OCCURRENCE AND REMEDIATION OF COAL MINE BUMPS: A HISTORICAL REVIEW

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ABSTRACT

One of the most difficult, longstanding engineering problems associated with coal mining is the catastrophic failure of coal mine structures known as *bumps*. For more than 70 years, researchers and practitioners have assembled a wealth of technical information on coal bumps in an attempt to understand and control them. However, many technical issues raised long ago are still being debated today. This paper examines past experiences and recognizes achievements in the realm of coal bumps. U.S. Bureau of Mines (USBM) researchers collected and analyzed 172 coal bump incident reports and compiled the pertinent statistics into a database. Actual field studies are also discussed. Examination of past experience has shown that there is no one set of defining characteristics that is responsible for coal bumps. In all cases, bumps occur when complex arrangements of geology, stress, and mining conditions interact to interfere with the orderly dissipation of stress. However, it is evident from the database that a tremendous reservoir of knowledge has been established from past experience that has unquestionably limited the severity of coal mine bumps in the United States.

INTRODUCTION

Coal mine bumps have presented serious mining problems in the United States throughout the 20th century. Fatalities and injuries have resulted when these destructive events occurred at the working face of the mine. Persistent bump problems have caused the abandonment of large coal reserves and have led to premature mine closure.

Through the years, a variety of techniques were proposed and implemented to mitigate bumps. Mining history is rich with examples of innovative proposals that, at best, temporarily alleviated this complex problem. From the 1930's to the present, the U.S. Bureau of Mines (USBM) has conducted fundamental research on the geologic environments and failure mechanisms responsible for coal mine bumps and on methods to control them. This work supports the USBM's mission to improve safety for miners by eliminating their exposure to hazardous underground conditions.

During the 1930's, USBM research indicated that both geology and mining practice (geometry and sequence) play key functions in bump occurrence. Strong, stiff roof and floor strata not prone to failing or heaving were cited as contributing factors when combined with deep overburden. Various poor mining practices that tended to concentrate stresses near the working face were identified and discouraged. Although such qualitative geologic descriptions and design rules-of-thumb have persisted through the years, the need to better quantify bump-prone conditions remains.

Mine operators find little comfort in generalities when they have experienced a bump and must determine if another is imminent. Specific questions about the influence of individual factors and the interaction among factors arise but are often difficult to answer owing to the limited experience at a given mine site. Often, many

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parameters change simultaneously (for example, strength and stiffness of roof and floor, proximity of strong lithologic units to a coalbed, depth of overburden, mine geometry, and mining rate).

To better establish the range of circumstances under which bumps take place, the USBM compiled the Coal Bump Database, which contains information about bumps that have occurred in the United States since 1936. More than 172 coal mine bumps have been identified from various documents, including U.S. Mine Safety and Health Administration (MSHA) Reports of Investigation (Fatal and Nonfatal), USBM reports, mining conference proceedings, and mining company reports and memoranda. Information pertinent to mine design and geologic characterization of bump-prone ground has been extracted from the documents and assembled in a spreadsheet. It is the mining community's charge to rethink its understanding of bump phenomena while exploring innovative techniques to mitigate occurrences. Presentation of historical information in this format facilitates a reevaluation of the broad range of geologic and operational conditions under which bumps have been encountered and will help preserve knowledge acquired through experience.

BACKGROUND

The earliest U.S. coal mine bump included in the USBM Coal Bump Database dates back to 1936. However, several reports indicate that bumps had constituted a serious problem even earlier. For example, Watts (*30*)[3] reported bumps at the Sunnyside No. 1 Mine in Utah, and Rice (*27*) documented several bumps in the Cumberland Coalfield in eastern Kentucky. Bryson (*3*) indicates that bumps occurred in the Cumberland Coalfield as early as 1923 and became very troublesome from 1930 to 1934. In most cases, specific information on the events as described by these experts is not available, and thus these events have not been included in the database. However, the descriptions of various causes and attempted remedies for bumps provide valuable anecdotal information.

Notable among the early work on coal mine bumps are reports by Rice (*27*) and Holland and Thomas (*14*). Rice classifies bumps into two general types: *pressure bumps* and *shock bumps*. According to Rice, pressure bumps are caused when pillar stress exceeds bearing strength. Shock bumps are induced by breaking of thick, massive strata at a considerable distance above the coalbed, which causes the immediate mine roof to transmit a shock wave to the coal. Rice indicates several conditions favoring bumps, including thick overburden, strong overlying strata, and a strong floor not prone to heaving. Holland and Thomas define a similar range of conditions based on their examination of more than 117 instances of bumps in West Virginia, Kentucky, Utah, and Virginia. Their investigation also demonstrated that most bumps had been caused by improper mining methods and practices.

Reports from the 1950's document technical advances for mining in bump-prone ground. For example, Talman and Schroder (*29*) describe a novel barrier-splitting technique called the thin-pillar mining method. In thin-pillar mining, the barriers are segmented into a series of yield pillars too small to maintain significant stress levels or stored strain energy. Efforts in both Eastern and Western U.S. coalfields were also directed to maintaining low stress levels through planned destressing activities, such as large-hole auger drilling (*28*) and volley firing (*25*).

Despite technical advances in the 1950's, analyses of bump records from 1959 to 1984 (*12*) indicate that bumps still occurred at an alarming rate. Current information shows that bump-related accidents resulted in 42 fatalities since 1960 (table 1), 14 in the Eastern United States and 28 in the Western United States. Continuing bump problems probably stemmed in part from the same unfavorable mining conditions and practices discussed by Holland and Thomas.

Table 1.—Chronological distribution of bump events included in USBM Coal Bump Database

Time period	Number of bumps	Fatalities	Injuries
1930-39	1	1	0
1940-49	9	7	18
1950-59	38	28	43
1960-69	27	13	36
1970-79	30	10	21
1980-89	52	19	32
1990-present	9	0	8

The advent of the continuous mining machine resulted in different problems requiring new control solutions. The mobility and versatility of the continuous miner led to the development of novel pillar splitting and extraction sequencing designs for bump control.

With the widespread utilization of the longwall mining method over the last 15 years in the United States, bump problems have continued to threaten the safe mining of coal. One fatality on an advancing longwall face, several

[3]Italic numbers in parentheses refer to items in the list of references at the end of this paper.

injuries on retreating longwall faces, and at least one mine closure have been attributed to bumps (*18*). However, ingenuity and experience have prevailed, and several innovative designs for controlling bumps in longwall mines have been developed. Two designs focus on altering the size and shape of gate entry pillars. The conventional pillar design approach relies on increasing the gate pillar dimensions so that the pillars will prevent abutment load ride-over onto the active longwall face (*32*). The yield pillar approach effectively reduces gate pillar dimensions so that the pillars will yield in a controlled fashion, thereby eliminating tailgate pillar bumps and aiding in the controlled fracturing of the main roof (*7, 21*). A third approach, the advancing longwall method, eliminates the need for developing gate road pillar systems; advancing longwalls were first used in the United States at Mid-Continent Resource's coal mines in the 1970's (*19, 26*). All of these methods have some drawbacks, but they generally represent innovative design philosophies for controlling bumps.

U.S. coal bumps have been associated with a variety of conditions. Perhaps the most general conditions conducive to bumps are stiff, massive strata and high stresses. In some instances, these conditions are pervasive; in others, they are altered locally by geology or mining. For example, geologic structures such as faults or sandstone channels have, in some cases, affected the occurrence of bumps. Similarly, extraction sequences and mine layouts (e.g., multiple-seam mining scenarios) influence the way stresses are concentrated around mine openings and thus play a role in bump occurrence. Holland and Thomas (*14*, p. 34) state that the relationship between factors and circumstances causing bumps "actually is very complex, especially in a quantitative sense." Unique combinations of geology and mining systems have required many site-specific bump-control designs. Such designs must continually evolve as new geologic and mining scenarios are encountered. Solutions to new design challenges can result from evaluating past experiences.

OVERVIEW OF USBM COAL BUMP DATABASE

The USBM Coal Bump Database includes 172 specific bump events that occurred in four Eastern States and three Western States (figure 1). The database was constructed from USBM and MSHA coal bump accident and incident reports written between October 12, 1936, and January 21, 1993. A total of 87 fatalities and 163 injuries were identified. The 1980's witnessed the greatest outbreak of bumps, accounting for 31 pct of the total, while the second largest percentage occurred during the 1950's (23 pct). West Virginia recorded the greatest number of documented bumps (53), followed by Virginia (40), Colorado (30), Utah (26), and Kentucky (19). Alabama and Washington each had one reported bump event.

Analysis of information in the Coal Bump Database indicates that bumps have occurred in a variety of mining systems and operations. For example, pillar retreat mining accounted for 35 pct of the bumps, barrier-splitting for 26 pct, longwall mining for 25 pct, and development mining for 14 pct. Of the longwall incidents, 33 pct affected the longwall face, 19 pct the tailgate entries, 36 pct both the longwall face and the tailgate entries, and 6 pct the headgate entries. Generating 67 pct of the total, the act of excavating was associated with the greatest number of incidents. The coal-loading operation at the face accounted for another 22 pct of the total. Other, less-frequent bump incidents occurred during shot firing (5 pct) and installation of support (6 pct). Additionally, 22 pct of the bumps took place during nonproduction shifts. One event reportedly occurred in an abandoned section.

The database includes reports on individual bump events from more than 50 mines. As table 2 indicates, some mines account for a single bump record, whereas 20 or more events have been documented at two sites. With such high numbers of bumps at individual mines, it is not surprising that an impressive list of bump-control efforts has been developed. Unique mine designs have been employed to redistribute excessive stress conditions, for example, the thin-pillar method at the Gary No. 2 Mine and pillar-splitting methods at the Olga, Beatrice, and Cottonwood Mines. Innovative support strategies have been documented, ranging from yielding leg arches used at the Sunnyside Mines to material-filled cribs employed at several eastern Kentucky drift mines. The virtues and shortcomings of destressing techniques, including shot firing, auger drilling, and water infusion, have been identified. For example, extensive use of auger techniques with hole diameters ranging from 9 to 49 cm was attempted in the Gary district until a major bump during drilling resulted in fatalities in the early 1950's.

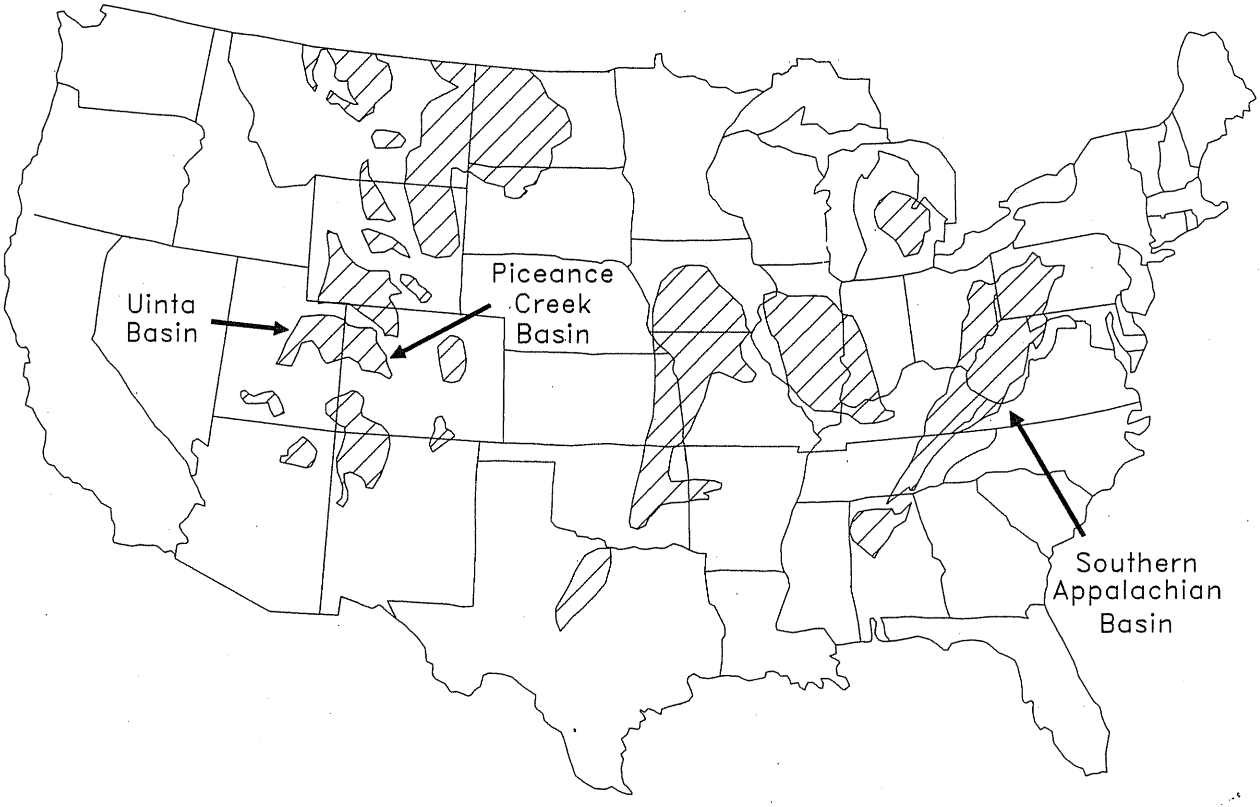
Information pertinent to mine design and geologic characterization of bump-prone ground was extracted from source documents for each mine and assembled into a computer spreadsheet. The spreadsheet format facilitates the identification of common conditions contributing to bumps and provides a means of readily evaluating the broad range of experiences. Moreover, the range of documented experiences shows that bumps manifest themselves in different ways with varying effects.

Table 2.—U.S. coal mines included in USBM Coal Bump Database

Mine	Company	City	County	State	Coalbed	No. of bumps
Bartley No. 3	Island Creek Corp.	Bartley	McDowell	WV	NA	1
Beatrice	Beatrice Pocahontas Co.	Keen Mountain	Buchanan	VA	Pocahontas No. 3	24
Belina No. 1	Valley Camp of Utah, Inc.	Clear Creek	Carbon	UT	Upper O'Connor	1
Braztah No. 3	Braztah Corp.	Helper	Carbon	UT	Subseam No. 3	2
Brookside	Kentucky Jellico Coal Co.	Brookside	Harlan	KY	Harlan	3
Buchanan No. 1	Consolidation Coal Co.	Mavisdale	Buchanan	VA	Pocahontas No. 3	2
C-2	Harlan Cumberland Coal Co.	Dione	Harlan	KY	Creech	1
Castle Gate	Castle Gate Coal Co.	Helper	Carbon	UT	Subseam No. 3	2
Castle Gate No. 2	Carbon Fuel Coal Co.	Helper	Carbon	UT	NA	1
Cottonwood	Energy West Mining Co.	Huntington	Emery	UT	Hiawatha	1
Deer Creek	Energy West Mining Co.	Huntington	Emery	UT	Blind Canyon	2
Dehue	Youngstown Mines Corp.	Dehue	Logan	WV	Eagle	2
Dutch Creek No. 1	Mid-Continent Resources, Inc.	Redstone	Pitkin	CO	B	16
Federal No. 1	Federal Mining Corp.	Elkhorn City	Pike	KY	Elswick	1
Gary No. 2	U.S. Steel Mining Co., Inc.	Gary	McDowell	WV	Pocahontas No. 4	20
Gary No. 6	U.S. Steel Mining Co., Inc.	Gary	McDowell	WV	Pocahontas No. 4	6
Glen Rogers No. 2	Raleigh Wyoming Mining Co.	Glen Rogers	Wyoming	WV	Beckley	2
H-2	Harlan Cumberland Coal Co.	Louellen	Harlan	KY	Harlan	1
Harewood	Allied Chemical Corp.	Longacre	Fayette	WV	Eagle	1
Holden	Howe Sound Co.	Holden	Chelan	WA	NA	1
Kenilworth	Carbon Fuel Coal Co.	Kenilworth	Carbon	UT	Castlegate D	2
L. S. Wood	Mid-Continent Resources, Inc.	Redstone	Pitkin	CO	B	10
Lynch No. 37	Arch of Kentucky, Inc.	Cumberland	Harlan	KY	Harlan	5
Maple Meadow	Maple Meadow Mining Co.	Fairdale	Raleigh	WV	Beckley	1
Marathon No. 1	Harlan Wallins Coal Co., Inc.	Verdo	Harlan	KY	Darby	1
Mary Helen No. 2	Mary Helen Coal Corp.	Coalgood	Harlan	KY	Harlan	1
Mary Helen No. 3	Mary Helen Coal Corp.	Coalgood	Harlan	KY	Harlan	1
Milburn No. 4	Milburn Colliery Co.	Milburn	Fayette	WV	No. 2 Gas	1
Mine No. 10	Wisconsin Steel Coal Mines	Benham	Harlan	KY	Harlan	1
Moss No. 2	Clinchfield Coal Co.	Clinchfield	Russell	VA	Tiller	5
Moss No. 3	Clinchfield Coal Co.	Duty	Dickenson	VA	Thick Tiller	1
No. D-1	Wisconsin Steel Coal Mines	Benham	Harlan	KY	D above Kellioka	1
No. 1	Turtle Creek Coal Co.	Coalgood	Harlan	KY	Harlan	1
No. 2	Chafin Coal Co.	Rita	Logan	WV	Upper Cedar Grove	2
No. 2	Clinchfield Coal Corp.	Dante	Russell	VA	Upper Banner	3
No. 4	Jim Walter Resources, Inc.	Brookwood	Tuscaloosa	AL	Blue Creek	1
No. 9	Jewell Eagle Coal Co.	Melville	Logan	WV	Eagle	2
No. 17	Island Creek Corp.	Red Jacket	Mingo	WV	Cedar Grove	1
No. 21	W-P Coal Co.	Stirrat	Logan	WV	Chilton	1
No. 27	Island Creek Corp.	Ragland	Mingo	WV	NA	1
No. 31	Peabody Coal Co.	Kenvir	Lee	VA	Darby	1
Olga	Olga Coal Co.	Coalwood	McDowell	WV	Pocahontas No. 4	12
Price River No. 3	Price River Coal Co.	Helper	Carbon	UT	Castlegate sub 3	1
Soldier Canyon	Soldier Creek Coal Co.	Wellington	Carbon	UT	Rock Canyon	1
Somerset	U.S. Steel	Somerset	Gunnison	CO	C above Kellioka	2
Sunnyside No. 1	Kaiser Steel Corp.	Sunnyside	Carbon	UT	Lower Sunnyside	7
Sunnyside No. 2	Kaiser Steel Corp.	Sunnyside	Carbon	UT	Upper Sunnyside	3
Trail Mountain No. 9	Beaver Creek Coal Co.	Orangeville	Emery	UT	Hiawatha	1
VP No. 3	Virginia Pocahontas Co.	Vansant	Buchanan	VA	Pocahontas No. 3	3
VP No. 6	Island Creek Corp.	Mavisdale	Buchanan	VA	Pocahontas No. 3	1
Wilberg	Emery Mining Corp.	Orangeville	Emery	UT	Hiawatha	3
NA	NA	NA	NA	CO	B	1
NA	NA	NA	NA	KY	NA	1
NA	NA	NA	NA	KY	NA	1
NA	NA	NA	NA	CO	Middle B	1

NA Not available.

Figure 1
Major U.S. Coal Basins Where Coal Mine Bumps Have Historically Been a Problem.



FACTORS CONDUCIVE TO BUMPS

Although specific mechanisms that trigger coal mine bumps are not well established, it is generally recognized that high stresses play a key role in bumps. Retreat mining and barrier-splitting often intensify the stresses. Abutment loading on pillar retreat lines and longwall gate roads can be extreme, especially when mining is conducted between stiff subjacent and superjacent strata. By design, barriers are intended to carry abutment loads in various situations, and thus barrier-splitting operations often involve high-stress environments. In development mining, stress redistribution generally affects areas near the openings. In areas of thick overburden (for example, >600 m), the redistribution of stresses caused by development mining alone may generate coal mine bumps.

High-stress conditions conducive to generating coal mine bumps are associated with a variety of factors. Caving characteristics of main roof units may have a significant impact on stress levels at a room-and-pillar retreat line or retreating longwall face. Geologic structures such as displacement faults, massive sandstone paleochannels, and rolls are important because of their ability to concentrate stress and control the caving and heaving characteristics of strata. Unfavorable mining practices or configurations (for example, multiple-seam interactions) can concentrate stresses in specific locations. Undoubtedly, these factors play a role in many of the bumps included in the USBM Coal Bump Database. Nevertheless, the simplest indicator of bump potential appears to be the presence of thick overburden. Overburden information is included in the database for more than 50 mines that have experienced bumps. Overburden thickness at these sites ranges from 143 to 760 m, but at most of the sites, overburden ranges from 400 to 550 m. Only 10 mines experienced bumps where overburden thickness was less than 300 m, while 9 were operating under more than 600 m when bumps occurred.

