GEOLOGICAL FACTORS IN ROCK BURSTS IN THE COEUR D'ALENE MINING DISTRICT: STRUCTURE

By B. G. White,[1] J. K. Whyatt,[2] and D. F. Scott[1]

ABSTRACT

Research conducted by the U.S. Bureau of Mines indicates that both rock bursts and nonviolent wall rock deformation in the Coeur d'Alene Mining District are strongly controlled by preexisting structures. These structures include sheared, steeply dipping bedding; gouge-filled faults; and variably oriented joints. The locations and extent of burst damage are strongly influenced by the orientation of mine openings with respect to these structures.

Burst damage related to preexisting structures results primarily from (1) buckling of narrow, tabular rock masses into mine openings and (2) fault-slip on bedding planes or preexisting faults. Buckling-type failures occur when development openings intersect bedding, faults, or joints at acute angles. Fault-slip failures most typically occur along bedding or fault planes that intersect veins near pillar-stope margins as wall rock moves into mine openings.

Rock-burst damage and related ground support problems may be reduced by (1) planning development openings so they cut bedding, faults, and joints at angles greater than 50°, (2) giving extra attention to ground support in situations where unfavorable geometries cannot be avoided, and (3) destressing or eliminating pillars.

INTRODUCTION

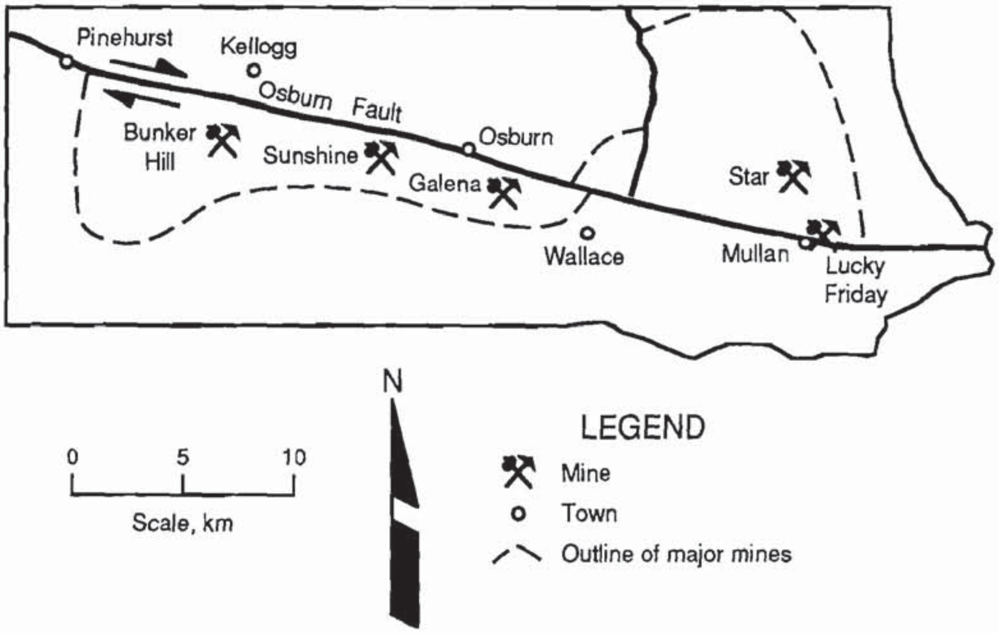
To reduce the risk of injury and death from rock bursts, the U.S. Bureau of Mines has conducted rock-burst research in the Coeur d'Alene Mining District for more than 40 years. Much of this research has addressed the seismic aspects of rock bursts. Such work has made it increasingly evident that rock bursts are often associated with specific geologic features such as faults. The present research has been directed toward better understanding the mechanical influence of geology on the generation of rock bursts.

The Coeur d'Alene Mining District (figure 1) has produced more than 110,000,000 t of high-grade lead-zinc-silver ore in little more than a century of nearly continuous operation. Only two mines are currently active. One is the Sunshine Mine, which has produced more than 8,500 million grams of silver from numerous veins. The second is the Lucky Friday Mine, a lead-silver mine with minor zinc production. Recently, reopening the silver-rich Galena Mine, which has been temporarily closed because of low silver prices, has been under consideration. All three of these mines have experienced rock bursts. In particular, the Lucky Friday Mine has experienced abundant low-level seismicity and several rock bursts each year, which have caused damage to major haulageways. Conclusions presented in this paper are strongly influenced by observations made at this mine.

Once mining in the district had progressed to depths of more than 800 m, rock bursts became fairly common. Their frequency has usually been attributed to the presence of hard, brittle quartzite or to the high horizontal stresses documented by various researchers. We believe each of these factors is locally important in rock-burst and general ground-control problems. However, we also believe most rock bursts and other ground failures in the

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

Figure 1
Selected Major Faults and Mines of Coeur d'Alene Mining District.



Note that Osburn Fault offsets productive parts of district (dashed lines).

district result directly from the presence of preexisting, planar rock discontinuities. These discontinuities are primarily steeply dipping beds and faults, but locally include closely spaced joints. All of these structures promote failure under less stress than would be required if the host rocks were unfractured and unlayered.

In this paper, we emphasize the influence of these structures on rock bursts and ground-control problems. Understanding the specific mechanics of ground failure caused by such structures should increase the effectiveness of ground-control measures. We conclude with specific suggestions that may reduce rock-burst hazards.

