis is considered successful (stable), whereas a design whose performance falls below the horizontal axis is considered unsuccessful (unstable).

An important aspect of this concept is the rate at which a successful gate road design can become unsuccessful. Ground conditions deteriorate more gradually in abutment pillar systems as pillar size decreases. Changes in performance are observed as the onset of minor amounts of floor heave, increases in audible coal popping and minor bumping, and increases in the frequency of roof-related problems (DeMarco, 1994). In comparison, the performance of yield-pillar-based gate roads may rapidly decline with only a few meters of increase in pillar size; the transition between a fully successful yielding gate road and the worst of possible conditions for a critical pillar is often abrupt.

It cannot be overemphasized that increasing pillar width toward the critical-pillar range only invites the full weight of the overburden to be transmitted to a gate system that cannot possibly support it. As a result, critical pillars are to be considered *extremely* bump prone, even at shallow depths, when strong mine roof and floor conditions exist. Unlike the abutment-to-critical-pillar transition, where coal bumps are generally first witnessed in the tailgate, the yield-to-critical-pillar transition allows severe bumping in the headgate entries immediate to the face. An all-too-graphic example of this problem recently occurred at a Western operation where unyielded pillars adjacent to the face in the headgate bumped violently as the first panel abutment was mined. Although it was fortunate that no one was injured, considerable damage was sustained by the stage loader and face-end belt structure. In settings not readily conducive to pillar bumping, prolonged loading of the gate pillars will certainly result in severe roof, floor, and/or rib instabilities, requiring at least extensive supplemental support along the entire tailgate entry, assuming that gate closure can be avoided.

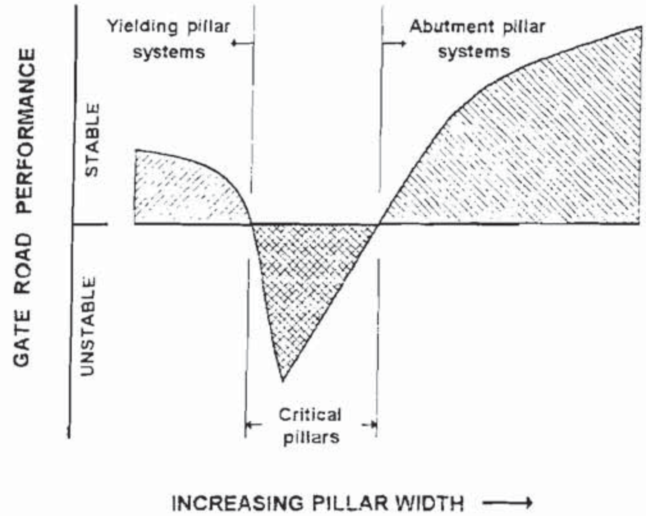
Figure 11 is a useful graphic representation of the critical-pillar concept; however, it should not be used to suggest that pillar width (or size) alone determines whether a pillar design falls in the critical range. Other mining parameters, such as seam height, depth of cover, and the physical properties of the roof and floor strata, can have a profound effect on the final disposition of a specific pillar geometry. For example, a pillar configuration that readily and gently yields under moderate roof conditions may bump violently under strong roof members. In this comparison, the pillar configuration that is considered a successful yield pillar application in one setting becomes an unsuccessful critical pillar in another. Similar changes in pillar behavior have been noted by mine operators when significant increases in mining depth appear to have hindered pillar yielding, possibly because of added roof and floor confining stresses, thereby requiring *smaller* pillar dimensions to avoid bump-prone, critical-pillar designs.[5] DeMarco (1994), in a qualitative analysis of case histories of Western mines, noted that, in general, yield pillars should be sized with width-to-height ratios less than 5 to ensure proper yielding and that a Coal Mine Roof Rating (CMRR) (Molinda and Mark, 1993) of greater than 50 should exist to ensure roof stability in a high-deformation environment. Maleki (1988) has also suggested additional criteria based on pillar postfailure behavior for yield pillar design.

Because the range of pillar widths that make up the critical-pillar zone is unquestionably different for each

[4]Private communication from J. M. Mercier, supervisory geologist, Cyprus Plateau Mining Corp., Starpoint No. 2 Mine, Price, UT.

[5]Private communication from M. Moon, chief engineer, Energy West Mining Co., Huntingdon, UT.

Figure 11
Conceptualization of Critical-Pillar Concept.



This figure shows transition from successful yield pillar systems through unsuccessful critical designs to successful abutment pillar systems for cases with competent roof rock.

mine setting, so is the failure mode (as described by the influence of pillar failure on the surrounding ground conditions). Critical pillars have been shown to fail in one of three ways, depending on the pillar size employed and the geologic conditions present: coal bumps, roof falls, and floor heave (DeMarco, 1994).

The primary mode of failure of the critical pillars-gate-entry system studied during the recent Sunnyside Mines investigation was coal bumping. In contrast, a field study of a three-entry, critical-pillar configuration at another deep Western U.S. coal mine by DeMarco and others (1988) revealed the primary entry-pillar failure mode to be roof falls. Although one of these three types of ground instabilities is usually the predominant or primary mode of failure, it is also possible that a combination of primary and secondary modes of failure can be experienced along the length of a gate road because of variations in geology. For example, whereas coal bumps proved to be the primary mode of failure of the critically sized pillars at the Sunnyside test site, localized floor heave and roof falls were also observed during adjacent panel mining.

In the section on "Recent Examples of Critical Pillars and Gate Road Bumps" in this paper, the importance of the critical-pillar concept will be emphasized with a recent case study at the Sunnyside operation, where a variety of pillar sizes were employed under various conditions. It cannot be overstated that perhaps the single, most-frequent contributor to gate road bumps is the use of designs that result in critical-pillar behavior.

ABUTMENT-YIELD PILLAR GATE ROAD SYSTEMS

Full yielding-pillar gate road systems are largely unique to mining in the West and are most generally preferred to cope with the deep, multiseam, bump-prone conditions common to most of the region's operations. However, the use of the three-entry, abutment-yield pillar configuration should not be discounted as it has some advantages in bump-prone ground when subseam mining is not an issue. The application of this design stems from two considerations: (1) a transition at a given property from traditional full-abutment systems (common among Eastern mine operations) toward yield-pillar-based designs and (2) the need to cope with thin seams or extremely strong roof and floor conditions that preclude the successful deployment of yield pillars; that is, pillar sizes that initiate effective yielding are too small to satisfy operational needs and/or requirements mandated by law. While the first consideration may be largely based on the marginal-to-significant economic advantages gained in switching from costly full-abutment systems, the second consideration is firmly rooted in the need to maintain a safe, travelable tailgate escapeway *in a bump-prone environment*.

