Role of fault slip on mechanisms of rock burst damage, Lucky Friday Mine, 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, suggest that many 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 sudden failures of rock and cemented sandfill surrounding stopes. We believe that the reduction of rock burst hazards must be based on a clear understanding of the basic mechanisms involved. The current work emphasizes the mechanical role of wall rock movement and seismicity in generating conditions that promote rock burst damage. Based on our interpretations of these mechanisms, we briefly address several hypothetical practices that could influence rock burst hazards in similar mining situations. The overall goal of this research is to advance the NIOSH mission of improving the health and safety of the nation's workers.

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. At recent mining depths of nearly 2,000 m, Hecla Mining Co.'s Lucky Friday Mine has been one of the most active mines in North America in terms of seismic energy per tonne of ore mined (Jenkins et al. 1990).

Here, as elsewhere, a major challenge is to understand the contributions of mining-induced movements and seismicity in wall rocks to localized rock burst damage. As considered in this paper, "rock bursts" are violent outbursts of broken rock, and "damage" refers to damage to openings involving rock and rock support structures. During a rock burst, hundreds of tonnes of pulverized rock may be expelled into openings. A sudden, sharp sound, a seismic signal, an air blast, and a dense cloud of dust are typical indicators that a burst has occurred. In most cases, elastically driven buckling of layered rock caused by high local stress is a plausible explanation for actual damage (White et al. 1995; Maleki and White 1997), but most mining-induced seismicity requires a different explanation.

To better evaluate these factors, researchers at the Spokane Research Laboratory of the National Institute for Occupational Safety and Health (NIOSH) examined many rock burst sites at the Lucky Friday Mine to identify the mechanical behavior of the rock during rock bursts. In examining these sites, we attempted to distinguish clearly between the mechanisms of local rock burst damage and those that cause seismicity unassociated with immediate damage. In particular, we looked for evidence of movement in wall rocks that might explain the damage observed, and we tried to identify relationships among movement, seismicity, and damage. We consider that the existence of high ground stresses at burst sites prior to these events is characteristic, and that damage is ultimately caused by this high stress.

Development openings that coincide with zones of intensified mining-induced seismicity provide a unique opportunity to identify wall rock movements that are the source of seismicity. This paper focuses on the more frequent rock bursts that affect stopes. Ribs or rib-abutment junctures are most commonly damaged, but abutments and backs are occasionally affected also. In the underhand stopes of the Lucky Friday Mine, damage to overhead cemented sandfill is often linked to rock bursts.

We believe that the reduction of rock burst hazards must be based on a clear understanding of the basic mechanisms involved. The current work emphasizes the mechanical role of wall rock movement and incidental seismicity in generating conditions that promote rock bursts.

2 GEOLOGY AND IN SITU STRESS

The Lucky Friday vein (Figure 1) is hosted by slightly metamorphosed Precambrian sedimentary strata. Early mapping of the stratigraphy by Hecla geologists 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. The burst-prone strata are dominated by strong, thick-bedded, vitreous quartzite, but thin laminations in the quartzite create planes of weakness that may greatly alter the failure characteristics of this rock. In addition, thin, weak interbeds of soft argillite separate the quartzite beds at intervals of 0.5 to 5 m. Argillite interbeds have commonly been sheared by tectonism, forming a weak clay gouge. Widespread