GEOLOGY

HOST ROCK

Host rocks of Coeur d'Alene ore bodies are slightly metamorphosed sedimentary strata of the Precambrian-aged Belt Supergroup (Hobbs and others, 1965). These strata are characterized by great thicknesses of relatively uniform, thin-bedded, fine-grained rock types. Most formations contain only silt- and clay-sized original sediment, now siltite-argillite. A few Belt formations important as ore hosts are characterized by original sand, now metamorphosed to quartzite. However, thick-bedded quartzitic strata of the district are often thinly laminated and contain numerous thin interbeds of argillite. These bedding features greatly influence the mechanical response of quartzite and its role in rock bursts and other ground-control problems (Scott, 1993).

All district production is closely associated with quartzite. Most of this production has been hosted by the Revett Formation, which is particularly characterized by the presence of quartzite layers (Hobbs and others, 1965). At the Lucky Friday Mine, rock bursts have been frequent in quartzite-dominated strata of upper and lower members of the Revett (Blake and Cuvelier, 1990; Scott, 1993). In contrast, bursts were uncommon when mining took place in the middle Revett member, which contains mostly softer, weaker, siltite-argillite strata. Elsewhere in the district, rock bursts are also commonly associated with quartzite.

STRUCTURE

The long history of diverse tectonism in the Coeur d'Alene district[3] began with the formation of tight, large-scale folds that created uniformly steep bedding dips on the scale of individual mines. The steeply dipping vein-type ore bodies postdate these folds. In addition, post-mineralization tectonism in the form of normal faults and strike-slip faults has been intense. The younger tectonism also caused extensive shearing along steeply dipping argillite interbeds and locally intense fracturing of quartzite.

Most Coeur d'Alene ore bodies trend west-northwest, roughly parallel to the strikes of faults and bedding. Some veins cut directly across these usual trends and directly truncate bedding. The Lucky Friday ore body is unusual in that the Lucky Friday vein follows the trend of beds that have been locally reoriented to northeast strikes by prior tectonism. Consequently, the vein has the more typical habit of lying relatively parallel to bedding strike, despite its northeasterly trend.

ROCK BURST TYPES

In this paper, a rock burst is considered to be a violent expulsion of highly stressed rock into a mine opening. However, the authors recognize that the term is also used in a more practical sense to include any mining-induced seismic event that causes damage to openings.

Three basic types of rock bursts are known to occur in district mines. Hedley (1992) distinguishes these as strain bursts, pillar bursts, and fault-slip bursts. At the Lucky Friday, and probably at other mines, specific geologic and geometric aspects of a burst site influence the type of burst that occurs.

1. *Strain bursts* result from the concentration of stress and high stress differentials near the surfaces of openings. These bursts typically affect development openings such as crosscuts, raises, and initial cuts in overhand stopes. Shafts and raise boreholes are also damaged by strain bursts. Similar deformation patterns develop in small-diameter drill holes, such as diamond drill holes.

Strain bursts are commonly thought to represent failure at the immediate surface of a mine opening. However, the failure of a surficial layer of rock exposes yet another surface, which may fail and expose a third layer, and so on. A progressive series of surface-type failures to great depth in the rock may ultimately involve a substantial volume of rock. If such deformation at a given site occurred almost instantaneously, the result would be a fairly massive strain burst. Consequently, we regard strain bursts as bursts that include deformation that penetrates to some depth beneath the initial surface of an opening, to several meters or more in the case of an extensive strain burst.

The most characteristic strain bursts at the Lucky Friday Mine affect ribs and rib-back and floor-back junctures (figure 2). Rock bursts that affect ribs are generally thought to characterize mining districts with high vertical stress loading, rather than horizontal loading, as is the case in the Coeur d'Alene district. This observation emphasizes that factors other than in situ stress often influence rock bursts.

2. *Pillar bursts* are caused by the instantaneous crushing of pillars. In the Coeur d'Alene district, by the time pillars have been mined to heights that would make them unstable, about 20 m or less, the pillars have commonly been destressed by drilling and blasting. Destress blasting of pillars has been used successfully in the district for more than 20 years. However, in highly stressed pillars, destress drilling has occasionally proven impossible because of the difficulty of keeping the drill holes open. In these cases, abandonment of the pillars has sometimes been the only reasonable recourse.

