GEOTECHNICAL FACTORS INFLUENCING VIOLENT FAILURE IN U.S. MINES

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ABSTRACT

Sudden, violent failures of rock around mine openings influence access, ventilation, and safety in both hard-rock and coal mines. To develop predictive tools for assessing the potential for violent failure, the authors initiated a comprehensive study using (1) multiple linear regression and numerical modeling analyses of geological and mining conditions at 25 sites to identify the most significant factors contributing to stress bumps in coal mines and (2) investigations of the geological and mining factors contributing to rock bursts in the Coeur d'Alene Mining District of northern Idaho, particularly the influence of preexisting structures on rock bursts.

Twenty-five factors were initially considered in the study of coal bumps. The most important variables were identified as (1) mechanical properties of strata, (2) gate road geometry and/or gate pillar factors of safety, (3) roof beam thickness, joint spacing, and stiffness characteristics, and (4) stress gradients associated with previous mining and anomalous geologic conditions.

In the Coeur d'Alene district, burst damage related to preexisting structures results primarily from (1) sudden buckling and crushing of rock layers where surfaces of development and production openings lie at low angles to bedding, faults, or other planar structures and (2) disturbance of loose ground caused by seismic fault-slip on preexisting faults or previously sheared bedding planes that intersect veins near pillar-stope margins.

INTRODUCTION

Coal bumps and rock bursts are defined as sudden and violent failures that occur near openings and that are of such a magnitude that they expel large amounts of material into the opening. Such violent failures are not only a safety concern in U.S. mines but have also affected safety and resource recovery in other countries, including Canada, Germany, England, Poland, France, Mexico, China, India, Norway, and South Africa.

The geomechanics of conditions leading to violent failure are similar in both hard-rock and coal mines in that stresses exceed the strength of the rock mass near a mining excavation or at a geologic discontinuity. In coal mines, excavation takes place in near-horizontal seams under near-vertical maximum principal stress fields. Most geologic discontinuities are horizontal but are intersected by near-vertical cleats and joints. In burst-prone hard-rock mines of the Coeur d'Alene Mining District of northern Idaho, where much of the work on rock bursts has been done, maximum principal stresses are horizontal; however, geologic discontinuities tend to be near-vertical. In this study, the authors used the wealth of geotechnical data from coal mines in four states and hard-rock mines in the Coeur d'Alene Mining District to address the significant factors contributing to violent failure.

FACTORS INFLUENCING COAL BUMPS

In an attempt to identify the most significant factors that contribute to coal bumps, the authors analyzed geologic, geotechnical, and in-mine monitoring data from 25 sites in 6 room-and-pillar coal mines and 19 longwall mines in Colorado, Utah, Virginia, and Kentucky. Both computational and statistical techniques were used in the analyses, and both violent and nonviolent failures were studied. The scope of these studies involved—

- Obtaining mechanical property values for roof, floor, and coal seams through laboratory tests of samples of near-seam strata. The in situ strength of coal seams was estimated using procedures suggested by Maleki *(1)*.

- Calculating both maximum and minimum secondary horizontal stresses using overcoring stress measurements from one to three boreholes *(2)*.

- Calculating pillar and face factors of safety in individual case studies using both two- and three-dimensional, boundary-element techniques *(3-5)*. Results were compared with field data when such data were available.

- Calculating energy release from a potential seismic event using both boundary-element modeling and analytical formulations as suggested by Wu and Karafakis *(6)* to estimate energy accumulation in both roof and coal, and energy release *(7)* in terms of Richter magnitude (M_l) using the following formula:

  $$1.5\ M_l = a \times \log(E) - 11.8, \qquad (1)$$

  where E = total accumulated energy in roof and seam, ergs,
  and A = coefficient depending on joint density,

- Assessing the severity of coal bumps using a damage rating developed by and based on the authors' observations of physical damage to face equipment and/or injury to personnel, as well as observations by other researchers as cited in the literature. Damage levels were arbitrarily assigned a ranking between 0 and 3. Level 1 signifies interruptions in mining operations while level 3 signifies damage to both face equipment and injuries to mine personnel.

The first step of the analyses involved the identification of 25 geologic, geometric, and geomechanical variables that might have had the potential to contribute to coal bump occurrence (tables 1, 2, and 3). Typical frequency histograms are presented in figures 1, 2, and 3 and show that these case studies provided good coverage of the variables.

- *Roof beam thickness*. Roof beam thicknesses varied between 1.5 and 12 m. The thickness chosen for evaluation was the strongest beam of the near-seam strata located between 1 and

Table 1.—Statistical summary of geologic variables.

