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Differential wall rock movements associated with rock bursts, Lucky Friday Mine, Coeur d'Alene Mining District, Idaho, USA

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ABSTRACT: Various methods of monitoring slip movements on bedding planes, as well as examination of rock burst damage in stopes, suggests that rock bursts in the Lucky Friday Mine are closely associated with these movements. Slip displacements along bedding simultaneously reduce the physical dimensions of stopes and increase compressive stress along stope margins. Such changes, in turn, contribute directly to rock bursts and the sudden failure of volumes of rock and cemented sandfill surrounding stopes.

The distribution of seismicity and several mining-induced and premining structures resemble those described in South African gold mines. These suggest fundamental similarities in seismic sources and mechanisms of rock burst damage.

1 INTRODUCTION

The Coeur d'Alene Mining District in northern Idaho is the second largest silver mining district in the world as well as a leading U.S. producer of lead and zinc. The Lucky Friday Mine alone has contributed more than 680,000 tonnes of lead, 86,000 tonnes of zinc, and 108,000,000 oz of silver during 55 years of operation.

At recent mining depths of nearly 2,000 m, the Lucky Friday has been one of the most active mines in North America in terms of seismic energy per ton of ore mined (Jenkins et al., 1990). Rock bursts at the mine have necessitated cleanup of several hundred tons of rock debris per month in recent years.

As used in this paper, rock bursts are defined as violent outbursts of broken rock. Hundreds of tons of pulverized rock may be expelled into openings during such events. A sudden, sharp sound, a seismic signal, an air blast, and large quantities of dust are typical indicators of a rock burst. The existence of high ground stresses at burst sites prior to these events are common and may be characteristic.

Although rock bursts affect development openings, this paper is focused on rock bursts in stopes. Ribs or rib-sill junctures are most commonly damaged, but sills and backs are occasionally affected also. In the underhand stopes of the Lucky Friday Mine, damage that affects overhead, cemented sandfill is basically identical to bursts that affect rock, so these events are also included as rock bursts.

The results of various investigations have been reviewed and reconsidered. On the basis of this reconsideraton, the authors propose that most, and possibly all, rock bursts in Lucky Friday stopes are associated with differential movements in the surrounding wall rocks. These movements involve slip on bedding planes and faults and contribute directly to rock burst damage. Slip movements are believed to promote localized stress concentrations that cause stress fracturing of wall rocks and cemented sandfill.

1.1 *Geology and in situ stress*

The Lucky Friday vein is hosted by slightly metamorphosed Precambrian sedimentary strata. Burst-prone strata are dominated by strong, vitreous, thick-bedded quartzite, but thin laminations in the quartzite create planes of weakness. Thin, weak interbeds of soft argillite separate the quartzite beds at intervals of 0.5 to 5 m. Early mapping of the stratigraphy showed that rock bursts were prevalent in the quartzitic lithologies that characterize the upper and lower members of the Revett Formation, but were uncommon in the argillitic middle Revett member. However, the structural complexity of the mine has hindered under-

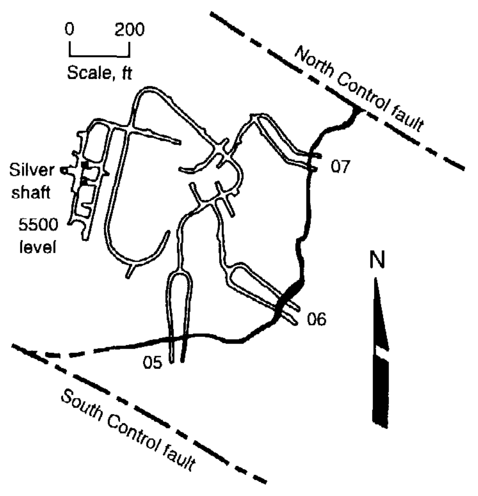

Figure 1. Plan view of Lucky Friday Mine, 5500 sublevel

standing of the processes that cause damage.

On a larger scale (tens to hundreds of meters), beds are tightly folded about steep axes and are truncated by the steeply dipping ore body. However, strata generally dip into the vein from the footwall side and away from the vein into the hanging wall. Argillite interbeds have commonly been sheared by premining tectonism, resulting in a weak clay gouge. Widespread core drilling demonstrates that wall rocks have been abundantly, but irregularly, fractured by tectonism. These fractures are believed to aggravate rock burst problems in the stopes.