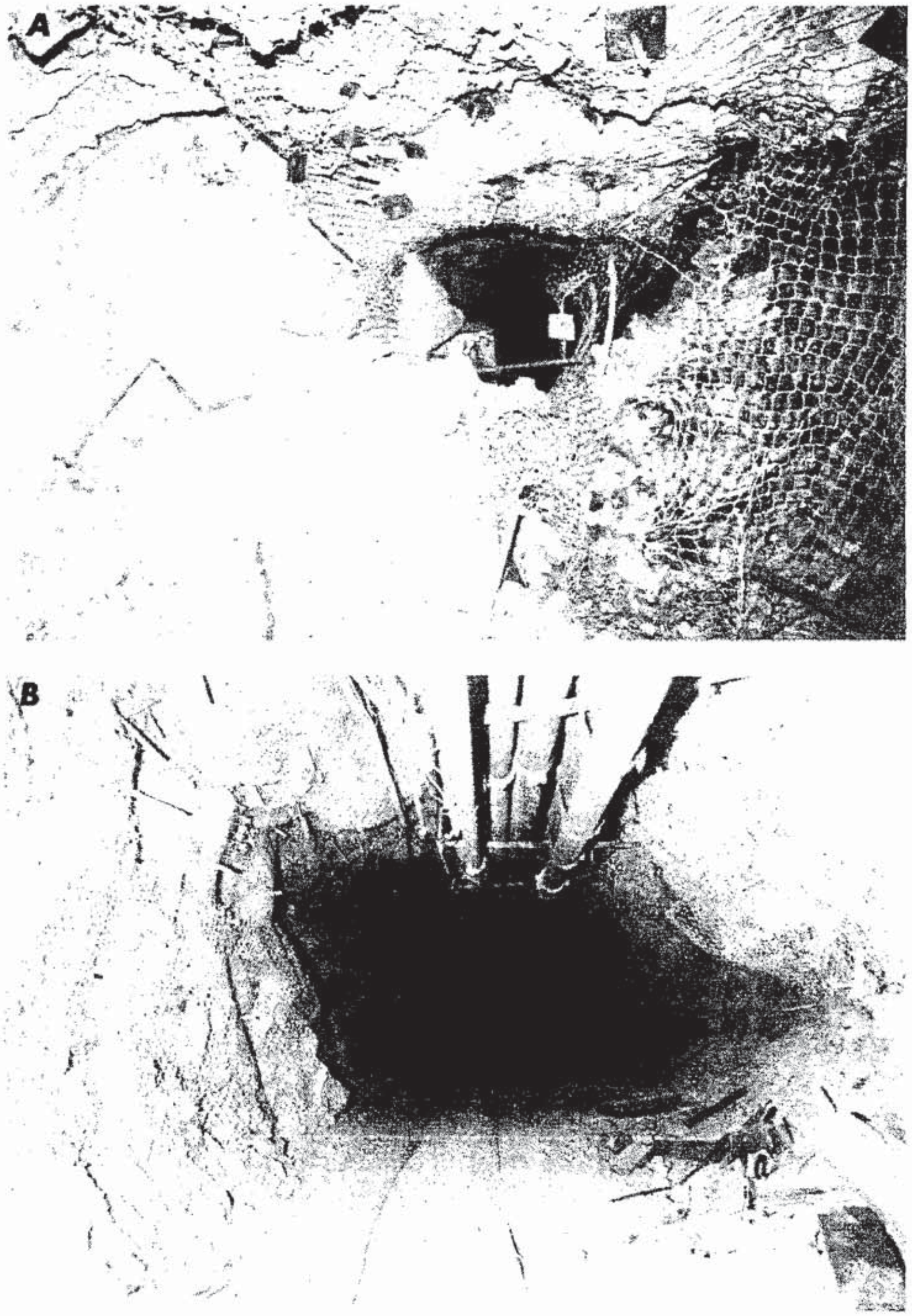
3. *Fault-slip bursts* have been documented in the district by distinctive seismic signatures and through interpretations of burst damage and local geology (Scott, 1993; Williams and others, 1992). Damage caused by fault-slip bursts involves rock being heaved into mine openings and typically accompanies a fairly large seismic event. Such events are frequently centered some distance from the damage site.

CONCEPTS OF ROCK BURSTING: MASSIVE ROCK

Nearly all rock bursts at the Lucky Friday Mine seem directly controlled by preexisting planes of weakness represented by bedding, faults, and joints. However, to fully appreciate the importance of these structures on development of bursts, a review of rock burst mechanisms in rock where such structures are absent or ineffective is useful. The immediate discussion is most relevant to

[3]A detailed discussion of this topic will be published early in 1995 in the proceedings of Belt Symposium III in the paper, "Diverse Tectonism in the Coeur d'Alene Mining District, Idaho," by B. G. White.

Figure 2
Rib Failures at Lucky Friday Mine.



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.

strain bursts and pillar bursts. Slip bursts will be considered separately.

In massive rocks, both strain bursts and pillar bursts result from high in situ stress that is locally concentrated and reoriented around mine openings. These two burst types are fundamentally identical in their failure mechanism. They differ primarily in scale, the result of the mine geometries involved and the effect of these geometries on the ability of surrounding wall rock to contribute the energy that ultimately drives the burst.

It has been suggested (Fairhurst and Cook, 1966; Cook, 1966) that bursting involves two separate, independent mechanisms. Observations at the Lucky Friday support this concept. These two fundamental mechanisms are thought to operate whether failure is instantaneous, producing rock bursts, or gradual, causing undramatic opening failures.

1. First, the involved rock develops discontinuous fractures parallel to the surfaces of the openings. Affected mine openings include crosscuts, drifts, shafts, raises, stopes, and drill holes. If fracturing is not extreme and fractured rock remains in place, significant ground-support problems may not arise. However, if conditions are such that these fractures continue to develop, they begin to separate the wall rock into slabs that approximately parallel the surfaces of the opening.

2. Second, the slabs ultimately deform by buckling into the opening. Buckling, in turn, causes brittle rock to fracture. This failure mode is active when the discontinuous fractures develop to such an extent that the tabular rock layers formed can no longer support load and become unstable. According to descriptions of buckling behavior found in standard references on material strength (e.g., Timoshenko and Gere, 1961), this point is reached at a certain ratio of thickness to length for the load and material involved. While gradual buckling may only cause nuisance damage, instantaneous buckling may represent a rock burst.

The elastic strain energy that exists within individual slabs when buckling deformation is initiated is regarded as inadequate to drive violent failure of the slab (Blake, 1972; Hedley, 1992). To generate a burst, elastic energy must be supplied from the rock mass surrounding the buckling rock. This extra contribution of elastic energy has been called "following load" (e.g., Fairhurst, 1986).

A fundamental difference between pillar bursts and strain bursts lies in the relative capability of the surrounding wall rock to supply following load. This can be illustrated by first comparing these types of bursts with a simpler case. For example, if only a single unstable slab were to develop adjacent to a mine opening (figure 3*A*), attachment of the ends of the slab to adjoining, rigid wall rock would limit the capability of the surrounding rock mass to contribute elastic energy. The adjoining rock is regarded as "stiff" relative to the deforming slab. The surface rock layer could detach itself or spall, but such an event would necessarily be relatively low in energy.