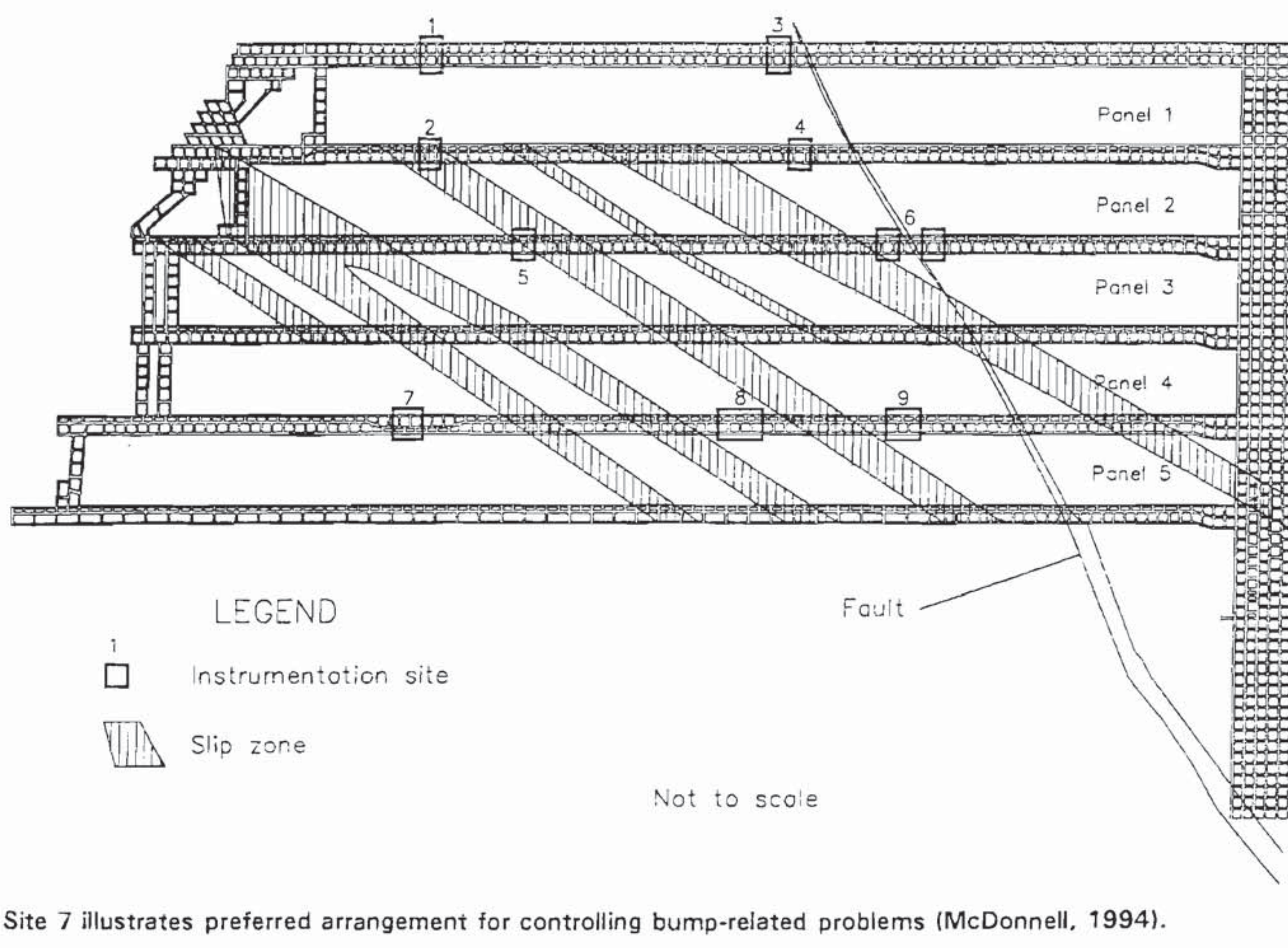
When deploying an abutment-yield pillar gate system design, *where the primary purpose of the design is to mitigate coal bumps*, it is often a prudent practice to place the larger abutment pillar against the first panel gob and the smaller yield pillar adjacent to the tailgate entry (although there are some variations; for example, in nonbump-prone conditions, operational advantages may be realized by reversing this configuration). Appropriately sizing the abutment pillar ensures that excessive loads from the first panel side abutment are shielded from the future tailgate. The end result is an effective barrier (abutment pillar) established between the first panel abutment loads and the new tailgate, and a softened tailgate entry system (yield pillar) that is incapable of bumping with the advance of the second panel.

This arrangement should be considered very practical under strong roof and floor conditions where the presence of the larger abutment pillar allows the width of the yield pillar to be minimized beyond the limits mandated for full-yielding gate system designs. For instance, whereas a full-yielding design may limit minimum pillar widths to no less than 9 m (30 ft) for operational reasons, the abutment-yield design may employ yield pillars much smaller without the need to consider these same concerns. An added advantage is that in the event the abutment pillar bumps because of insufficient design (the critical-pillar case described previously), the yield pillar will act as an effective "bump curtain" protecting the tailgate entry from ejected coal (Zelanko and Heasley, 1995). This entire system approach may not be conducive to adequate caving, however, and may be less desirable than a full-yielding pillar gate design, particularly when multiseam mining is a concern.

The potential for bumps to occur may actually increase when the configuration is reversed; that is, when the yield pillar is placed against the first panel gob. As the pillar yields, the overlying roof cantilevers onto the adjacent large pillar abutment. Not only are side abutment loads transferred, but so are the additional loads from above the yield pillar and the entry span between the yield and abutment pillars. For the case of a 9-m (30-ft) wide yield pillar, the additional span cantilevering onto the abutment pillar is nearly 15 m (50 ft), plus whatever overhang has developed on the gob side of the yield pillar. Although the yield pillar will support a portion of this additional span, the combined effect of these cantilevered sections is to concentrate higher loads onto the abutment pillar. If the abutment pillar is marginally designed to handle side abutment loads, considerable pillar yielding may occur along the gob side of the pillar. The end result is effectively to concentrate the highest of the side abutment loads immediate to the tailgate escapeway.

In the presence of strong ground conditions (the sandstones and siltstones described previously), this pillar configuration may create an environment with severe bump potential, as described in the previous section on "Critical-Pillar Gate Road Systems." In weaker ground conditions, failures often appear as severe floor heave and roof falls. In either case, the stress concentrations within the vicinity of the tailgate entry are often excessive compared to the preferred configuration, as was recently illustrated at a Colorado operation where the "typical" configuration placed the yield pillar against the first panel gob. A USBM comparative study of abutment-yield and yield-abutment designs (figure 12) gave the following results, as reported by McDonnell (1995):

Figure 12
Plan View of Study Site Locations.



Site 7 illustrates preferred arrangement for controlling bump-related problems (McDonnell, 1994).

USBM and mine personnel conducted on-site observations of tailgate conditions throughout longwall mining at the study mine. At each gate road instrumentation site with the typical pillar layout [yield pillar against the first gob] during second panel mining, significant cutter-type roof problems were observed within 23 m (75 ft) outby the face at the panel-roof line. Cutter-type roof problems and floor heave in the zone immediately outby the tailgate end of the longwall panel face were observed at numerous locations during longwall panel mining at the study mine. While panels 2, 3, and 4 had experienced cutter-type roof failures and dynamic floor heave events at the panel-tailgate edge outby the face, the roof and entry conditions outby the panel 5 face through the site 7 gate road area were generally good [section where abutment pillar was against the first gob].

High pressures, as measured by borehole pressure cell (BPC) instrumentation, surrounded the tailgate entry during second panel mining through all the gate road test areas with the typical pillar arrangement (sites 2, 4, 6, 8, and 9). Conversely, the measured pressure in the mine structure around the tailgate entry at site 7 during panel 5 mine-through was considerably less. The abutment loads from longwall mining at site 7 were shifted away from the tailgate entry and the panel edge and were being carried by the big pillar core and the panel, away from the tailgate entry.

Had mining conditions been more conducive to bumps [the mine has a moderate roof and floor and operates under 330 m (1,100 ft) of cover], severe conditions would likely have prevailed long before the study determined that the preferred configuration may actually be an improvement for this operation. Figure 13 demonstrates the pillar loading sequences along the tailgate that make this configuration especially viable for deployment in more bump-prone conditions. It should not, however, be concluded from this study that the "typical" configuration was unacceptable for this particular operation. Decisions regarding the appropriate configuration must take into account both ground control and operational considerations.