The Lucky Friday ore body is composed primarily of massive galena with lesser amounts of quartz, siderite, and other sulfides. Width of the ore body ranges from 0.5 to 8 m, but averages about 1 m. Narrow galena stringers commonly parallel the main vein. These stringers evidently are planes of weakness, as they often form the walls of stopes. The northeasterly striking part of the vein is approximately vertical, while the more westerly trending portions dip steeply southward.

Various investigators (Whyatt et al., 1995) have consistently identified the direction of greatest in situ stress, both at the Lucky Friday and in the district, as nearly horizontal and trending northwest. This direction is nearly normal to the northeast-trending part of the vein and oblique to the west-trending part.

2 MINING-INDUCED WALL ROCK MOVEMENTS

The mechanics of wall rock movement can be substantially understood by comparing deformation at the mine to deformation in the walls of highway cuts or in the walls of open-pit mines. Strata that dip toward open cuts, as in the footwall of the Lucky Friday vein, are vulnerable to slippage, and buckling sometimes occurs in the lower part of slipping layers. Layers that dip away from walls, as in the hanging wall of an ore body, fail by toppling. While sliding movements have been frequently documented in the Lucky Friday Mine, toppling is generally not evident at active operating levels and may be manifested primarily in the concentration of vertical stresses in the hanging wall sides of stopes. Actual movements are restrained by the cemented sandfill and the narrow width of the mined-out vein, but visible squeezing of the sandfill confirms that such movement does take place.

2.1 Seismicity

An extensive seismic monitoring system installed within the mine records seismic events and identifies source locations. Approximately 90% of all seismicity originates within a zone centering on the active stopes and extending about 100 m into the footwall. These events are believed to reflect primarily slip on bedding planes. It is notable that the remaining 10% of the seismic events, which mainly originate outside of this zone, includes events with the greatest magnitudes and accounts for about 90% of all seismic energy released in a mine (Williams, unpublished data). The highest-magnitude events seem to lie close to known major faults and are interpreted as indicating wall rock movement toward the mined-out part of the ore body (Fig. 1). As in other mining districts, the larger seismic events usually produce significant damage, while major damage to both stopes and development openings may be associated with low-energy seismicity. This suggests a minimal role for seismic impulses in the generation of rock bursts and, probably, a greater role for movements over time.

The distribution of seismicity about Lucky Friday stopes resembles that in longwall stopes in South African gold mines (e.g., Joughin & Jager, 1983), but with one major difference. In contrast to seismicity in the gold mines, which occurs symmetrically about a stope, Lucky Friday seismicity occurs asymmetrically and is essentially limited to the footwall side. This coincides with the marked asymmetry of the bedding structure of Lucky Friday wall rocks and emphasizes

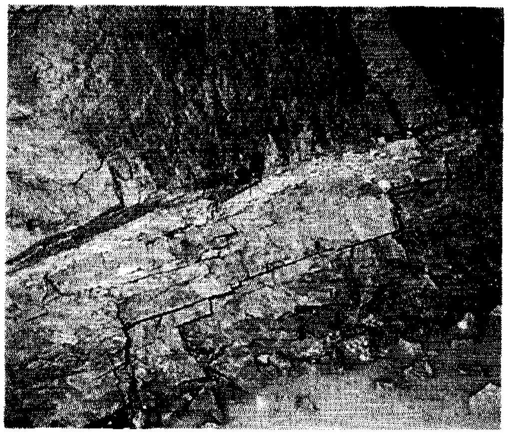

Figure 2. Soft, white gouge on slip plane in argillite interbed in hanging wall rib.

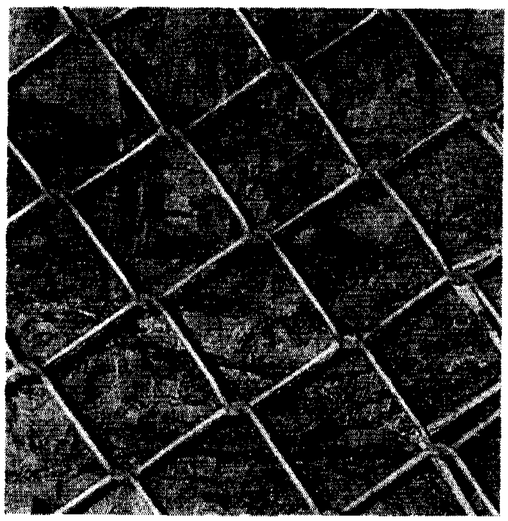

Figure 3. Mining-induced extension fractures in stope ribs.

the role of this structure in the generation of seismicity.

