MECHANICS OF A LARGE, STRAIN-TYPE ROCK BURST AND DESIGN FOR PREVENTION

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ABSTRACT. Detailed mapping and examination of the site of a large rock burst at the Lucky Friday Mine, Mullan, ID, demonstrated conclusively that damage was caused by a splitting and buckling failure mechanism initiated by separation of rock into layers along steeply dipping metamorphic shear foliation subparallel to the affected crosscut. The thin tablular layers then buckled into the crosscut from both sides. Rigorous control of the burst by these layers suggests practical measures for avoiding bursts in crosscuts in the future by repositioning and reorienting openings so that splitting and buckling are reduced or precluded.

1. INTRODUCTION

Many of the lessons that have been learned about rock bursts in the Coeur d'Alene district of northern Idaho were recently summarized by Whyatt et al. [1]. However, a comprehensive understanding of rock burst damage mechanisms has remained elusive.

Fairhurst and Cook [2] considered stress-induced buckling of rock layers as a rock burst mechanism, but most researchers have limited this mechanism to fairly minor events. White et al. [3], White and Whyatt [4, 5], Maleki and White [6], and Whyatt and White [7] described field examples of large rock bursts and other rib deformation that they inferred to have resulted from buckling. The evidence for one large burst described as caused by buckling, the Craig drift rock burst (Strathcona Mine of Falconbridge, Ltd., in Ontario, Canada), is suggestive but not compelling (see [8]). Many studies simply sidestep consideration of damage mechanisms or ascribe damage to a seismic impulse or to crushing, with no specific damage mechanism specified.

We have noted many examples of time-dependant buckling in soft, argillitic strata at district mines, so it is clear that this deformation mechanism is common. We have also discerned a strong tendency for rock bursts to damage crosscuts and ramps driven subparallel to steeply dipping bedding and faults. However, actual data confirming that buckling was involved in these bursts have been limited. The site of an extensive rock burst (Richter magnitude 2.4) that took place on December 27, 2000, at the Lucky Friday Mine provides unusually compelling evidence for a buckling failure mechanism.

A case study of this rock burst was conducted as part of a project to reduce rock burst hazards being undertaken by the Spokane Research Laboratory (SRL) of the National Institute for Occupational Safety and Health (NIOSH). These efforts are made possible through a longstanding cooperative research relationship between the SRL and Hecla Mining Co.'s Lucky Friday Mine, Mullan, ID.

2. GROUND CONDITIONS

The Lucky Friday ore body is a narrow, steeply dipping galena-quartz vein that has been mined over a vertical extent of 1500 m and to depths of nearly 2000 m. The vein is currently mined from successively developed sublevels, each of which enables development of a number of up- and down-ramps to the vein (fig. 1) [9].

Crosscuts to 06 stopes are driven southeastward from a primary sublevel haulage (fig. 1), which is the best practical location and orientation in the area for avoiding a known major fault. The 06 crosscuts are developed at the same elevation as the highly stressed abutment. Rock bursts affecting 06 crosscuts and ramps have been a recurrent problem, with major

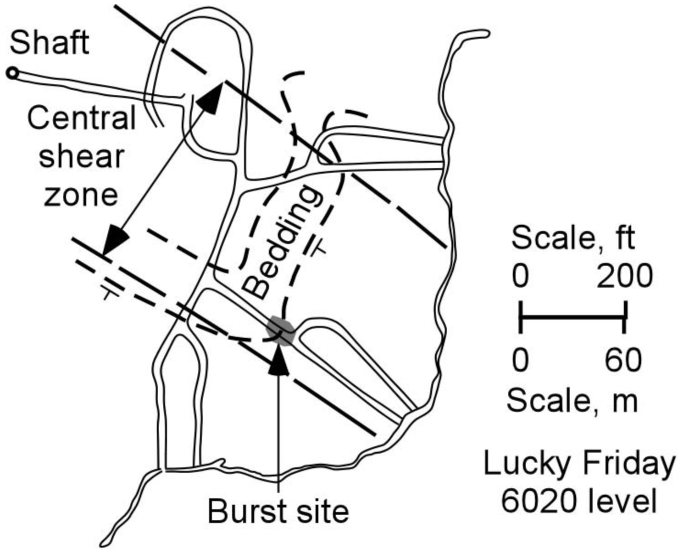

Figure 1.—Map of typical sublevel showing 06 crosscut, central shear zone, and folded quartzite.

damage usually involving the ribs and lesser damage affecting the back, floor, or corners.