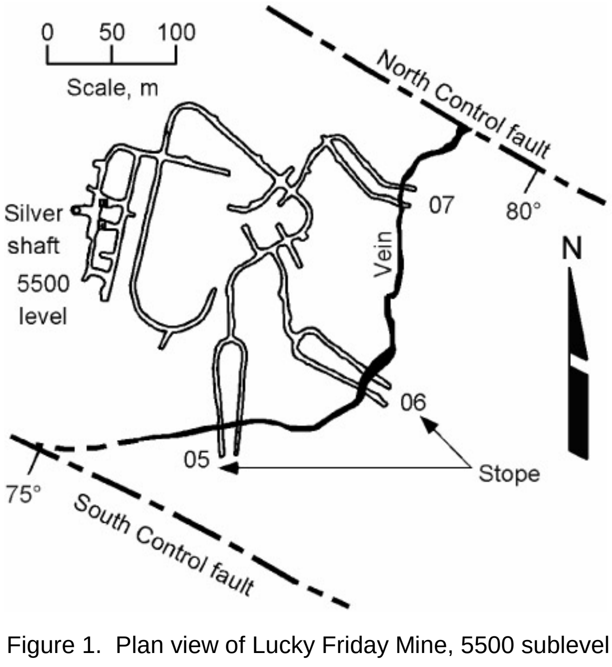

Figure 1. Plan view of Lucky Friday Mine, 5500 sublevel

core drilling in the vicinity of the vein demonstrates that wall rocks have been abundantly, but irregularly, fractured by tectonism. These fractures are believed to aggravate rock burst problems in the stopes. On a larger scale (tens to hundreds of meters), beds are tightly folded about steep axes, and these folds, in turn, are truncated by the steeply dipping vein. A series of subparallel faults intersect the vein and also form bounding faults at its ends. Strata generally dip into the vein from the footwall side and away from the vein into the hanging wall. This structural complexity has greatly hindered understanding of the processes that cause damage.

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

Various investigators (see Whyatt et al. 1995 for a critical review) have consistently identified the direction of greatest in situ stress at mines throughout the district as nearly horizontal and trending west to northwest. At the Lucky Friday Mine, the greatest in situ stress is nearly normal to the northeast-trending part of the vein and oblique to the west-trending part. The direction of greatest stress is also approximately parallel to the set of faults that intersect the vein and bound its ends.

3 DAMAGE

Rock burst damage may affect ribs, the cemented sandfill, or the abutment, and may involve several of these locations in the same event (Figure 2). A common pattern of damage is one that affects the lower footwall rib and adjacent abutment and the diametrically opposite upper hanging wall rib adjacent to the sandfill. In these cases, damage in the hanging wall frequently extends a short distance up along the side of the sandfill. Such diametrically symmetrical damage is frequently seen at the mine and resembles the pattern formed by dog-eared breakouts in holes drilled in highly stressed ground. Failure resulting from elevated stress normal to the plane containing the damage is suggested. However, since cemented sand is relatively weak, the damage to wall rock abutting the sandfill requires extensive fracture development unrelated to the immediate burst event. Other distinctive types of damage involve floor heave across the entire width of the abutment and failures of sandfill. Although the softness of sandfill probably precludes violent failure, the appearance of sandfill failures resembles those caused by rock bursts, which leads us to include sandfill failures as "rock burst damage."

Significant damage to drift walls is also common. Corners between the ramp crosscut and stope are particularly vulnerable, and minor damage at the contact between ribs and sandfill at this location is frequent. Persistent raveling of rock in the upper part of the footwall near the sandfill-rib contact suggests that intense fracturing often occurs here, most likely during mining of the previous cut, when such sites were probably subjected to high stress.

3.1 *Inferred damage mechanisms*

A characteristic of burst sites both in development openings and in stopes is that the rock has a generally tabular character, with the layers lying approximately parallel to the affected surface. The layers may be mining-induced fractures, bedding planes, or other preexisting structures. Localized stress fractures and buckling of rock layers (Maleki and White 1997) containing such fractures suggests that burst damage commonly results from shortening of layered rock to a point where the rock fails suddenly. Confirmation of the essential role of rock layers in burst damage was obtained when new development openings in a burst-prone part of the mine were realigned with respect to the strike of steeply dipping beds. When openings were driven directly across bedding instead of nearly parallel to bedding, rock bursting ended.

Layered rock at burst sites at the Lucky Friday Mine typically resembles the layered appearance of rock behind the face of long-

Figure 2. Rock burst damage in the 5750-05 stope. Note that both ribs, as well as the overhead sandfill, were damaged in this event.

wall stopes in South African reef mines (e.g. Joughin & Jager 1983:Figure 1), where rock bursts are a persistent hazard. In the reef mines, failure of layered rock has been identified as a fundamental mechanism of rock burst damage. However, in contrast to Joughin & Jager, who concluded that the expulsion of layered rock in bursts resulted from interleaving of rock layers by compressional movement, we prefer the view that it is buckling of such layers that causes fracturing and expulsion (e.g. White et al. 1995; Maleki & White 1997). We note that interleaving of rock layers would necessarily result in 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 creating rock burst damage.