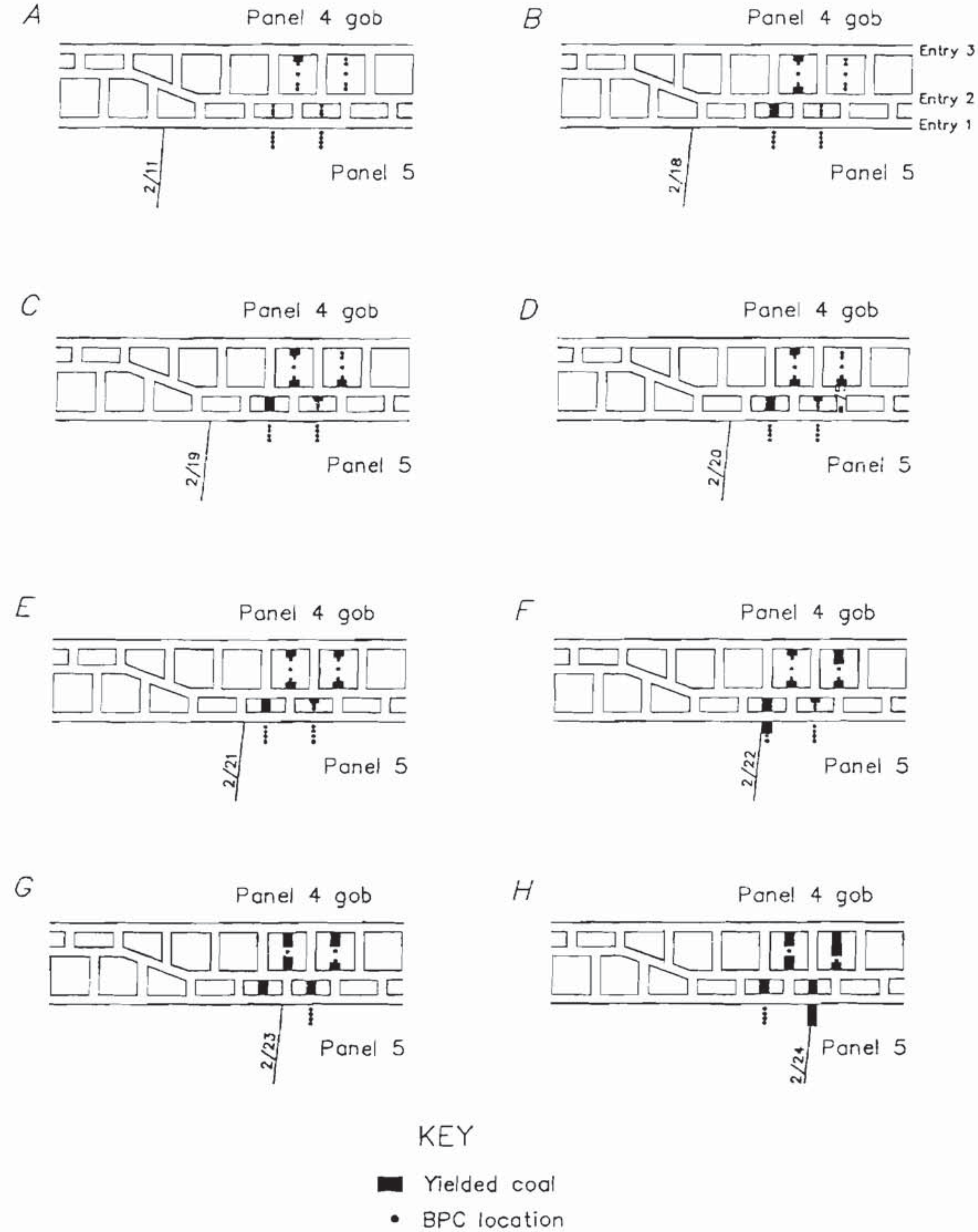
It should also be noted that although strong roof and floor conditions have been encountered by most operations in the Wasatch Plateau and Book Cliffs Coalfields, and have been dealt with most effectively with full-yielding-pillar gate road systems, conditions do exist that may preclude the sole use of yield pillars. As previously mentioned in the discussion on critical pillars, failure to achieve a successful yield pillar at a property can be catastrophic in terms of creating severe bump conditions. This situation can arise in exceptionally strong ground, as was the case at the Castle Gate No. 3 operation near Helper, UT (Barron, 1994). Over the course of mining several panels at this mine, a successful yield pillar was never achieved, and the mine opted to use larger abutment pillars instead. Evidence suggests that the maximum width for a successful yield pillar design at this property falls within the range of 4.6 to 6.1 m (15 to 20 ft), which is below the minimum allowed by law in a two-entry configuration. In this particular case, the use of the abutment-yield pillar configuration may have offered relief to the persistent tailgate bumping problem that plagued the operation.

MULTIPLE-ENTRY VERSUS TWO-ENTRY GATE ROAD SYSTEMS

Two-entry systems have evolved over the years in Western mines as the preferred design when employing full-yielding-pillar gate configurations. The basis for this preference is largely rooted in historical practice rather than in the economics of developing additional entries. It was determined many years ago, shortly after longwalling was introduced to Western U.S. coalfields, that in bump-prone conditions, the less ground opened up, the better (Koehler, 1994a, 1994b). Past studies have shown that multientry gates may incur higher loads than two-entry systems, but room does exist to consider the use of multientry systems when the quality of the roof warrants allowing wider gate spans (DeMarco, 1988; Koehler, 1994a).

One situation that calls for minimizing the number of entries involves the presence of sand channels in overlying roof strata. As previously mentioned, these structural features are common to many Western mines and are notorious for creating poor roof conditions along the margins. Minimizing entry development reduces the overall areal exposure of this potential roof-fall hazard (Maleki, 1988). This hazard is exacerbated by the large amount of deformation imparted to the immediate roof in the yielding gate system. Also, a potential problem is created by the additional length of cantilever arm possible when channels span a multientry system. The result may be to increase loading on the tailgate region of the face and possibly the initiation of more frequent bump events. This was suspected to be the case for at least one Western operation in recent years where the use of a three-entry yielding system was replaced with a two-entry system to minimize tailgate face-end loading resulting from the possible cantilevering of stiff channel sandstones. Escapeway conditions improved greatly in the forward abutment zone [45 to 75 m (150 to 300 ft) outby the tailgate face corner] when the entry system was switched to the two-entry design (though it should be noted that no quantitative data exist to prove the contribution of the channel cantilever to the face-end bumps experienced).

Figure 13
Overall Yield Sequence of Site 7 During Panel 5 Mining.



Face positions are given at end of day shift from 2/11/93 to 2/24/93 (McDonnell, 1994).

RECENT EXAMPLE OF CRITICAL PILLARS AND GATE ROAD BUMPS

To develop a clearer understanding of critical-pillar behavior, a field investigation was recently completed at the Sunnyside No. 1 Mine in a two-entry gate road where pillars were uniformly decreased in width from 17 to 10 m (56 to 32 ft) along the length of the entry system from the startup room outby. Ground pressure and probehole drilling measurements collected during the study provided a physical explanation for the ground conditions observed at several sites during adjacent panel mining. The following sections present an overview of the mine setting, as well as study results, from the perspective of graphically demonstrating the critical-pillar concept.

STUDY SITE HISTORY

The Sunnyside Nos. 1, 2, and 3 Mines are located in eastern Carbon County, UT, approximately 44 km (26 mi) east of the town of Price. Under varied ownership, underground coal mining has been conducted on the Sunnyside property since at least 1896. In March 1989, the Sunnyside Coal Co. reopened the mines after they had been idle for approximately 2 years; unfortunately, the mines were once again idled for business reasons in March 1994.

The longwall mining system was first introduced at Sunnyside in 1961 to improve worker safety in the difficult, bump-prone conditions found on the property. Natural factors conducive to coal bumps at the mines include great depth [as much as 900 m (3,000 ft)], rapid variations in relief, tectonic movement associated with faulting, and massive sandstone strata above and below the coalbeds (Jackson, 1971; Wong, 1985). Through a lengthy trial-and-error process during which many different gate road configurations were tried, Sunnyside engineers developed a two-entry, yield-pillar-based entry system that provided excellent ground control in the face of these difficult conditions. This system, which employs nominal 10-m (32-ft) wide chain pillars, virtually eliminated pillar bumps, greatly reduced face bumps, and substantially mitigated floor heave (Koehler, 1994a).

During the evolution of this system, several panel entry configurations were tried that employed critical-pillar designs. These designs were quickly abandoned because of severe coal bumps, bump-related roof falls, and floor heaving associated with their use. In fact, critical-pillar designs would likely have never been used at Sunnyside again if not for an accidental surveying error that resulted in the development of a tapered two-entry gate road.

STUDY SITE GEOLOGY

The mine portals are located near the base of the steep western Book Cliffs. The cliffs rise sharply approximately 1,000 m (3,330 ft) above the valley floor, resulting in abrupt changes in mining cover depth over very short horizontal distances. Cover depth ranges from 100 m (330 ft) at the outcrop to nearly 900 m (3,000 ft) within the current mining area. The strata comprising the Book Cliffs dip 3° to 12° to the north-northeast. The coalbeds of economic significance in the Book Cliffs Coalfield are confined to the Blackhawk Formation of the Mesaverde Group (figure 14). The coal-bearing portion of the Blackhawk Formation lies above the Kenilworth Sandstone and includes the Sunnyside member. The Sunnyside member is dominated by massive cliff-forming sandstone, but near the top there are lagoonal deposits that include the Upper and Lower Sunnyside Coalbeds.

The cliff-forming Castle Gate Sandstone overlies the Blackhawk Formation. It is approximately 55 m (180 ft) thick in the mine area and is composed mainly of fine- to medium-grained sandstone. The 150-m (490-ft) thick Price River Formation overlies the Castle Gate Sandstone and is composed of interbedded sandstones and shales, the sandstone grading from thin-bedded to massive ascending through the sequence.[6] The remaining overburden at the mine site is composed of the geologic units of the North Horn, Colton, Wasatch, and Green River Formations.