The minimum standard ground support used in crosscuts includes 5-by-5-cm, 9-gauge chain link fencing that is pinned to the back with Dywidag[1] and Split-Set rock bolts. Across the back, three rows of 1.8-m-long Dywidag bolts are installed along with 0.9-m-long Split-Set bolts at a maximum bolt spacing of 0.9 m. The walls are screened and bolted with 1.2-m Split-Set bolts on 1.2-m centers to within 0.9 m of the floor. In crosscuts, a 5-cm-thick layer of steel-fiber-reinforced shotcrete is also standard.

3. GEOLOGY

Strata at the burst site are massive sericitic quartzite beds (fig. 2) that sometimes split into thin layers along bedding laminations, evidently because of high stress along bedding and the absence of confining pressure.

The 6020 crosscut approximately follows the axial plane of a prominent, nearly overturned anticline that plunges about 30° at this location, resulting in the relatively low bedding dips seen along part of the crosscut (figs. 1 and 2). Steep dips are mapped on the north limb of the fold.

The burst site lies within a structural zone referred to as the "central shear zone," which is defined by steeply dipping, metamorphic shear foliation and an anastomosing network of minor faults (fig. 1). It is evident that foliation creates important planes of weakness, as the rock often splits into layers parallel to this fabric. Most faults in the central shear zone have little or no gouge, but one fault containing several centimeters of gouge forms the effective northern limit of the damage zone. The strike of the central shear zone structures traverses the crosscut at a slight angle in its most extensively damaged part, but changes to a more northwesterly direction toward the west, where damage diminishes.

No in situ stress data are available from near the burst site, but the orientation of stresses can be reasonably inferred. The direction of greatest stress in quartzite strata at all mines in the district is subhorizontal and usually trends northwest, with a magnitude approximately twice that of the least and intermediate stresses [10]. At the site, the direction of least stress is probably oriented toward the mined-out part of the vein, which is grossly upward and southeastward. Thus, it is likely that the direction of greatest stress plunges moderately toward the abutment, approximating the plunge of the local folds, and roughly parallel to structures of the central shear zone.

4. OBSERVED DAMAGE

The rock burst expelled approximately 320 tons of broken rock from both ribs, approximately doubling the width of the access (fig. 2). Additional rock came down from the back. After the displaced rock had been removed and new ground support installed, an extensive cavity was exposed on each side of the crosscut. A series of cross sections along the crosscut (figs. 3*A* through 3*E*) shows that the damage along opposite sides, both major and minor, is diagonally opposed and centered at different elevations on the respective sides.

Where the burst cavities are most extensive and deepest, they coincide with a location where the back exceeded design height by 1 to 2 m. However, it was not clear whether the added height resulted from overbreak or rock burst damage. In either case, it is likely that conditions in the back created an *effectively* greater height at the time of the burst, for inspection showed that bedding exposed in the back was intensely split and loosened along bedding plane laminations, conditions that probably caused the ground to cave.

[1]Mention of specific products and manufacturers does not imply endorsement by the National Institute for Occupational Safety and Health.