Variable	Mean	Stan. dev.	Range	No. of cases
Joint sets	1.4	0.6	1-3	25
Cleat sets	1.8	0.4	1-2	25
Inseam partings	1	0.9	0-3	21
Joint spacing, m	6.7	5.5	1.5-15	24
Rock Quality Designation	77	18	50-100	15
Depth, m	500	134	275-820	25
Roof beam thickness, m	4.3	3.3	1.5-12.2	25
Young's modulus, coal, MPa	3310	830	2410-4620	25
Young's modulus, roof and floor, MPa	20,700	6900	6900-33,000	25
Uniaxial strength, MPa	22	5.2	13.8-32	25
Uniaxial strength, roof and floor, MPa	100	23.8	55-150	25
Max. horizontal stress, MPa	13	7.6	0.7-26	25
Interacting seams	1.2	0.4	1-3	25
Local yield characteristics	0.8		0-2	25

Table 2.—Statistical summary of geometric variables.

Variable	Mean	Standard deviation	Range	No. of cases
Pillar width, m	19	10	9-42	23
Pillar height, m	2.5	0.3	1.7-3	25
Entry span, m	5.8	0.3	5.5-6	25
Barrier pillar width, m	50	27	15-73	6
Face width, m	167	40	61-244	25
Mining method	1.2	0.4	1-2	25
Stress gradient	0.9	0.6	0-2	25

Table 3.—Statistical summary of geomechanical variables

Variable	Mean	Standard deviation	Range	No. of cases
Pillar factor of safety	0.8	0.3	0.5-1.4	23
Face factor of safety	0.9	0.2	0.6-1.5	22
Energy (M_T)	3	0.5	2-4	22
Damage	1.4	1	0-3	25

4 times the total seam thickness in the immediate mine roof. Although there is some evidence that massive upper strata have contributed to coal bumps in some mines *(8)*, their influence was not directly evaluated in this study because of the lack of geological and mechanical property data.

- *Local yield characteristics.* Local yield characteristics of immediate roof and floor strata influence coal pillar failure and the severity of coal bumps. This factor varied from 0 to 2,