2.2 *Structures caused by mining-induced movement*

Several types of recurrently seen structures are believed to indicate mining-induced wall rock movements. These structures include mining-induced thrust faults, or shear-ruptures; disrupted, mining-induced extension-fracture zones; and bedding plane faults containing a distinctive gouge. That is, in most cases, shear planes contain compact, gray or greenish-gray gouge. This color contrasts with the soft, white gouge found along bedding planes near active stopes and within inferred mining-induced shear ruptures

Figure 4. Disrupted zone of closely spaced mining-induced extension fractures indicating activation of zone as a flat fault.

(Fig. 2). The presence of the white gouge in structures that are believed, for other reasons, to have been caused by mining and the absence of the white gouge at locations away from the ore body suggests that this gouge results from mining-induced slip.

Flat-dipping extension fractures are locally seen in the stope walls and in the advancing stope face (Fig. 3). These fractures are sometimes densely concentrated within zones 5 to 10 cm thick. Concentration of these fractures in the upper one-third of mining faces confirms that they are caused by mining and that they form in the immediate sill. Thin, tabular rock layers within these zones are occasionally broken, rotated, and disrupted (Fig. 4) Evidence of slip has been established by offsets of veins up to several tens of centimeters. Thus, these extension-fracture zones may evolve into flat-dipping thrust faults.

Flat-to-moderate-dipping thrust fault shear ruptures containing the soft, white gouge offset the ore body by as much as 10 to 20 cm (Fig. 5). Indirect evidence that the thrust faults result from mining is seen in a consistent angle of about 30° between the faults and adjacent mining-induced extension fractures, even where the extension fractures locally possess greater-than-normal dips. These shear ruptures may reflect a recurrent fault plane solution obtained from seismic data. However, correlation of structures with specific seismic events, as has been done for some similar structures in South Africa (Gay & Ortlepp, 1979), has not been possible.

Figure 5. Inferred mining-induced thrust fault or shear rupture cutting Lucky Friday vein. Extension fractures lie about 30° to fault.

2.3 *Identification and measurement of wall rock movement*

Movements taking place in wall rocks in response to mining have been documented or inferred by various investigators through the use of strain gages and pressure cells, closure measurements, the appearance of fractures in shotcrete, offsets in artificial markers (paint marks and reflective reference lines), calculations of seismic source locations and fault plane solutions, and repeated leveling and surveying traverses. However, efforts to record movements carefully and thoroughly over time have been frustrating because of raveling of wall rock, disturbance of reference points, and transi-tory access to active parts of the mine. As a result, definitive data are scarce.

Slip on northwesterly striking faults has been inferred from localized clusters of seismic events and from visible evidence of differential squeezing of sills and cement-ed sandfill. The largest seismic events, up to Richter magnitude 4, have occurred along the large faults that bound the ends of the ore body. When rock bursts damage stopes during these larger seismic events, the damage is not notably different from damage seen after minor seismic events and is not necessarily more severe. However, following large events, damage and rock fall may be found widely distributed about the mine, suggesting that the large seismic events cause damage by triggering smaller, localized events. The most common movements identified in the wall rock at the Lucky Friday Mine involve dilation and slip on sheared, gougy argillite interbeds that separate thick, vitreous quartzite beds.

Closure measurements in stopes and development openings have been made by numerous investigators and Lucky Friday mine personnel, but much of this work is unpublished. Gradual closure and step increases that may or may not correspond to recorded seismic events have been identified (Hsiung et al., 1992a, 1992b; Whyatt et al., 1992; Williams et al., 1992). Reported measurements have commonly been in the range of 3 to 25 cm during the 6- to 8-week period required to mine a single cut. These measurements are consistent with physical evidence of squeezing seen in the overhead sandfill.