3.2 *Cause of damage*

Violent, compressive failures of rock in bursts require the existence of stress sufficiently high to initiate failure, as well as a sustained application of stress in the form of "following load," such as may be provided by a soft loading system (e.g. Hedley, 1992). Evidence of elevated compressive stress is provided by flat-dipping extension fractures and thrust faults that form in cemented sandfill and the abutment and in diametrically opposite patterns of damage, as described earlier. The existence of high stress may also be inferred from documented shortening of stope dimensions and from the occasional development of mining-induced folds seen in stope walls.

Evidence of progressive or sudden reductions in the physical dimensions of stopes suggests that rock burst damage results, in particular, from shortening along stope margins. Significant shortening necessarily causes increased stress in the affected material and may lead to failure. At the same time, the violence of such a failure (hence, a rock burst) may also require that the rock or cemented sandfill have been under compression prior to failure so that initial resistance to failure enabled the storage of elastic strain energy in the surrounding rock and resulting rapid movement toward the burst. As an alternative, bedding slip may at first have been prevented by some asperity within the slip plane.

4 MINING-INDUCED WALL ROCK MOVEMENTS

4.1 *Seismicity*

An extensive seismic monitoring system installed within the mine records seismic events and identifies source locations. Approximately 90% of all seismicity originates near the active stopes (Figure 3*A*). The largest of these events is believed primarily to reflect slip on bedding planes (Whyatt & White 1998). 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 at the mine.[1] The highest magnitude events lie close to known major faults and are interpreted as indicating wall rock movement toward the mined-out part of the vein (Figure 1). The larger seismic events cause major damage primarily where stopes and development openings are intersected by a major slip plane (Whyatt et al. 1997). This suggests a minimal role for seismic impulses in the generation of rock bursts and probably a greater role for wall rock movements over time.

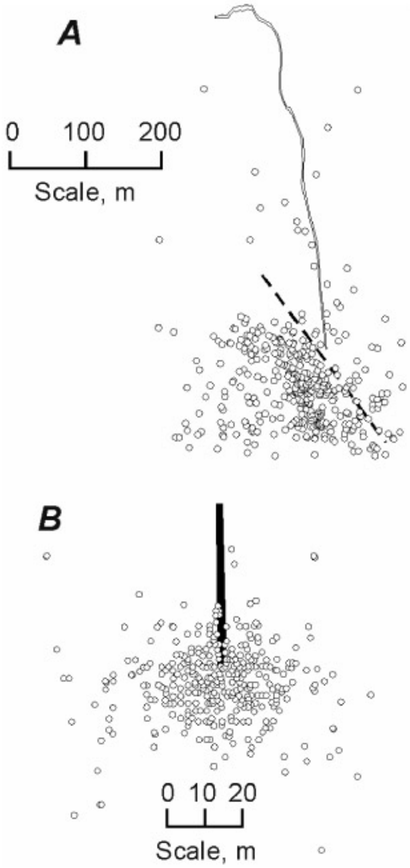

Figure 3. Representative cross sections. *(A)* Part of Lucky Friday vein showing distribution of seismicity. Data from 17 cuts are superimposed about a common stope position. *(B)* South African gold reefs. Reef and data are rotated 90° from horizontal for more direct comparison with Lucky Friday. (Joughin and Jager, 1983).

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 (Figure 3*B*). In contrast to seismicity in the gold mines, which occurs symmetrically about stopes, Lucky Friday seismicity is highly asymmetric and most abundant on the footwall side. This coincides with the marked asymmetry of the bedding structure of Lucky Friday wall rocks and emphasizes the role of bedding plane slip in the generation of seismicity.

4.2 *Structures caused by mining-induced movement*

Several types of recurrently seen structures are believed to indicate mining-induced wall rock movement. These structures include mining-induced thrust faults or shear ruptures; disrupted, mining-induced extension fracture zones; and bedding plane faults containing a distinctive, soft white gouge. The presence of the white gouge (Figure 4) 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 vein suggest that the gouge originated from mining-induced slip.

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[1] T.J.Williams, SRL-NIOSH, unpublished data collected during field work 1988-1995.