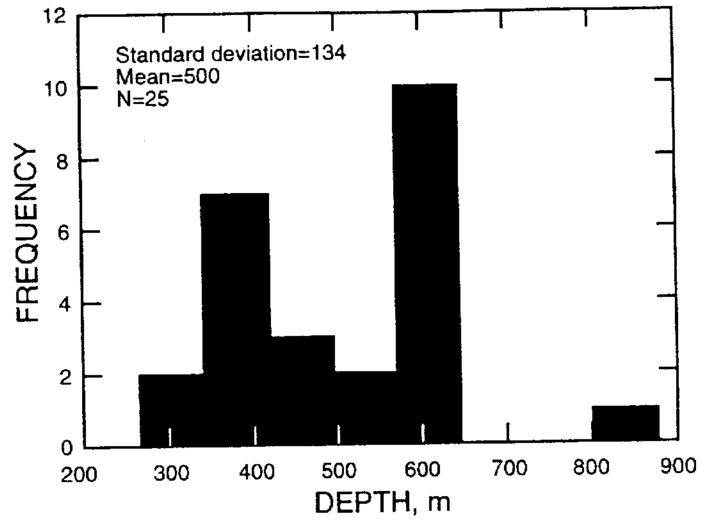

Figure 1.—Frequency diagram for depth

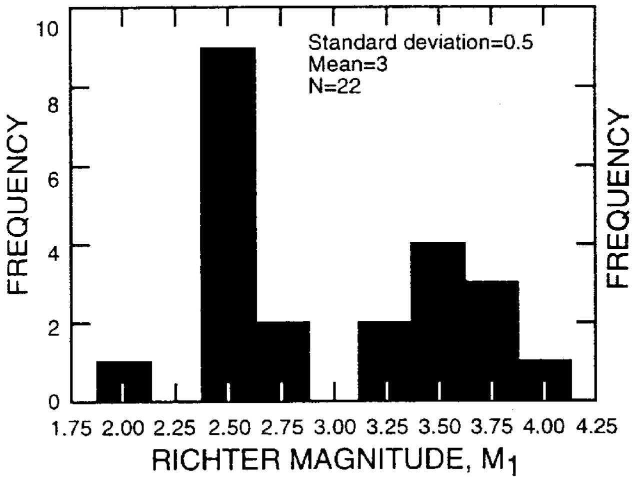

Figure 2.—Frequency diagram for released energy

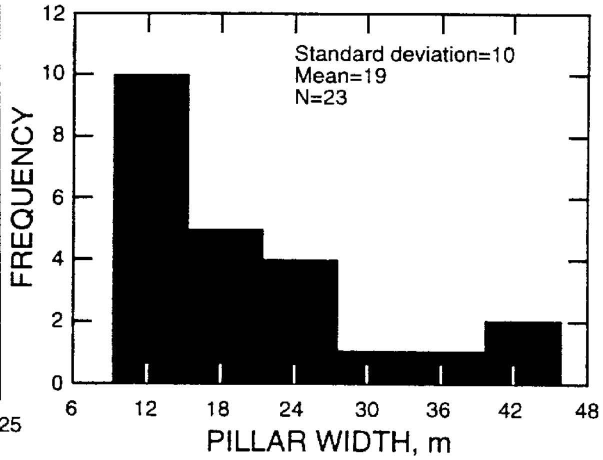

Figure 3.—Frequency diagram for pillar width

where 0 indicates insignificant yielding in the roof and floor and 2 indicates favorable, gradual yielding.

- *Stress gradients.* Stress gradients varied from 0 to 2, depending on whether or not mining proceeded toward an area of high stress (resulting either from previous mining or rapid changes in topography) and/or abnormal geologic conditions such as occasionally found near faults or grabens.

Bivariate Correlations and Data Reduction

Based on preliminary bivariate correlations among all geologic, geometric, and geomechanical variables, the number of variables was reduced by combining some variables into new ones. In addition, the cause-and-effect *(9)* structure in the data was identified, helping to tailor the procedures for multiple regression analysis using forward stepwise inclusion of dependent variables. The new variables were as follows:

Pqratio	Ratio of maximum principal horizontal stress (P) to minimum stress (Q).
Strenrc	Ratio of uniaxial compressive strength of the roof to the coal.
Jointrf	Joint spacing times roof beam thickness divided by mining height.
Gradyield	Ratio of roof and floor yield characteristics to stress gradient.
Panelwd	Ratio of panel width to depth.
Youngrc	Ratio of Young's modulus of the roof to the seam.

Table 4 presents the bivariate correlation coefficients between the variable "damage" and selected geologic and geometric variables. Energy (M_l), face factor of safety, stress gradient, pillar factor of safety, joint spacing, and uniaxial compressive strength of roof to coal were the most significant. Other variables were poorly correlated with damage, including the ratio of P to Q, pillar width, and Young's modulus of roof to coal.

Table 4.—Bivariate correlation coefficients between damage and selected other variables

Significant variables[1]	Coefficient	Insignificant variables	Coefficient
Damage	1	Pillar width	0.1
Energy	0.65	Ratio of P to Q	0.1
Gradyield	-0.57	Young's modulus of roof to coal	0.07
Jointrf	0.52		
Pillar factor of safety	-0.44		
Uniaxial strength of roof to coal	0.36		
Face factor of safety	-0.33		
No. interacting seams	0.33		
Panel width to depth	-0.31		
Mining method	0.26		

[1] Two-tailed tests

Multiple Linear Regression Analysis

There are two methods used by engineers and researchers as tools to help predict conditions in the future: statistical and computational. Starfield and Cundall *(10)* identify rock mechanics problems as "data-limited," that is, one seldom knows enough about a rock mass to use computational models unambiguously. Statistical methods, on the other hand, are uniquely capable of being applied where there are good data but a limited understanding of certain natural phenomena, such as coal bumps

In this study, the authors combined the strength of both methods to identify important variables and to develop predictive capabilities. Computational methods have been used to assess the influence of a combination of geometric variables into single variables, such as pillar factor of safety and released energy. This was very useful for increasing goodness-of-fit and enhancing multiple regression coefficients. Statistical methods were used to identify significant variables, to build confidence intervals, and so forth.

The multilinear regression procedure consisted of entering the independent variables one at a time into an equation using a forward selection methodology *(9)*. In this method, the variable having the largest correlation with the dependant variable is entered into the equation. If a variable fails to meet entry requirements, it is not included in the equation. If it does meet the criteria, the second variable with the highest partial correlation will be selected and tested for entering into the equation. This procedure is very desirable when there is a cause-and-effect structure among the variables. An example of the cause-and-effect relationship is shown when a greater depth reduces pillar factor of safety, contributes to an accumulation of energy, and ultimately results in greater damage. Using the above procedures, any hidden relationship between depth and pillar factor of safety, energy, and damage is evaluated and taken into account during each step of the analysis.