The most extensive and detailed measurements have never differentiated among movements resulting from slip or dilation along bedding or other preexisting structures, movement from dilation of mining-induced extension fractures parallel to surfaces of openings, or movement caused by mining-induced buckling. In these studies, the data can be interpreted in terms of both dilational and slip movements on bedding planes, although dilation of mining-induced fractures and buckling-type deformation may also have be involved. Most data suggest that deformation increases toward the vein

The more definitive observations have often been the simplest. These are progressive fracture development in shotcrete and offsets in reference marks painted across bedding planes. However, movements recorded by these means are rather qualitative, because it has never been possible to obtain thorough coverage within stopes or along the length of individual ramps for extended periods of time.

Differential movements in the ribs of access ramps are most obviously shown by fractures that begin developing in shotcrete soon after it is applied. In addition to fractures that parallel bedding, en echelon fractures cross bedding at about 45°. Both dilation and slip along bedding planes are common, with dilation more frequently seen than slip. The direction of dilation is consistently toward the mined-out part of the ore body. Dilation in the absence of slip may be a result of the buckling occasionally seen in the lower portions of steeply inclined layers in pit walls, although development of buckling-type folds is constrained because of the narrowness of the available open space. The most common sense of slip is normal, although reverse movements have occasionally been identified.

Near the vein where ramp sections are too short lived to warrant application of shotcrete, other indicators of movement have been used. Paint marks applied across gougy argillite interbeds have shown progressive slip up to about 10 cm over a period of 1 month. It is notable that slips of this amount have involved bedding planes that intersect the sill. Thus, it is apparent that the shear planes sometimes pass into the unmined vein.

2.4 *Examples of bedding plane slip*

A paint mark applied across bedding near the 5850-06 stope during 1998 underwent total slip of 18 cm during the 6 weeks required to complete a cut. The bedding slip plane was seen in the access ramp 4 m from the ore body, indicating that the plane intersected the sill. During mining of the next cut, this slip plane was viewed cutting across the vein and offsetting it a total of about 25 cm.

A rock burst extensively damaged the 5750-05 stope on August 28, 1998, in a Richter-magnitude 3.1 seismic event. Rock was expelled from both ribs and the overhead cemented sandfill to an average depth of 1 m for a distance of about 25 m along the length of the west half of the stope. The event occurred during blasting, and no injuries resulted. Bedding slip believed to have resulted from this event could be documented by offsets in marks that had been painted across all exposed argillite interbeds for 50 m in the access ramp. A 2-cm slip was found 30 m from the stope, and a 13-cm slip was found 27 m from the stope. Because rock on one side of the slip detached from the rib and may have moved independently of the substrate, a greater amount of apparent slip could not be confirmed. Evidence of slip could not be seen on any other argillite interbeds, but many paint marks had been destroyed by raveling during in the event. Thus, the minimum net slip in the event was 15 cm.

Eastward and downward, the slip planes of the August 28 event were projected to the location of the 5840-06 stope, which had been mined deeper than the 5750-05 stope, but which had become temporarily inactive and inaccessible while the 5850-05 stope continued to be advanced. It seems likely that slip on these planes was controlled primarily by the presence of the 5840-06 stope, but that the slip planes projected westward so that they intersected the 5750-05 area deep in the sill. Based on this, minimum dimensions of the slip zone can be estimated as being 90 m long by 30 m along dip.

Damage to the stope in this event included apparent compression of the sandfill to failure. Damage that involved ribs can also be attributed to shortening in the vertical dimension and buckling of the affected rock mass, as discussed in the following section. However, no bedding slip could be documented in or near the stope that may have caused such shortening, as all reference points were disrupted.