As indicated earlier, a variety of geologic factors have influenced the occurrence of bumps. In describing natural conditions conducive to coal bumps, a common factor in both U.S. and foreign mines is the proximity of the bump-prone coalbed to strong, thick, rigid strata (*2*). Of the 172 events comprising the USBM Coal Bump Database, lithologic descriptions of the mine roof are included for 95 bump sites. In 86 instances, reference is made to the presence of *sandstone* immediately above to within a few meters of the coalbed. Terms such as "strong," "firm," "massive," and "thick" are used to describe the sandstone units. In 30 instances, a shale, sandy shale, siltstone, or mudstone unit of varying thickness was found to occur between the coalbed and the overlying sandstone units. Geologic descriptions of the mine floor are included for more than 80 sites. *Shale* is the predominant floor lithology in the database; the presence of sandstone in the floor is noted in only 25 pct of the site descriptions. Terms such as "hard" and "dense" are common descriptions of floor lithologies.

The implications of multiple-seam mining interactions in generating strata control problems are well documented (*5-6*). These problems can be the result of both stress concentration or strata displacement and can be experienced when the interburden is as thick as a few hundred meters. However, problems are more severe when the interburden is less than 100 m thick. Ground conditions in upper coalbeds may be disturbed by strata movements associated with previous workings in a lower coalbed. This type of interaction may result in difficult mine roof conditions but has not been identified as a factor contributing to bumps. Stress concentrations occurring in multiple-seam mining scenarios, however, have been associated with bumps; 15 bumps in the database occurred in such settings. In most cases, mining in a lower coalbed encountered zones of high stress beneath barriers or isolated pillar sections in a previously mined upper coalbed.

Rice suggested that "a structurally strong coal" not prone to crushing easily would favor bumps (*27*, p. 4). However, more recent research suggests that the physical properties of coal are not necessarily key factors in bump occurrence. For example, Babcock and Bickel (1984) performed laboratory studies on coal samples from 15 mines in 11 coalbeds. Their study concluded that many, if not most, coals can fail violently given the proper conditions of stress and constraint. The database appears to support this conclusion, for it demonstrates that coal bumps have been experienced in at least 25 U.S. coalbeds (table 3). The height of Eastern U.S. coalbeds ranged from 1 to 3 m; Western U.S. coalbeds were significantly higher, ranging from 1.8 to 4.3 m.

HAZARDS ASSOCIATED WITH BUMPS

Coal mine bumps are dynamic phenomena; numerous fatalities and injuries have been a direct result of miners being struck by coal forcefully ejected during a bump. Approximately 80 pct of the fatalities documented in the database were caused directly by displaced coal either hitting the individual or by forcing the individual into nearby equipment or mine ribs. However, other hazards have also been associated with coal mine bumps, including roof falls and ignitions of methane and coal dust.

Table 3.—U.S. coalbeds associated with coal mine bumps

Coalbed	State	Thickness, m
Eastern United States:		
Beckley	WV	1.8
Blue Creek	AL	1.8
Cedar Grove and Upper Cedar Grove	WV	1.0-1.8
Chilton	WV	1.1
Creech	KY	2.1
Darby	KY-VA	1.0-1.1
Eagle	WV	1.1
Elswick	KY	1.1
Harlan	KY	1.1-2.7
No. 2 Gas	WV	1.5
Pocahontas No. 3	VA	1.3-1.8
Pocahontas No. 4	WV	1.2-2.0
Tiller	VA	1.3-3.0
Upper Banner	VA	1.6
Western United States:		
B	CO	1.9-3.0
Blind Canyon	UT	4.3
C	CO	2.1-2.7
Castlegate D	UT	3.8
Dutch Creek M	CO	2.4
Hiawatha	UT	2.1
Middle B	CO	2.7
Rock Canyon	UT	
Subseam No. 3	UT	1.8-2.4
Upper and Lower Sunnyside	UT	2.1-3.2
Upper O'Connor	UT	2.7

Ten incidents in the database document mine roof falls that occurred in conjunction with bumps. Prior to the widespread use of roof bolting for primary support, bumps had the potential to create roof instabilities simply by dislodging posts and crossbars. With the introduction of roof bolting, however, the effect of bumps on supports was lessened. Nevertheless, bumps appear to continue to contribute to roof falls by disturbing the stability of the roof rock directly. In one case, for example, a bump caused roof rock to be released along a slip between longwall chocks and the face, resulting in a fatality. This associated hazard appears to be most prevalent during pillar mining, particularly in the Uinta Coalfields of Utah.

Ignitions of methane gas and dust associated with coal bumps are somewhat rare, but they are among the most devastating incidents in terms of the numbers of miners killed or injured. For example, on March 14, 1945, a pillar bump at the Kenilworth Mine caused the trailing cable of a loading machine to be pulled with such force that it was severed and created a short circuit that led to arcing (*15*). Thick coal dust resulting from the violent bump, coupled with methane gas, probably from the adjacent gob area, ignited, severely burning 12 miners. Seven of the injured miners eventually died as a result of the accident.

Ignitions are more prevalent in deep pillar extraction areas and during longwall mining. However, one bump-related ignition reportedly occurred during development mining. Mid-Continent Resources has experienced severe problems with extensive methane gas emissions in association with bumps at its mines, which have been referred to as gas outbursts. The most devastating gas-driven bump occurred on April 15, 1981, at the Dutch Creek No. 1 Mine in Colorado. A massive outburst of gas and coal occurred approximately 2 h after mining through a fault on the development section for the No. 102 longwall. Fifteen miners were killed and three were injured in the resultant mine explosion. Five less severe events occurred at the company's L. S. Wood Mine, where significant quantities of methane gas were measured in the mine air after face bumps.

COMPARATIVE MAGNITUDE OF BUMPS

A sense of relative event magnitude can be gained by assessing observed destruction and measured seismicity for a number of events documented in the USBM Coal Bump Database. In terms of observable damage underground, bumps ranged in magnitude from those that dislodged a portion of a single rib to three that partially destroyed large sections of pillars. On June 3, 1985, the Olga Mine in southern West Virginia experienced a series of bumps that eventually affected, to varying degrees, approximately 100 coal pillars (*8*). Fortunately, this event occurred over an idle weekend when no miners were on the section. However, only a few meters of bumped rib coal can have devastating effects. For example, a continuous mining machine helper at the Belina No. 1 Mine was seriously injured on March 19, 1981, while standing next to a rib where only a few meters of coal were expelled.

Numerous reports have been made concerning the degree to which bumps are felt on the surface, sometimes as far as 3 km away. Seismological observatories around the world have recorded some of the more powerful incidents. Eleven bumps from the database have Richter magnitudes of 3 or greater, with three in Virginia having magnitudes of 4 or greater (table 4).

Table 4.—Levels of mining-induced seismicity registered at U.S. coal mines

Mine	State	Richter magnitude	Date
Olga	WV	3.4	Apr. 26, 1965.
Moss No. 2	VA	[1]3.5 and 4.5	July 30, 1970.
Moss No. 2	VA	4.0-4.2	May 20, 1972.
Beatrice	VA	1.0	May 15, 1974.
Jim Walter Resources, Inc., No. 4	AL	3.6	May 7, 1986.
VP No. 3	VA	3.0	Mar. 4, 1987.
Buchanan No. 1	VA	4.0	Apr. 14, 1988.
Buchanan No. 1	VA	3.6	Apr. 10, 1989.
Lynch No. 37	KY	2.3	Nov. 22, 1989.
Deer Creek-Cottonwood	UT	3.0	Mar. 15, 1991.
Soldier Creek	UT	3.6	Jan. 21, 1993.
Lynch No. 37	KY	3.8	Aug. 3, 1994.
Lynch No. 37	KY	3.6	Oct. 5, 1994.

[1]Prebump shock 12 h and 6 h, respectively, before bump occurrence underground.

An explanation for the range in levels of observed seismicity may be found by examining the mechanisms responsible for many of the rock bursts in deep South African and Canadian hard-rock mines. Morrison and MacDonald (*22*) have shown that rock bursts are often associated with slip along preexisting geologic discontinuities adjacent to mine openings. Stick-slip movements on these discontinuities produce a sharp, instantaneous acceleration within the strata around the mine structure. As seismic waves propagate through the mine, pillars are compressed, then extended. This causes an immediate increase in load, resulting in a potentially unstable stress state. During the next instant, load is removed, which lowers confinement and can initiate an unstable state.

The level of mining-induced seismic activity coming from U.S. coalfields suggests that earthquake-like sources may indeed be partially responsible for pillar damage underground. Evidence at one site suggests that the seismic source was over 30 m above the mine opening and may have been associated with slip between large blocks of strata over or adjacent to longwall gob areas. At other sites, the source of the seismicity appears to be within the mine structure. These events generally have lower values of seismicity, possibly resulting from the dissipation of energy into a mine opening. These data suggest that there is a weak correlation between the magnitude of surface shaking and the degree of destruction experienced underground.

EXAMPLES FROM THE USBM COAL BUMP DATABASE

BUMP EXPERIENCES AT SPECIFIC MINES

The sections below provide an overview of many events represented in the USBM Coal Bump Database. The authors refer often to the L. S. Wood, Gary No. 2 and No. 6, Moss No. 2, and Beatrice Mines to highlight various aspects of U.S. bump experiences. Therefore, a brief description of these operations is warranted.

L. S. Wood Mine

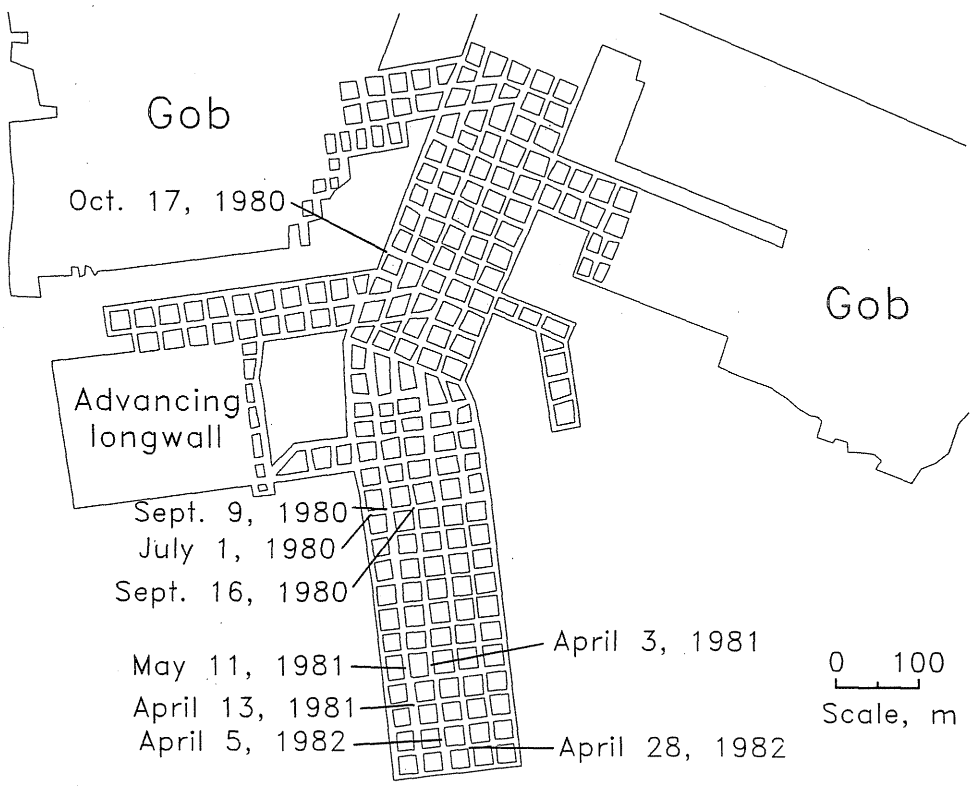
The L. S. Wood Mine near Redstone, CO, was developed in the 2-m-thick B Coalbed in the early 1970's by Mid-Continent Resources. Initially, the mine employed approximately three continuous mining machines and developed pillar sections to the left and right of its main entry system (figure 2). Because the mine was originally a drift mine, overburden in the early years was low. However, overburden rapidly increased as the main entries were developed downdip. By the time the first longwall became operational, the overburden was approaching depths of 500 m. The mine was plagued with methane gas emissions and displacement faults.

Gary No. 2 and No. 6 Mines

The Gary No. 2 and No. 6 Mines, operated by U.S. Steel Mining Co., were first opened in 1903 in the Pocahontas No. 4 Coalbed (*9*). These mines are located adjacent to each other in McDowell County in southern West Virginia. The coalbed crops out on the mine property, but rugged terrain accounts for overburden thicknesses approaching 460 m. In conjunction with thick overburden, strong roof and floor lithologies are present. The mine roof over much of the property includes a massive sandstone up to 45 m thick.

The Gary Mines have a long, fairly well-documented coal bump history. Duckwall (*9*) noted that bumps

Figure 2
Location and Dates of Bumps Reported at L. S. Wood Mine, Redstone, Pitkin County, CO.



occurred as early as 1930 on the mine property, but they did not appear to be serious events. Records were not maintained until 1945, when injuries were associated with bumps. From 1945 through the 1950's, the history of bumps at these mines and U.S. Steel's efforts to prevent them were well documented through company memoranda, USBM reports, journal articles, and conference papers.

Bumps at the Gary Mines in the 1950's were associated with a variety of factors (figure 3). Mining in the first half of the 20th century undoubtedly resulted in the bump-prone mining scenarios faced in the 1950's. For example, mining was conducted adjacent to gob areas created decades earlier, retreat sections operated on groups of pillars of irregular sizes and shapes, and much of the mining was directed to recovering barriers between old workings.

Moss No. 2 Mine

The Moss No. 2 Mine near Dante, VA, was extensively mined by Clinchfield Coal Co., from the 1950's to the 1970's in 1.2 m of the Tiller Coalbed. During this time, five bumps were recorded and are part of the USBM database (figure 4). The mine utilized a multientry development system, followed by room-and-pillar mining. Extraction of pillars was accomplished primarily by the split-and-fender method. Rooms were typically driven 23 m apart and 6 m wide with crosscuts every 23 m. More than 100 sections were developed and pillared using some variation of this method. One of the first longwall sections in the United States was employed at this site in the late 1960's and 1970's. Twenty-two longwall panels of varying length were extracted.

Many conditions associated with bumps were found at this mine. Overburden at the mine ranged from zero at outcrop to greater than 400 m under the highest ridges. The roof stratum was dominated by thick sequences of massive sandstone. Numerous paleochannels scoured the coalbed, limiting the development of the mine in several areas. Locally, this massive roof had the ability to span large areas of the gob. Additionally, thick pockets of shale were noted adjacent to the sandstone channels. The floor stratum was almost always referred to as a hard, dense, silty shale. The Moss No. 2 Mine property was also overlain by the minable Upper and Lower Banner Coalbeds. The Upper Banner Coalbed was about 250 m above the Tiller Coalbed, but it undoubtedly had a considerable effect on the stress transfer process.

Beatrice Mine

The Beatrice Mine near Keen Mountain, VA, reported 24 bumps between 1972 and 1981 (figure 5). This high number of occurrences spanned the spectrum of mining conditions. Therefore, examples from this operation will be referred to often in this paper. The Beatrice Mine worked about 2 m of the Pocahontas No. 3 Coalbed at overburden ranging from 300 m near the shaft bottom to over 700 m under the highest ridges. A massive, quartzite-rich sandstone was found throughout the property. In places, this extremely hard stratum came in direct contact with the coalbed. However, in most locations, a very competent siltstone occupied the interval between the coalbed and the overlying sandstone. The floor was often reported as a sandy shale. No mining occurred above or below the Beatrice Mine.

BUMPS ASSOCIATED WITH VARIOUS MINING METHODS

The examples below have been grouped according to the type of mining system at various bump sites. These mining systems can generally be categorized as (1) development mining, (2) pillar retreat mining, (3) barrier splitting, and (4) longwall mining. This grouping facilitates descriptions of the impact of the particular mining method on bump occurrence. Examples of bumps associated with the various mining methods are intended to highlight the shortcomings and/or successes of each mining method and related practices and to indicate the influence of conditions and circumstances unrelated to mining method.

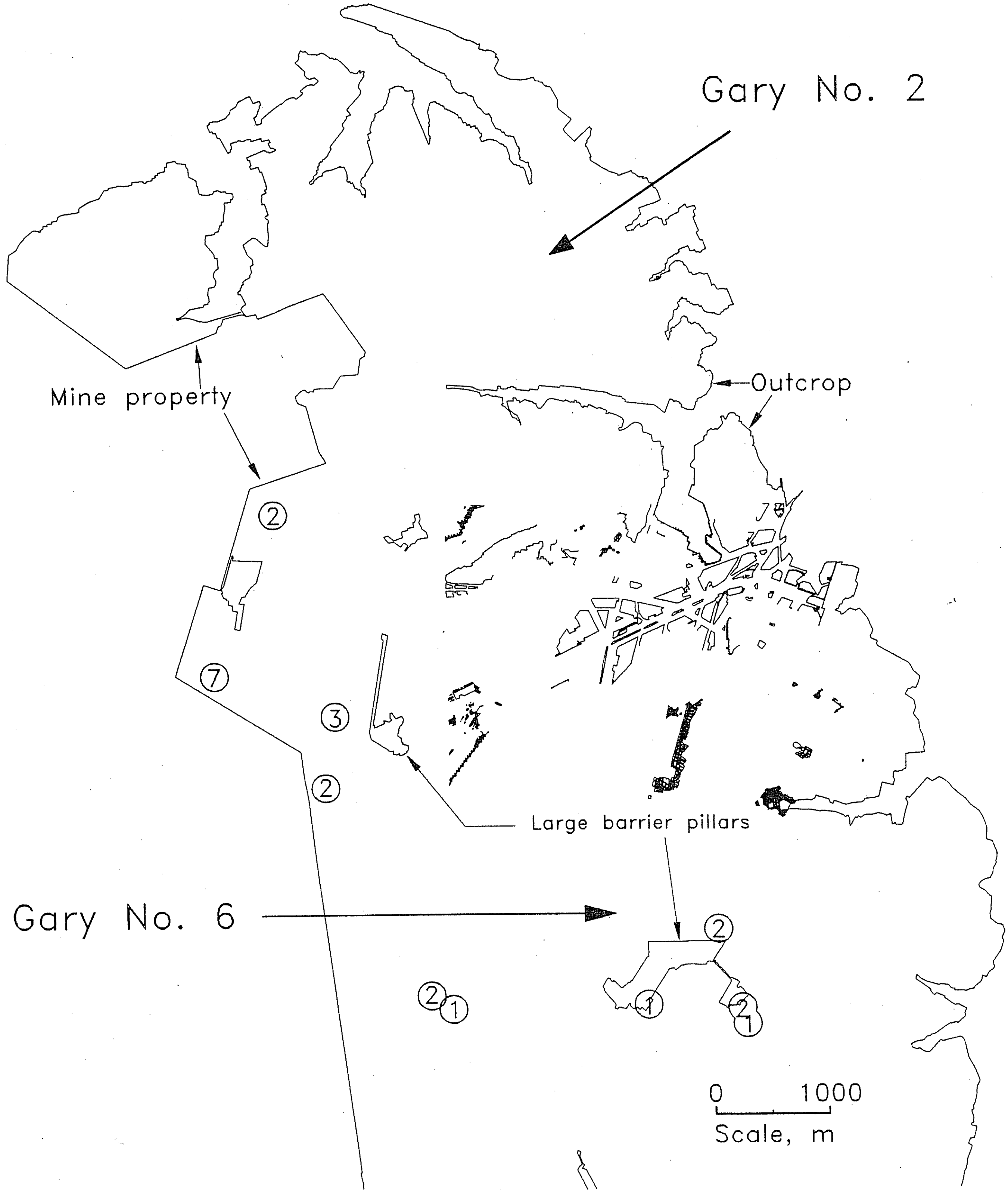
Development Mining

Development mining refers to the extension of entries and crosscuts into undeveloped portions of the coal reserve. Generally, extension of mains, submains, butt sections, gate roads, and setup and bleeder entries represent development work. Because this activity involves the initial stages of mining and does not produce abutment loading, bumps should be generated less frequently.

Twenty-one bumps were identified in the total USBM database as occurring during development mining (table 5). Three were in the Eastern United States and 18 were in Utah and Colorado.