Figure 4. Soft, white gouge due to slip along argillite interbed

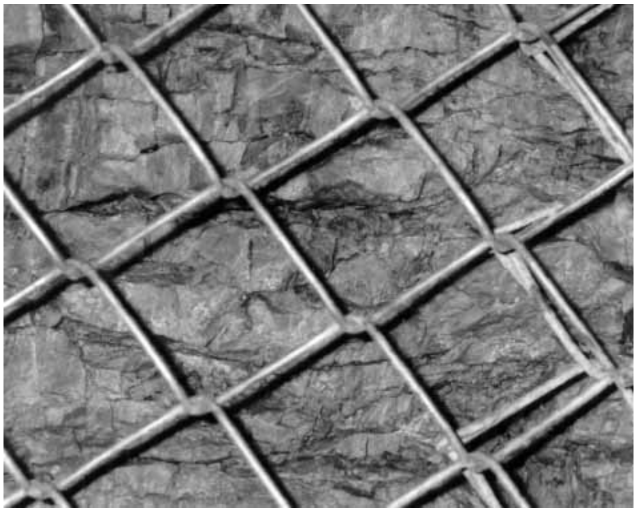

Figure 5. Mining-induced extension fractures in stope walls.

Figure 6. Disrupted zone formed by shearing within 4-cm-wide zone of closely spaced mining-induced extension fractures in stope walls.

Figure 7. Inferred mining-induced thrust fault or shear rupture offsetting Lucky Friday vein. Extension fractures lie about 30° to fault.

Flat-dipping extension fractures are common in the stope walls and in the advancing stope face (Figure 5). Concentration of these fractures in the upper one-third of mining faces and their persistence up to 10 m into the ribs confirm that they are caused by mining and that they form in the immediate abutment. These fractures are sometimes densely concentrated within zones 5 to 10 cm thick. Thin, tabular rock layers within these zones are occasionally broken, rotated, and disrupted (Figure 6). 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 seen in stope faces offset the vein by as much as 10 to 20 cm (Figure 7). Like the mining-induced bedding plane faults, these crosscutting shear ruptures also contain finely granulated white gouge. 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. The 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.

4.3 *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, repeated leveling and surveying traverses, and modeling. However, efforts to interpret and document movements over time have been frustrated because of raveling of wall rock, disturbance of reference points, localization of slip, and transitory access to active parts of the mine. Thus, the practical difficulties in obtaining definitive data over time at the Lucky Friday are great, and useful data are scarce. In some cases, the simplest, most expedient methods have been the most effective, even though results are more qualitative than quantitative.

While fault plane solutions have provided imporatant insights into many large seismic events, they have not significantly aided the understanding of rock bursts at the Lucky Friday. In a detailed, year-long study of 1750 seismic events (Jung et al. 1995), 50% were found to be all-dilatational. Such events are typically small and so abundant they are not recorded during routine operations. Thirty-six percent of the solutions were ambiguous, and the remaining 14% were a mix of strike-slip, normal, low-angle thrust, and a few oblique-reverse, with no obvious, systematic relationships to damage. It is also evident that the largest and best-documented seismic events are not necessarily associated with the greatest damage, while significant damage may result from small seismic events (Whyatt et al. 1997). Finally, as described in this paper, damage in the stopes appears to be only indirectly related to some major seismic events.

Slip on northwesterly striking faults has been inferred from localized clusters of seismic events and from visible evidence of differential squeezing of abutments and cemented sandfill. The largest seismic events, up to Richter magnitude 4, have occurred along the large faults that bound the ends of the vein. When rock bursts damage stopes during these larger seismic events, the damage is not notably different from damage associated with smaller seismic events and is not necessarily more severe. However, following particularly large seismic events, minor amounts of shakedown may be found widely distributed about the mine, suggesting that the large seismic events may promote damage by triggering smaller, localized events.

Closure measurements in stopes and development openings have been made by numerous investigators and Lucky Friday Mine personnel. Much of this work is unpublished. Gradual closure and step increases in closure that may or may not correspond to recorded seismic events have been identified (Hsiung et al. 1992a, b; 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 more definitive observations have often been the simplest. These include 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.

Shear and dilational movements in wall rock are most obviously shown by fractures that began developing in shotcrete soon after it was applied in access ramps (Figure 8). The two most common movements involve dilation and dip-parallel slip on sheared, gougy argillite interbeds that separate thick vitreous quartzite beds. Dilation is seen more frequently than slip. The direction of dilation is consistently toward the mined-out part of the vein, and gaps 1 to 2 cm wide may be seen along bedding planes. The most common direction of slip is normal (hanging wall down), although reverse movements have occasionally been identified. Net slips of 1 to 2 cm are common. In addition to fractures that parallel bedding, en echelon fractures may cross bedding at about 45° and also identify dip-parallel slip.