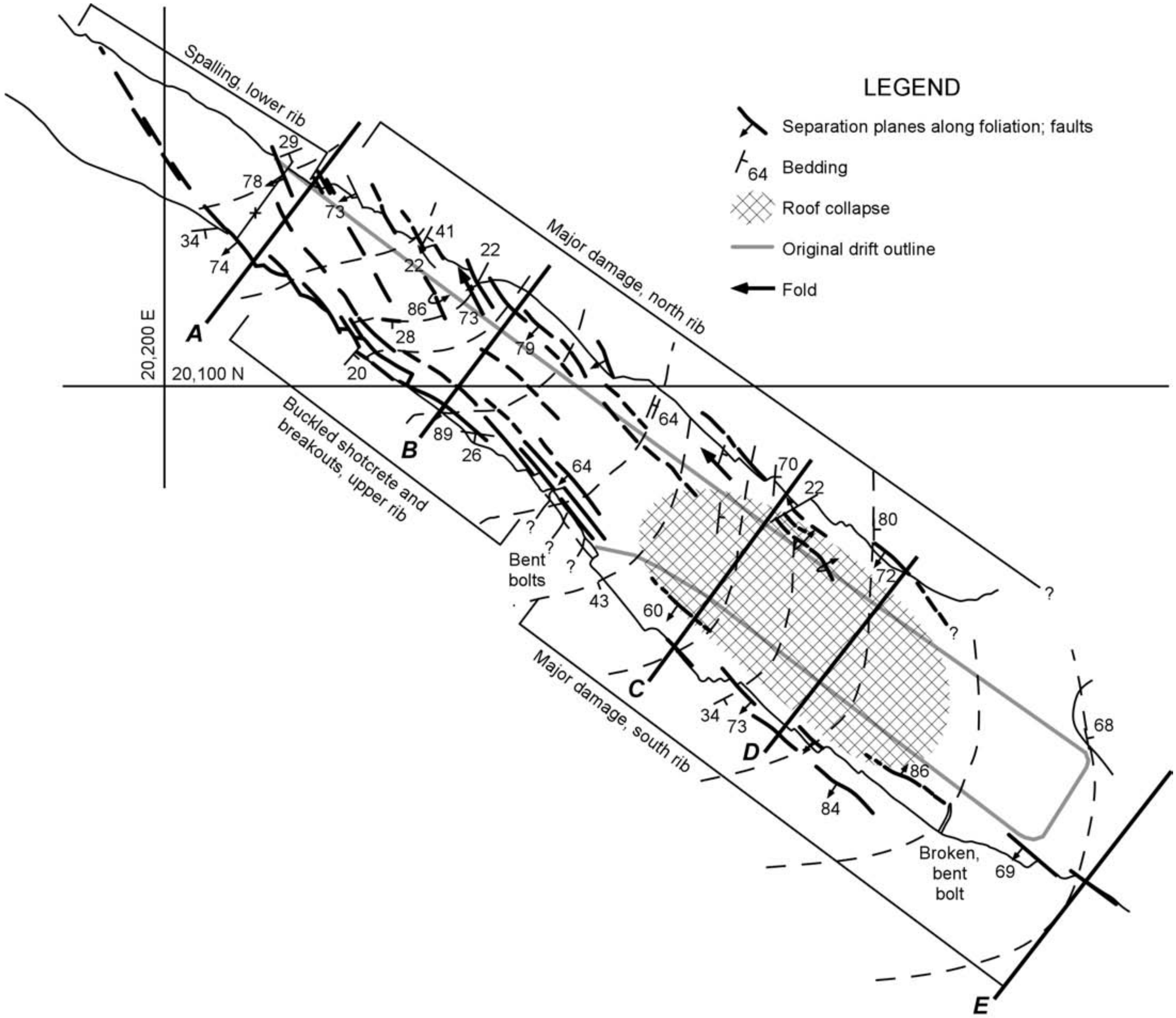

Figure 2.—Map of burst site.

West of the major damage, minor breakouts and buckled shotcrete persisted along the upper part of the south rib, whereas spalling affected the lower north rib. Thus, the locations of minor burst damage were diagonally opposed, just as the more extensively damaged parts of the crosscut.

Immediately west of the south-side cavity, inspection of in-place Split-Set bolts showed that they were bent by shearing displacements at depth. Elsewhere, a single broken and bent Split-Set bolt remained in place. These examples serve to emphasize a common observation at burst sites: That a large percentage of the rock bolts involved in bursts–typically about half–have been bent as a result of shearing among rock layers.