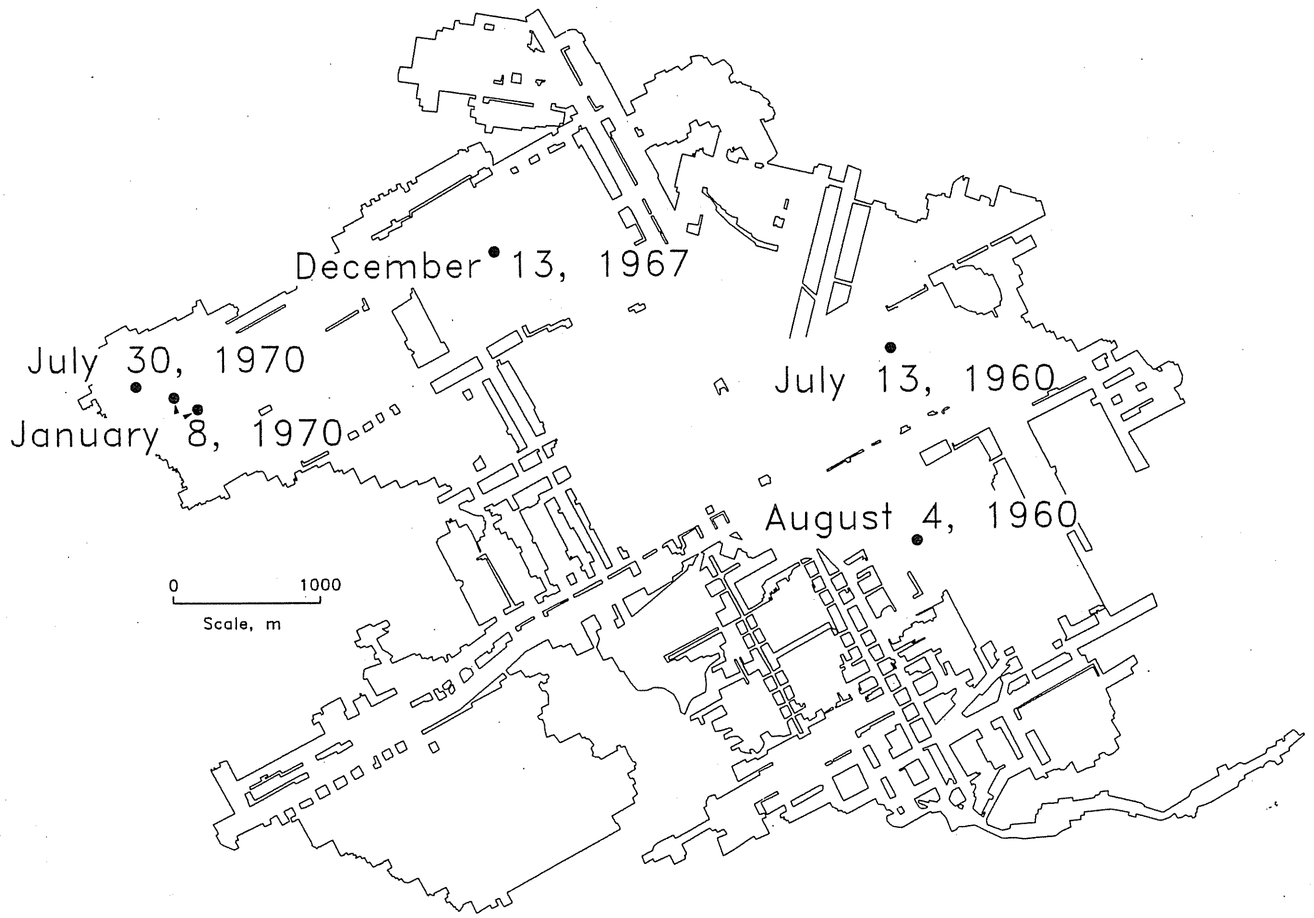
The L. S. Wood Mine experienced nine bumps during development of the Main Slope section between July 1980 and April 1982. All these bumps were associated with overburden greater than 600 m. Four bumps took place near one of two adjacent gobs (figure 2). Although the bumps exhibited tremendous force, the skilled work force at the mine was always able to avoid being "caught" by the bump so no miners were injured in any of these events. Eight bumps occurred during or shortly after mining and displaced large volumes of rib coal near the mining zone.

Figure 3.
Location of Bumps Reported at Gary No. 2 and 6 Mines, McDowell County, WV.



Circled numbers indicate number of bumps at various locations.

Figure 4
Location and Dates of Bumps Reported at Moss No. 2 Mine, Russell County, VA.



Significant quantities of methane gas were liberated in association with several bumps. After the bump on April 13, 1981, methane concentrations measured as high as 5 pct. Five of the bumps occurred under more than 750 m of overburden far from the gob or faults. In situ coalbed gas pressures were undoubtedly high, for these bumps showed high methane emission characteristics. These events may be better defined as gas outbursts. The bump problems at the L. S. Wood Mine and two other Mid-Continent operations were severe enough to warrant the elimination of gate entries by employing the advancing longwall system.

At the Beatrice Mine, development work was underway in the No. 9 unit section off the Skip South Mains, approximately 70 m from an adjacent gob area (figure 6), when there was a violent bump in the face area on July 24, 1976, that injured three miners. Abutment loading from the adjacent gob area may have contributed to the bump. Therefore, this event could be explained as resulting from the barrier-splitting operations. However, because the gob was 70 m away and the solid block of coal being mined was approximately 230 m wide, it appears more appropriate to categorize it as a development bump. Other significant factors at this site were the very massive, stiff, siltstone roof and floor strata and overburden averaging 600 m in depth.

Table 5.—Conditions associated with development mining

Mine	Number of bumps	Condition
L.S. Wood	4	Close to gob section.
	9	Overburden deeper than 600 m.
	2	Destressing.
Beatrice Mine ..	1	Close to gob section.
	1	Overburden deeper than 600 m.
Deer Creek	1	Close to gob section.
Dutch Creek No. 1	1	Displacement faults.
Sunnyside No. 2	1	Displacement faults.
Total ...	21	

Figure 5
Location and Dates of Bumps Reported at Beatrice Mine, Buchanan County, VA.

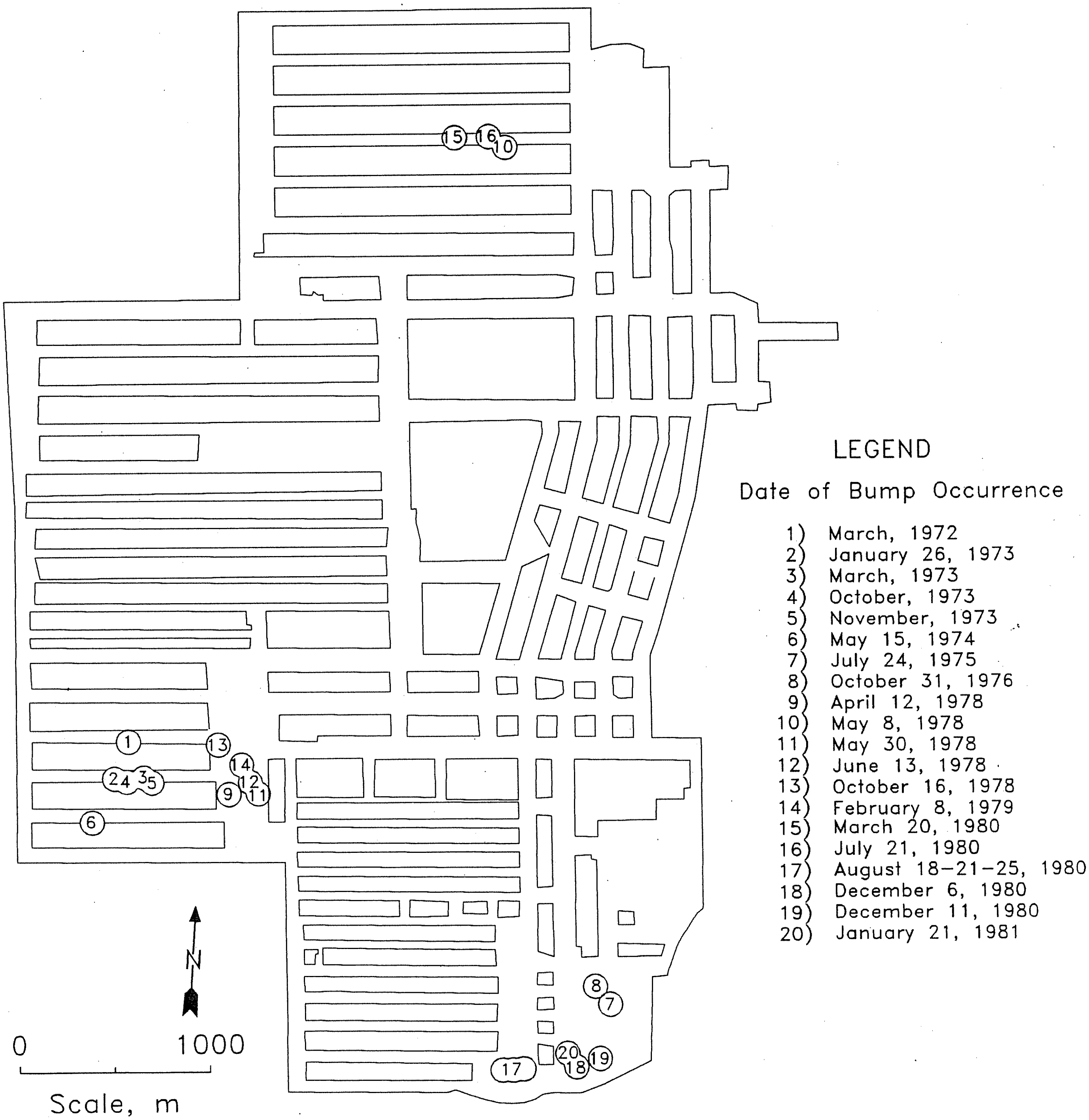
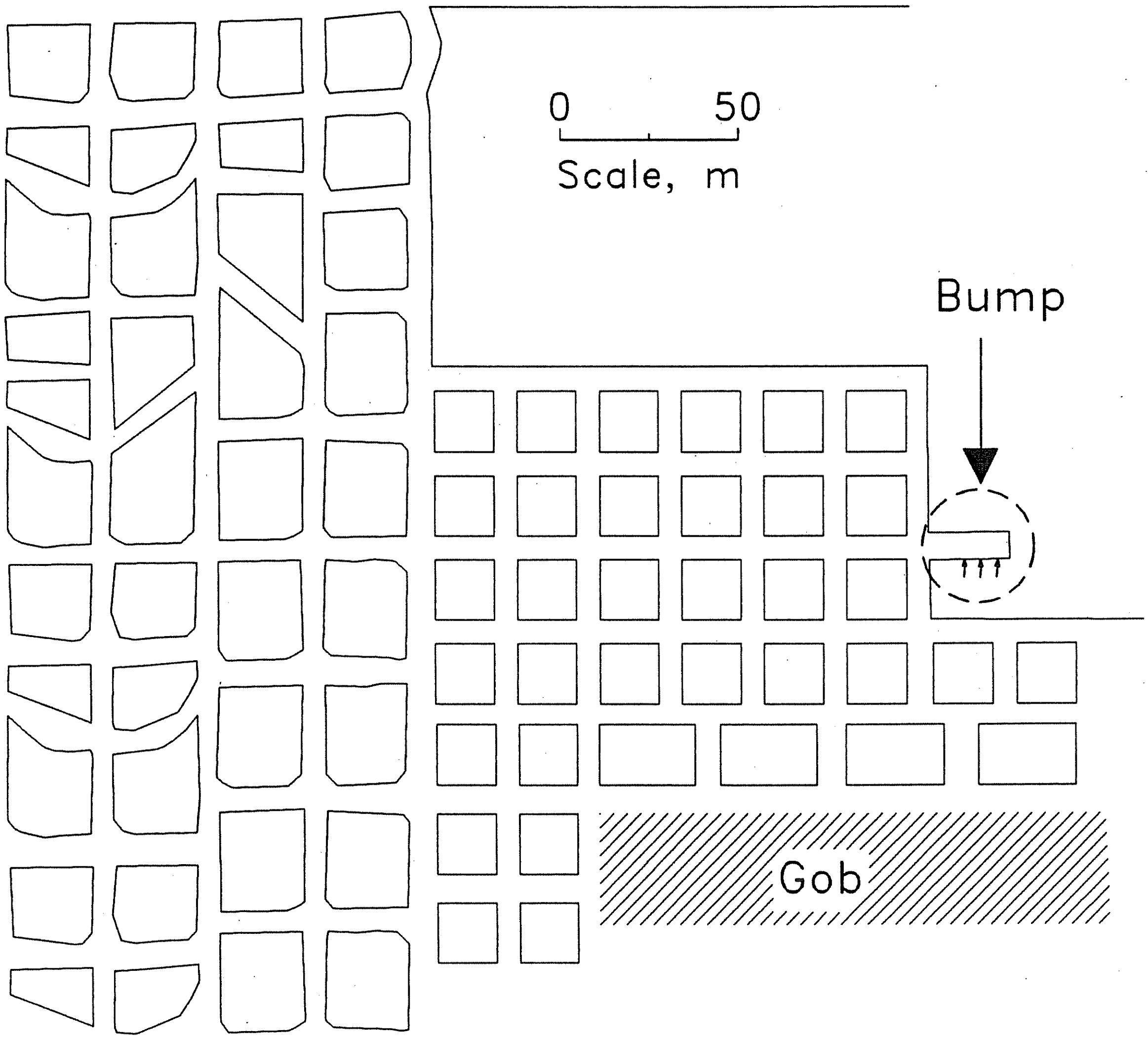


Figure 6
Violent Bump During Development of Pillar Section Within Beatrice Mine That Injured Three Miners.



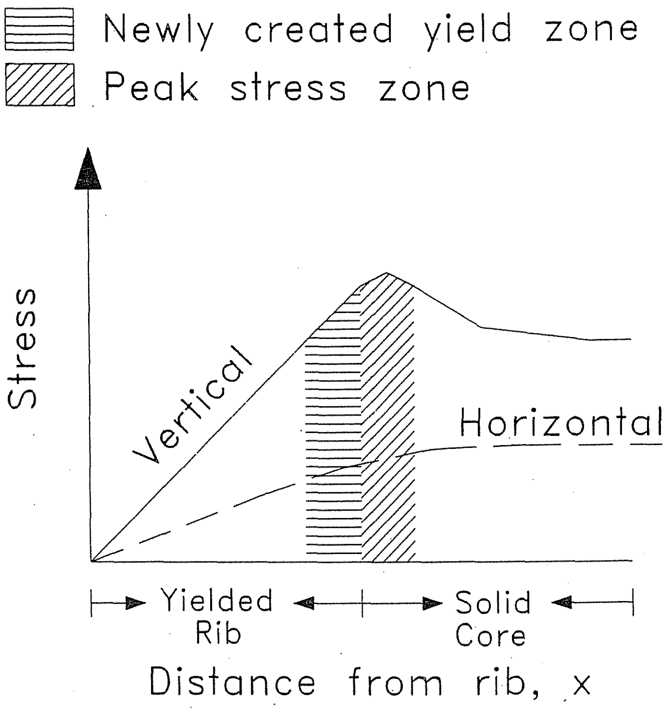
Pillar Retreat Mining

Many bumps have been recorded on continuous miner sections where rows of chain pillars 15 to 30 m wide were extracted near the gob. Individual chain pillars are extracted very rapidly, causing loads to shift before the adjacent pillars can redistribute load in a controlled manner. Pillars in such a range of sizes appear to have difficulty accommodating excessive amounts of strain energy, thereby increasing the likelihood that the pillars will bump. When a pillar is adjacent to the gob, the combination of considerable rib crushing and abutment loading can produce great confining pressures on the solid core (figure 7). With few exceptions, massive strata exist in the immediate and main roof overlying bump-prone coal. These strata can cantilever, adding load to the pillar. Mining in the yielded rib releases confinement and may result in violent solid-core failure.

Pillars adjacent to gob areas experience elevated loading conditions from the unsupported strata above the gob (figure 8*A*). Certain mining geometries, such as a large pillar surrounded by smaller pillars, can concentrate stress (figure 8*B*). Large pillars can be imagined as stiff structures that tend to deform or converge less than smaller, less stiff pillars. These larger structures tend to gather load, increasing the potential for violent failure as the smaller pillars are extracted within and around them.

In addition, section-wide mine plans and extraction sequences can contribute to bumps. For example, overlapping abutment pressures from converging gob lines

Figure 7
Generalized Vertical Stress Distribution Within Coal Pillar.



(figures 8*C* and 8*D*) and overlying large pillars or barriers in multiple-seam mining operations can cause excessive pressures (figure 8*E*). Fortunately, all of the preceding conditions lend themselves to engineering solutions, many of which are discussed later with actual examples.

Fifty pillar retreat bumps have been identified in the USBM database. Forty-eight occurred in conjunction with full-extraction mining, whereas two occurred during partial pillar mining. Geology, destressing, and multiple-seam mining were the principal contributing conditions associated with bumps during pillar retreat mining operations. Six events were associated with unique geologic conditions, three with destressing, and two with multiple-seam mining.

On February 16, 1951, a large bump occurred in the Gary No. 2 Mine, killing four miners and injuring six (figure 9). The force of the bump threw four miners against the loading machine, while others were thrown against cribs and timbers. One miner 50 m away was injured by the force of the bump. Earth tremors were felt on the surface within a 3-km radius of the bump's center. This bump, however, dislodged only a relatively small amount of coal. This event may well exemplify mining-induced seismicity with magnitudes similar to those shown in table 4. Possibly the overlying strata had shifted by a considerable amount toward the gob, releasing large amounts of energy but not significantly damaging the mine workings.

Three pillar retreat bumps were reported at the Moss No. 2 Mine. The first occurred on August 4, 1960, in the 2 Right section (figure 10). Extensive arrangements of pillars and pillar remnants had been left during mining, giving the strata above the gob a support system that inhibited the roof caving process.

The second bump occurred on December 12, 1967, in the 6 Right section (figure 11). This bump was associated with a small overhang of roof that was in turn associated with a distinctive change in roof lithology. The inby part of the section had been free of bumps because of the weaker interbedded shale-and-sandstone roof. The second bump took place within the transition zone to the more competent sandstone roof.

The third bump, on July 30, 1970, had several contributing factors (figure 12). The Upper Banner Coalbed was mined 250 m above the Moss No. 2 Mine. The bump occurred as the section was retreating from under the overlying remnant pillars. A considerable amount of stress must have been transferred through these remnant pillars. The bump was obviously violent, for it displaced the continuous mining machine several meters (figure 13).

A bump in the No. 1 South section of the Beatrice Mine on May 30, 1978 (figure 14), was similar to those experienced earlier at the Olga Mine, which had led to the development of the Olga pillar extraction sequencing technique. This method is discussed in greater detail on page 60. Such a sequence uses a continuous mining machine to mine certain highly stressed pillars selectively and move abutment stresses within a mine section in a controlled manner.

Barrier-Splitting

Barrier-splitting is generally done in association with full-extraction pillar operations, most often during the final stages of a mine's life when the barrier pillars along the main access entries are extracted. However, a barrier block is sometimes mined in conjunction with a pillar retreat section for some operational reason. Typically, a mine will begin to extract barriers in the most remote portions of the mine and work back toward the main portal areas. Use of the barrier-splitting technique has decreased owing to inherent difficulties associated with this process.

The USBM database contains references to 36 bumps associated with barrier-splitting operations. As indicated earlier, barrier-splitting often involves high-stress environments because these pillars are designed to carry abutment

Figure 8
Generalized Examples Showing How Different Full-Extraction Mining Scenarios Transfer Load to Pillar Structures.