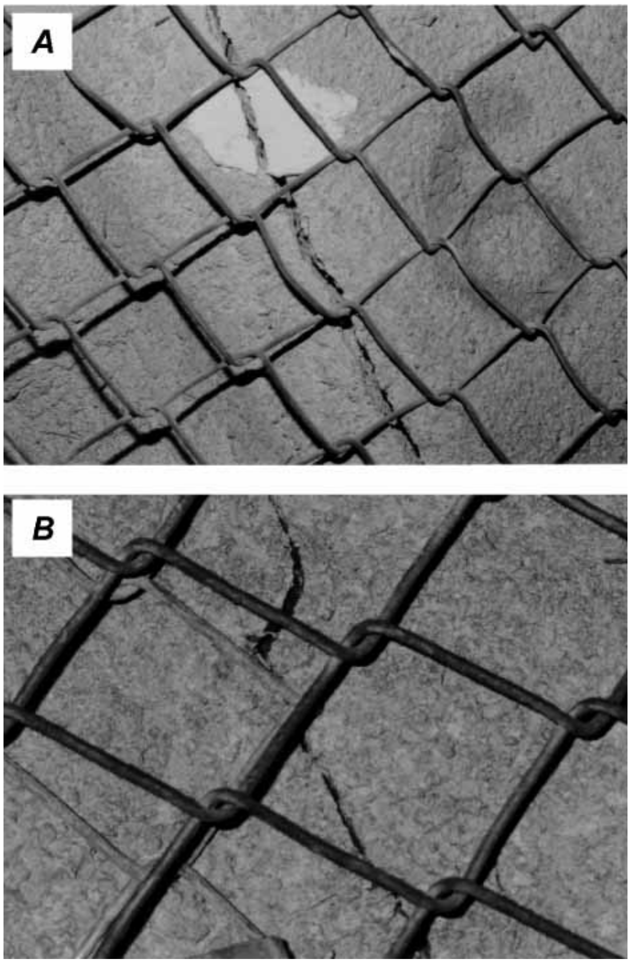

Figure 8. Fractures formed in shotcrete because of mining-induced movement along bedding. *(A)* Extension fracture overlying argillite interbed. Extension is toward mined-out part of vein to the right. *(B)* Fracture parallel to bedding showing normal slip. Note wider gap at irregularity near top of photo.

Near the vein, where ramp sections are too short lived to warrant application of shotcrete, other indicators of movement have been used. Marks painted across gougy argillite interbeds have shown progressive normal (hanging wall down) slip along bedding planes up to about 10 cm over a period of 1 month, and rapid movement up to at least 15 cm is thought to have occurred during an individual rock burst event (Figure 9). It is notable that slips of these amounts have occasionally involved bedding planes that intersect the abutment. Thus, it is apparent that normal bedding plane faults sometimes pass into the unmined vein.

The most extensive, longest lasting, and detailed closure and strain gage measurements have never differentiated among movements resulting from slip or dilation along bedding or movement caused by dilation of mining-induced extension fractures. In these studies, the data can be interpreted as indicating both dilational and slip movements on bedding planes, although dilation of mining-induced fractures and buckling-type deformation may also have been involved. Most data of this type suggest that all displacement associated with closure increases toward the vein.

The various mining-induced fractures, bedding plane slips, and shear ruptures seen near Lucky Friday stopes are summarized in Figure 10.

Estimates of the expected distribution of seismicity in Lucky Friday wall rocks caused by slip on bedding (Board 1994:Figure 11) suggest a preponderance of reverse faulting. However, the displacement documented in access ramps indicates a preponderance