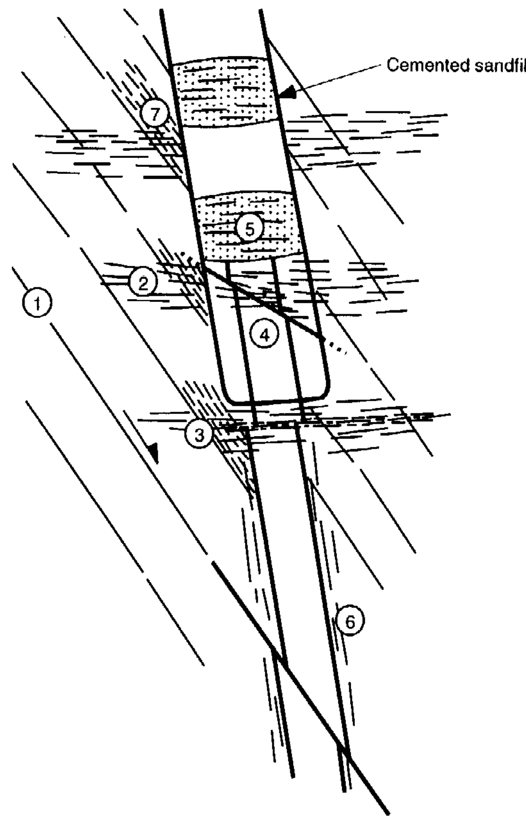

Figure 6. Cross section of Lucky Friday vein identifying mining-induced structures. 1, Bedding fault; 2, flat extension fractures; 3, shear-activated zone of closely spaced extension fractures; 4, thrust fault-shear rupture in face; 5, flat fractures in sandfill; 6, galena-filled stringers; 7, delaminated quartzite bedding.

The various mining-induced fractures, bedding plane slips, and shear ruptures seen at the Lucky Friday Mine are summarized in Figure 6.

3 DAMAGE

Rock burst damage may affect either ribs, the cemented sandfill, or the sill, and may involve several of these locations in the same event (Fig. 7). A common pattern of damage is one that affects the lower footwall rib and adjacent sill and the diametrically opposite upper hanging wall rib and the adjacent sandfill. In these cases, damage in the hanging wall frequently extends a short distance up the side of the sandfill. Such damage resembles the pattern formed

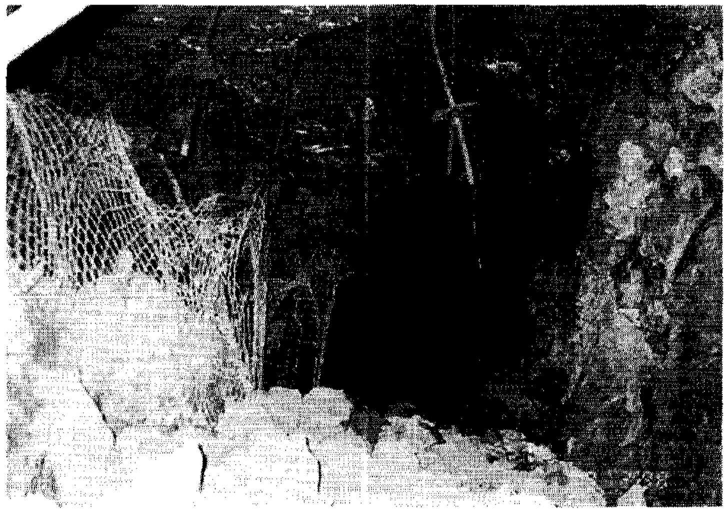

Figure 7. Rock burst damage in the 5750-05 stope. Note that both ribs and the overhead sandfill were damaged.

by dog-eared breakouts at the margins of drill holes in highly stressed ground. Considerable stress must be being transmitted through the sandfill, and damage to the wall rock probably requires extensive fracture development prior to driving the present cut. Other distinctive types of damage involve failures of sandfill or floor heave across the entire width of the sill. Damage to the ribs or at the contact between rib and sandfill is particularly common at the corners between the ramp crosscut and the stope. Damage and extensive raveling at these locations suggests that intense fracturing occurs here, probably during mining of the previous cut, when such sites were probably subjected to high stress.

3.1 Cause of damage

In many, or possibly all, cases, ground damaged in rock bursts has undergone intensified compressive stress prior to failure, and it is believed that such compression plays a vital role in most or all rock bursts. In cemented sandfill and in the sill, evidence for compression is provided by flat-dipping extension fractures and thrust faults. Similarity of the patterns of diagonal damage at the junctions of (1) the sill and the lower footwall rib and (2) the sandfill and the hanging wall rib to dog-eared breakouts suggests compression in a direction approximately parallel to dipping beds. Compression within the ribs of horizontal openings is shown by mining-induced folds with flat-plunging axes that are occasionally seen at these locations. These folds are the equivalent of folds caused by the buckling that sometimes occurs at the toes of inclined slabs in open pits.