Several geomechanical variables (table 3) were initially used as dependent variables. The "damage" variable, however, resulted in the highest multiple regression coefficient. The multiple correlation coefficient (R), which is a measure of goodness-of-fit, for the last step was 0.87.

The assumptions of linear regression analysis were tested and found to be valid by an analysis of variance, F-statistics, and a plot of standardized residuals (figure 4) *(9)*. Residual plots did not indicate the need for inclusion of nonlinear terms because there was no special pattern in the residuals.

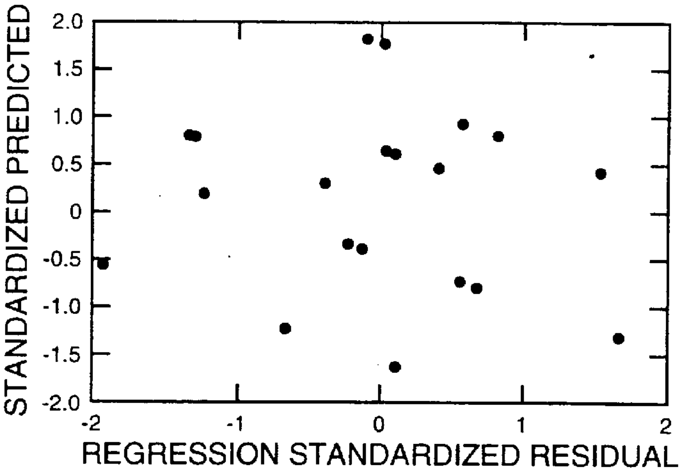

Figure 4.—Standardized scatterplot for dependent variable, "damage"

Important Variables Contributing to Bump-Prone Conditions

Based on an examination of standardized regression coefficients (table 5), the following variables best explain variations in damage and thus statistically have the most significant influence on coal bump potential.

- *Energy release.* This variable includes the effects of the mechanical properties of the roof and coal, depth, stress field, and joint density, and thus directly relates to damage.

- *Method.* Mining method has a bearing on coal bump potential. The room-and-pillar method is associated with a higher degree of damage than is longwall mining.

- *Pillar factor of safety.* Gate pillar geometry contributes directly to the severity of damage.

- *Stress gradient and yield characteristics*. Mining toward areas of high stress creates a potential for coal bumps, while localized yielding roof and floor conditions encourage gradual failure, which reduces the amount of damage.

Table 5.—Standardized regression coefficients and statistical significance

Variable	Standardized coefficient	T-significance
Energy	0.28	0.049
Pillar factor of safety	-0.34	0.011
Method	0.26	0.064
Gradyield	-0.55	0.0004
Constant	NA	0.234

NA Not applicable.

ROLE OF PREEXISTING STRUCTURE IN VIOLENT FAILURE IN HARD-ROCK MINES (COEUR D'ALENE MINING DISTRICT)

Despite obvious differences in host rocks and mine layouts, violent failures in coal and hard-rock mines have important things in common. However, the settings for rock bursts in mines of the Coeur d'Alene district are diverse, often making it difficult to identify specific mechanisms involved in violent failures. As a result, geologic factors affecting bursts in hard-rock mines have not been studied as intensively as they have in coal mines. Much of the data concerning mechanisms of damage is observational. In addition, all workers do not agree on the extent or nature of the mechanisms involved. Efforts by the mines to minimize rock burst damage often involve trial and error, and the effectiveness of these efforts is often difficult to measure.

Major mines of the Coeur d'Alene Mining District are the Bunker Hill, Sunshine, Star, Galena, and Lucky Friday, but only the Lucky Friday, Sunshine, and Galena currently operate on a large scale. In all cases, steeply dipping veins containing lead, zinc, and silver have been mined. Recent operating depths extend to as much as 2,000 m beneath the surface. Most mining has involved overhand cut-and-fill techniques, but recently, the Lucky Friday Mine has changed to an underhand cut-and-fill technique in which cemented sand is used as backfill. Rock bursts have been most frequent at the Lucky Friday Mine, but have also affected the Sunshine and Galena mines.

Host rocks of Coeur d'Alene ore bodies are slightly metamorphosed Precambrian sedimentary strata *(11)*. The thick-bedded quartzitic strata of the district are often thinly laminated and separated from each other by thin interbeds of argillite. These bedding features appear to greatly influence the mechanical response of quartzite and its role in rock bursts and other ground control problems *(12-13)*.