The Sunnyside Seam varies in thickness from 10 cm (4 in) in the west near Kenilworth, UT, to as much as 7.3 m (24 ft) in a single bed in parts of the Sunnyside district. At the mine site, the coal seam often separates into two distinct beds with as much as 23 m (75 ft) of siltstone intervening; however, in general, the upper and lower beds are considered localized splits of the same formation (Osterwald and others, 1981). The gate road in which this study was conducted was located in the Lower Sunnyside Seam. Typically, the Lower Sunnyside Seam is 1 to 2 m (3 to 7 ft) thick and is characteristically very hard and relatively unfractured, and forms a competent rib.[7]

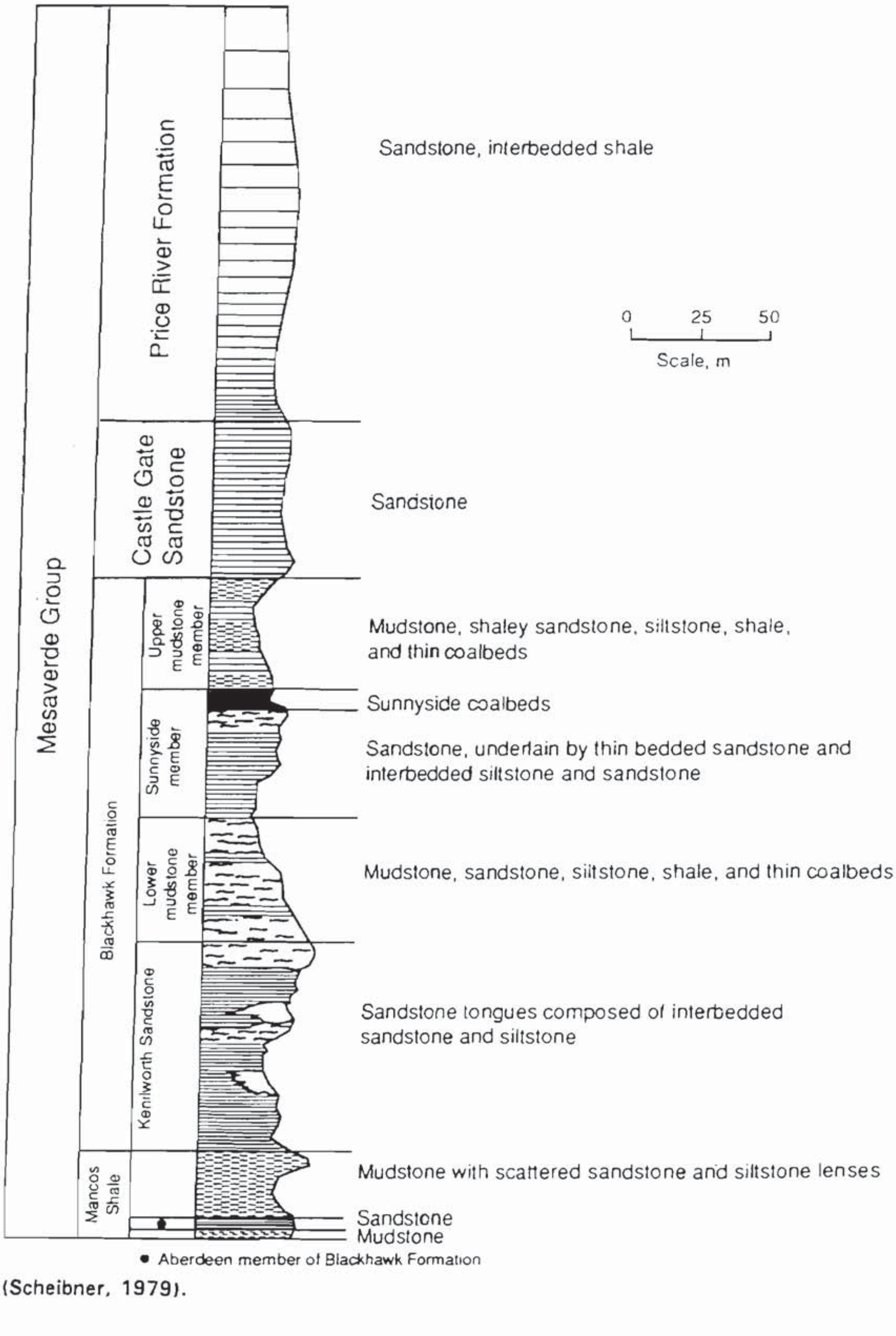
The composition of the roof and floor of the Lower Sunnyside Seam can vary substantially over distances as little as 100 m (330 ft). Five basic rock types are found in the immediate roof, floor, and interburden surrounding the Lower (and Upper) split. They are (1) dark brown mudstone, (2) gray-brown silty sandstone, (3) interbedded siltstone and sandstone, (4) fine-grained quartzose sandstone, and (5) fine-grained calcareous sandstone. In general, the dark brown mudstone occurs immediately above and below

[6]Dames and Moore. Report to Kaiser Steel Company for coal slurry pond permit application, 1973, 9 pp., available upon request from J. R. Koehler, Denver Research Center, USBM, Denver, CO.

[7]Diamond, W. P. (Pittsburgh Research Center, USBM, Pittsburgh, PA). Private communications, 1977; available upon request from B. J. Scheibner, Spokane Research Center, USBM, Spokane, WA.

Figure 14

Generalized Stratigraphic Section of Mesaverde Group for Sunnyside Mining District.



(Scheibner, 1979).

the Lower Sunnyside Seam and varies in thickness from 10 cm (4 in) to 8 m (26 ft). The gray-brown sandy siltstone is generally found in the rock parting between the splits and varies in thickness from 0.3 to 2.4 m (1 to 8 ft). The interbedded siltstone and sandstone usually occurs as "sandbar-type" features in the parting between the seams and can be as much as 8 m (26 ft) thick. Lastly, the fine-grained quartzose and calcareous sandstones occur irregularly as lenses or channel-fill deposits above, below, or between the coal splits (Koehler, 1994a; Scheibner, 1979).

STUDY SITE INSTRUMENTATION AND MEASUREMENTS

The location for the field study was the two-entry 23rd Left gate road in the Sunnyside No. 1 Mine (figure 15). As previously reported, an accidental surveying error resulted in the development of diverging entries and chain pillars that uniformly decreased in width from 17 m to 10 m (56 ft to 32 ft) with further outby positions. Two permanent instrumentation sites were established along the gate in pillars 17 and 12 m (55 and 40 ft) wide (figures 16 and 17). A planned third set of instruments in pillars 10.6 m (35 ft) wide was not installed because mining operations were prematurely halted; however, probehole drilling in two chain pillars and at two locations within the adjacent panel (figure 18) at the planned site 3 was completed before the No. 1 Mine was closed.

Permanent instruments at sites 1 and 2 consisted of USBM hydraulic borehole pressure cells (BPC's) installed in the pillars and adjacent 24th Left panel and oriented to measure changes in vertical ground pressures. Circular chart-type hydraulic pressure recorders attached to the BPC's with steel tubing ensured nearly continuous collection of ground-pressure data during adjacent panel mining. As at site 3, probehole drilling was conducted at sites 1 and 2 to delineate high-stress zones and determine the degree of pillar and panel yielding.

All probehole drilling was accomplished using a hand-held pneumatic auger-type drill. Boreholes 5 cm (2 in) in diameter and up to 9 m (30 ft) in length were drilled approximately midseam at all three sites. Data collected during the probehole drilling program included estimates of the depth of yielded or high-stress zones based upon the difficulty of drilling experienced by the operator. Also, a qualitative evaluation of the relative rock noise emitted during the drilling process was utilized to further indicate the presence of high stress levels.

ANALYSIS OF FIELD DATA

The locations of the three instrument-drill sites in the 23rd Left gate road are shown in figure 15. The 23rd Left panel was mined first but was not completed because of mine closure; the 24th Left panel was not mined. The "actual face stopline" marker found on figure 15 indicates the extent of 23rd Left panel extraction.

Site 1

Site 1 was established in the chain pillars and a section of the adjacent 24th Left panel between crosscuts 46 and 48 (figure 16). The pillars at site 1 were 17 m (55 ft) wide by 32 m (105 ft) long, and the cover depth was approximately 800 m (2,600 ft). Installed BPC's included four cells placed at regular intervals across the width of one chain pillar and five cells placed up to 16 m (52 ft) deep in the 24th Left panel. Twelve stress-detection probeholes were drilled in two pillars and at two locations in the 24th Left panel during instrument installation.

The probehole drilling data, collected when the face was approximately 185 m (607 ft) inby site 1, indicated pillar and panel rib yield zones were only about 1 m (3 ft) deep. Zones of competent coal under moderate stress began approximately 1.5 m (5 ft) into the ribs and extended as much as 3 m (10 ft) deep into both the chain pillars and the 24th Left panel. These data suggest that little yielding of either the pillar or panel ribs at site 1 occurred during the 6 months between development of the area and initiation of panel retreat operations.