At the other extreme, pillar bursts involve complete pillar failure. Pillar bursts apparently develop from the formation and essentially simultaneous buckling of many unstable slabs throughout the pillar (figure 3*B*). Here, stored elastic energy from a large volume of surrounding wall rock is released by initiation of buckling. This enables elastic strain energy from this large volume of a rock mass to be directed to the bursting pillar. An extensive strain burst involving development of multiple slabs that buckle essentially simultaneously (figure 3*C*) represents an intermediate case, and stored elastic energy from a moderate volume of a surrounding rock mass becomes available to drive the burst.

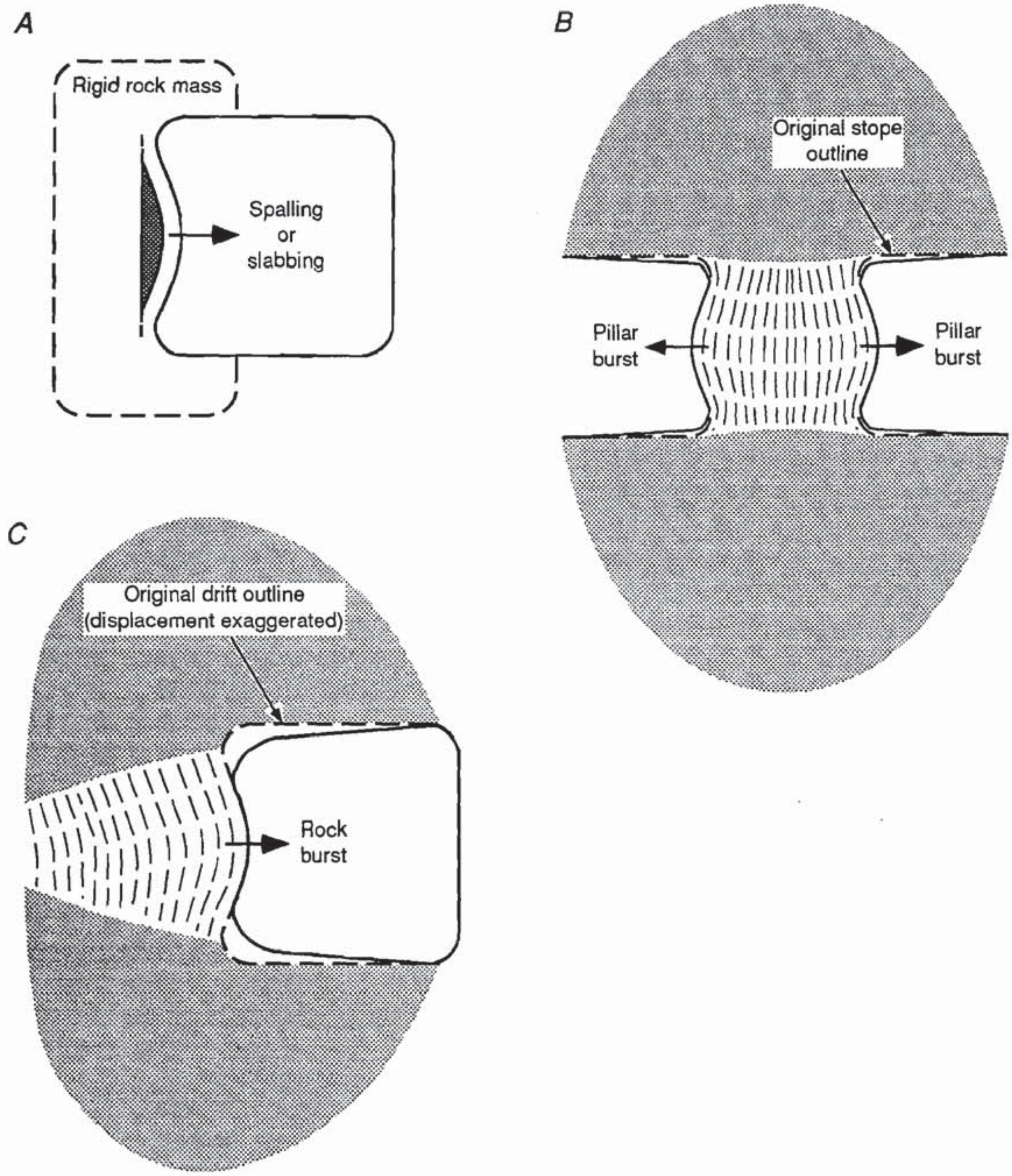
CONCEPTS OF ROCK BURSTING: LAYERED ROCK

Consideration of rock bursts in massive rock highlights the contrast in rock behavior in the Coeur d'Alene district that results from the presence of preexisting structures. Wall rock in this district is everywhere layered as a result of its sedimentary origin. In all mines, these layers mainly dip steeply, the product of tight, large-scale folding during the early tectonic history of the district (Hobbs and others, 1965). Subsequent tectonism has split apart many of these sedimentary layers. Even thick, relatively homogeneous beds are internally layered on a fine scale and have been subjected to partial mechanical delamination as a result of tectonism. Wall rock and ribs are thus inherently separated into steeply dipping slabs of variable thickness. As a result, the mechanism of ground failure is reduced to a single stage of buckling-type deformation.

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 columns that are frequently involved in bursts.

The pervasive layering of wall rocks has two direct effects on ground support that greatly contribute to rock bursts and ground-support problems in general. These two factors may be most responsible for the high incidence of rock bursts in the district.