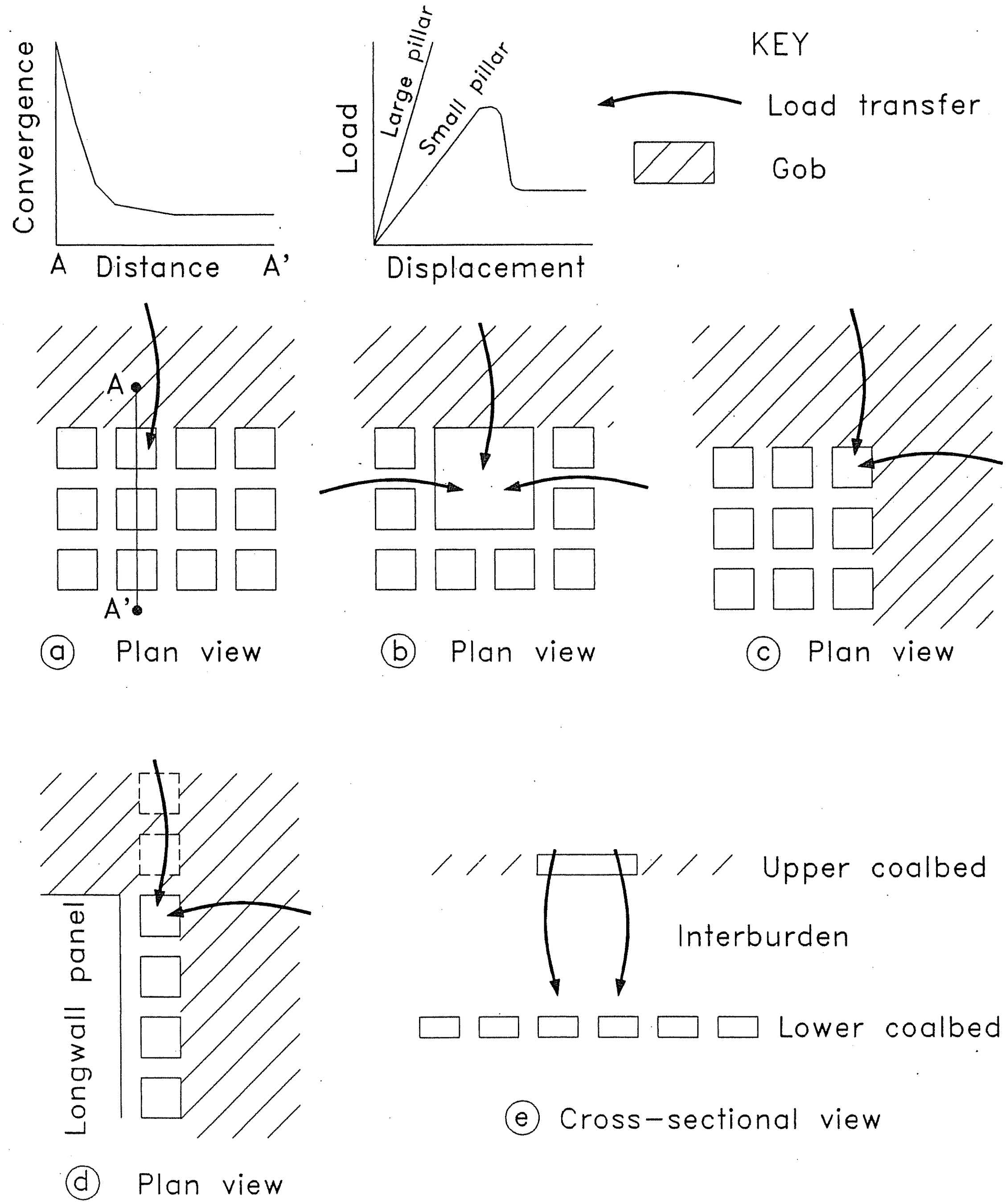


Figure 9
Fatal Pillar Retreat Coal Bump at Gary No. 2 Mine, February 16, 1951.

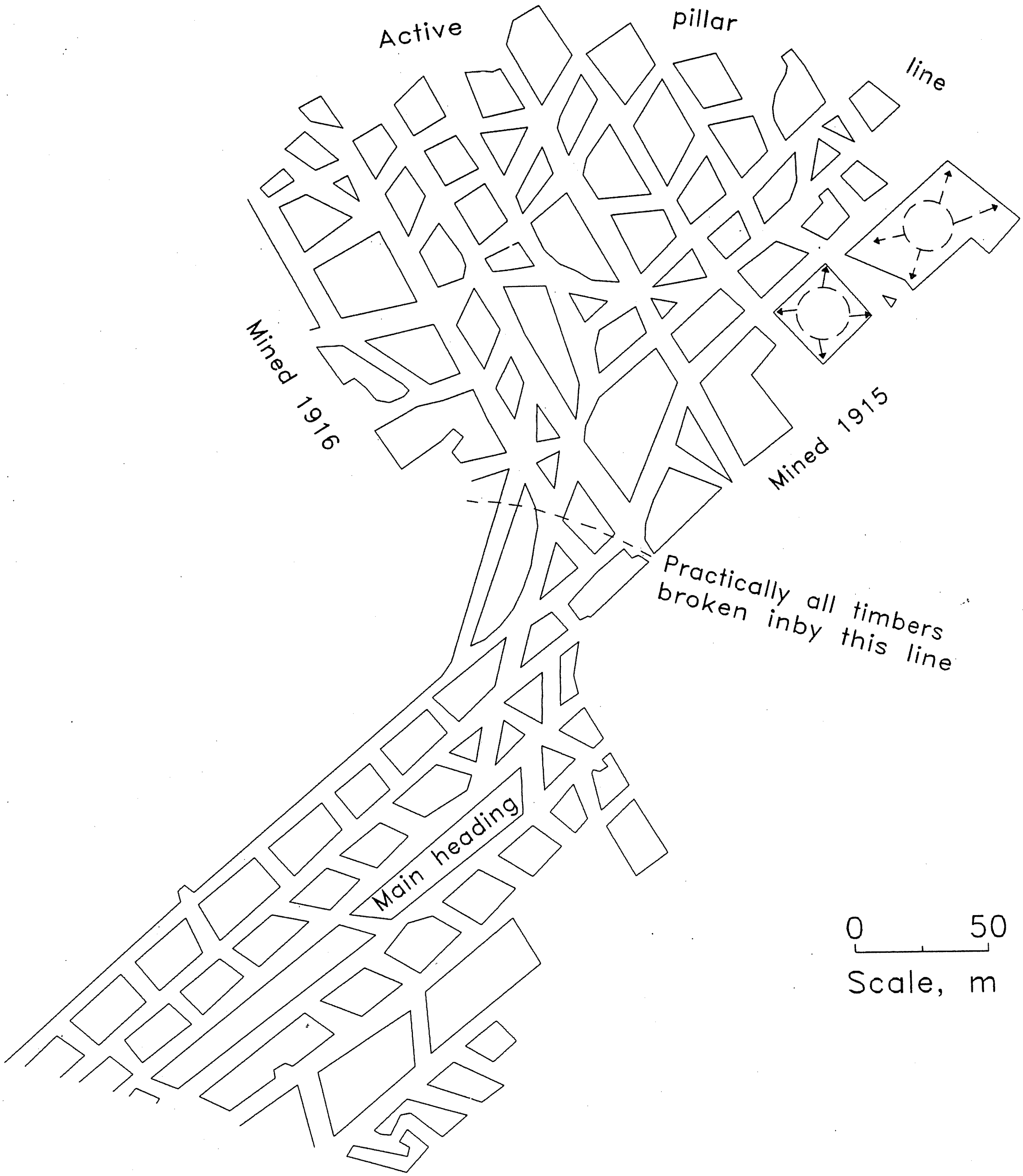
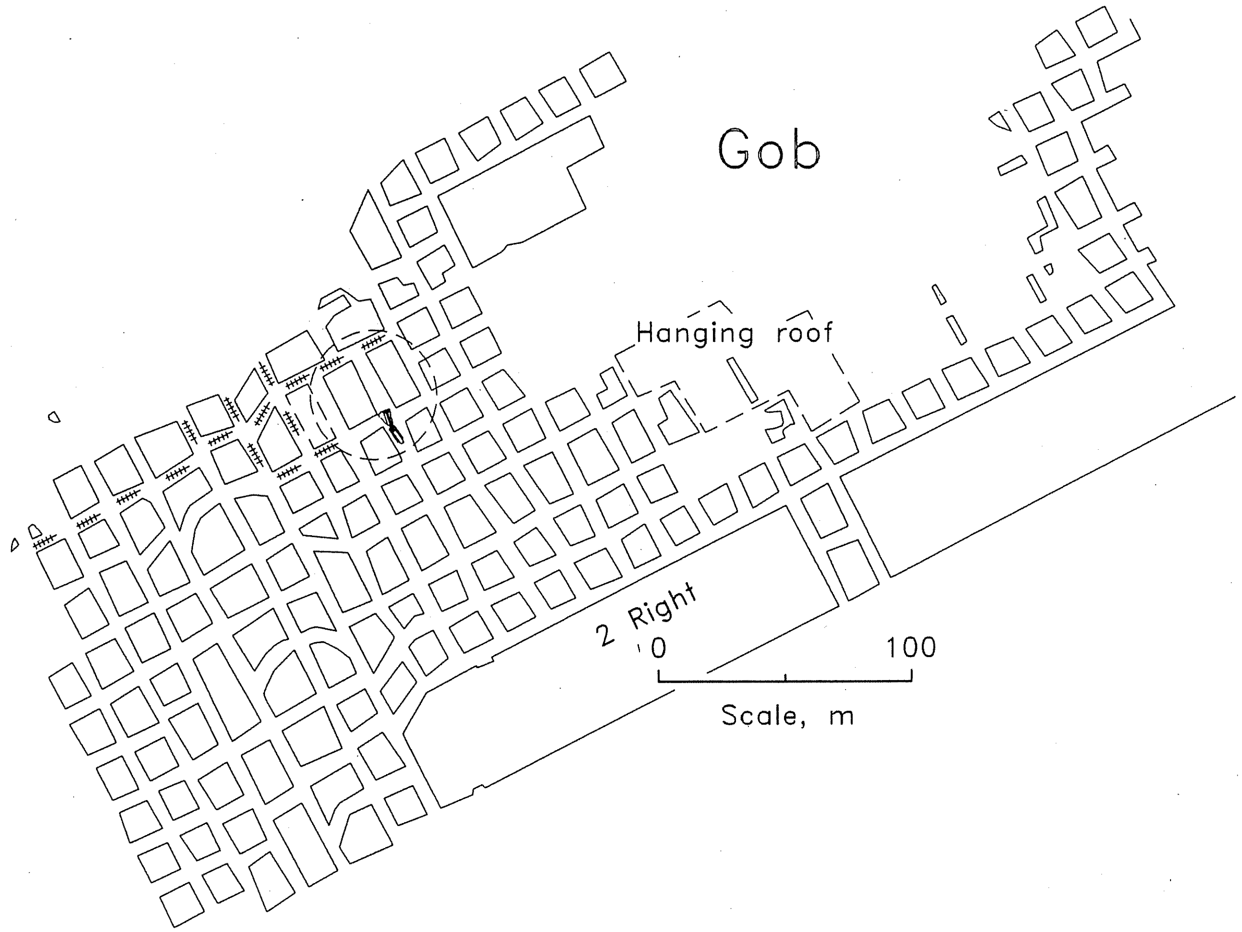


Figure 10
Effects of Pillar Remnants and Hanging Roof Strata on Pillar Retreat Bump at Moss No. 2 Mine, August 4, 1960.

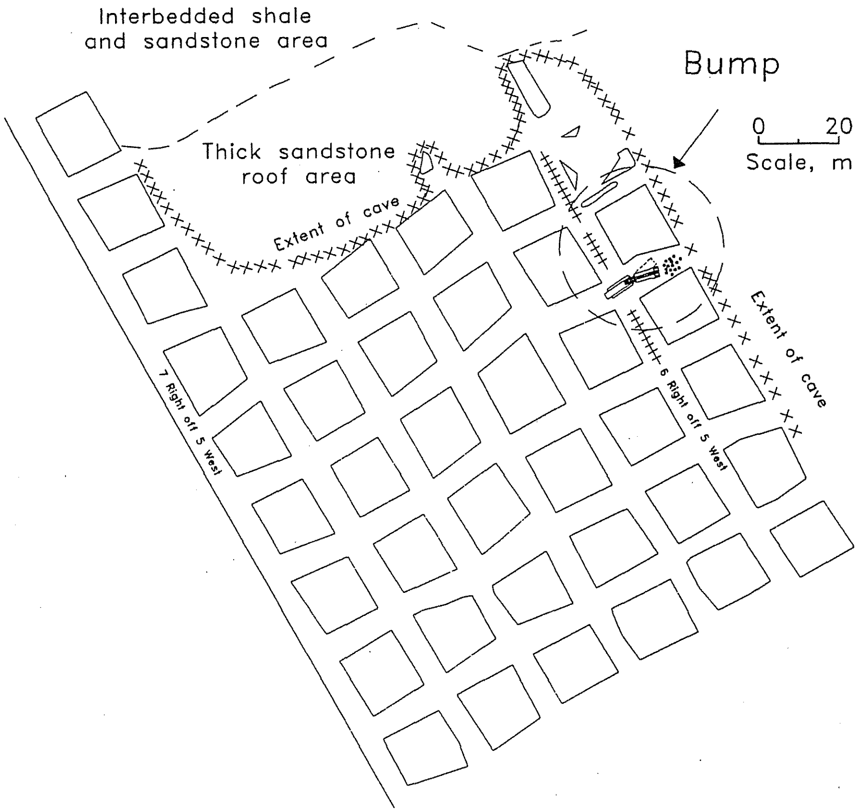


loads. The stress fields and geologies at these operations generally provide conditions conducive to bumps. There were a few instances in which anomalous factors controlled the occurrence of bumps during barrier-splitting. Of the 36 bumps associated with barrier-splitting operations, only two were associated with multiple-seam mining and four were associated with destressing techniques. Also, in most cases, injuries were the result of contact with bumped coal. Associated hazards were limited to one roof fall at the Peabody No. 31 Mine and an ignition at the Gary No. 6 Mine.

Bumps at the Gary No. 2 and No. 6 Mines in the early 1950's illustrate the nature of events typical of barrier-splitting operations. At the No. 6 Mine, barrier-splitting was used in several locations as sections developed decades earlier were retreated. Development of the mine over a long period by hand-loading resulted in an irregular mine plan; bumps occurred under a variety of circumstances and often involved complex geometries that resulted in excessive stress concentrations. Cut sequencing in bump-prone areas at the No. 6 Mine apparently evolved on a case-by-case basis to accommodate the irregular nature of the remaining coal reserves. However, over time, reserves at the Gary No. 2 Mine were developed and retreated using a more consistent method that eventually evolved into the thin-pillar mining system, described on pages 60-61.

Figure 15 illustrates the Gary No. 2 Mine plan in the vicinity of a bump in the 12-Left section in January 1951. In this mining plan, four-entry development sections were driven at intervals off a set of main entries. Sections were separated from one another by a barrier block that was developed just ahead of the retreat line during second mining. However, as indicated in figure 15, bumps were

Figure 11
Effects of Roof Strata Characteristics on Pillar Retreat Bump at Moss No. 2 Mine, December 12, 1967.



encountered in some locations. USBM researchers, including Holland, found several factors they believed influenced bumps in this system and elsewhere in the Gary No. 2 and No. 6 Mines. For example, pillars of irregular sizes were located adjacent to the retreat line, secondary development was done within the abutment zone, and rooms were not driven in proper sequence. As a result of these and several other related issues, U.S. Steel, the owner, developed another mine plan for the Gary No. 2 Mine.

The next-generation mine plan differed from earlier ones in several respects. Figure 16 indicates, for example, that secondary development took place farther outby the retreat line and adjacent sections were retreated simultaneously; when all sections were activated, the length of the pillar line was approximately 670 m. Nevertheless, bumps were encountered in early 1952. Company personnel indicated that poor caving in the gob inby 18 Left contributed to squeeze and bump conditions. Secondary development well in advance of the retreat line appeared to allow the pillars to crush and the massive sandstone main roof to settle into the gob rather than breaking and falling. Duckwall (c. 1952) notes that "it was possible to travel a distance of [60 m] or more into the mined-out area which was free of falls" in 18 Left. Based on observations of strata behavior and bump experiences at the Gary No. 2 Mine, U.S. Steel engineers sought to incorporate beneficial aspects of each of the mining systems into a new system, which became known as the thin-pillar mining method.

The Gary mines exhibited a long history of coal bumps under a variety of circumstances. The same held true for both the Moss No. 2 Mine (figure 17) and the Beatrice Mine (figure 18). In contrast, the Moss No. 3 Mine in Dickenson County, VA, experienced an isolated bump occurrence; that is, conditions conducive to bumps apparently were not pervasive at the site. Mining began in 1958 at the Moss No. 3 Mine, portal A, and proceeded for nearly 20 years without a reported coal bump event. However, on November 4, 1977, bump conditions were encountered during barrier-splitting operations, resulting in the death of a continuous mining machine helper (figure 19).

The Thick Tiller Coalbed reportedly averaged 3 m thick, in the area of the Moss No. 3 bump. The barrier

Figure 12
Effects of Overlying Remnant Pillars on Pillar Retreat Bump at Moss No. 2 Mine, July 30, 1970.