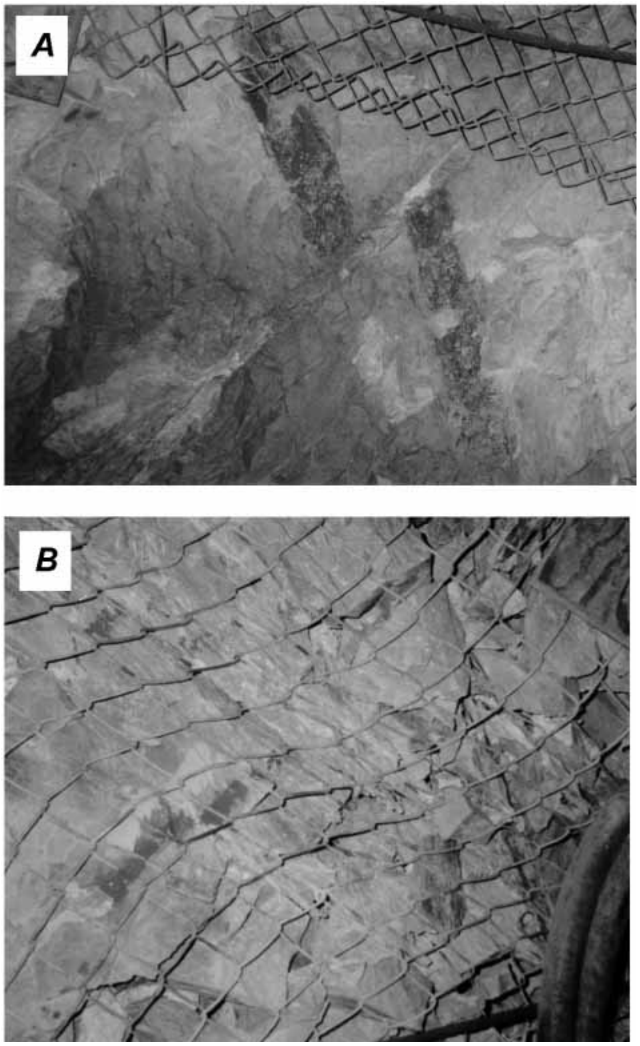

Figure 9. Offset paint marks resulting from bedding plane slip. *(A)* Mark offset by gradual slip during 6-week period. *(B)* Offset paint marks and deformed chain link fencing developed during August 28, 1998, rock burst.

of normal slip. Furthermore, seismicity is concentrated in the footwall of the stope, where normal slip is most frequently identified, in an elongate pattern that extends up-dip and down-dip (Figure 11). [2] The predicted distribution of events resulting from reverse faulting along bedding is not apparent. Thus, normal faulting on bedding appears to reflect the dominant seismic slip mechanism near the stope.

The movements identified above can be compared to common types of failure that occur in the walls of highway cuts and 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 cut walls, as in the hanging wall of an vein, are displaced by toppling, although toppling in the mine would be greatly constrained by the cemented sandfill and the narrow width of the mined-out vein. While slip has been frequently documented, toppling is not evident at active operating levels. However, it is reasonable to expect toppling at higher mine elevations, in parts of the mine no longer accessible. At present operating levels, the effects of toppling may be manifested primarily as a concentration of vertical stresses in the hanging wall sides of stopes.

Although a comparison of wall rock movements at the mine with those in walls of open cuts and pits is illustrative, it is likely that a major component of closure is elastic, the result of stress relief. Since dilation is present along bedding planes, it is likely that the direction of greatest stress relief in each individual cut is approximately parallel to bedding dip. Stress relief is also likely to extend a considerable distance up-dip—possibly 100 m or more to the up-dip extent of seismicity—so that the net bedding-parallel component of closure from stress relief may be somewhat large. We presume that the dip-parallel component of stress relief is also the major contributor to rock burst energy at some burst locations in stopes.

4.4 *Examples of bedding plane slip events*

A rock burst extensively damaged the 5750-05 stope on August 28, 1998 (Figure 2), in a Richter-magnitude 3.1 seismic event. Rock was expelled from both ribs, and the overhead cemented sandfill failed to an average depth of 1 m for a distance of about 25 m along the length of the stope. As is common, the event occurred during blasting. Bedding slip believed to have taken place during this event could be documented by offsets in marks painted across exposed argillite interbeds in the access ramp. A 2-cm slip was found 30 m from the stope, and a 13-cm slip (Figure 9*B*) was found 27 m from the stope. Possibly even greater slip took place, but this can not be confirmed because some rock on one side of the larger slip detached from the rib and may have moved independently of the substrate. Evidence of slip could not be seen on any other argillite interbeds, but many paint marks were destroyed by raveling during the event. Thus, the minimum net slip in the event was 15 cm.