Ground pressure profiles across the instrumented pillar and panel for three longwall face positions (FP) relative to the line of BPC's are presented in figure 19. The 78-m (256-ft) inby FP profile shows pillar and panel pressures as the forward stress abutment began to affect the site noticeably. Both pillar and panel stresses remained relatively low at this point in the mining cycle; however, observations taken in the gate road at this time noted an increase in the frequency and magnitude of rock noise emanating from the coal and surrounding strata. No significant bump events had been reported as yet.

As mining progressed to the 8-m (26-ft) inby FP, pillar pressures increased dramatically as a result of the onset of the full forward abutment. Examination of the 8-m (26-ft) inby pressure profile shows that peak BPC pressure was nearly 65 MPa (9,425 psi); the remaining functional BPC's were reporting pressures between two and three times those recorded at the 78-m (256-ft) inby FP. BPC data suggest that the 23rd Left panel side of the chain pillar had yielded to a depth of 3 to 4 m (10 to 13 ft); however, most of the pillar was still intact as evidenced by the very high loads on the remaining cross section.

At the 8-m (26-ft) inby FP, ground stresses in the 24th Left panel also increased substantially. BPC data suggest that the first 3 to 5 m (10 to 16 ft) of the panel rib had yielded, and the stress abutment had moved deeper into the 24th Left panel. In-mine observations made at this time noted excessive, often severe, rock failure noise at the

Figure 15
Study Site locations in 23rd Left Gate Roads, Sunnyside No. 1 Mine.

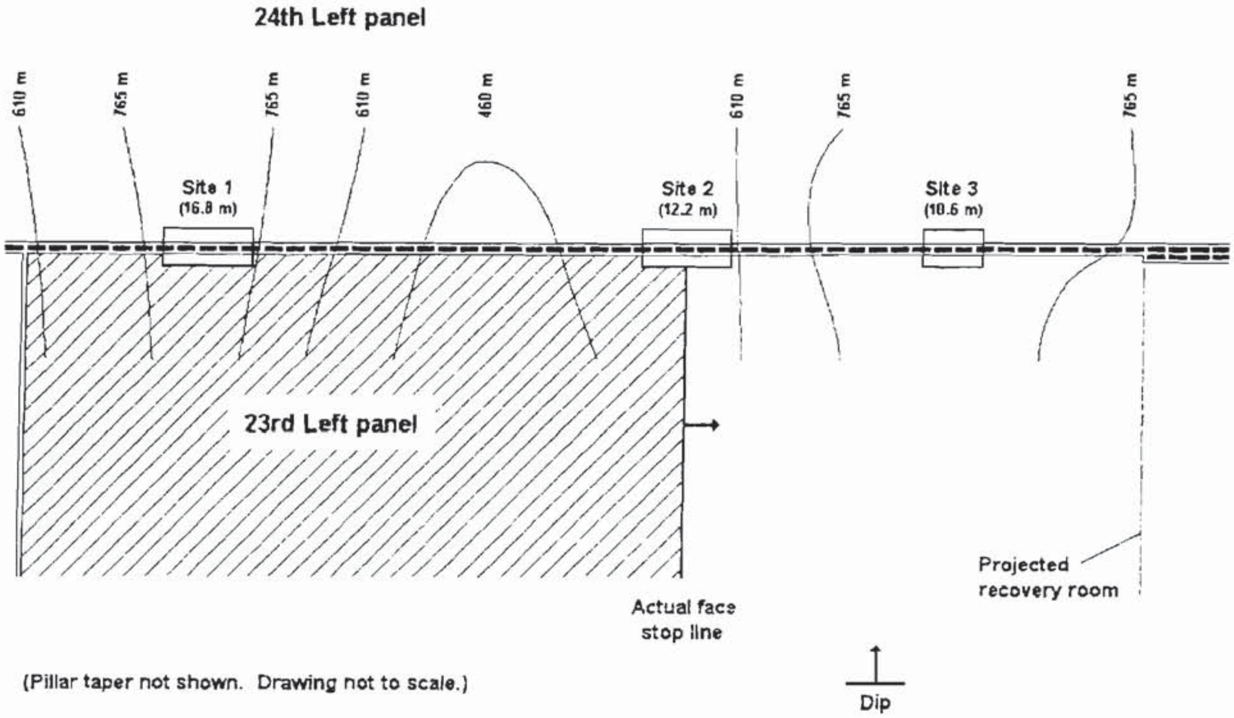


Figure 16
Instrumentation and Probehole Drilling Map for Crosscuts 46 to 49, Site 1.

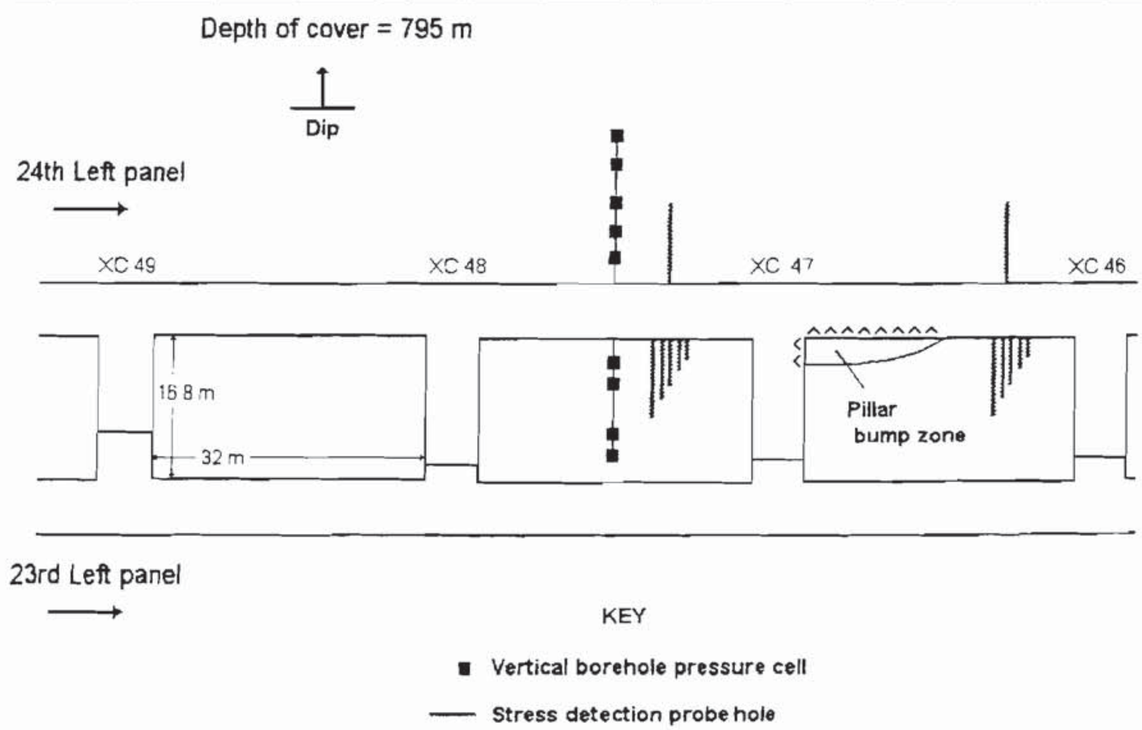


Figure 17
Instrumentation and Probehole Drilling Map for Crosscuts 24 to 27, Site 2.