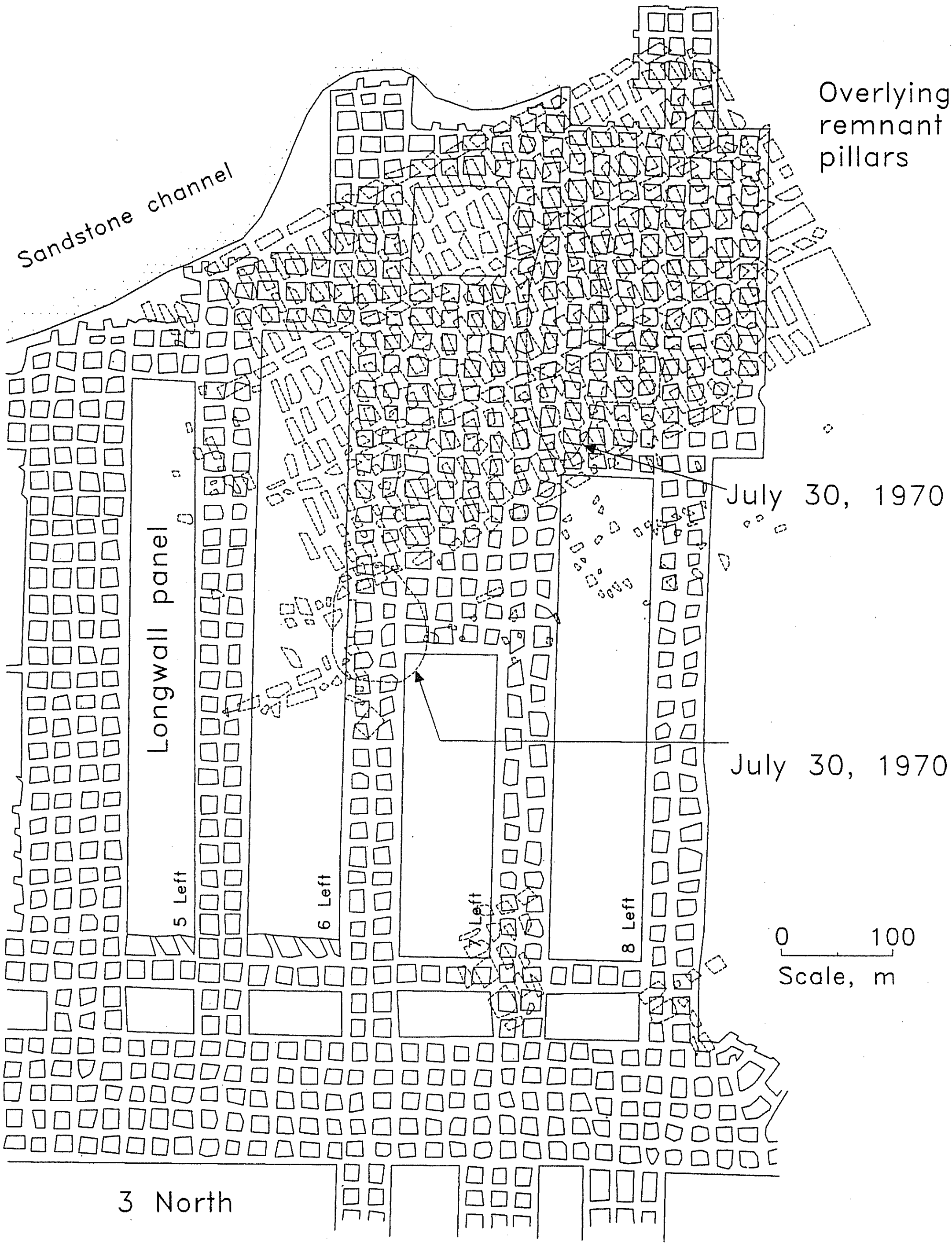
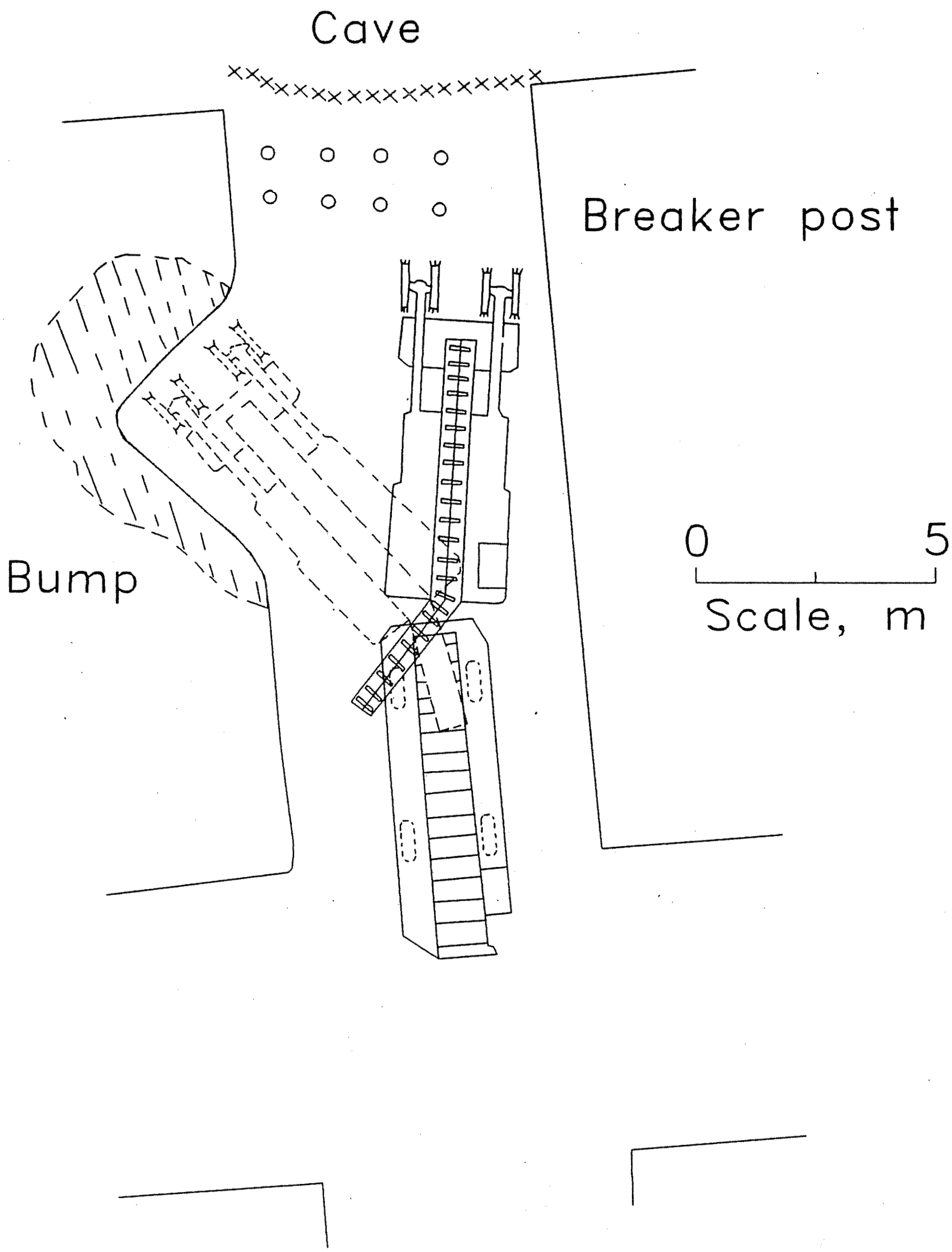
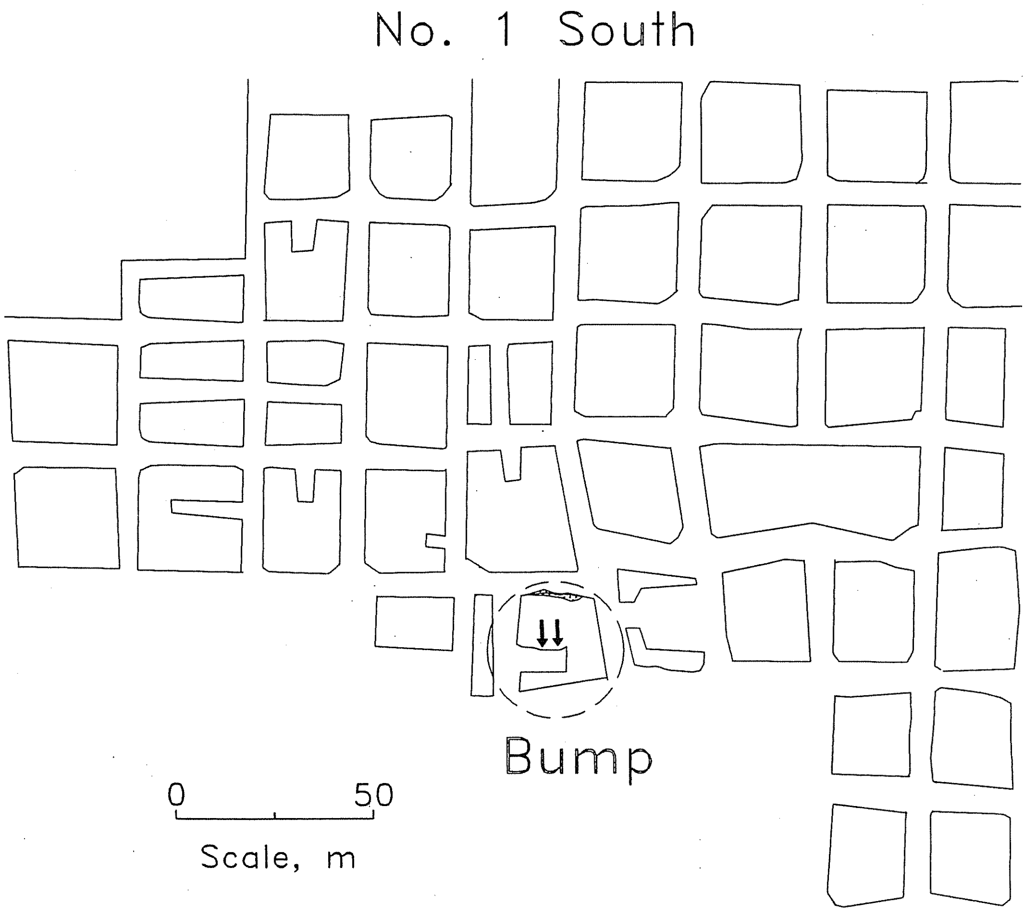


Figure 13
Detailed View of Bump at Moss No. 2 Mine, July 30, 1970.



Note position of caved roof line and postbump continuous mining machine (solid lines).

Figure 14
Pillar Retreat Bump at Beatrice Mine, May 30, 1978.



Note use of sequential pillar mining technique.

Figure 15
Barrier-Splitting Bumps in Adjacent Sections With Similar Layout Positions, Gary No. 2 Mine, January 1951.

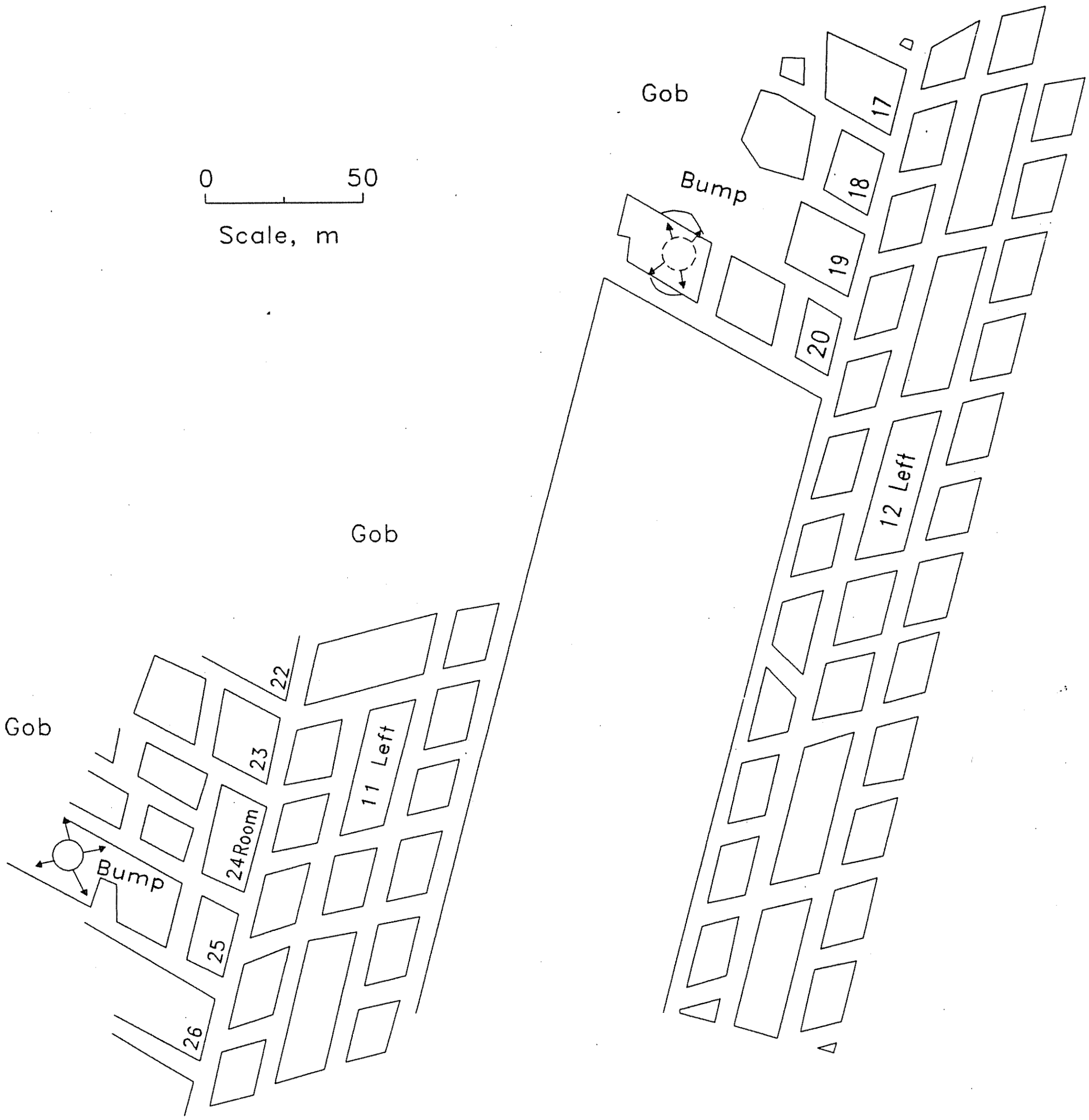
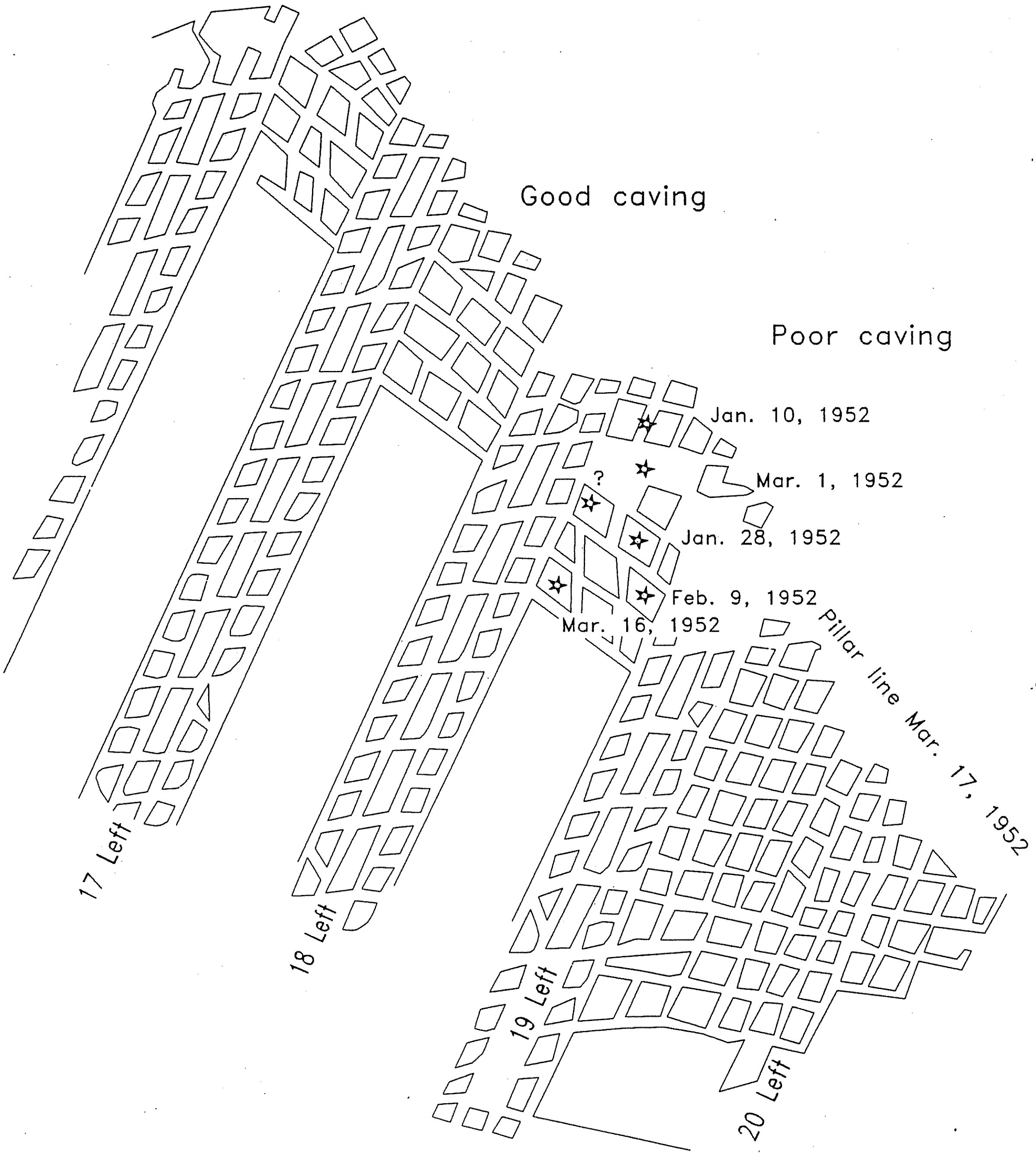


Figure 16
Multiple Bump Events During Splitting of 18 Left Barrier at Gary No. 2 Mine, 1952.



Star denotes location of mountain bump.

Figure 17
Barrier-Splitting Bump at Moss No. 2 Mine, July 13, 1960.

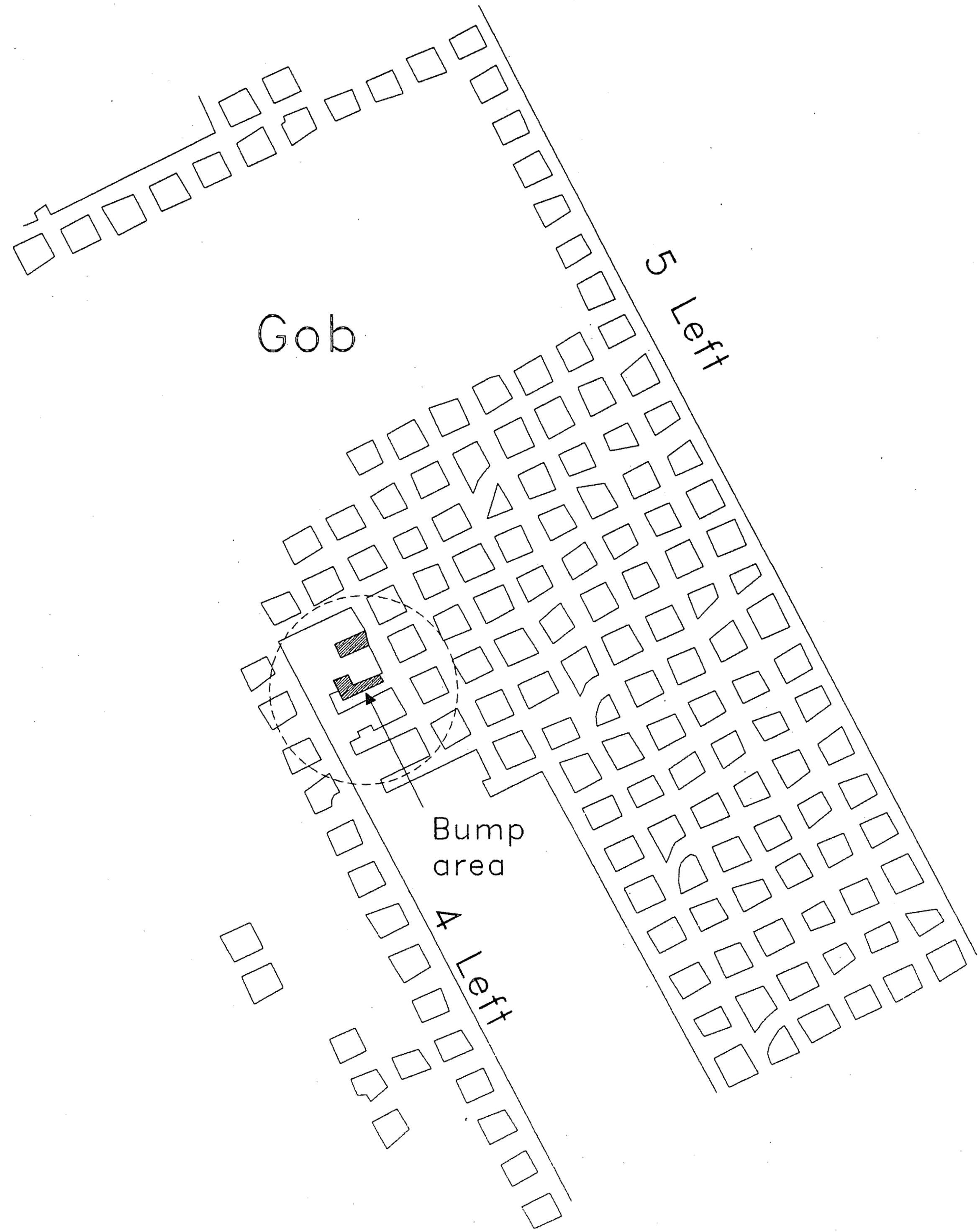


Figure 18
Barrier-Splitting Bump at Beatrice Mine, December 11, 1980.