3.2 Inferred damage mechanisms

Evidence that movement in the footwall commonly causes a reduction in the physical dimensions of the stope suggests that rock burst damage in particular results from shortening along stope margins. Significant shortening, as identified in the various studies cited, has the potential for squeezing rock or cemented sandfill at stope margins to the point of failure. The resulting violence of such a failure (a rock burst) requires that the rock or cement-ed sandfill be under compression prior to failure and that initial resistance to failure enabled the storage of elastic strain energy in the surrounding rock.

Except where rock is so extremely fractured that no systematically oriented fractures can be identified, a characteristic of burst sites is that the affected rock has a generally tabular character, either because of mining-induced fractures, delamination of quartzite along bedding planes, or the existence of other pre-existing structures. In contrast to Joughin & Jager (1983), who concluded that the expulsion of rock in bursts results from interleaving of rock layers by compressional movement, we favor the view that buckling of such layers leads to fracturing and expulsion (e.g., White et al., 1994; Maleki & White, 1997). We note that interleaving of rock layers would necessarily cause the appearance of buckling as layers double up and slip past each other in the central part of the affected volume of rock. Perhaps both phenomena have a role in rock bursts.

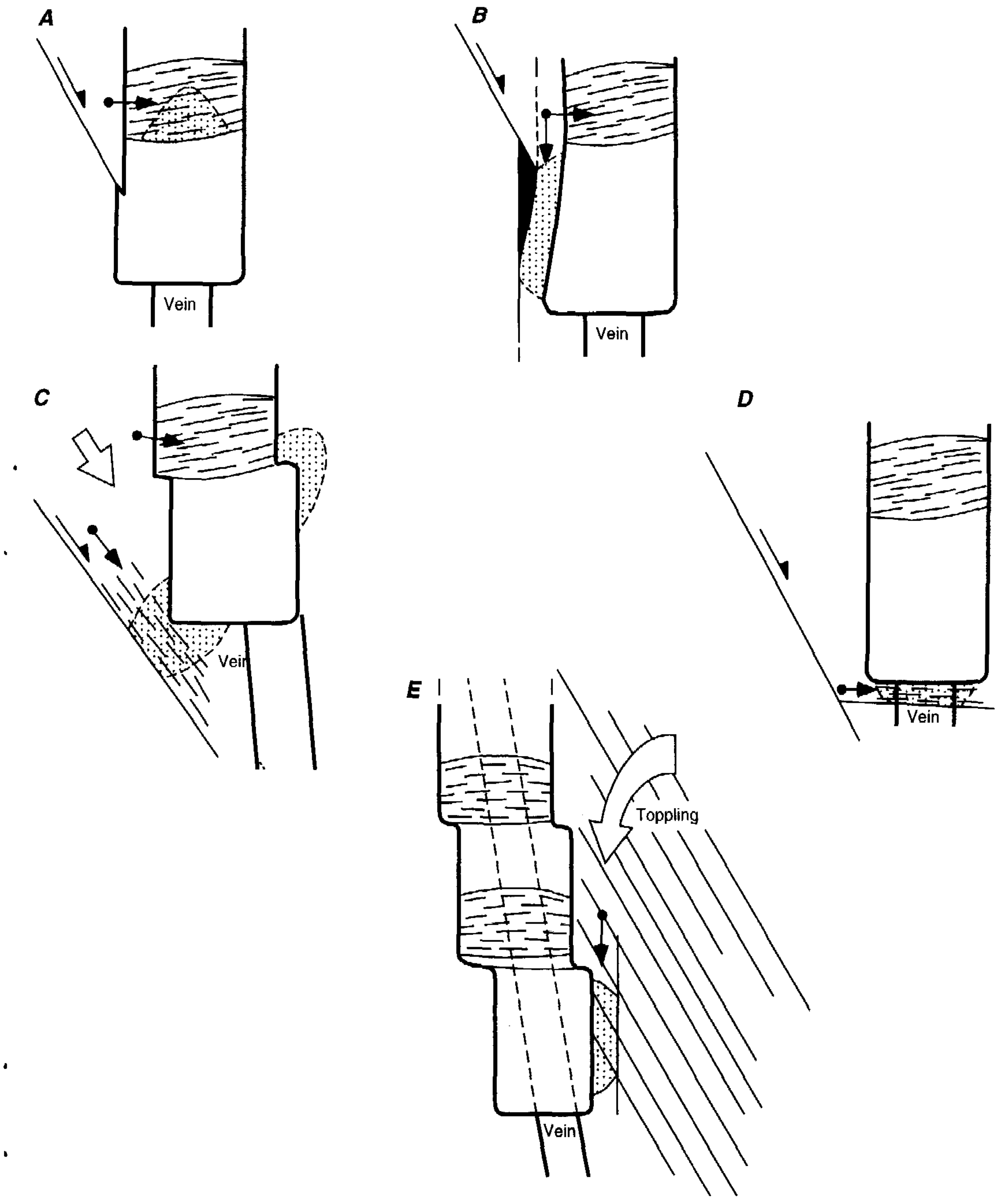

Figure 8. Interpretations of rock bursts in stopes caused by movement within the surrounding wall rock. Stippled areas indicate rock burst locations; arrow with ball identifies inferred direction of shortening responsible for damage at sites.
A, Bedding slip identifies inferred direction of shortening responsible for damage at sites;
B, bedding slip that fails to cut rock layers in rib compresses both thc rib and the sandfill;
C, shortening parallel to bedding delaminates quartzite bed at sill and damages upper hanging wall rib at sandfill;
D, bedding slip compresses sill;
E, inferred toppling in hanging wall increases vertical stress concentration along hanging wall rib.

4 DISCUSSION AND SUMMARY

Progressive movements in the footwall of the Lucky Friday vein generally cause a reduction in the physical dimensions of the stope. Compression of sandfill is a necessary and obvious consequence of downward bedding slip. However, bedding slip may also reduce various stope dimensions in a variety of other ways (Fig. 8). Except for bursts that affect the hanging wall rib, shortening of stope margins is likely to be a consequence of normal slip on bedding planes. The nature of the resulting damage depends partly on the elevation at