The most prominent geologic structures seen in the ribs were steeply dipping separation planes parallel to the northwest-trending central shear zone (fig. 2). These structures split the rock into 5- to 20-cm-thick layers. The layers were conspicuous at the edges of the burst cavities, where they formed extensive planar surfaces that also tended to form the deeper limits of the cavities (figs. 2 and 3), but were poorly developed across the central part of the back. This contrasts with separations along bedding plane laminations, which, while prominent in the back, were not present at all in the ribs. In each case, the direction of splitting was at a low angle to the respective surfaces and close enough to the predicted orientations of mining-induced fractures that splitting along inherent planes of weakness due to high stress was likely.

All damage, including the relatively trivial spalling and shotcrete buckling at the west ends of the affected area, was confined to a 7- to 8-m-thick zone parallel to central shear zone structures. This damage also

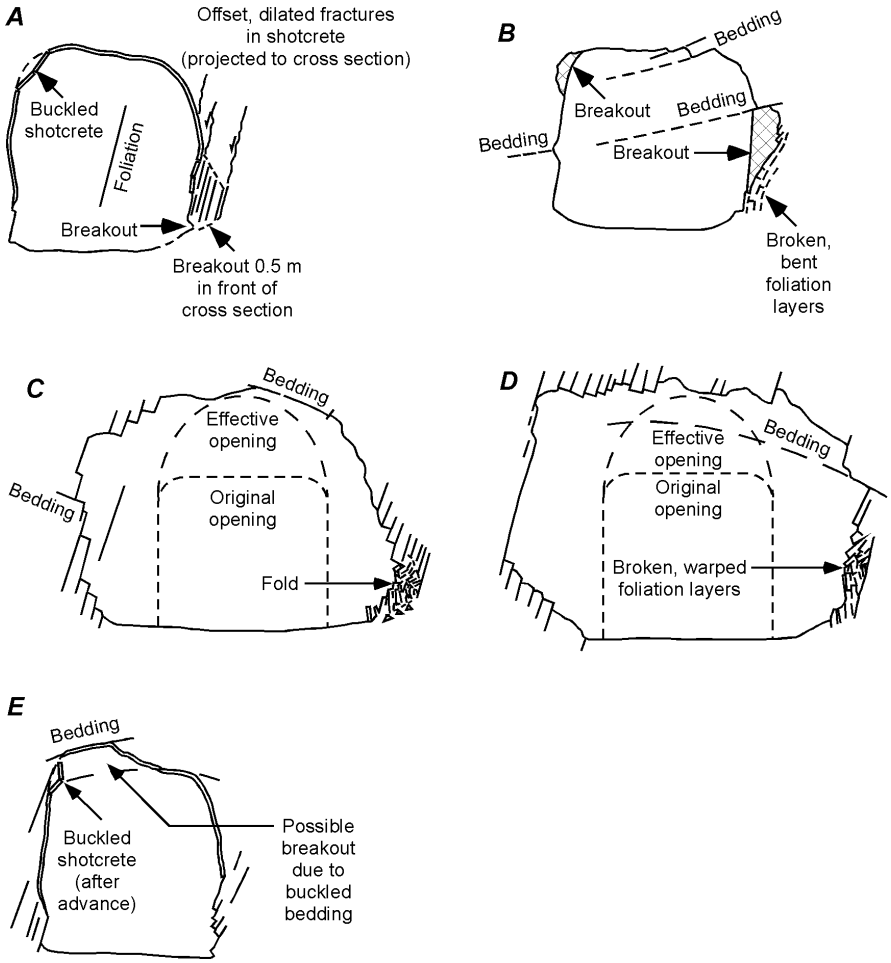

Figure 3.—Cross sections across burst site. Locations are shown in Figure 2.

extended deepest and highest where the back was highest. The burst cavity on the south side developed in layers that included all the minor damage to the west on both sides of the crosscut. However, the northern portion of the 7- to 8-m-thick unit trends eastward along the center of the crosscut, although it could not be mapped further because of temporary use of the ramp for waste storage.

6. STRESS AND MOVEMENT INDICATORS

The directions and relative magnitudes of ground movements involved in the burst were identified by a burst-created fold preserved deep in one of the burst cavities and by bent Split-Set bolts. The fold is defined by intensely broken foliation layers that wrap discontinuously about an axis (fig. 3*B*, 3*C*, and 3*D*). The fold plunges northwest, with its plunge locally measured at 22° as viewed along the side of the fold where the broken layers dip approximately vertically. The amount of shortening represented by the fold can be roughly estimated from the amount of curvature and locally is at least 0.1 to 0.2 m, which identifies significant vertical convergence.