Figure 3
Mechanisms of Buckling-Type Failures.



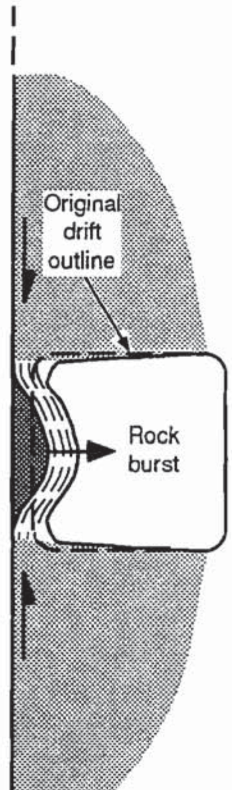
***A*, Single slab failure; *B*, pillar failure; *C*, extensive strain burst failure. Shaded areas identify inferred source of elastic strain energy that drives bursting. Bending of rock slabs is exaggerated; brittle deformation is expected before bending reaches the extent shown.**

1. Less stress is required to buckle preexisting layers of rock than to split massive, unfractured rock of the same composition into comparable layers. This can be illustrated by reference to general equations that describe critical stress necessary to cause buckling as a function of thickness divided by length (e.g., Timoshenko and Gere, 1961). For example, the critical stress necessary to cause a rock layer to buckle approaches 0 as thickness approaches 0. Thus, unbolted, thinly layered, near-vertical-dipping strata should be easily deformed by buckling at relatively shallow depths because of the load generated by the overlying rock alone. Closely spaced, preexisting joints are also locally involved in rock bursts for this reason.

2. Faults and bedding planes physically isolate buckling layers from the adjoining rock mass. Slip along these planes is unimpeded by attachment to the rock mass on the opposite side of the structure (figures 4 and 5). This enables elastic strain energy from a fairly large volume of a surrounding rock mass to actively supply following load to the deforming rock. We define this as a *fault-bounded strain burst*. We believe the capability of rock to fail by this mechanism is a major reason for the high incidence of rock bursts in district mines. Fault-bounded strain bursts in steeply dipping structures also account for the common occurrence of rib bursts in the district, which would not ordinarily be expected in mines where the greatest tectonic loading is horizontal.

Fault-bounded strain bursts, like ordinary strain bursts and pillar bursts, derive their relatively large energies from elastic strain energy contributed by the surrounding rock mass. We speculate that the rock mass can deliver this energy from the greatest volume of rock when the affected

Figure 4
Mechanism of Fault-Bounded Strain Burst.



Bedding or fault plane physically separates rock mass involved in burst from adjacent portions of rock mass. Slip along these planes enables relatively large amounts of elastic strain energy to be supplied to relatively small volumes of bursting rock. Compare to figure 3*A*.

Figure 5
Fault-Bounded Strain Burst.

Burst damage in Lucky Friday 5400-01 haulage ramp. Plates have been stripped from roof bolts by downward impulse and localized back failure. Most expelled rock came from narrow rock column in right rib formed between rib and fault immediately behind original surface of rib. It is not known whether these fractures formed during or preceded burst event.

layers nearly parallel the longest dimension of an available opening. As a result, the stress direction that is most effective in causing a burst is relatively perpendicular to drifts, crosscuts, or other linear openings. Where structures dip steeply, bursts that occur in drifts and crosscuts inevitably affect ribs, a result that would ordinarily be interpreted as indicating that greatest loading is steep. Instead, such bursts may primarily reflect the orientation of the long dimension of the opening in relation to planar features.

FACTORS THAT PROMOTE FAULT-BOUNDED STRAIN BURSTS

Several factors greatly increase the likelihood of fault-bounded strain bursts. For example, where mine openings cross strata or faults at a low angle, the probability increases that the opening will expose layers that are at a critical level of stress. Some of these layers are also likely to be "fault-bounded" along sheared bedding planes or actual faults and therefore to be vulnerable to the fault-bounded strain burst mechanism. In addition, steeply dipping strata that are truncated at low angles by drifts and that are mechanically detached from adjacent strata by gouge-filled argillite bedding planes have greater effective spans across openings than does competent unstratified rock. These conditions amplify the load parallel to the surface where these strata form ribs. Strata that are cut off by a fault on one side of an opening are also thought to acquire disproportionately high loads on the opposite side of the opening. Finally, because quartzite has a higher elastic modulus than argillite, an equal amount of layer-parallel strain causes disproportionately higher load in quartzite layers (and correspondingly less load in adjacent argillite beds). This partially accounts for the higher incidence of rock bursts observed in quartzite.

Although ground failure resulting from buckling ribs is strongly favored when the affected layers are nearly parallel to the ribs, we have observed instances of this type of deformation at locations where bedding strikes were as great as 50° from the trend of subhorizontal development openings and where bedding dips were as low as 50°. In these cases, ground failures have tended to be gradual, resulting in progressive breakup of shotcrete, loosening of rock bolts, and localized rib collapse (figure 6). These observations emphasize the effectiveness of preexisting structures on promoting ground support failures.

As noted, fault-bounded strain bursts affect horizontal openings, such as crosscuts and drifts. However, steep openings, such as shafts, raises, and raisebore holes, are particularly susceptible to this type of failure. Because faults and strata in district mines generally dip steeply, steeply oriented openings generally lie at a low angle to these structures. In addition, the common west-northwesterly strikes of steeply dipping strata and faults approximate the direction of greatest tectonic loading. Thus, the direction of greatest stress also coincides with the direction of greatest following load potential. At the Lucky Friday Mine, ore passes where these relationships are evident have been sites of especially bothersome ground-control problems.

Figure 6
Buckling Failure in Rib.