A complex tectonic history in the Coeur d'Alene district includes formation of large-scale folds that created steep bedding dips on the scale of individual mines. The ore bodies postdate these fold episodes. In addition, postmineralization faulting has been intense. Younger tectonism caused extensive shearing along the steeply dipping argillite interbeds and caused locally extensive fracturing of quartzite.

All district production is closely associated with the quartzite, which commonly forms the immediate wall rock of vein ore bodies and development openings. This rock type is also most frequently involved in violent ground failures. Violent ground failures in district mines are classified as either strain bursts or fault-slip bursts *(13)*.

Strain Bursts

Strain bursts result from concentrated stress near mine openings. These bursts typically affect development openings such as crosscuts, raises, and initial cuts in overhand stopes. Shafts and raise boreholes are also sites for this type of rock burst damage. Although strain bursts are commonly thought to represent relatively surficial failures, pillar bursts and more extensive violent bursts that disrupt rock to a depth of several meters beneath the affected surfaces are also considered strain bursts *(13)*. These more extensive strain bursts are responsible for most of the violent damage that occurs in district mines. The most characteristic strain bursts involving wall rock cause damage to ribs, the junctions of ribs and the back, or the junction of the floor and the back (figure 5). Strain bursts that affect ribs are generally thought to characterize mining districts with high vertical stress loading, rather than horizontal loading, which is the case in the Coeur d'Alene district. This observation particularly emphasizes the fact that geologic factors other than in situ stress often influence rock bursts.

The sedimentary origin of the host rock assures that the wall rock in all mines in the district is divided into layers. Even thick, relatively homogeneous quartzite beds are internally layered on a fine scale and have often undergone partial mechanical delamination as a result of tectonism. Wall rock and ribs are thus inherently separated into steeply dipping slabs of variable thickness.

In addition to nearly ubiquitous, steeply dipping sedimentary layers, steeply dipping, gouge-filled faults are common in all mines of the district. Where these structures are subparallel to ribs and lie a short distance behind the surface of a rib, they form narrow, steeply dipping slabs that are frequently involved in strain bursts.

Fairhurst and Cook *(14)* suggested that strain bursting involves instantaneous buckling of slabby rock. Examination of rock burst damage at district mines supports this concept. Preexisting structures that divide the rock mass into layers promote strain-type rock bursts when these structures approximately parallel the surfaces of openings. High ground stresses parallel to the wall rock layers and to these surfaces apparently cause the slabs to buckle to the point of brittle failure. Once brittle fracture is initiated, stored elastic strain energy contained in the surrounding rock mass instantly and thoroughly crushes the buckled slabs.

The major distinction between large and small strain bursts is thought to lie in the relative capability of the surrounding wall rock to supply the elastic strain energy, or "following load," that drives the burst. Surficial strain bursts may involve only one slab. An extensive strain burst involves many slabs that buckle essentially simultaneously (figure 6), releasing stored elastic energy from a substantial volume of the surrounding rock mass.