Eastward and downward, slip planes were projected to the location of the 5840-06 stope, which had been mined deeper than the 5750-05. The 5840-06 stope had become temporarily inactivated and was (and remains) 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 abutment (Figure 12). Based on these observations, minimum dimensions of the slip zone are estimated as being 90 m long by 30 m wide along dip. We presume that most of the seismic energy originated from slip on these two bedding planes.

Damage to the stope in this event included apparent compression of the sandfill to failure. Damage that involved ribs could also be attributed to vertical shortening 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 could have caused such shortening, as all reference points were disturbed.

Several months earlier, a paint mark across bedding near the 5850-06 stope was progressively offset for a total 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 vein, indicating that the slip plane intersected the abutment. In the next cut, this slip plane cut across the vein and offset it about 25 cm. No seismicity could be specifically related to the progressive slip.

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[2] The cross section displaying seismicity about a Lucky Friday stope shows low density close to the stope. A systematic error that causes event locations to be calculated as originating too far from the stope is suspected.

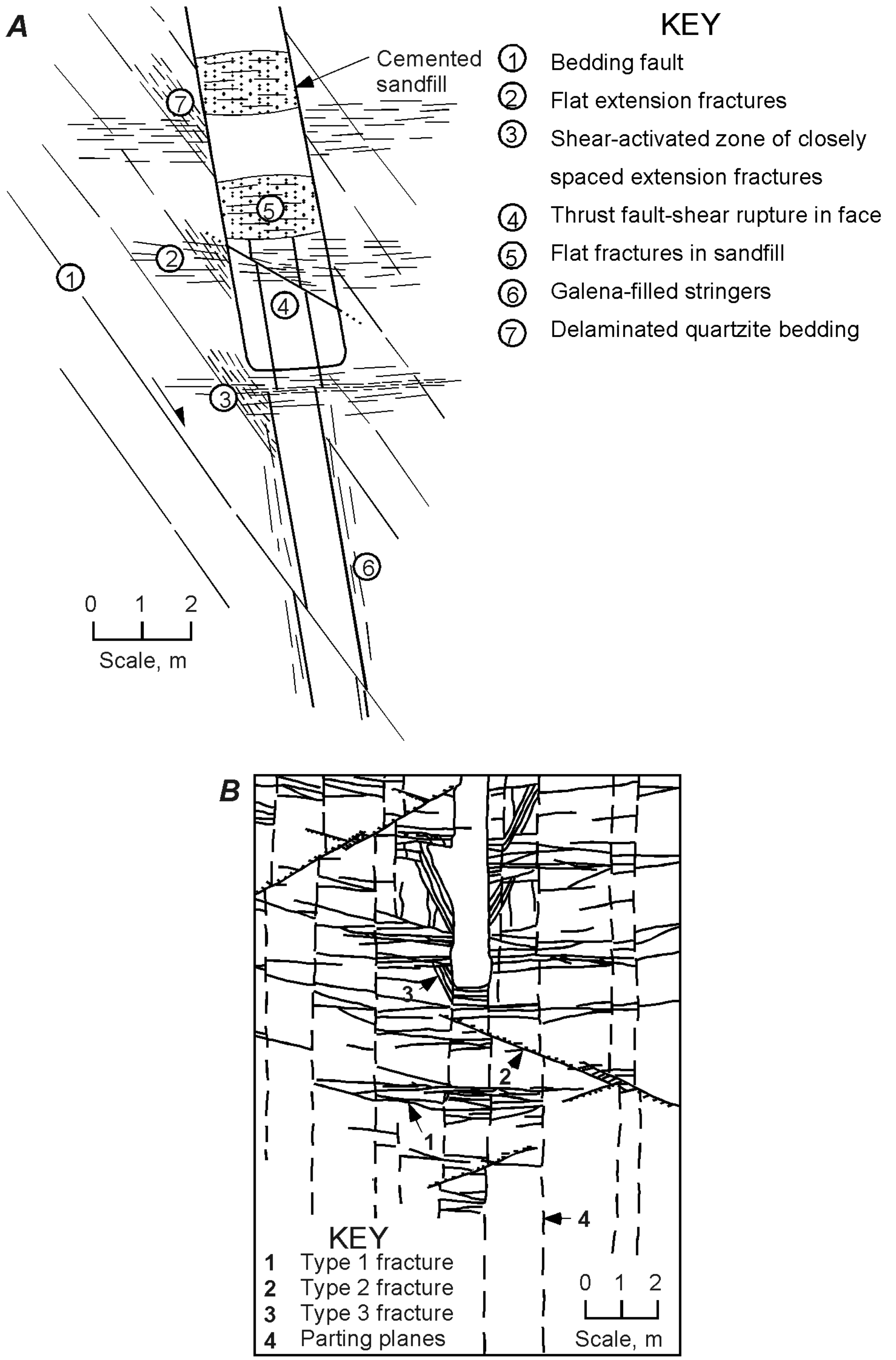

Figure 10. Comparison of structures at Lucky Friday Mine and Witwatersrand gold reef. *(A)* Cross section of Lucky Friday vein identifying structures activated or caused by mining; *(B)* comparable structures about Witwatersrand gold reef (rotated 90° from horizontal [Joughin & Jager 1983]).

4.5 *Interpretation of effect of bedding slip on rock bursts*