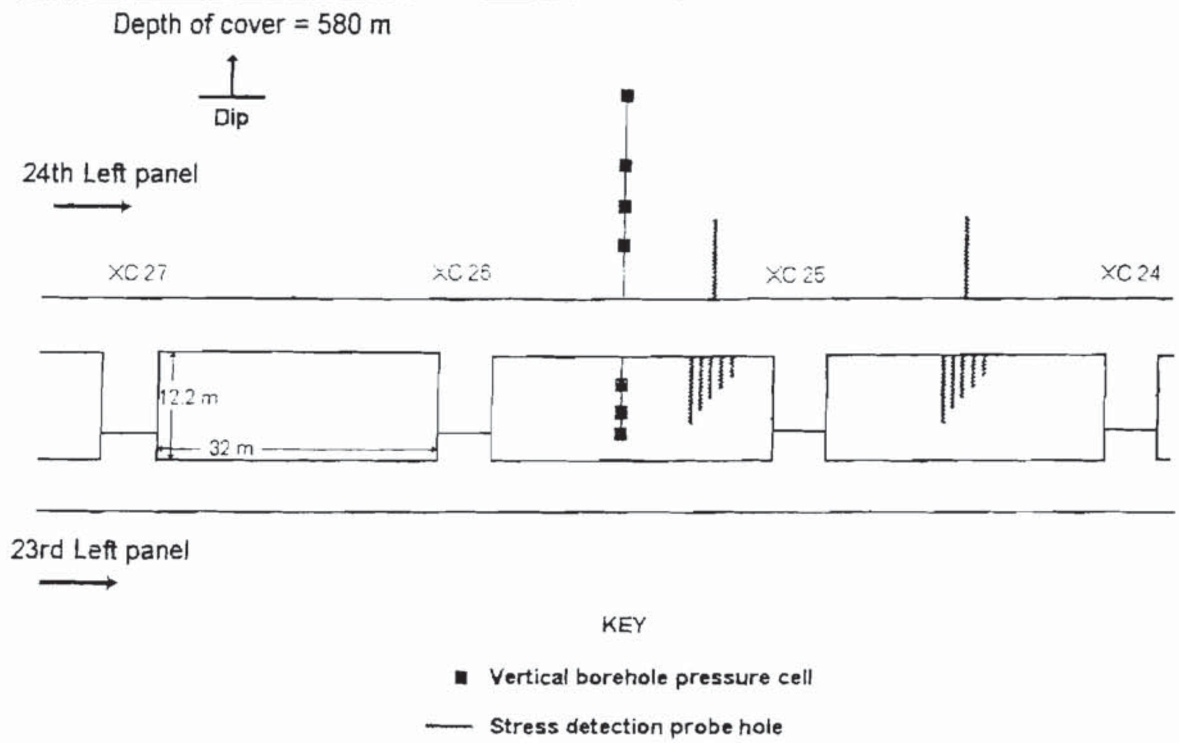


Figure 18
Probehole Drilling Map for Crosscuts 12 to 15, Site 3.

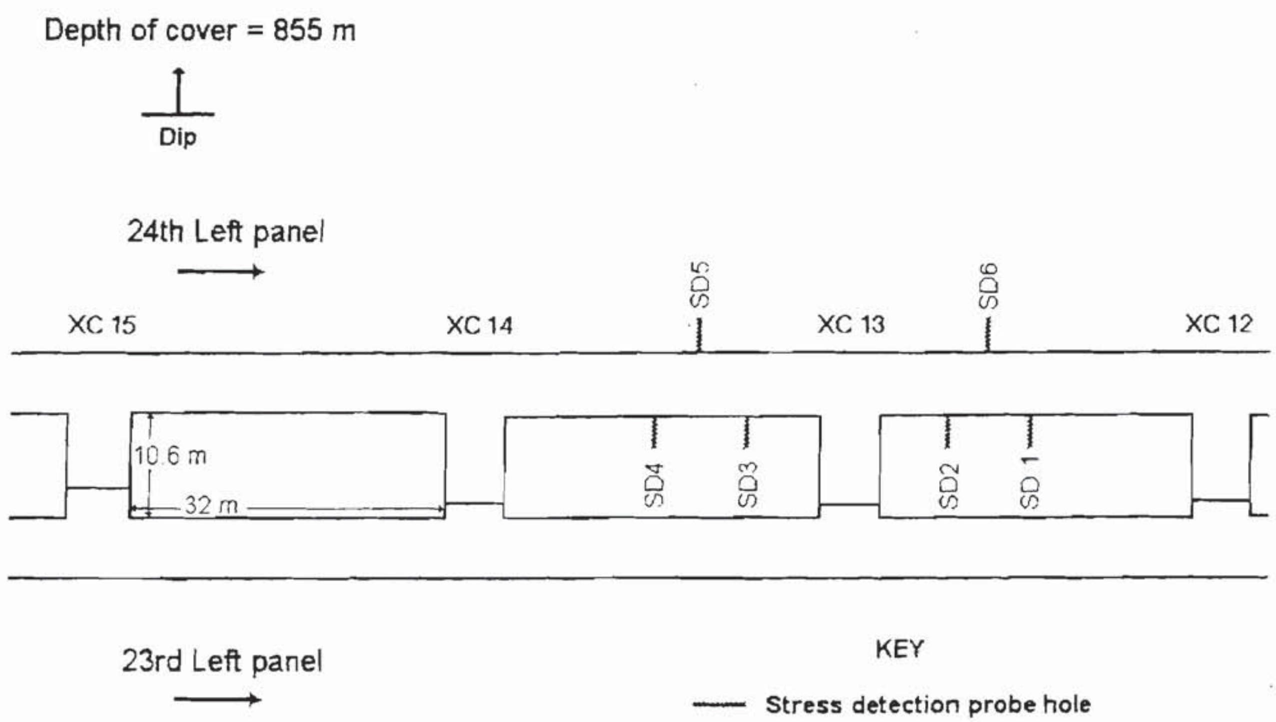
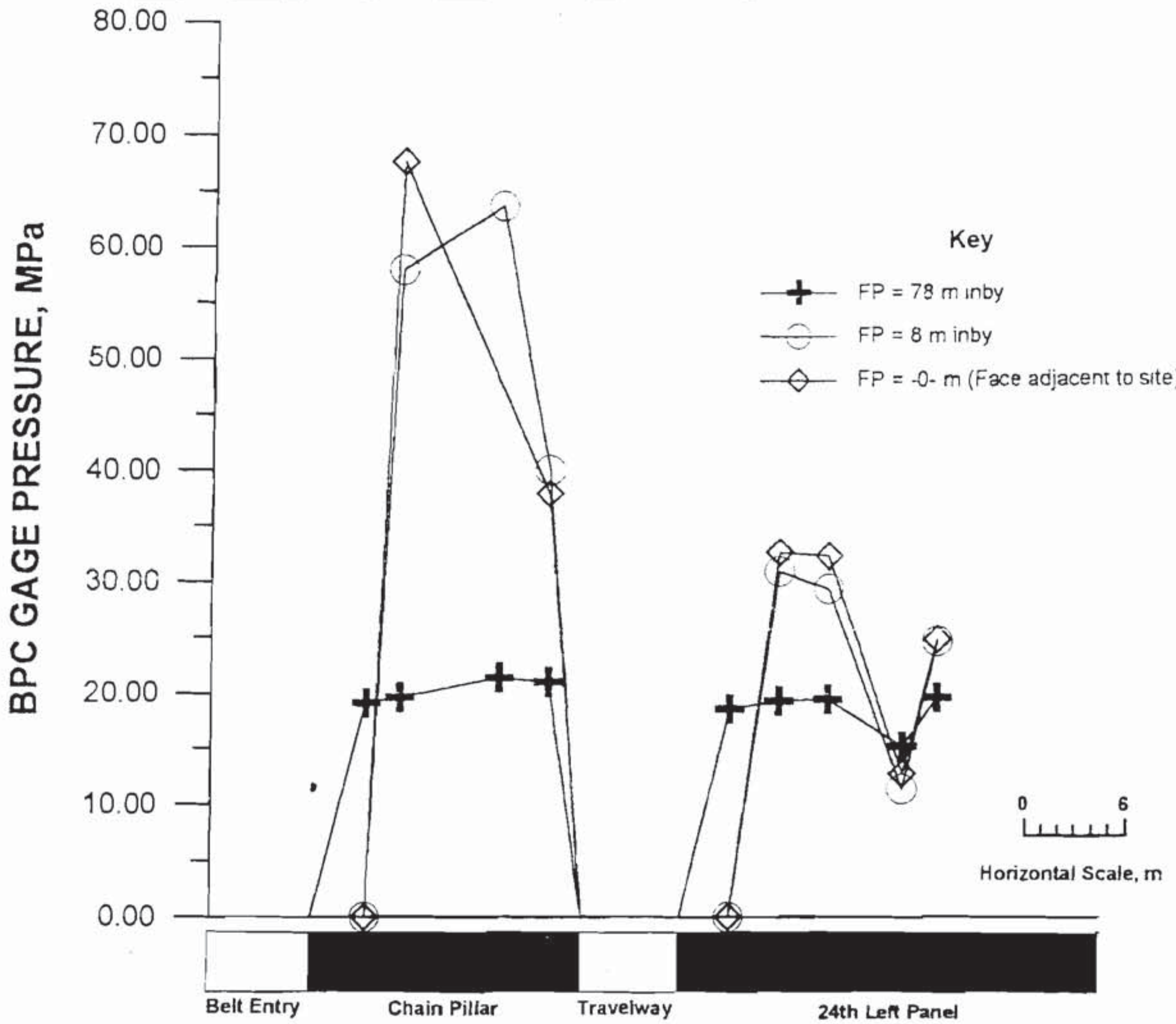


Figure 19
Ground Pressure Profiles for Select Longwall Face Positions, Site 1.