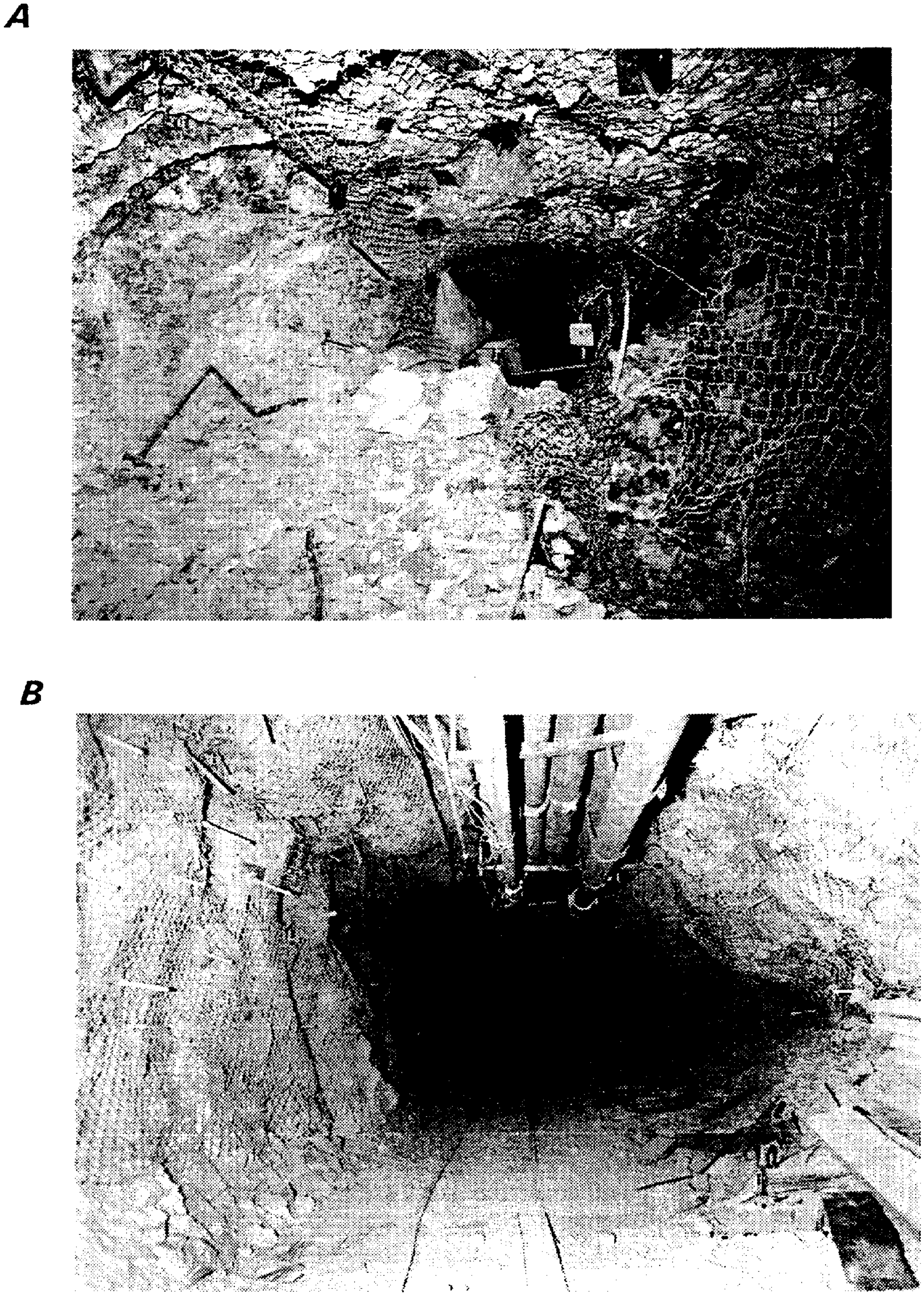

Figure 5.—Rib failures at the Lucky Friday Mine. Bedding is near-vertical and parallel to the opening. Both ribs were equally damaged. *A*, Typical burst damage. Note undamaged back and rock bolts and mesh displaced from ribs. *B*, Burst-modified shape of lateral from original rectangular cross section. Damage affected upper left and lower right ribs. Bedding dips steeply to the left.

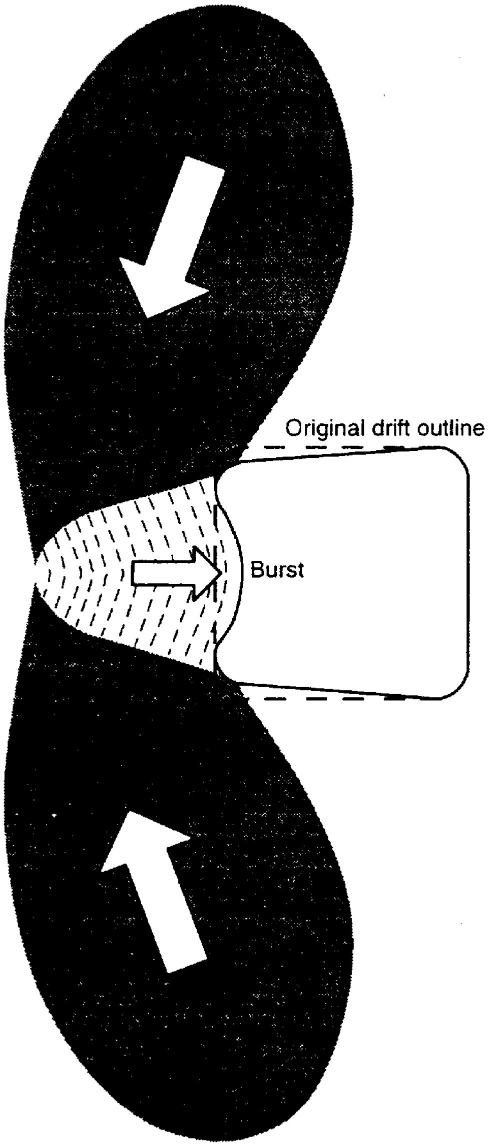

Figure 6.—Mechanism of failure from strain burst. Shaded areas identify inferred source of elastic strain energy, or following load, that drives bursting. Bending of rock slabs is exaggerated; brittle deformation would be expected before bending reaches the extent shown.