which a particular slip intercepts a stope. If the slip plane intercepts the rib, only the sandfill may be affected (Fig. 8*A*). However, a bedding plane slip that fails to pass through relatively tabular rock layers formed between a stope and weak, galena-filled stringers may cause shortening and failure of the rock while compressing the sandfill (Fig. 8*B*). Bedding slips that intersect the underlying sill may concentrate stress at the sill-footwall junction and fracture quartzite along its internal laminations, enabling the layers to buckle in a rock burst (Fig. 8*C*). However, the diametrically opposite corner, at the juncture of the hanging wall rib and the sandfill, probably fails as a result of weakening by earlier fracturing.

The high horizontal component of in situ stress documented at the mine may be enough to cause mining-induced extension fractures and shear ruptures to form in the sill and for slip to take place on these fractures without associated bedding plane slip. However, bedding slip could also promote formation of fractures and thereby contribute to sill bursts (Fig. 8*D*).

Movements associated with bursts that affect the hanging wall rib have not been documented. It is likely that these bursts are promoted by high vertical stress in the hanging wall rib resulting from toppling of overlying strata toward the mined-out vein (Fig. 8*E*).

Despite their steep dips, mining-induced structures at the Lucky Friday Mine have similarities to those in South African gold mines, discussed by Joughin & Jager (1983), Pretorius (1966), and Adams et al., (1981). The mining-induced extension fractures that form in the sill of the Lucky Friday ore body seem identical to the fractures most closely associated with the rock bursts that affect faces in South African mines. Slip identified on extension fracture zones in the Lucky Friday duplicates slip along such fractures in South African stopes (Joughin & Jager, 1983). The shear ruptures seen in the Lucky Friday stopes are also iden-tical in disposition and geometry to those found in the South African mines.

In the Lucky Friday Mine, bedding in the footwall approximates a common type of mining-induced extension fracture documented by Joughin & Jager (1983) in South Africa. Although dilation occurs on both, shear is present only at the Lucky Friday Mine. Unlike in the South African mines, where mining-induced fractures parallel to the face seem to be implicated in rock bursts (Joughin & Jager, 1983), bursts in Lucky Friday stopes affect all margins and several corners. However, planar discontinuities parallel to the affected margins in the Lucky Friday represent the same scenario as the extension fractures parallel to the face in South African mines.

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