Gradual buckling-type deformation in Lucky Friday 5570-07 ramp. Deformed layers have separated from intact layers by slip along bedding plane. Beds strike 50° from rib and dip 70° to the right. Rock layers have broken into short pieces.

BUCKLING STABILITY OF SLABS AND EFFECTIVENESS OF ROCK BOLTS

The critical stress necessary to cause buckling failure of narrow slabs is actually proportional to the square of thickness divided by length (e.g., Timoshenko and Gere, 1961). The dependence of critical stress on the square of thickness divided by length partially accounts for the effectiveness of rock bolts as ground support, in that bolts reduce the effective length of slabs that could potentially fail by buckling. While bolts that bisect slabs reduce length by one-half, the critical stress necessary to cause buckling increases by a factor of four. Experience in deep South African mines (Wagner and Godfrey, 1976) has led to several standard bolting guidelines that take advantage of this concept for burst-prone ground. These are (1) bolt length in ribs should equal or exceed one-half the height of the opening and (2) bolt spacings should not exceed one-half the length of the bolt. Bolts used in such a manner clamp rock together to produce units of greater total thickness and reduce the effective length of thin slabs.

We reason that intact slabs are able to support significantly greater loads than partially buckled slabs. Similarly, we infer that greater bolt strength is required to restrain a partially buckled slab than is required to prevent buckling from being initiated. Consequently, it would be best to prevent the start of buckling failure by bolting slabbed rock solidly at the outset (Cook, 1966). Highly rigid (high-modulus) rock bolts should be most effective in preventing the initiation of buckling-type failures (Cook, 1966). However, once buckling has begun, bolts that resist breaking are probably most effective (Wagner and Godfrey, 1976). Yieldable bolts, such as the South African cone bolt, may be particularly well adapted for such situations (Ortlepp, 1992). In many cases, a combination of high-modulus rigid bolts and yieldable bolts may prevent most problems.

Since buckling-type deformation requires the existence of slabs, it follows that bolting practices should emphasize containment of these slabs. Bolts are likely to be most effective where they cross bedding or other tabular structures at nearly right angles. Such an orientation maximizes the component of clamping stress and also penetrates the greatest thicknesses of rock layers. This suggests that bolts should be installed more nearly perpendicular to rock layers than to mine surfaces or at some intermediate, compromise angle.

FAULT-SLIP BURSTS

Burst damage in the district sometimes results from slip on faults or other structures, but evidence for such slip is rarely observed directly (Williams and others, 1992; Scott, 1993). However, hypocenters frequently approximate the locations of known faults, and seismic data support the fault-slip interpretation.

Major damage caused by these events occurs primarily where slip surfaces intersect mine openings. Such damage appears to result from rock being heaved from the surfaces of openings. It is also thought to result when seismic waves from fault-slip events encounter openings. Such damage is thought to especially affect ground that is already highly fractured, usually as a result of prior tectonic deformation, so such ground is already unstable.

Fault-slip bursts at the Lucky Friday 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 tending to close mined-out stopes.

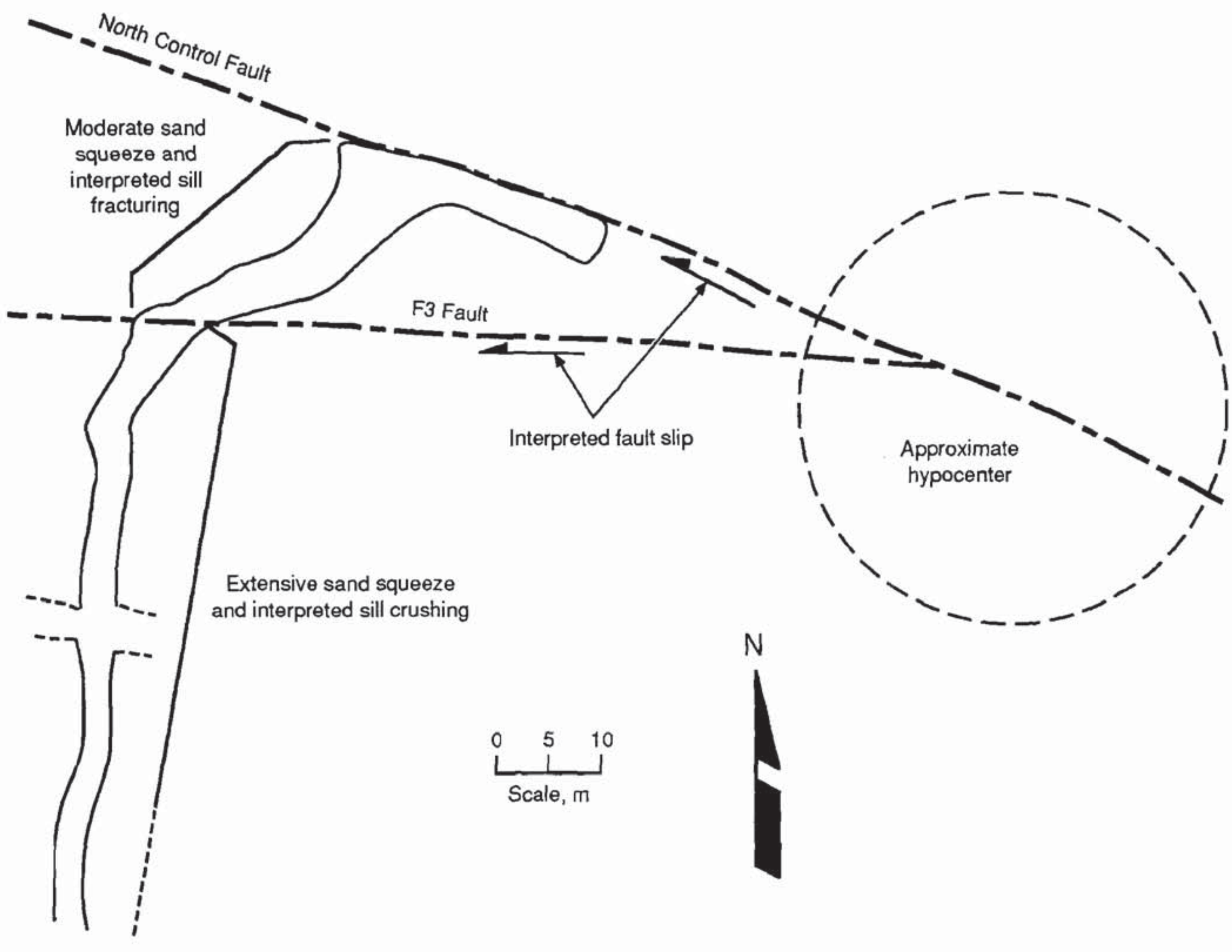
Much low-level seismicity and shotcrete damage in Lucky Friday development ramps appear to reflect nearly continuous movements along bedding planes in the immediate footwall of the Lucky Friday vein. Such movements apparently represent progressive accommodation of the wall rock to mining. These movements also suggest that slip-type seismic events are probably inevitable. Consistent ground-support measures are needed that are adequate to contain the most commonly occurring types of damage.