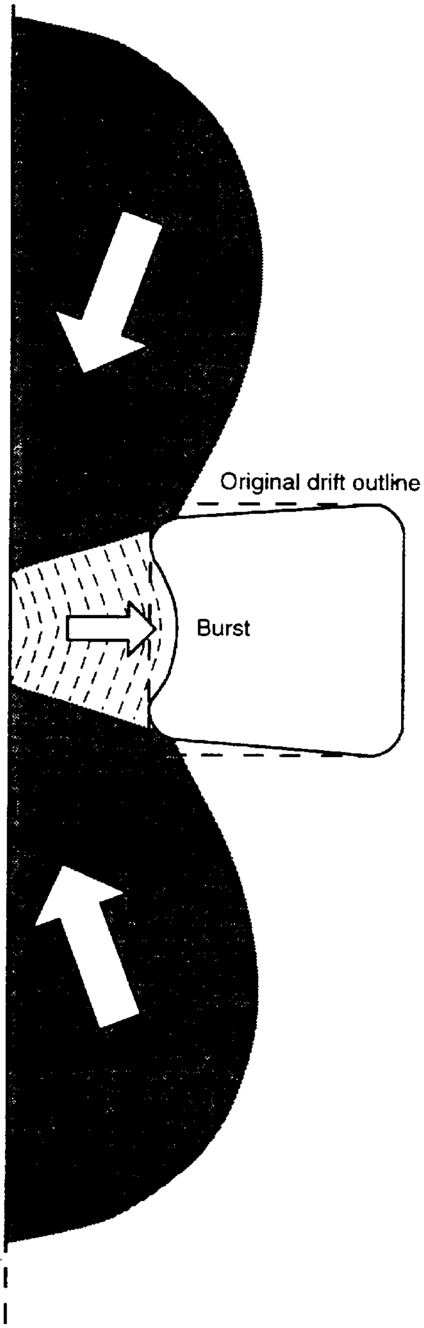

Figure 7.—Mechanism of failure from fault-bounded strain burst. Bedding or fault plane physically separates rock mass involved in burst from adjacent portions of rock mass. Slip along this plane enables a relatively large amount of elastic strain energy to be supplied to a relatively small volume of rock. Compare with figure 6.

Applying Fairhurst and Cook's hypothesis to rock bursts in the Coeur d'Alene district means that—

1. Less stress is required to buckle preexisting layers of rock than is needed to split massive, unfractured rock of the same composition. Thus, unbolted, very thinly layered strata may be deformed by buckling under relatively modest levels of stress loading. Closely spaced cleavage and joints are also locally involved in rock bursts for this reason.

2. Faults and bedding planes physically isolate buckling layers from the underlying rock mass. Slip along these planes is unimpeded by bonding to the adjacent rock mass (figure 7). This probably enables elastic strain energy from a large volume of a surrounding rock to supply following load to the deforming layers. White and others *(13)* defined strain bursts influenced by faults in this manner as *fault-bounded strain bursts*. Repair of rock burst damage often reveals that the rock burst cavity terminates at depth against a such a fault or bedding plane, thus identifying this type of strain burst.

As noted, extensive strain bursts and fault-bounded strain bursts often affect horizontal openings such as crosscuts and drifts. However, steeply inclined linear openings, such as shafts, raises, and raisebore holes are particularly susceptible to buckling failure. Because faults and strata in district mines generally dip steeply, openings intersect structures at low angles, a condition that favors buckling of rock layers into the opening. In addition, the common west-northwesterly strikes of steeply dipping strata and faults approximate the direction of greatest in situ stress *(15)*. Thus, the direction of greatest stress and following load potential also coincides with the direction of rock layering. At the Lucky Friday Mine, ore passes where these relationships are evident have been sites of especially bothersome ground control problems.

The strong relationship of strain bursts to structures that nearly parallel the surfaces of mine openings suggests that bursts can be avoided if openings are aligned so that they cross geologic structures at a large angle. This has been successfully tested in a part of the Lucky Friday Mine that had been plagued with large strain bursts involving the ribs (figure 5*A*). Ramps on the sublevels where strain bursts were occurring were found to have been driven nearly parallel to steep bedding. When access ramps were driven nearly perpendicular to these structures, rock bursts affecting the ribs ended in this part of the mine.