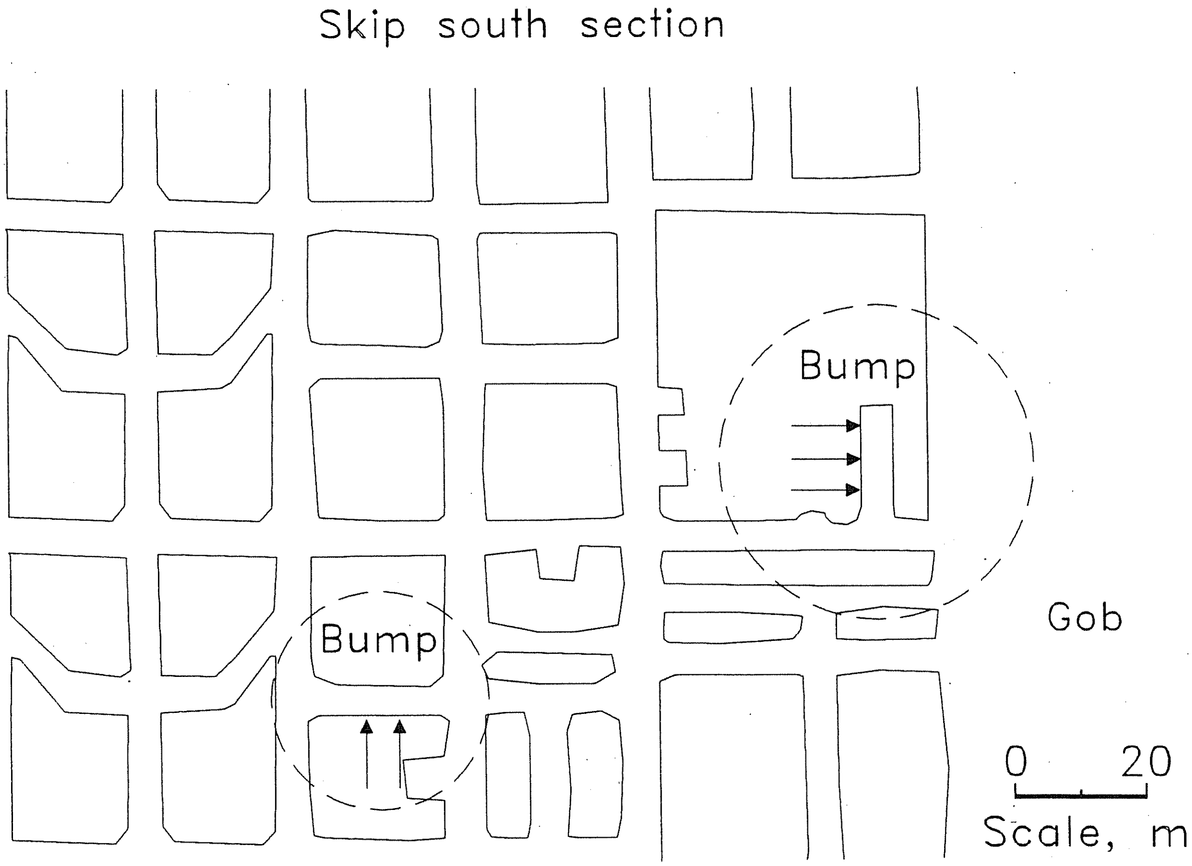
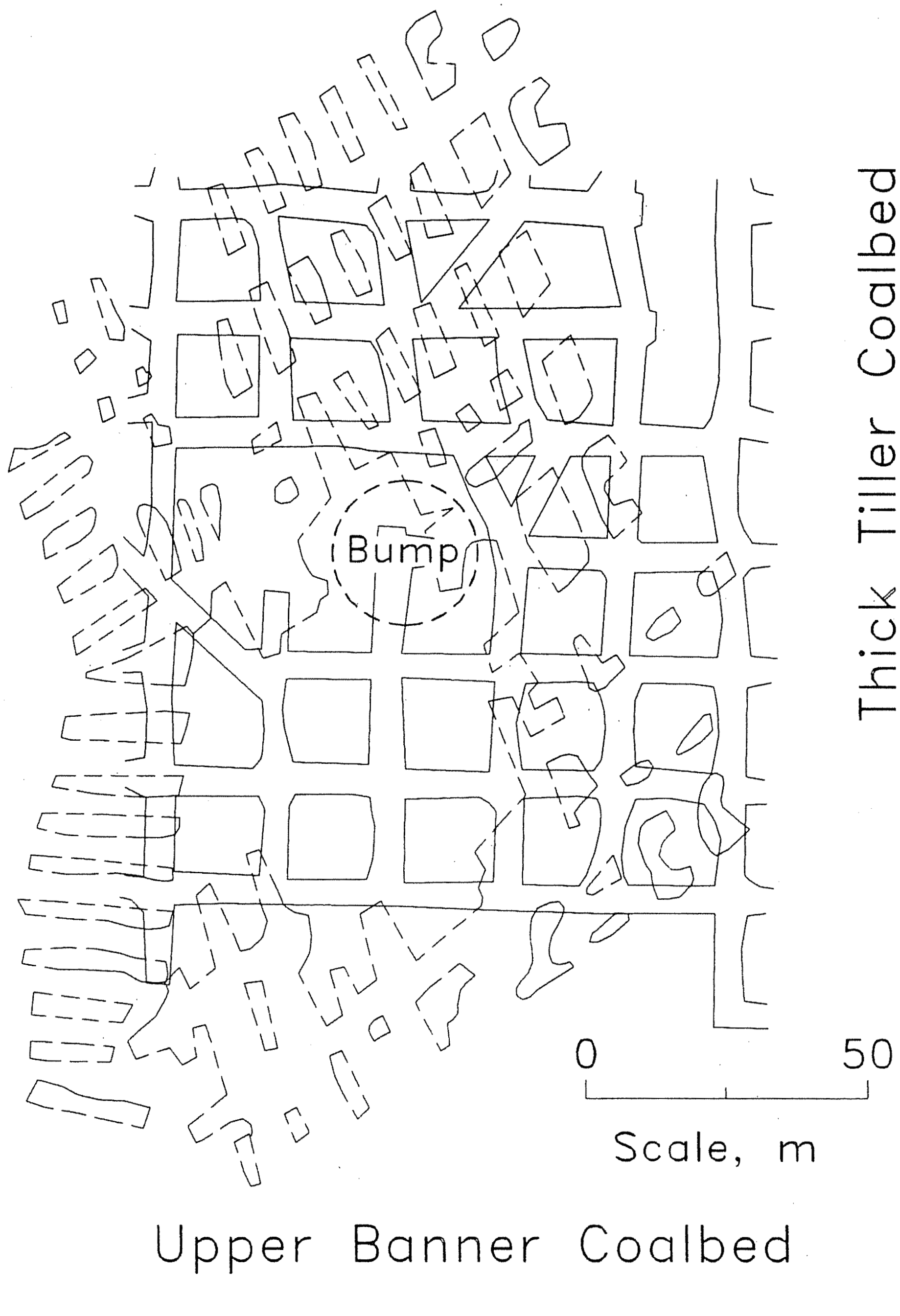


Figure 19
Effects of Multiple-Seam Mining on Barrier-Splitting Bumps at Moss No. 3 Mine, November 4, 1977.



pillar measured about 116 m long by 43 m wide. Adjacent pillars were generally square and appeared to be spaced on 24-m centers. Reports of the Moss No. 3 coal bump did not indicate overburden or interburden thickness between the Thick Tiller and superjacent Upper Banner Coalbeds at the bump site. However, it was concluded that the combined effects of abutment loads generated as a result of barrier-splitting and retreating, along with concentrated stresses caused by overmining, created an excessive stress condition. Isolated pillars that were left in the Upper Banner Coalbed during second mining apparently intensified the stress interaction (figure 19).

Longwall Mining

Since 1970, coal bumps have occurred within gate entry systems and along the faces of U.S. longwall mines. In many cases, these bumps were located where the gate entry pillars were unable to prevent abutment loads from "riding over" onto the mined longwall panel (*17*). In other instances, the bumps responded to either gob caving adjacent to the longwall face or were associated with excessive gas pressures.

The USBM database contains 36 longwall coal bumps. Of these, 12 occurred along the longwall face, 7 within the tailgate, 2 within the headgate, 13 both along the face and within the tailgate entries, and 2 in setup or bleeder entries adjacent to the longwall panels. The most influential condition was the presence of multiple-seam mining, which was found in seven of the events. Five bumps occurred during destressing. Rolls in the structure of the coalbed being mined played an important function in two bumps at the Beatrice Mine. The most significant hazard associated with longwall mining bumps was ignition. Four such events were identified in the database, all of which occurred in Western U.S. longwall mines.

The early experience of longwall mining at the Moss No. 2 Mine clearly exemplifies how inadequate gate entry pillar design can contribute to bumps. Clinchfield Coal Co., the owner, was one of the first companies to implement longwall technology in the United States. The first longwall was laid out next to a mined-out room-and-pillar section approximately 480 m long and 170 m wide. This longwall panel was 60 m wide and 530 m long and was completed on October 11, 1969. Owing to the industry's lack of experience with the longwall mining system at that time, chain pillars measuring 17 by 17 m were believed to be an appropriate size between the first and second longwall panels (figure 20). The second longwall was 80 m wide and 600 m long. At the time of the bump, in which the longwall foreman was injured, the longwall face had retreated approximately 400 m.

Several contributing conditions were readily apparent. Multiple-seam mining occurred in the overlying Lower and Upper Banner Coalbeds. At the time of the bump, the longwall itself was progressing from under a group of unmined pillars (figure 20). Additionally, a large sandstone channel was located about 450 m inby the face and evidently contributed to the poor caving characteristics in the main roof member. Finally, the chain pillars left to protect the longwall panel were of inadequate size and too weak to withstand abutment loading from the adjacent gob areas.

The Beatrice Mine had extensive experience with bumps during longwall mining in its southern portion during the early 1970's (figure 5). Early longwall equipment included a plow and 94 hydraulic legs and canopy units having a capacity of 127 t. Many of the same conditions responsible for bumps at the Moss No. 2 Mine were also found at the Beatrice Mine. Overburden in the south longwall district ranged from 700 to 760 m. Roof strata in these areas apparently changed from a laminated shale and sandstone sequence with coal streaks to predominately sandstone intermixed with siltstone layers. The gate entry design at the Beatrice Mine consisted of a yield-yield-abutment system. The pillars were 24 m long and none were offset. The yield and abutment pillars were 9 and 24 m wide, respectively.

The first coal bumps associated with longwall mining at the Beatrice Mine took place in March 1972 on the tailgate of No. 3 development. At approximately the same panel location on the next panel, another bump occurred on January 26, 1973 (figure 21). Twenty minutes before, the section had been quiet. The bump exploded three chain pillars and completely filled the adjacent entries with loose coal. Several more bumps occurred during the mining of this and the adjacent panel. These events did not appear to be particularly difficult to address and did not result in any injuries.

A devastating bump two panels later in the tailgate entry of No. 6 development (figure 22) killed one miner and significantly injured three others. One of these miners was approximately 150 m away from the immediate bump location. The event was 350 m from the startup rooms in a longwall panel 140 m wide by 910 m long. A stall machine was utilized to keep the tail side of the longwall face advanced about 10 m ahead of the face conveyor (figure 23). This system was used to eliminate removal of the previously set cribs during retreat of the longwall face. James Gilley, a recognized authority on coal bumps (*31*), referred to this occurrence as a "shock impact bump." The

Figure 20
Effects of Overlying Remnant Pillars and Underdesigned Entry Pillars on Longwall Pillar Bump at Moss No. 2 Mine, January 8, 1970.

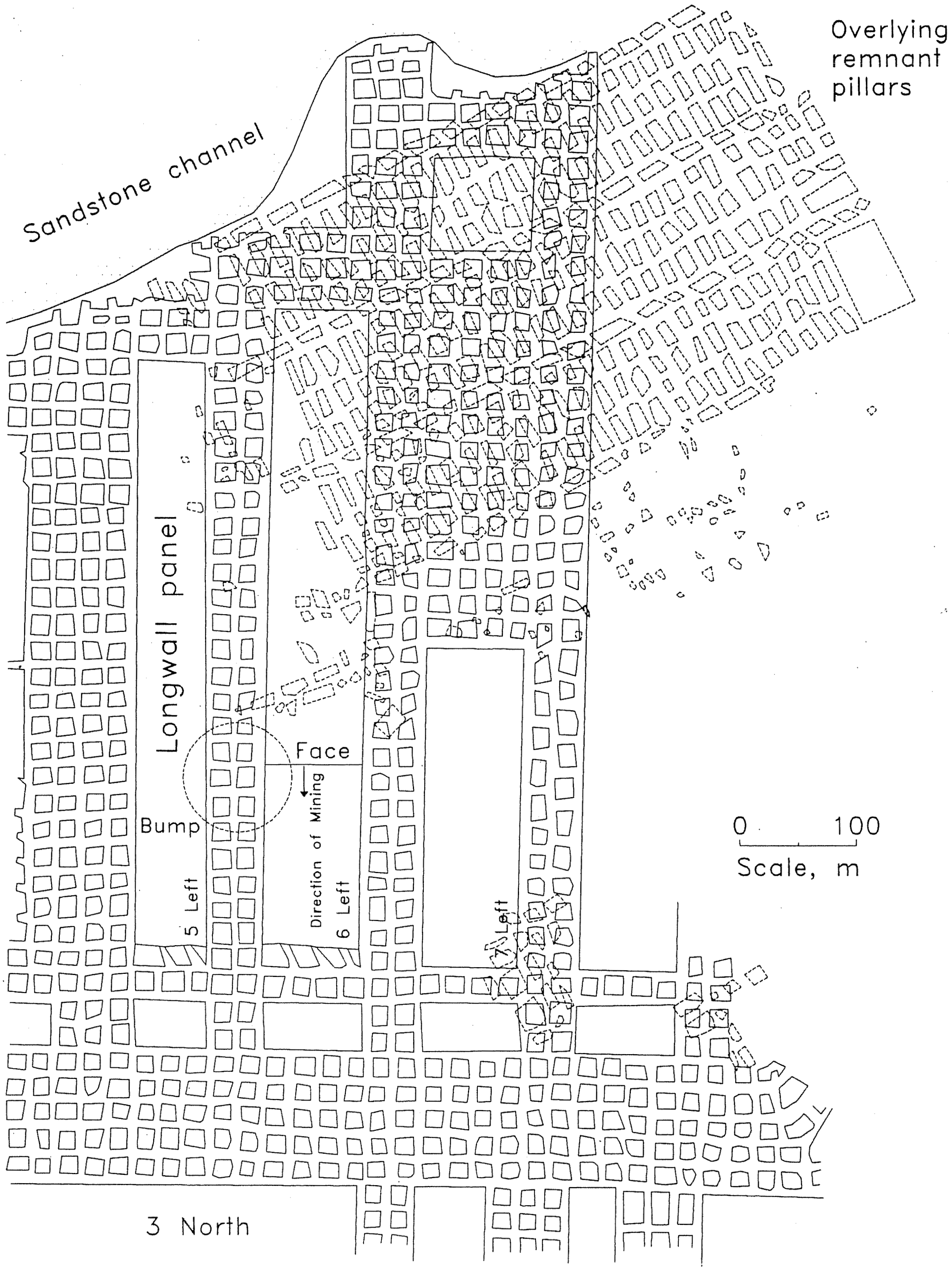


Figure 21
Longwall Tailgate Entry Pillar Bump at Beatrice Mine, January 26, 1973.

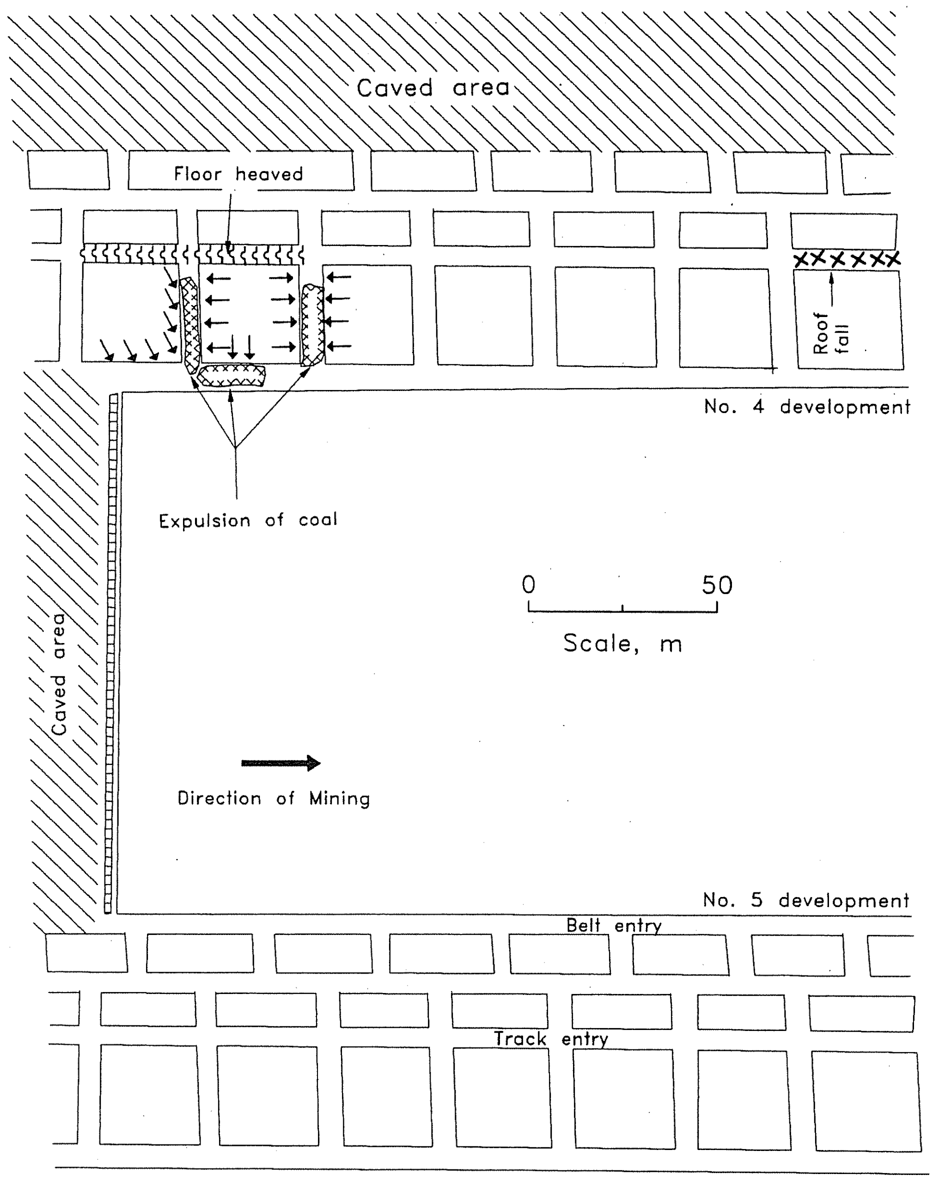


Figure 22
Fatal Longwall Panel Bump Near Tailgate Entry at Beatrice Mine, May 15, 1974.

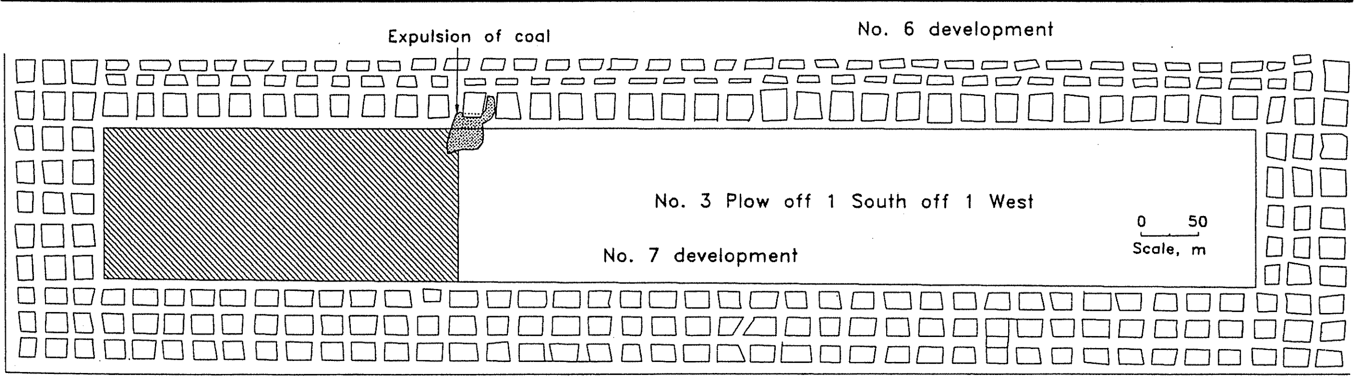
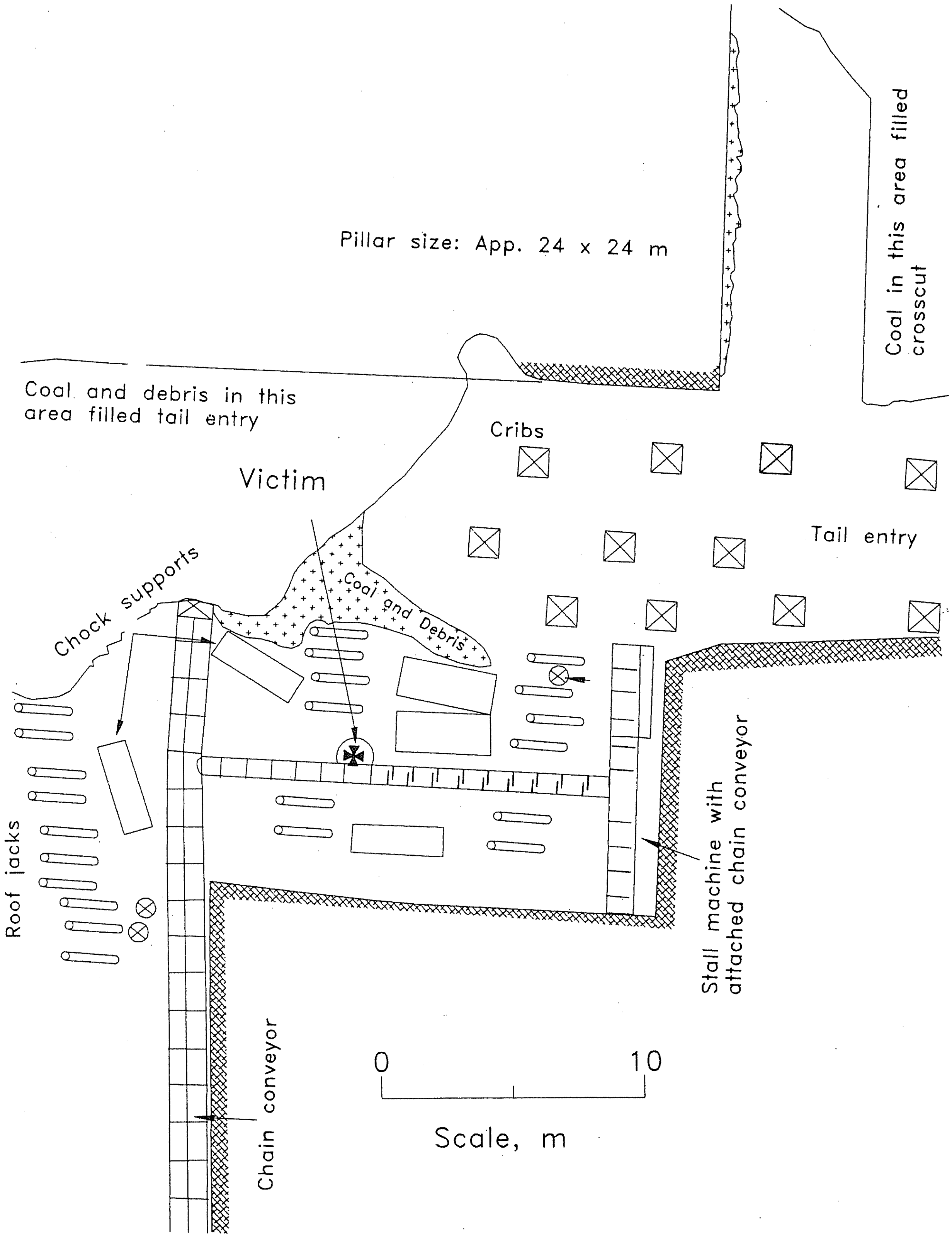


Figure 23
Detailed View of Bump at Beatrice Mine, May 15, 1974.