Large fault-slip-type events in the Richter magnitude range of 2 to 4 have been documented in the hanging wall of the Lucky Friday vein. These events typically have hypocenters 30 to 70 m from the nearest mine workings. Such events seem best interpreted as indicating closure of mined-out stopes by movement on preexisting faults. Despite the amount of energy released in such events, actual damage is often minor and is expressed as sand squeeze, sill fracturing, and localized, relatively nonviolent rib failures. We interpret an August 1994 burst at the Lucky Friday Mine (figure 7) as resulting from strike-slip movement when highly stressed wall rock moved by slipping along preexisting fault planes. 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.

During previous overhand mining at the Lucky Friday, fault-slip bursts that affected access crosscuts were somewhat common. Damage to the crosscuts was usually dominated by sill heave on the pillar side of a bedding slip plane and down-drop on the opposite side (figure 8). Damage was usually interpreted as indicating a significant dip component of slip (figures 8 and 9). This type of damage has been less frequent and less severe since underhand mining replaced the overhand method.

Fault-slip seismic events may also cause secondary damage as seismic waves intersect mine openings, displacing rock into the opening. "Shakedown" is thought to originate from highly fractured, weak back and wall rocks, which are dislodged relatively nonviolently. "Flyrock" originates when rock is conspicuously flung away from its parent surface. Seismic waves may also trigger buckling failure in layers that have already been stressed almost to their critical points. In such cases, the ensuing damage may bear no direct relationship to the mechanism most responsible for the event.

Figure 7
Interpretation of Fault-Slip Burst Near 5570-07 Stope.

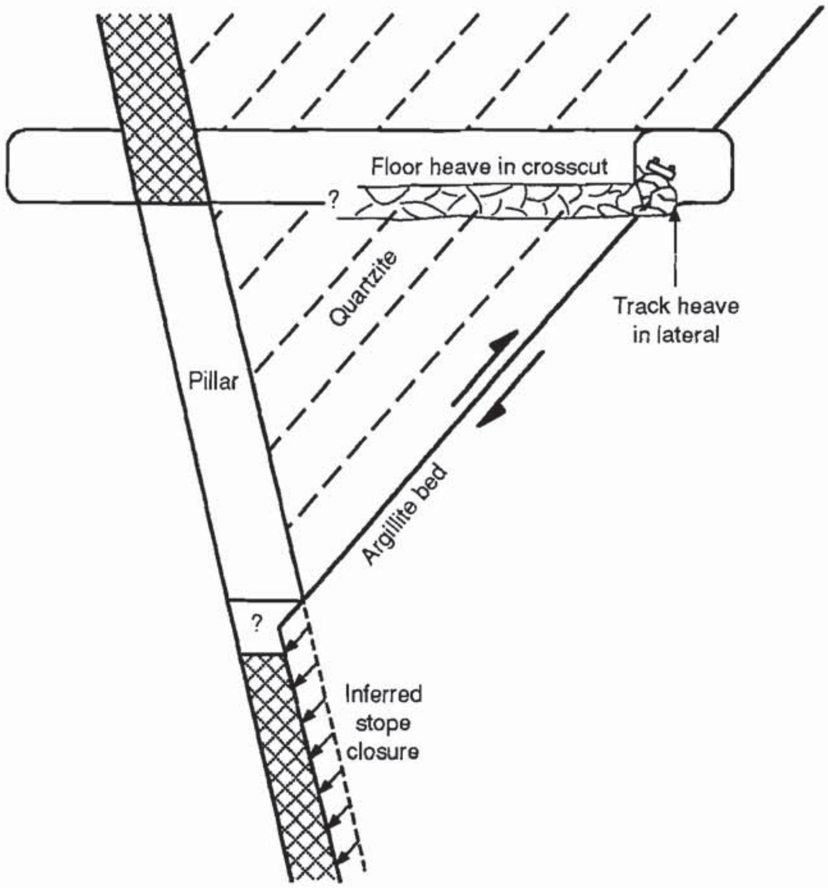


A Richter-magnitude 4 event centered east of 5580-07 stope in Lucky Friday Mine squeezed sand and locally fractured and heaved sill. This event probably resulted from strike-slip movements on known faults, which tended to close stope.