The fold developed above a planar substrate formed by a basal foliation separation plane or minor fault (fig. 3*C* and 3*D*). However, the fold appears to die out in the direction of plunge, as planar layers ultimately cover the layers involved in the fold (fig. 3*A*). This gives the fold a conical shape. These geometries require that slippage took place on a series of basal shear planes, with movements converging toward the center of the fold from one side or the other, or both. The displacement must die out along strike over a distance of 5 to 15 m from the original rib (as estimated from plan view). Since the fold axis plunges at a low angle to the northwest, compressive shortening along a line raking steeply southeast is indicated.

The second indicator of movement is provided by bent Split-Set bolts that remained relatively intact in a surviving part of the original south rib (fig. 2). Inspection of the interiors of the bolts showed that the collars had moved several centimeters upward and northwestward relative to the deeper part of the bolts. Bending was concentrated at individual foliation separation planes intersected by the bolts, as verified by projection along a plane, while the outer layer of rock moved relatively diagonally upward toward the elevation of the deeper part of the burst cavity. The bolts were bent within a plane about normal to the fold axes on the north side of the crosscut. Hence, movements on both sides were consistent with slightly diagonal displacement of rock layers toward the central parts of the burst cavities. We note that interlayer slip with displacement of outer layers toward the axial plane of the fold is characteristic of concentric-style folding, which buckling represents. Thus, the slip displacement expressed by the bent bolts may have resulted from incipient buckling, although no conspicuous buckling was observed.

7. INTERPRETATION

If a seismic impulse had been involved in breaking and heaving rock from the burst cavities, the intensely broken rock that defines the fold would certainly have also been ejected, or at least become so disrupted as to be unrecognizable as a fold. Only compressive shortening in the plane of the shears, accompanied by slippage along a basal shear plane, can account for the fold (fig. 4). If crushing were instantaneous, which is implicit, bulking of broken rock would have briefly created confining pressure within the interior of the broken mass, enabling the fold to develop without being ejected. Damage to both ribs was accompanied by displacement toward the central part of each cavity and is reasonably explained by buckling and breakage of the rock layers. Damage to diagonally opposed parts of the opening, frequently seen with large rock bursts in crosscuts, also argues for the burst resulting from compressive stress.

As is well known, the critical load required to cause buckling varies directly with the square of the slenderness ratio (ratio of thickness to length). Hence, the coincidence of the most extensive damage with the site where the back had exceeded design height also supports the interpretation that the damage resulted from buckling of foliation layers, since the slenderness ratio would have been significantly reduced at this location. This may also help explain preservation of the western portion of the south rib where the bent rock bolts were found, as well as the general decrease in damage westward.

8. BREAKOUT GEOMETRY

Fairhurst and Cook [2] described how layers parallel to a free surface fail through buckling. In the present case, where the involved layers are slightly inclined to the walls of the opening in both strike and dip, the geometries that would result from buckling can still be estimated and compared against what was actually seen. Fairhurst and Cook [2] emphasized that cavities formed by buckling narrow with depth as a result of an increase in "normal stress" at the ends of the layers. Where layers dip at about 75°, as in the current example, the limits of buckling would be inclined accordingly, and breakouts would appear as in figure 4, with one side being the inverted mirror image of the other. This is a good representation of what was actually seen at the site.