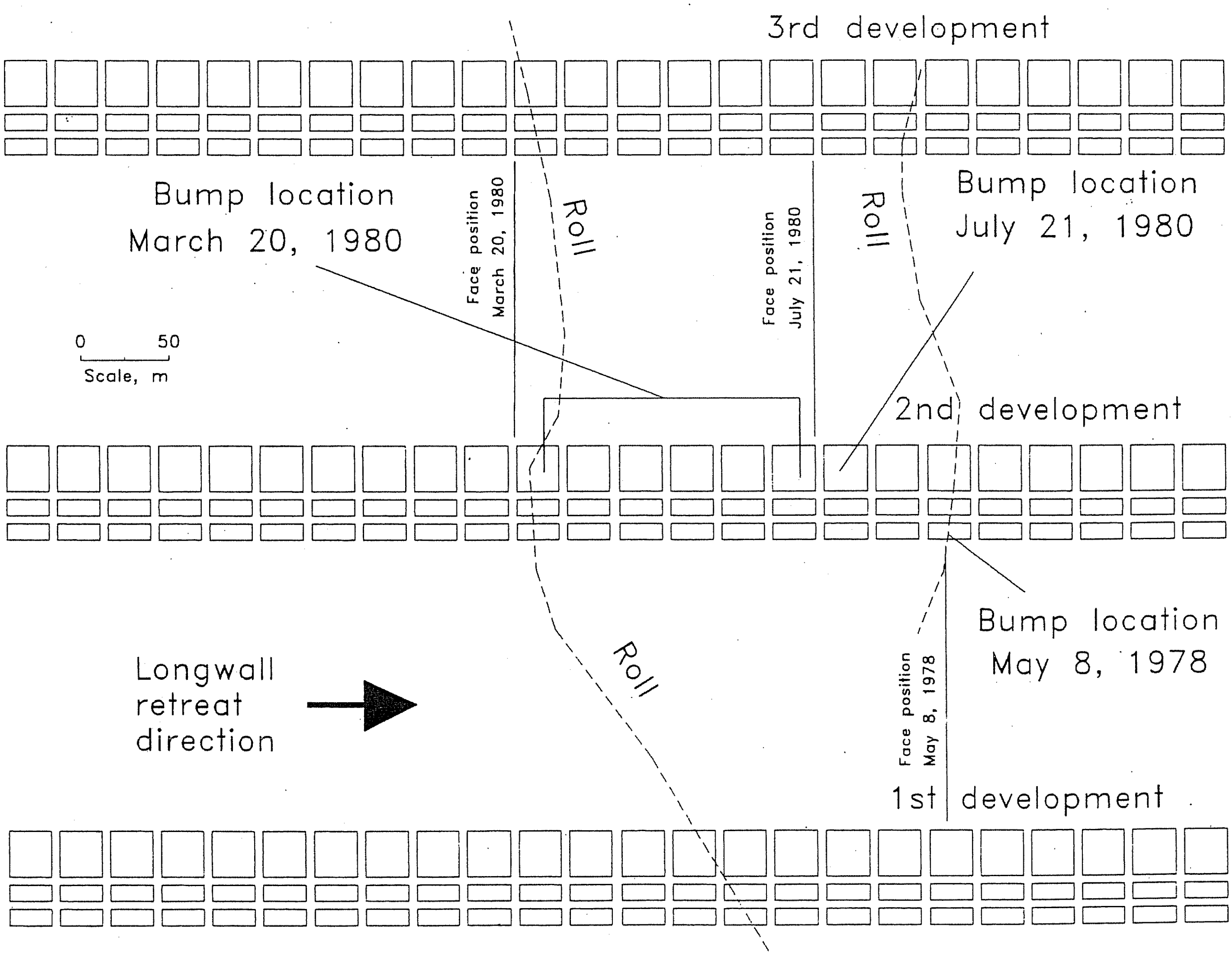
This section of longwall panel was referred to as the "stall area." ⊗ indicates miners.

Virginia Polytechnic Institute and State University's Seismological Observatory in Blacksburg, VA, registered this event as 1.0 on the Richter scale. The destruction underground did not translate into the high levels of seismic energy that had been recorded for several other events.

Several years later, during mining in the northern portion of the Beatrice Mine, three bumps occurred in one location at different times, but in association with a distinctive geologic condition. A large "swag," or roll, in the Pocahontas No. 3 Coalbed was reported across the No. 1-3 developments (figure 24). In this area, the structural elevation of the coalbed changed rapidly with an associated thickening of the coal. Because of the lack of detailed data, one can only infer the exact manner in which this geologic condition influenced bump occurrence. However, rolls are often associated with changes in depositional environments, which are in turn responsible for significant stratigraphic changes. Indeed, a localized increase in floor strength was suggested because of a decrease in the degree of floor heave within the roll area (*10*). The localized thickening of coal may have also contributed to lower pillar strength in the roll area, for the 670 m of overburden in the area did not appear to be excessive for this mine.

The first of these three bumps was generated in a narrow pillar of the No. 2 development headgate entry on May 8, 1978. No miners were injured, but there must have been considerable concern because headgate pillar bumps are rare. In addition, the headgate pillar next to the longwall face was one of the most heavily traveled areas in the mine. Owing to the importance of this area and the significant changes in the character of the floor rock and coalbed, it was recommended that floor holes be drilled and shot along the middle gate entry (*10*). No other bumps were reported until the face of the next

Figure 24
Effects of Large-Scale Structural Roll on Three Headgate and Tailgate Entry Bumps at Beatrice Mine.



longwall panel approached this same roll (figure 24). Then, on March 20, 1980, six narrow pillars bumped, two of them violently (*11*). No miners were injured in this tailgate bump. Because the floor in the roll area resisted heaving for a distance of 200 m, the operator decided to volley fire or shot fire ribs of three abutment pillars outby the longwall face. The final bump in this area was on July 21, 1980, approximately 50 m from the location of the bump occurring on May 8, 1978. The July 21 bump took place over a weekend, so no miners were on the section; the exact time of occurrence could not be estimated.

SUMMARY OF RECOMMENDATIONS TO MITIGATE COAL MINE BUMPS

When coal pillar bumps first occurred in eastern Kentucky (*3*), local mine officials, workers, mining engineers, and many others tried to explain their cause. Numerous methods of prevention were suggested and attempted unsuccessfully. Most of the bumps were located along the retreating pillar line where several of the following conditions existed: (1) uneven pillar lines, (2) irregular pillar sizes, (3) overburden greater than 300 m, (4) strong mine roof and floor strata, and (5) overhanging or cantilevering gob. Since that time, several prominent mining engineers, consultants, inspectors, and researchers have developed recommendations and methods to mitigate bump hazards in room-and-pillar mines.

RECOMMENDATIONS BY HISTORICAL EXPERTS

Recommendations by Rice

Rice (*27*) proposed that two types of bumps, termed "pressure bumps" and "shock bumps," caused the observed mining problems. Pressure bumps were caused when stress on moderately sized coal pillars became too great for the pillars' bearing strength. Shock bumps were induced by breaking of thick, massive strata above the coalbed, which transmitted a shock wave through the rock to the stressed coal pillars. Faulty mining methods were then identified where (1) pillars were too small, (2) projecting pillars were left behind the retreat line, (3) pillars were narrowed to points, and (4) pillars were extracted in separate groups without any attention being paid to a long, continuous retreat line.

Based on these observations, Rice recommended two operational methods for controlling bumps: straight retreat lines and rock-filled cribs. Keeping retreating pillar lines straight eliminated pillar points projecting into the gob. This practice was fairly easy to initiate and had favorable results. Rock-filled cribs, for a cushioned support of the roof rock, were also tried with positive results. Generally, the cribs were ordinary mine post timbers 1.1 m long, not less than 0.2 m thick, set on 6-m centers. Each crib was tightly packed with a fill of rock material. The cribs were designed and placed so that the mine roof could converge gently without rupture of the immediate strata. This action decreased the potential for sandstone breaks within the gob, which were believed to cause many shock bumps.

Bryson (*3*) described a detailed field test of this design method at a deep mine in the Harlan Coalbed, Cumberland Mining District, under 430 m of cover. Bumps had killed five miners at this particular site. Figure 25 shows the test area, which was approximately 210 m wide and adjacent to a large gob area. Rooms were driven approximately 91 m between the support entries, which were about 10.7 m wide. Prior to the extraction phase, the study area was composed of a series of narrow (10.7 m wide) and large (43 m wide) pillars. As the section was mined, 16 roof-to-floor convergence stations and 64 rock-filled cribs were installed.

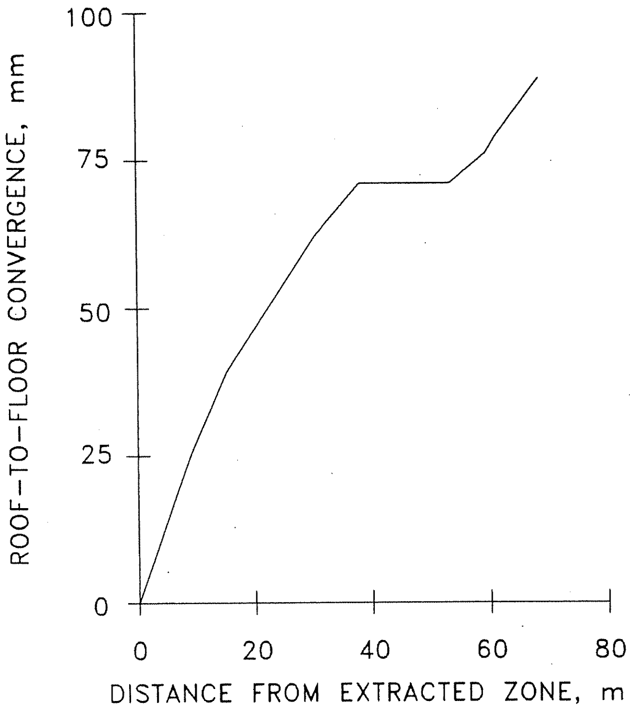
After the area was extracted, convergence began. Bryson reported that a few roof rock cracks gradually widened to as much as 41 cm without causing mine roof collapse. Convergence continued until the roof and floor almost met. In general, the strata settled by cracking and grinding noisily, but did not develop many large breaks. Only one bump occurred during coal extraction when the pillar line was not kept straight.

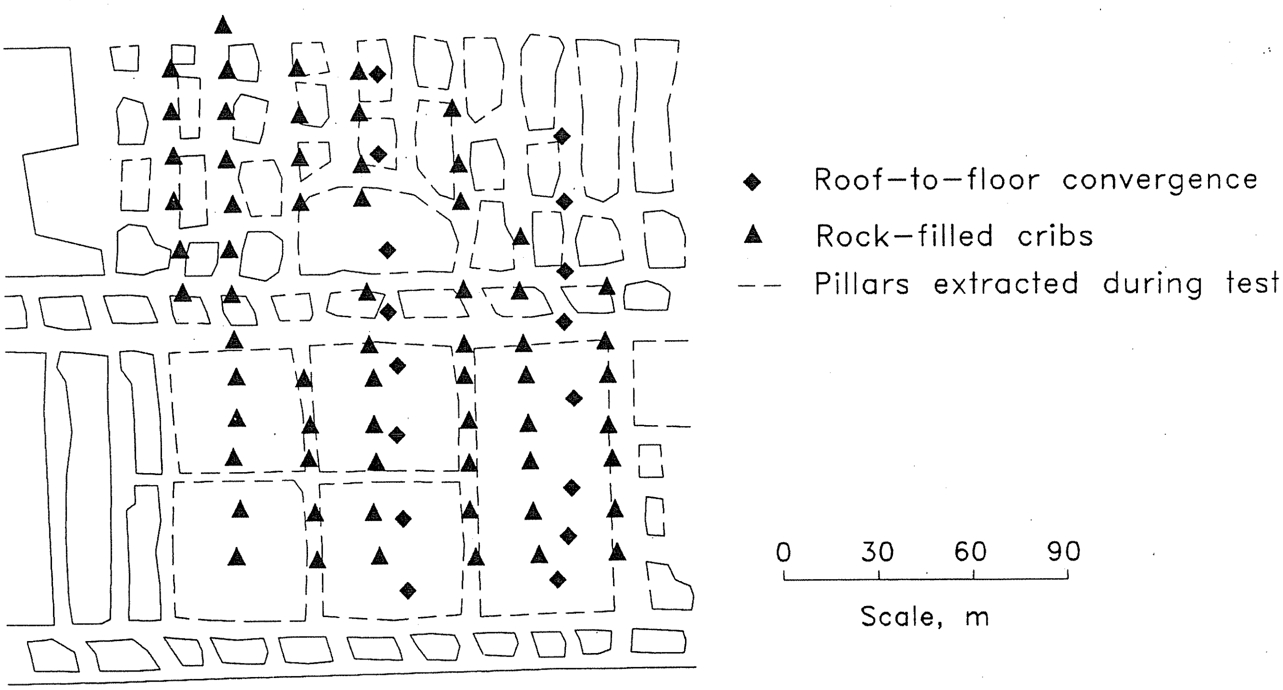
Recommendations by Holland and Thomas

Holland and Thomas (*14*) expanded on Rice's general recommendations regarding pillar extraction procedures and offered the following 10 measures to minimize pillar bumps:

1. Recover all coal in a pillar operation.
2. Avoid pillar line points.
3. Keep the roof spans projecting over the gob as short as possible or provide support so that the roof beds do not fracture.
4. Do not conduct development work in abutment areas.
5. Do not split pillars on or near the extraction line.

Figure 25
Suggested Plan of Pillar Extraction Under Deep Cover Using Rock-Filled Cribs (After *17*).





6. Use the open-ended extraction technique with lifts of not more than 4.3 m.
7. Leave one or two rows of pillars adjacent to old gob areas.
8. Maintain pillars at the same size and shape.
9. Keep development entries narrow, approximately 4.3 m.
10. Note areas of rolls, changes in dip, and changes in coal thickness and hardness. Use this information in designing the mining system.

Although many of the rules still apply to modern room-and-pillar operations, several are no longer pertinent by today's standards, however they may be useful as new mining methods are developed. For example, continuous mining machines require regular mining patterns and entries larger than 4.3 m to operate. It is also necessary to conduct development work in abutment areas during the final stages of a mine's life. This is necessary as the mine pulls back along main entries, extracting the remaining large barriers. The practice of a retreating longwall through existing openings may change this assumption.

Recommendations by Peperakis

Peperakis (*25*) summarized experiences in the use of novel engineering designs at the Sunnyside Mines prior to the introduction of longwall mining techniques in the early 1960's. Many of Sunnyside's bumps initiated roof falls of the immediate shales and thin laminated sandstones beneath the massive main sandstone roof rock. Bumps initiated during development were associated with a series of faults trending along strike. Displacements ranged from 1 to 8 m. Peperakis identified the following seven measures to minimize bumps:

1. Conduct long-hole shooting.
2. Cut up large blocks into smaller, more uniform pillars ahead of the retreating pillar line.
3. Do not split large blocks during development.
4. Break large development blocks ahead of retreat pillar lines into uniformly sized blocks.
5. Use substantial supplemental support.
6. Use yieldable steel arch supports to minimize roof falls associated with bumps.
7. Use hydraulic backfill to reduce stress transfer during bumps.

Osterwald (*23*) noted that many other oriented structural features (for example, shatter zones, cleavage, pyrite veins, and cylindrical and smooth fractures) were found in bump-prone areas. He suggested that mine layouts could take advantage of these features to reduce stress concentrations, thereby decreasing bump incidences.

OTHER BUMP MITIGATION RECOMMENDATIONS

Olga Pillar Extraction Sequencing Technique

A novel pillar extraction sequencing technique was developed principally by Olga Mining Co. in the 1970's to control bumps. This technique involved mining numerous places over three to four rows of pillars to direct the overburden loads gradually away from the pillar line where most miners and machines were located. An idealized schematic of the extraction sequence is shown in figure 26. By design, all coal pillars three rows away from the retreating pillar line have at least a "bump" cut. This bump cut is a 6.1- by 6.1-m cut of coal taken from a typical size of chain pillar (18.3 by 21.3 m). The frequent audible thumps during extraction explain the terminology. The two pillar rows closest to the gob line are split in half by extending the bump cut entirely through the pillar. Finally, the pillar wings, or fenders, are extracted in the row closest to the gob line.

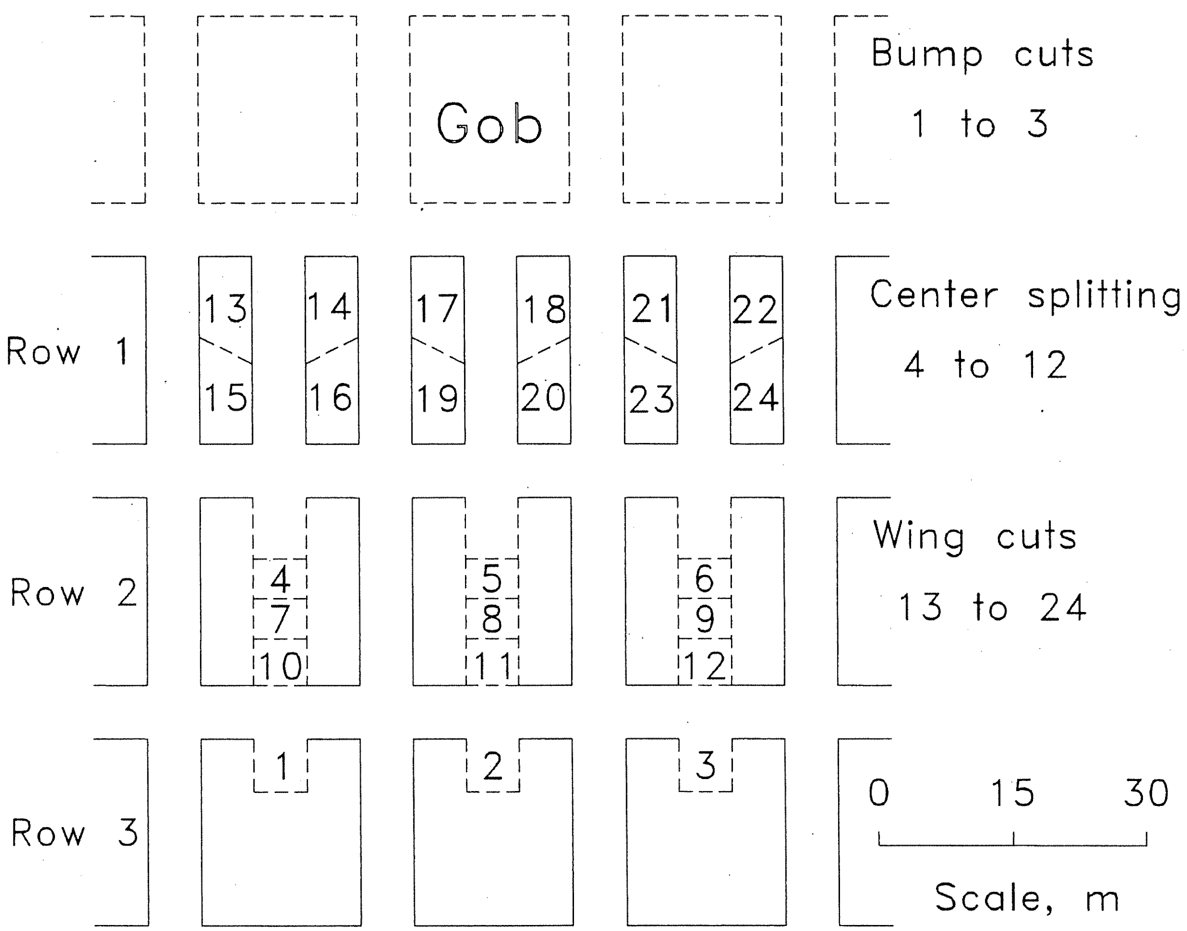
This innovative design was evaluated by the USBM using an extensive rock mechanics instrument array to determine how the strata responded during mining (*4*). The response of the strata was measured by 44 coal cells (borehole platened flatjacks) and more than 70 convergence stations. Observations at the field site indicated that the technique redistributed stress effectively. Pressures were transferred farther than would normally be expected—up to eight pillar rows away from the pillar line. This redistribution effectively transferred the load over a very large area, greatly minimizing bump hazards.