Figure 8
Burst Damage in Lateral, Lucky Friday Mine.

Photo shows that track heaved upward and illustrates inferred fault slip on an underlying bedding plane approximately beneath and parallel to exposed rail. Debris on track fell from right rib.

Figure 9
Stope Closure Resulting From Slip Along Bedding.



Interpretation of movement indicated by damage shown in figure 8. (After Williams and others, 1992.)

SUMMARY AND RECOMMENDATIONS

We conclude that, in the Coeur d'Alene Mining District, many rock bursts are controlled by steeply dipping bedding planes and faults. These structures are a major reason for the high incidence of rock bursts and mining-induced seismicity. We presume that these planes of weakness cause failure under significantly less stress than that required to cause bursts in massive, unlayered rock. In addition, the orientations of steeply dipping structures with respect to mine openings influence the surface that is damaged, regardless of the direction of greatest stress.

Consideration of the effects of preexisting structures on ground failure affirms the usefulness of several standard measures used to alleviate ground failure problems. These measures include (1) longwall underhand mining, which eliminates stress-concentrating pillars; (2) the use of shotcrete and mesh for containing shakedown and minor slabbing; and (3) use of bolts to stabilize the rock mass on a large scale.

We particularly emphasize that, where possible, openings should be planned so as to cross structures at large angles (as near to 90° as possible) rather than at low angles. In some cases, aligning accessways and positioning and inclining raise boreholes may enable them to be driven at large enough angles to inclined faults and bedding that many ground-control problems may be prevented.

Where development openings at low angles to steeply dipping beds or faults cannot be avoided, we recommend special attention to ground support. A primary objective should be to bolt rock layers tightly together so as to constrain these layers from buckling. We suggest that—

1. Bolts should be driven so as to cross bedding or faults at angles as near to perpendicular as practicable.
2. Rocks should be bolted as soon as possible after blasting and mucking to secure rock slabs before buckling is initiated and while the immediate face is still providing significant support.
3. Mine openings, such as slot ramps, that will later be deepened should be bolted with bolts that approach one-half the ultimate height of the opening; the use of stulls with blocking sufficient to permit limited squeeze without failure and extension of cemented sand into slots is also suggested.
4. If wall rocks are bolted before buckling begins, bolts with high modulus (resistance to stretching) should be most helpful. However, if buckling takes place despite initial bolting, strong, yieldable bolts are likely to provide the greatest long-term usefulness. A combination of high-modulus bolts and yielding bolts may be most useful.

REFERENCES

Blake, W. Rock Burst Mechanisms. CO Sch Mines Q, v. 67, No. 1, 64 pp.

Blake, W., and D. J. Cuvelier. Developing Reinforcement Requirements for Rockburst Conditions at Hecla's Lucky Friday Mine. Paper in Rockbursts and Seismicity in Mines, Proceedings of the 2nd International Symposium on Rockbursts and Seismicity in Mines, ed. by C. Fairhurst (Univ. of MN, Minneapolis, MN, June 8-10, 1988). Balkema, 1990, pp. 401-410.

Cook, N. G. W. The Design of Underground Excavations. Paper in Failure and Breakage of Rock. 8th Symposium on Rock Mechanics, ed. by C. Fairhurst (Univ. of MN, Minneapolis, MN, 1966). AIME, 1966, pp. 167-193.

Fairhurst, C. In-Situ Stress Determination—An Appraisal of Its Significance in Rock Mechanics. Paper in Rock Stress and Rock Stress Measurements: Proceedings of the International Symposium on Rock Stress and Rock Stress Measurements, ed. by O. Stephansson (Stockholm, Sept. 1-3, 1986). Centek, Lulea, Sweden, 1986, pp. 3-17

Fairhurst, C., and N. G. W. Cook. The Phenomenon of Rock Splitting Parallel to the Direction of Maximum Compression in the Neighborhood of a Surface. Paper in Proceedings of the First Congress on the International Society of Rock Mechanics (Lisbon, Portugal, Sept. 25-Oct. 1, 1966). V. 1, Nat. Lab. of Civil Eng., Lisbon, Portugal, 1966, pp. 687-692.

Hedley, D. G. F. Rockburst Handbook for Ontario Hardrock Mines. Spec. Rep. SP92-1E, CANMET, 1992, 305 pp.

Hobbs, S. W., A. B. Griggs, R. E. Wallace, and A. B. Campbell. Geology of the Coeur d'Alene Mining District, Shoshone County, Idaho. U.S. Geol. Surv. Prof. Paper 478, 1965, 139 pp.

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

Scott, D. F. Geologic Investigations Near an Underhand Cut-and-Fill Stope, Lucky Friday Mine, Mullan, ID. USBM RI 9470, 1993, 21 pp.

Timoshenko, S. P., and J. M. Gere. Theory of Elastic Stability. McGraw-Hill, 1961, 541 pp.

Wagner, H, and J. B. Godfrey. Location and Support of Tunnels in Deep-Level Gold Mines. Paper in Tunnelling '76, ed. by M. J. Jones (London, Eng., Mar. 1-5, 1976). Inst. Min. Metall., 1976, 341-347.

Williams, T. J., C. J. Wideman, and D. F. Scott, D. F. Case History of a Slip-Type Rockburst. PAGEOPH, v. 139, No. 3/4, 1992, pp. 627-637.

Special Publication 01-95

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

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

UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES
Rhea L. Graham, Director

Library of Congress Cataloging in Publication Data:

Maleki, Hamid N.

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

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

Includes bibliographical references.

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

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

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