23rd Left panel extraction, looking inby.

study site. In addition, two pillars 30 to 40 m (100 to 130 ft) inby the instrumentation site [20 to 30 m (65 to 100 ft) behind the face] bumped heavily, ejecting coal into the future tailgate and knocking down several cribs.

When the longwall face advanced to the study site (FP = 0), peak pillar pressures were approaching 70 MPa (10,150 psi), and only two functioning pillar BPC's remained. Examination of the pressure charts from the failed BPC's reveals the occurrence of *instantaneous* pressure spikes of as much as 40 MPa (5,800 psi), which apparently destroyed the hydraulic integrity of the instruments. These extreme pressure changes were believed to be caused by the heavy bump activity emanating from the chain pillars immediately inby the site. This speculation was later demonstrated to be true when a documented bump event in the adjacent outby pillar resulted in pressure spikes that ruptured the remaining pillar BPC's and most of the panel instruments.

Although the pillar pressure profile at 0 FP shows a very highly loaded chain pillar, 24th Left panel pressures had not increased substantially since the 8-m (26-ft) inby FP, and no further panel rib yielding was indicated. These data suggested that most of the chain pillar continued to behave elastically. After the 0 FP, BPC data collection at the site was discontinued because of the damage inflicted on the instruments by the aforementioned pillar bump. This bump occurred when the face was approximately 60 m (197 ft) outby site 1. Documented damage from this event included the shattering of many of the 20- by 20-cm (8- by 8-in) wooden blocks making up two 1- by 1-m (3- by 3-ft) four-point cribs, with an additional four cribs being blown down by flying coal. Also, an estimated *36 m*^{3}

1,270 ft^3) of in-place coal was forcibly ejected from the pillar rib (figure 16) into the future tailgate entry, making passage through this area very difficult.

In summary, the 17-m (55-ft) wide pillar at site 1 yielded little from the time of development until onset of the full forward stress abutment despite the 800-m (2,600-ft) depth. Limited yielding of the pillar did occur under the weight of the front abutment; however, a large, competent core of coal remained. As the longwall face passed the site, the already highly loaded pillar core was subjected to further loading from the side abutment. The addition of this load drove several of the pillars in this area to bump violently soon after the face passed. These data clearly indicate that the 17-m (55-ft) wide configuration was a critical-pillar design for the given mining conditions. In addition, the occurrence of these severe pillar bumps in the headgate strongly suggests that the 17-m (55-ft) wide pillar was probably closer in width to a successful yield pillar design than it was to a successful abutment design.

Site 2

Site 2 was established in the chain pillars and a section of the adjacent 24th Left panel between crosscuts 24 and 26 (figure 17). The pillars at site 2 were 12 m (40 ft) wide by 32 m (105 ft) long, and the cover depth was approximately 580 m (1,900 ft). Installed BPC's included three pressure cells placed at regular intervals across the width of one chain pillar and four pressure cells placed up to 24 m (77 ft) deep in the 24th Left panel. Twelve stress-detection probeholes were drilled in two pillars and at two locations in the 24th Left panel during instrument installation.

The probehole drilling data, collected when the face was approximately 600 m (2,000 ft) inby site 2, indicated pillar yield zones were from 2.5 to 3 m (8 to 10 ft) deep. Zones of moderate stress began approximately 3 m (10 ft) into the pillar ribs and were estimated to be approximately 1 m (3 ft) wide. Similarly, probehole drilling in the 24th Left panel indicated the existence of a 3- to 4-m (10- to 13-ft) deep yield zone along the panel rib. These data suggested that the chain pillars and 24th Left panel ribs at site 2 began yielding under gate road development loads.

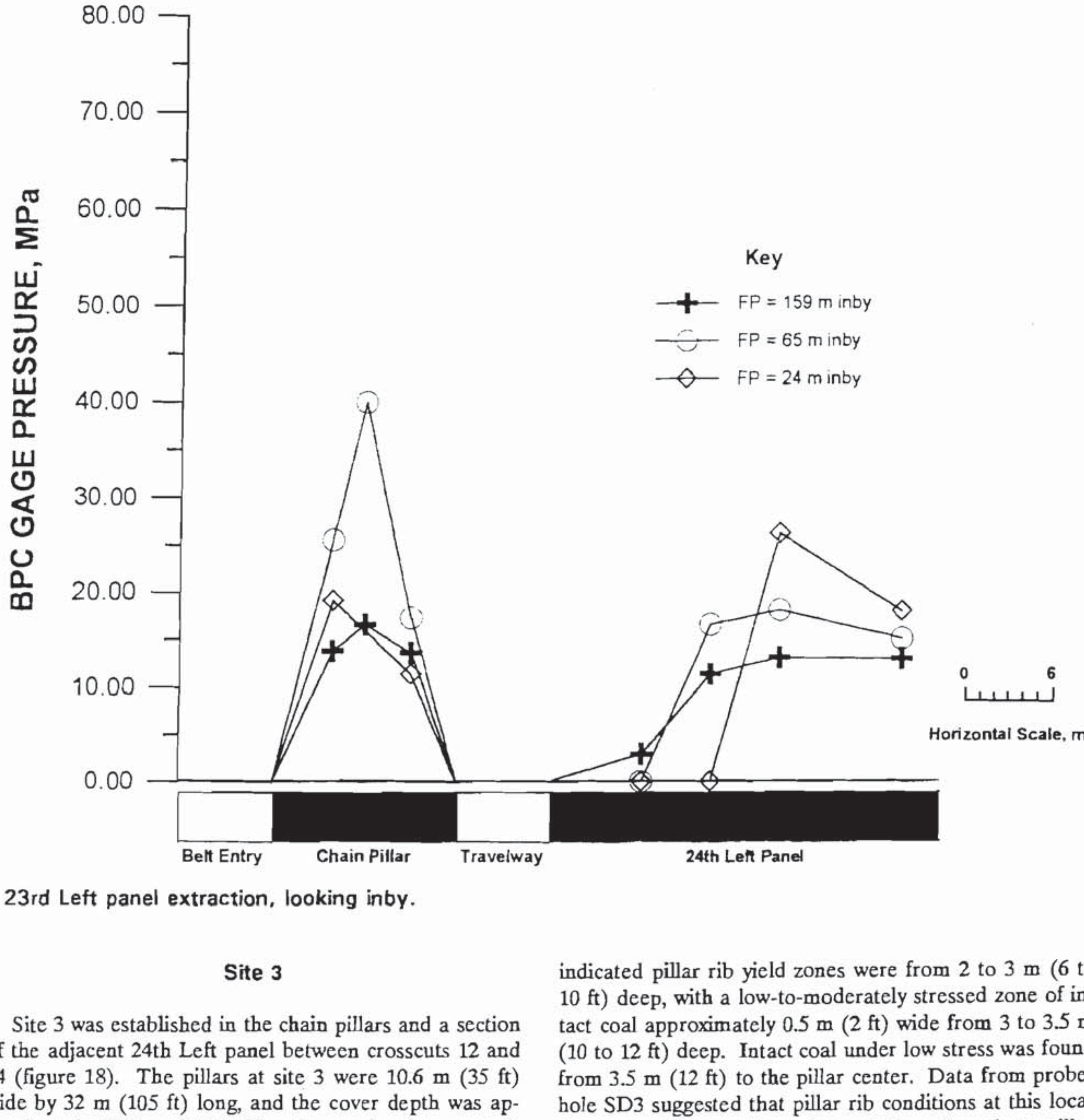
Ground pressure profiles across the instrumented pillar and panel for three longwall face positions relative to the line of BPC's are presented in figure 20. The 159-m (522-ft) inby FP profile shows pillar and panel pressures before the forward stress abutment had reached the instrumentation site. Pillar and panel ground pressures are seen to be low, and the 3- to 4-m (10- to 13-ft) deep panel rib yield zone indicated by the probehole drilling is reflected by the very low BPC pressure 6 m (20 ft) from the panel rib.

As mining progressed to the 65-m (213-ft) inby FP, panel and (especially) pillar pressures rose significantly with the initial onset of the forward stress abutment. In fact, the highest pillar pressures recorded during the study of site 2 occurred when the face was 65 m (213 ft) inby the line of BPC's. Peak pillar pressure was approximately 40 MPa (5,800 psi); however, pressures on either side of the pillar center dropped rapidly with proximity to the pillar rib. In comparison, substantially higher loads were seen across a much greater portion of the pillar width at site 1 than at site 2. The panel pressure profile for the 65-m (213-ft) inby FP suggests that the panel yield zone had expanded to approximately 7 to 8 m (23 to 26 ft) in depth. This finding indicates that the forward abutment loads were being more evenly distributed between the chain pillar and the panel and suggests the occurrence of widespread softening of the ground surrounding the openings.