Recently, USBM researchers have attempted to evaluate this extraction technique using numerical modeling (*33*). Several idealized mining scenarios were modeled by a USBM-developed boundary-element program with nonlinear material types and an energy-release-rate subroutine. The study found this novel pillar splitting and extraction sequencing method superior in reducing bump potential to more traditional techniques, such as single split-and-fender, pocket-and-wing, and open-ending.

U.S. Steel's Thin-Pillar Method

Coal bumps often occur during extraction of the large barriers adjacent to main entries. Violent bumps during barrier-splitting appeared to be especially troublesome during the 1950's in southern West Virginia. Engineers at U.S. Steel Mining Co., a major coal producer in the

Figure 26
Idealized Pillar Extraction Sequencing Technique for Bump Control During Room-and-Pillar Mining.



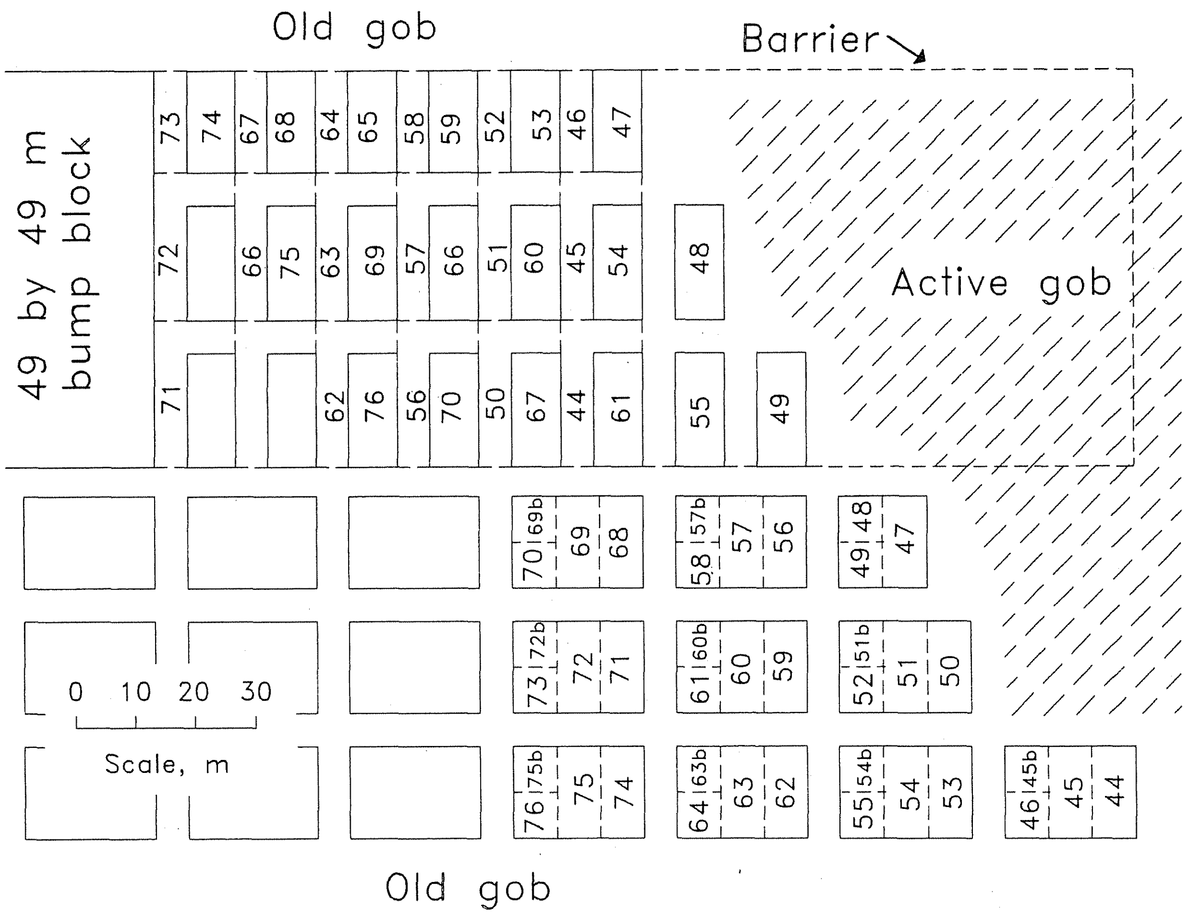
This technique was developed by Olga Mining in the 1970's. Numbers indicate cutting sequence.

region, developed a method of splitting large barriers adjacent to main entry systems (*29*). They found that pillars smaller than 14 m or larger than 49 m almost never bumped. An extraction method known as thin-pillar mining was developed that systematically cut the large barriers into pillars with widths smaller than 14 m, leaving a barrier pillar remnant, which was either destressed or left in place.

When implementing a thin-pillar mining system for barrier extraction, multiple entries are first driven within the barrier directly adjacent to the main entries. The remaining solid barrier is located between the newly advanced headings and the stabilized gob. The mining of barrier and predeveloped chain pillars proceeds simultaneously (figure 27). Barriers are split from the recently driven headings adjacent to the active gob back toward the next solid barrier. These headings are very close, isolating yield pillars about 6.1 m wide. These yield pillars fail in a controlled manner, shedding high stresses both to the active gob areas and farther into the solid barrier. When the remaining barrier approaches 49 by 49 m, a critical-size pillar is formed. This large abutment pillar is called a "bump block" and is left to avert a bump. These large blocks aid in breaking the roof at the pillar line and protecting the remainder of the section from excessive convergence.

The thin-pillar mining system has many forms, but it is generally employed when extracting the barriers left to protect main entries. The smaller pillars tend to yield to the high stresses imposed on them by overburden and normal mining. The adoption of this technique greatly reduced bumps in the Gary Mining District.

Figure 27
Typical Mining Sequence Utilizing Thin-Pillar Method.



This method was developed by U. S. Steel in the 1950's. Numbers indicate cutting sequence.

Longwall Gate Entry Design Techniques

As a result of the longwall gate entry bump problems discussed above, two different design philosophies have emerged in the United States based primarily upon regional geologic conditions and mining preferences. Standard gate entry designs in the Southern Appalachian coal basin consist of three or more entries with at least one row of *abutment* pillars, whereas two- and three-entry systems with *yield* pillars are a more common gate entry design in the Uinta and Piceance Creek Basins. Many mines in the Southern Appalachian Basin require multiple gate entries because of methane gas emission problems. Several of the bump-prone longwall mines operating in the Southern Appalachian Basin employ three- and four-entry designs with a combination of yield and abutment pillars. The most common designs used in the Uinta and Piceance Creek Basins consist of one or two yield pillars.

Abutment Design

A well-designed abutment gate entry design supports a considerable amount of the abutment loads generated from both the adjacent gob and the approaching longwall face. This method is well suited for longwalls of moderate depth (300 to 600 m) that have substantial methane gas emission problems. In bump-prone ground, typical sizes of gate entry pillars (15 to 25 m wide) fail prior to the passage of the longwall mining face. To control the abutment load ride-over problem, gate entry pillars have been widened so that they do not fail during panel extraction. Redesign of the gate entry was accomplished by increasing the width of the abutment pillar. This caused the abutment pillars to fail much later in the mining sequence (*13*). This design eliminated abutment load ride-overs from the adjacent gob panels onto the actively mined panel. As a result of implementing this technique, the incidence of bumps at problem mines has been greatly reduced. Although this method has proven successful, it may have limitations when overburden is extreme (about 750 m), depending on coalbed thickness. These conditions may require extremely large abutment pillars, which may be impractical.

Yielding Design

Yield pillar designs allow the gate entry system to deform under the weight of the approaching panel abutments, thereby diverting substantial load to the nearby solid coal panel. This method of stress control for gate entries is well suited for two-entry designs. The first U.S. applications were pioneered in the early 1960's at the Sunnyside Mine in the Uinta Basin (*16*). At that time, longwall mining had been practiced in the United States for only about 10 years, and entry design methods for bump-prone ground were not well developed. Perhaps without fully realizing the advantages of a two- versus a multiple-entry yielding system, operators made the decision to develop only two entries primarily to limit the amount of ground to be opened up prior to panel retreat. Nearly 30 years later, this system has continued to be successful in eliminating entry pillar bumps during panel development and retreat operations, especially in areas overlain by up to 600 m of overburden.

Not all mines have experienced Sunnyside's success with a yield pillar design. A nearby mine attempting to emulate this very profitable design had difficulties in developing small pillars without generating serious bumps and routinely lost significant portions of tailgate entries to large bumps. It soon became evident that the successful application of yielding designs depended partly on the geology surrounding the pillar system. Competent mine roof and floor conditions are necessary to maintain stability during the higher rates of entry closure experienced with this system.

Two-entry gate systems more commonly employ pillar designs that yield during or shortly after development. By design, the narrower gate entries typically generate significant side abutment stresses, which are capable of destroying most conventional chain pillars even at moderate overburden. Where two-entry systems are impractical, yield pillars have been used effectively in multientry systems, but such systems are more commonly used in conjunction with abutment pillar designs. In either application, yield pillar designs have proven to be an effective alternative in mitigating bump hazards in deep U.S. coal mines.

Destressing

Several forms of destressing were identified within the USBM Coal Bump Database. These included (1) volley firing or shot firing, (2) auger drilling, (3) water infusion, (4) hydraulic fracturing, and (5) partial mining. If conducted with deliberation, destressing generally aids in releasing excessive stresses in a controlled manner. However, many examples in the database demonstrate that bumps may occur in conjunction with destressing the coal.

Shot Firing

Shot firing fractures coal, thereby extending the yielded coal zone. This process injects energy into stressed coal, causing seismic shock. The shock waves temporarily release confinement, initiating violent failure under a controlled condition. However, there is little that is engineered about this method. Typically, the shot holes are loaded with explosives, but the amount of explosive needed is poorly defined. The most appropriate lengths and spacings of blastholes are also unknown. Generally, all shots are initiated simultaneously. It is commonly believed that the destressed zone is defined by the length of the blasthole. Jackson (*19*) noted that Mid-Continent Resources mines in Colorado used shot firing to move the peak stress zone into the solid core of the longwall panel when this zone was less than 5 m from the rib. Polish mines have long used shot firing to break and shear cantilevered roof strata.

Auger Drilling

Auger drilling was first practiced at the Gary No. 2 Mine in the mid-1950's when 61-cm holes were drilled from the sides of highly stressed barrier pillars (*29*). Unfortunately, these large-diameter boreholes were prone to triggering large bumps. Up to 1,000 t of coal was ejected from the coal ribs by the largest events, causing this method to be judged too hazardous to use routinely. As a result of European research, which suggested that auger holes less than 10 cm could not initiate a coal bump, auger destress drilling has regained limited favor in recent years.

The Olga Mine routinely used this method to redistribute stress away from active work areas (*4*). As the auger holes entered the more highly stressed coal 3 to 4 m from the rib, the amount of coal produced rose dramatically. Significant amounts of coal were recovered at a gradual pace, often 10 to 20 times the volume of a 10-cm-diam hole. In effect, augering affected the areas of highest stress in the pillars without removing any of the confining fractured and yielded rib coal. Undoubtedly, this technique is very effective in mining highly stressed coal pillars when other alternatives are unsuccessful.

Water Infusion

Water lubricates fracture surfaces within a rock mass; therefore, water infused into a coalbed can initiate slippage between rock surfaces, thus lowering the state of confinement on the surface and the amount of energy stored within the rock. This technique has been tried successfully in Europe, but has received only limited use in the United States. This probably stems from the difficulty of infusing water into U.S. coalbeds. Water infusion has been attempted in many mines to control respirable dust and methane gas migration. It has been most successful in coalbeds that have a well-developed cleat system that controls permeability.

Because water infusion is impractical when the coalbed is highly stressed, destressing must be completed prior to retreat mining, for holes will not remain open long. Successful water infusion generally requires the coalbed to accept and transmit fluid readily. The equipment must be capable of pumping water at or above hydrostatic pressure.

Two U.S. coal mines have attempted to use water infusion to destress coalbeds. Lessley (*20*) discusses use of the technique in a room-and-pillar section in a Virginia coal mine. Several 4- to 9-m-long holes were drilled into pillars. Injection pressures averaged 3.7 MPa, with the coal pillar accepting between 0.1 and 3 m^3 of fresh water. Microseismic monitoring indicated that only small amounts of energy were released during infusion.

Hydraulic Fracturing

In some mines, it has been difficult to achieve good caving into full-extraction gob areas. This is believed to be a function of the ability of massive units to span the gob. It has been proposed that caving could be induced with hydraulic techniques near vertical breaks within the main roof beam. This technique was attempted at Arch of Kentucky's Lynch No. 37 Mine in southeastern Kentucky, but little data from this experiment are available.

Partial Pillaring

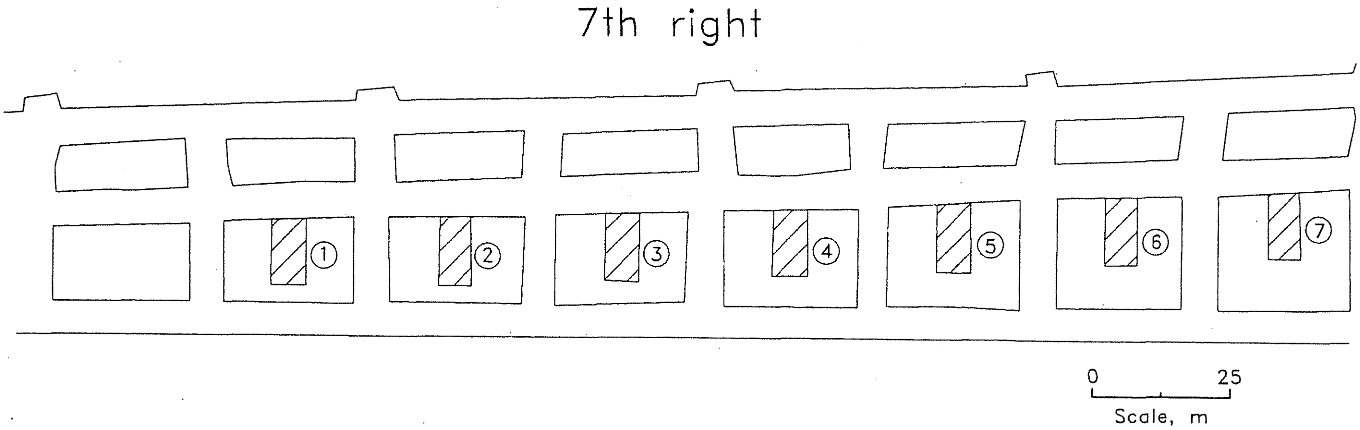
A unique application of pillar destressing was attempted at Energy West Mining Co.'s Deer Creek Mine in Utah in 1987. A remotely controlled continuous mining machine was used to split seven chain pillars outby a retreating longwall face. Pillars in the 7th Right gate entries were progressively narrowed from 12 to 9 m wide to accommodate the change from a three- to a two-entry gate design. Upon retreat, this longwall panel encountered severe pressure in the pillar transition zone, producing bumps and damaging the longwall shearer and adjacent tailgate pillars. It was determined that pillar splitting could provide the safest means of destressing the chain pillars in the transition area (figure 28). Several operational precautions were taken to decrease the dangers of initiating a bump during splitting, with apparent success.

Observational Techniques

Because many bumps are very sensitive to slight changes in geology, considerable attention should be placed on observing the condition of the yielded coal. The depth and character of the fractured coal zone reveals the location of the peak stress zone and therefore the potential for violent failure. Numerous techniques are available to acquire this information. If the ribs are generally crushed, but locally appear straight and solid, the peak stress zone may be close to the pillar edge. If the ribs are difficult to cut or drill, an abnormally high peak stress zone may be present. A sandstone channel scour may signal a change in the character of the contact zone. Generally, the irregular nature of the scours provide higher shearing resistance. The appearance of a "red-coal" zone within the contact zone is perhaps the most dramatic indicator of the imminent occurrence of a coal mine bump. This condition reflects the coalbed's inability to resist the shearing forces generated by the tremendous confinement applied to the coal in a localized area. The red-coal zone probably represents coal that has been mechanically altered because of the presence of excessive amounts of shear strain. USBM researchers have observed this condition at three bump-prone mines: the Olga and Gary Mines in southern West Virginia and the Lynch No. 37 Mine in eastern Kentucky.

Auger drilling also has been used to probe for areas of highly stressed coal (*24*). Often after a particular mining section has bumped, small-diameter (5 cm) auger holes are drilled into the face with hand-held units. Drill hole

Figure 28
Example of Partial Pillar Destressing Method Employed at Deer Creek Mine, Emery County, UT.



Numbers indicate mining sequence.

cuttings are often monitored, but generally the operator is most interested in determining when drilling difficulty or drill string seizures occur. At these points, it is assumed that the drill hole has entered an area of high stress. Several holes are drilled across the problem working face at distances of 2 to 6 m apart. If the peak stress zone (figure 7) is close to the entry (less than 2 m), the situation is generally considered critical, and mining is temporarily halted or some destressing technique is attempted. If the peak stress zone is greater than 5 m from the entry, conditions are generally considered safe for additional mining at the face. One should note that no reliable criteria exist to guide an operator in selecting how often a face should be probed or in choosing drilling parameters or patterns. Longwall mines such as the Dutch Creek No. 1 and Lynch No. 37 Mines have utilized auger drilling to choose areas to be destressed.

CONCLUSIONS

The Coal Bump Database compiled by the USBM contains a wealth of knowledge from past experience that has undoubtedly reduced the severity of coal mine bumps in the United States. This paper has elaborated on the most successful designs for both room-and-pillar and longwall mining. The following are the principal observations developed from mining in bump-prone strata:

1. The potential for bump occurrence increases when mining in stiff roof and floor rock. Strata of this nature are frequently found within the Southern Appalachian, Uinta, and Piceance Creek Basins.
2. Bumps can occur—
   a. In development sections when faults and igneous dikes are approached,
   b. In room-and-pillar sections when cantilevering roof is encountered,
   c. In longwall sections when geologic structures are encountered, and
   d. In either room-and-pillar or longwall sections when overburden, abutment, or shock loads are excessive.
3. Supplemental support has been useful in minimizing bump damage. Rock-filled cribs allow gob to converge gently without rupturing. Combinations of cribs, crossbars, and props reduce the severity of bumps in main entries. Wood cribs and yielding arches in combination with rock bolts help support weak, immediate mine roof during bumps, which reduces associated roof falls.
4. The use of straight retreating pillar lines and total extraction of all coal can eliminate projections of bump-prone material into the gob.
5. Developing or splitting large blocks of coal into smaller, uniform blocks ahead of the retreating pillar line causes the coal to yield in a controlled manner before it is extracted and allows the roof to bend gently.

6. Sequential splitting of pillars away from the retreating pillar line can effectively move excessive stress away from the working face in a controlled manner.

7. Sizing gate entry pillars large enough to contain induced stresses can effectively reduce bump occurrences.

8. Sizing gate entry pillars to yield in a controlled manner can assist fracturing of the main roof and, in some instances, decrease the magnitude of abutment and/or shock loads onto the longwall face.

Most past and present U.S. bump-control designs have helped control the manner in which the roof rock breaks and have regulated the manner in which stresses are redistributed. These techniques have mostly been very successful, but they have not been applied over a wide range of geologic and mining conditions. As production rates and overburden depths increase and new mining systems are designed, the mining industry will be required to engineer new bump-control techniques. By evaluating past experiences, analyzing current and projected conditions, and investigating innovative design techniques in the field, the requisite technology can be developed to keep bump-prone U.S. mines safer for underground mine workers.

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