On the side of the crosscut where layers dip toward the opening, the innermost layers would have become the most tightly folded (fig. 4). However, since the strike of the layers was also oblique to the crosscut, the outermost layers would have assumed the position of the innermost layers at some distance into the

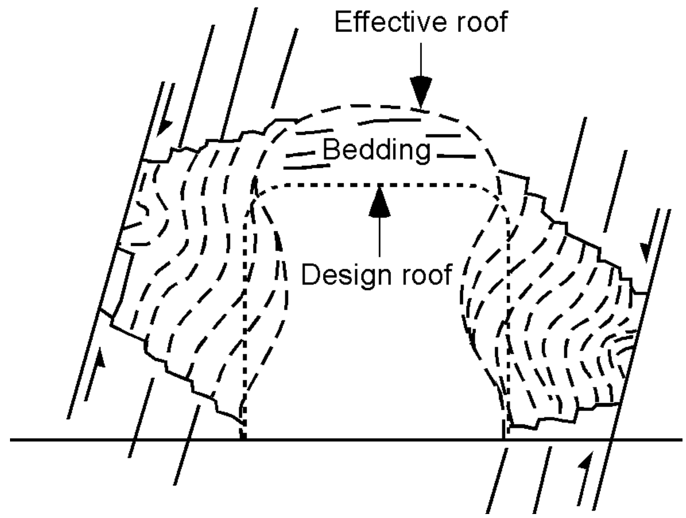

Figure 4.—Schematic of buckled, broken rock layers responsible for damage.

section. Consequently, the fold would be conical and plunge into the section, just as is seen at the burst site. Thus, the geometries predicted to be produced strictly by buckling are identical to those actually seen and provide additional support for the interpretation that the breakouts and the fold resulted from buckling caused by compression along a line raking steeply southwest.

Using the same reasoning, if the crosscut crossed foliation from its footwall side, the axis of folding would be constrained to plunge toward the vein. Compressive shortening would be along a line that extends toward the previously developed ramps and mined-out part of the vein. Since the stress in this direction would likely be reduced, buckling would be inhibited, and bursting would either involve less energy or would not occur at all. Of course, buckling would also be precluded if openings were at a large enough angle to the strike of the layers.

It is possible that the burst would not have taken place if the back had not been excessively vulnerable. Since the excessive height was apparently caused by back failures resulting from splitting of strata along bedding laminations, placement of 06 crosscuts a short distance to the north, where bedding dips steeply, would have eliminated this situation.

9. SEISMIC DATA

The location of the seismic source, as refined by Wilson Blake (personal communication, 2002), leaves little doubt that it originated very near or at the site of the damage. Assuming all the energy involved in the burst originated as strain energy, we used the reported local Richter magnitude and a reasonable assumption of strain density based on (1) an overcore test at a separate site at the Lucky Friday where a rock burst subsequently took place and (2) laboratory measurements of elastic rock properties to calculate the volume of rock necessary to supply this amount of strain energy (see[11] for details). It is in the range of 2450 to 4900 m^3, depending on seismic efficiency. This is equivalent to a volume of rock measuring 8 by 33 by 9.3 to 18.6 m and is roughly 25 to 50 times the volume of the rock ejected in the burst. Thus, the burst cannot be accounted for by strain energy contained in the broken rock. The additional energy was probably liberated by sliding on shear planes bounding the affected rock, which released elastic as well as gravitational potential energy. We note that slippage along faults is commonly apparent in magnitude 2.5 or greater events at the mine and that pure strain energy bursts larger than magnitude 1.0 are rare.

10. SUMMARY AND DISCUSSION

Our observations provide a reasonable basis for concluding that this burst resulted from buckling of structurally layered rock in response to high local stress and an unfavorable orientation of these layers with respect to a mine crosscut. The seismic energy was supplied by release of stored strain energy from broken rock combined with fault slip movement.

Although Fairhurst and Cook [2] apparently considered that buckling is a common mechanism by which rock fails, there have been surprisingly few descriptions of large failures involving buckling. They emphasized that the fundamental mode of mining-induced deformation begins with creation of fractures parallel to free surfaces and formation of slabs that deform further by buckling. However, we have demonstrated that geologic flaws in the form of foliation and bedding promote development of tabular layers that may buckle when the layers are slightly oblique to affected surfaces. This recognition is vital because it establishes the possibility of positioning and orienting openings so as to reduce or eliminate rock bursts under some circumstances.

A full understanding of such features provides a basis for optimizing the location and orientation of mine openings and matching the density of ground support and amount of detressing to the degree of rock burst hazard. Such efforts must be comprehensive. That is, hazards from all types of rock bursts must be understood, as well as the relationship of geologic structures and mining-induced stress changes. Otherwise, efforts to reduce hazards from a particular source or type of rock burst might inadvertently lead to increases from another type.