Ground pressures significantly changed once again as the longwall face moved to within 24 m (79 ft) inby site 2. Examination of the 24-m (79-ft) inby FP profile reveals that pillar pressures had returned to levels similar to those recorded at the 159-m (522-ft) inby FP. In addition, the panel pressure profile indicates that the panel rib yield zone extended to a depth of at least 10 m (33 ft). In-mine observations noted significant rock noise emanating from the coal and surrounding strata during the period of mining from the 65-m (213-ft) inby FP to the 24-m (79-ft) inby FP; however, *no* coal bumps were known to have occurred in and around site 2 during this time. Collectively, these data suggest that the pillars and a significant portion of the panel rib at site 2 had yielded in a nonviolent fashion, creating a protective "soft" zone of broken coal surrounding the gate entry.

In summary, the 12-m (40-ft) wide pillar at site 2 began yielding sometime after development but before the initial onset of the forward stress abutment; yielding of the adjacent 24th Left panel rib also started during this time period. As pillar and panel loads began to increase with the approach of the forward stress abutment, further pillar yielding occurred until pillar pressures returned to pre-longwalling levels. Forward abutment loads were consequently transferred to the 24th Left panel, causing additional yielding of the panel rib and completing the softening process around the gate. This information suggests that a 12-m (40-ft) wide pillar *approaches* proper yield pillar dimensions for the mining conditions found at Sunnyside. In fact, this configuration has been demonstrated to be a *marginal* yield pillar design at Sunnyside; in a previous study, Koehler (1994b) reported the occurrence of tailgate pillar bumps when a 12-m (40-ft) wide pillar was used. Incomplete pillar and panel rib yielding because of localized variations in geologic structure along the gate length was probably responsible for the behavior reported in that study.

Figure 20
Ground Pressure Profiles for Select Longwall Face Positions, Site 2.



23rd Left panel extraction, looking inby.

Site 3

Site 3 was established in the chain pillars and a section of the adjacent 24th Left panel between crosscuts 12 and 14 (figure 18). The pillars at site 3 were 10.6 m (35 ft) wide by 32 m (105 ft) long, and the cover depth was approximately 855 m (2,800 ft). As previously reported, BPC's could not be installed at site 3 because of the unexpected closure of the Sunnyside No. 1 Mine; however, six stress-detection probeholes were drilled in two chain pillars and at two locations within the 24th Left panel before the mine was closed.

The probehole drilling data from site 3 were collected when the face was approximately 425 m (1,394 ft) inby the site. Data from chain pillar holes SD1, SD2, and SD4 indicated pillar rib yield zones were from 2 to 3 m (6 to 10 ft) deep, with a low-to-moderately stressed zone of intact coal approximately 0.5 m (2 ft) wide from 3 to 3.5 m (10 to 12 ft) deep. Intact coal under low stress was found from 3.5 m (12 ft) to the pillar center. Data from probehole SD3 suggested that pillar rib conditions at this location were different from those at the other three pillar holes. The pillar rib at SD3 was found to be solid, and moderate loads were encountered for the first 2 m (6 ft) of probehole. Drilling data indicated the presence of intact coal under low apparent stress from 2 m (6 ft) to the pillar center. Following completion of hole SD3, moderate rock failure noise was emitted from the coal surrounding the hole collar for approximately 15 min.

The pillar probehole data suggest that the chain pillars at site 3, like those at site 2, began to yield sometime after development. The data from probehole SD3, however, indicated that pillar rib yielding was not entirely uniform along the pillar perimeter. This result is not surprising; field study of 9.6-m (32-ft) wide pillars in the 20th Left gate roads of the Sunnyside No. 1 Mine demonstrated that some variability in the degree of pillar yielding can be expected (Haramy, 1990).

Probehole drilling data from panel holes SD5 and SD6 indicate that the degree of yielding along the 24th Left panel rib was also variable at the time of data collection. At probehole SD5, the panel rib yield zone was approximately 3 m (10 ft) deep, with a 1-m (3-ft) wide zone of moderate-to-high stress between 3 and 4 m (10 and 13 ft) into the panel rib. In comparison, at probehole SD6 the yield zone was estimated to be between 1.5 and 2 m (4 and 6 ft), deep, with a 2-m (6-ft) wide zone of high stress between 2 and 4 m into the panel rib.

In summary, the 10.6-m (35-ft) wide pillars, as well as the 24th Left panel rib, at site 3 began yielding sometime after development. The degree of pillar and panel rib yielding at this site was found to be variable; however, in general, the pillars and panel at site 3 were in the same approximate state of yielding (at prelongwalling load levels) as those found at site 2. As previously reported, in-mine experience with the 12-m (40-ft) wide pillars at site 2 has demonstrated that this configuration is a marginally successful yield pillar design for Sunnyside conditions. In comparison, employing yield pillars ranging in width from 9 to 10.6 m (30 to 35 ft) has met with favorable results at Sunnyside (Koehler, 1994a, 1994b).

CONCLUSIONS

Experience in Western mining operations shows that gate road coal bumps are the often the result of a combination of in-mine ground conditions and the actual gate design employed. The primary setting influences have historically thick, competent sandstone units in the main roof, strong roof and floor strata immediate to the seam, sand channels in the immediate roof, strong and largely unstructured coal seams, and faults and shear zone structures immediate to the seam, all of which are subject to deep, variable cover. Gate design practices that aggravate adverse mine settings include the misapplication of abutment-yield pillar configurations, the use of too many entries with full-yielding entry system designs, and, above all, the use of critical pillars. It cannot be overstated that critical pillars are perhaps the single greatest design problem where gate road ground instabilities are of concern. Such instabilities are not just limited to bump occurrences, but the entire spectrum of entry ground-control problems, including roof, rib, and floor failures.

To develop a clearer understanding of critical-pillar behavior, a field study of a tapering gate road was conducted at the Sunnyside No. 1 Mine. Three study sites were established along the length of the 23rd Left gate road in chain pillars 17 m (55 ft), 12 m (40 ft), and 10.6 m (35 ft) wide. A summary of the results of this field investigation follows.

- The 17-m (55-ft) wide pillars yielded little from development until onset of the forward stress abutment, despite the 800 m (2,600 ft) of cover. As a result, most of the abutment loads were borne by the chain pillars and not the adjacent panel. The combined weight of the forward and side abutment loads drove several of the pillars in this area to bump violently soon after the first longwall face passed by. Damage from these bumps included shattered and blown-down cribs and partial blockage of the future tailgate by ejected coal. The data and observations collected at this site clearly indicate that the 17-m (55-ft) wide configuration was a critical-pillar design for the given mining conditions.

- The 12-m (40-ft) wide pillars began yielding sometime after development but before the initial onset of the forward stress abutment; yielding of the adjacent 24th Left panel rib also started during this time period. Further pillar yielding occurred with the onset of forward abutment loads until pillar pressures returned to prelongwalling levels. Consequently, load transfer caused additional yielding of the adjacent panel rib, completing the softening process around the gate. No pillar bumps were reported. The data and observations collected at this site suggest that the 12-m (40-ft) wide pillar configuration approaches proper yield pillar dimensions for the mining conditions found at Sunnyside.

- The 10.6-m (35-ft) wide pillars and adjacent 24th Left panel rib began yielding following development. The degree of pillar and panel yielding was variable; however, in general, the pillars and panel at this site were in the same approximate state of yielding (at prelongwalling load levels) as those at the 12.2-m (40-ft) wide pillar location. Although the collection of data from the 10.6-m (35-ft) wide pillars was prematurely terminated by mine closure, significant on-site experience employing yield pillars of this width suggests that a nominal 10-m (33-ft) wide pillar provides excellent gate road ground control through the complete mining cycle (Koehler, 1994a, 1994b).

The failure of yield pillar designs to provide adequate ground control and reduce or eliminate those conditions responsible for the initiation of bumps is primarily related to the misapplication of these designs in coal seams having unfavorable roof and floor characteristics and/or the use of critical pillars, which actually *promote* poor ground conditions. A critical pillar is defined as one that is too large to yield nonviolently or to yield before the roof and floor sustain permanent damage, but too small to support full longwall abutment loads. Often, yield pillar widths are mistakenly increased to accommodate deepening cover in the same manner that abutment pillar widths might be increased. This situation is to be avoided because the difference between a fully successful yielding gate road and the *worst* possible critical-pillar condition may be as little as a few meters of increase in yield pillar size. Mine operators who unknowingly employ a critical-pillar design often abandon the concept of yielding gate roads prematurely, mistakenly labeling them as inapplicable to their given minesite conditions.

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