Fault-Slip Bursts

Fault-slip bursts represent damage that results from slip on a fault plane, possibly at some distance from a damage site. Hypocenters of these events frequently approximate the locations of known faults. Physical evidence for fault slip is rarely observed directly, but such events have been documented in the district by distinctive seismic signatures and through interpretations of burst damage and local geology *(12, 16)*.

Despite the large amount of energy that is often released in fault-slip events, actual damage is often impressively minor. Damage is thought most commonly to affect ground that is already highly fractured, usually as a result of prior tectonic deformation. Common direct results of fault-slip events are squeeze of sandfill, fracturing and possible heave of sills, and localized collapses.

The most extensive damage associated with large fault-slip events occurs where slip surfaces intersect mine openings. The usual descriptions of actual damage tend to involve rock being heaved from the surfaces of openings or loose ground being shaken down, but triggering of local strain bursts is often suspected.

Fault-slip bursts at the Lucky Friday Mine have often been associated with pillar or stope margins. This suggests that stoping may increase shear stress on preexisting faults and argillite interbeds or may promote slip by decreasing normal stress on fault planes. Such slippage is commonly interpreted as closing mined-out stopes.

Much low-level seismicity and shotcrete fracturing in Lucky Friday development ramps appear to reflect nearly continuous movements along bedding planes that dip steeply toward the vein. These fault-slip movements apparently represent progressive accommodation of the wall rock to mining and usually are not large enough to cause damage.

An August 1994 seismic event at the Lucky Friday Mine (figure 8) has been interpreted as resulting from strike-slip movement when highly stressed wall rock slipped along a preexisting fault *(13)*. Interpretation is based, in part, on observations of locally intensified squeeze of sandfill in stopes and inferred fracturing and buckling-type heave of the unmined vein along mining-induced fractures. Relatively minor failure of loose, broken ground affected various ribs near the event.

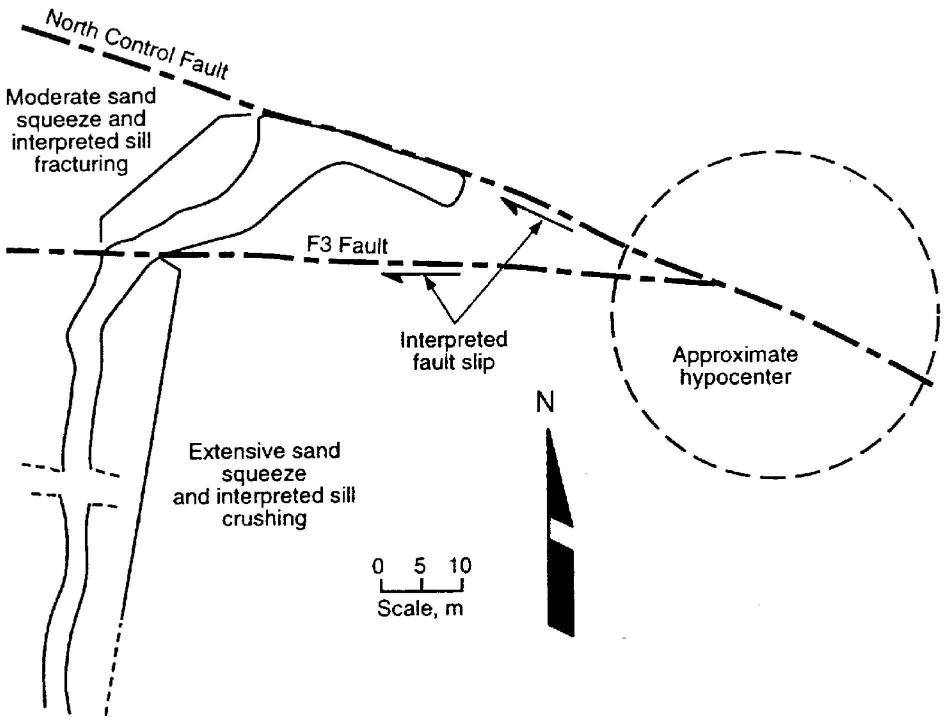

Figure 8.—Richter-magnitude 4 event centered eastward and above the stope in the Lucky Friday Mine squeezed sand and locally fractured and heaved the sill. Damage was most severe south of the F3 Fault. This event probably resulted from strike-slip movements on known faults, which tended to close the stope.

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