REFERENCES

1. Whyatt, J.K., W. Blake, and B.G. White. 2002. Sixty years of experience with rock bursts in the Coeur d'Alene Mining District. Presentation at Soc. of Min. Eng. annual meeting, Denver, CO, Feb. 27-Mar. 1. Available from author.

2. Fairhurst, C., and N.G.W. Cook. 1966. The phenomenon of rock splitting parallel to the direction of maximum compression in the neighborhood of a surface. In *Proceedings of the First Congress on the International Society of Rock Mechanics* (Lisbon, Portugal, Sept. 25-Oct. 1, 1966). Lisbon, Portugal: Nat. Lab. of Civil Eng., V. 1, pp. 687-692.

3. White, B.G., J.K. Whyatt, and D.F. Scott. 1995. Geologic factors in rock bursts in the Coeur d'Alene Mining District: Structure. In *Proceedings: Mechanics and Mitigation of Violent Failure in Coal and Hard-Rock Mines,* H. Maleki, P.F. Wopat, R.C. Repsher, and R.J. Tuchman, eds. U.S. Bur. Mines Spec. Pub. 01-95, pp. 217-230.

4. White, B.G., and J.K. Whyatt. 1999a. Differential wall rock movements associated with rock bursts, Lucky Friday Mine, Coeur d'Alene Mining District, Idaho, USA. In *Rock Mechanics for Industry. Proceedings of the 37th U.S. Rock Mechanics Symposium*, ed. by B. Amadei, R. L. Kranz, G. A. Scott, and P. H. Smeallie (Vail, CO, June 6-9, 1999). Rotterdam: Balkema, pp. 1051-1059.

5. White, B.G., and J.K. Whyatt. 1999b. Role of fault slip on mechanisms of rock burst damage, Lucky Friday Mine, Idaho, USA. In *SARES 99: 2nd Southern African Rock Engineering Symposium. Implementing Rock Engineering Knowledge*, T.O. Hagan, ed. (Johannesburg, S. Africa, Sept. 13-15, 1999). Johannesburg: Intern. Soc. Rock Mech., pp. 169-178

6. Maleki, H., and B.G. White. 1997. Geotechnical factors influencing violent failure in U.S. mines. In *International Symposium on Rock Support: Applied Solutions for Underground Structures,* E. Broch, A. Myrvang, and G. Stjern, eds. (Lillehammer, Norway, 22-25 June 1997). Pp. 208-221.

7. Whyatt, J.K., and B.G. White. 1998. Rock bursting and seismicity during ramp development, Lucky Friday Mine, Mullan, Idaho. In *Proceedings, 17th International Conference on Ground Control in Mining*, S.S. Peng, ed. (Morgantown, WV, Aug. 4-6, 1998). Morgantown, WV: Dept. of Min. Eng., WV Univ., pp. 317-325.

8. Ortlepp, W.D. 1997. Rock fracture and rockbursts: An illustrative study. SAIMM Monograph Series M9, 98 pp.

9. Williams, T.J., D.K. Denton, M.K. Larson, R.L Rains, J.B. Seymour, and D.R. Tesarik. 2001. Geomechanics of reinforced cemented backfill in an underhand stope at the Lucky Friday Mine, Mullan, Idaho. NIOSH Report of Investigations 9655, 18 pp.

10. Whyatt, J.K., B.J. White, and W. Blake. 1995. Structural stress and concentration of mining-induced seismicity. In *Proceedings: Mechanics and Mitigation of Violent Failure in Coal and Hard-Rock Mines,* H. Maleki, P.F. Wopat, R.C. Repsher, and R.J. Tuchman, eds. U.S. Bur. Mines Spec. Pub. 01-95, pp. 243-264.

11. Whyatt, J.K., F.M. Jenkins, and M.K. Larson. 1995. In situ stress at the Lucky Friday Mine (in four parts): 2. Analysis of overcore measurement from 5300 level. U.S. Bur. Mines Report of Investigations 9560, 34 pp.