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, slip on bedding planes that intersect or pass near the stope may reduce stope dimensions in various other ways (Figure 13). Except for bursts that affect the hanging wall rib, shortening of stope margins primarily results from normal (down-dip) slip on bedding planes. The nature of the resulting damage depends partly on the elevation at which a particular slip plane intercepts a stope. If the slip plane intercepts the rib, only the sandfill is likely to be affected (Figure 13*A*). However, bedding plane slip that fails to pass through relatively

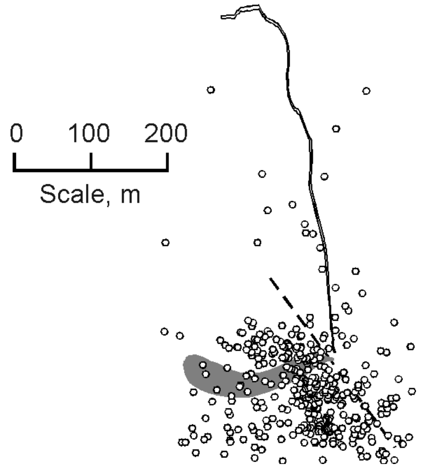

Figure 11. Actual seismicity around Lucky Friday stopes and comparison to distribution predicted by Board, 1994 (gray area). Dashed line represents orientation of bedding.

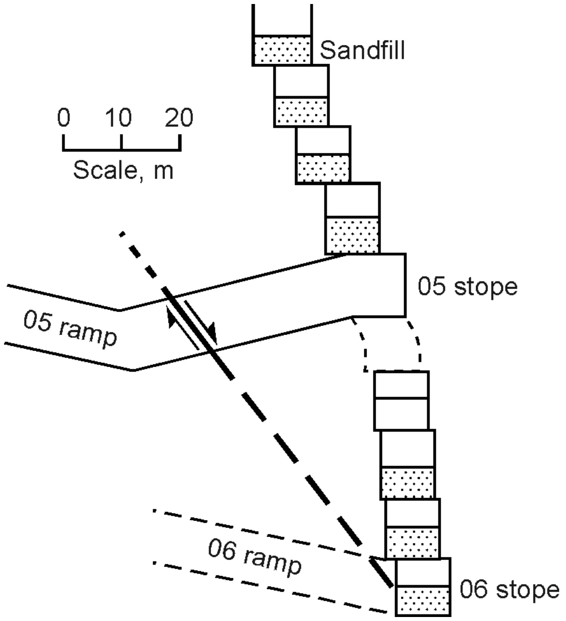

Figure 12. Schematic representation of slip zone from August 28, 1998, event, as seen in 05 ramp and projected to 06 stope.

tabular rock layers formed between a stope and weak, galena-filled stringers may cause shortening and failure of the rock while also compressing the sandfill (Figure 13*B*). Bedding slip that intersects the underlying abutment may concentrate stress at the abutment-footwall junction and fracture quartzite along its internal laminations, forming layers that may burst by buckling (Figure 13*C*). However, the diametrically opposite corner, at the juncture of the hanging wall rib and the sandfill, probably fails as a result of the sandfill exerting pressure on previously fractured rock.

The high horizontal component of in situ stress documented at the mine may be enough to cause mining-induced extension fractures and shear ruptures in the abutment 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 abutment bursts (Figure 13*D*).

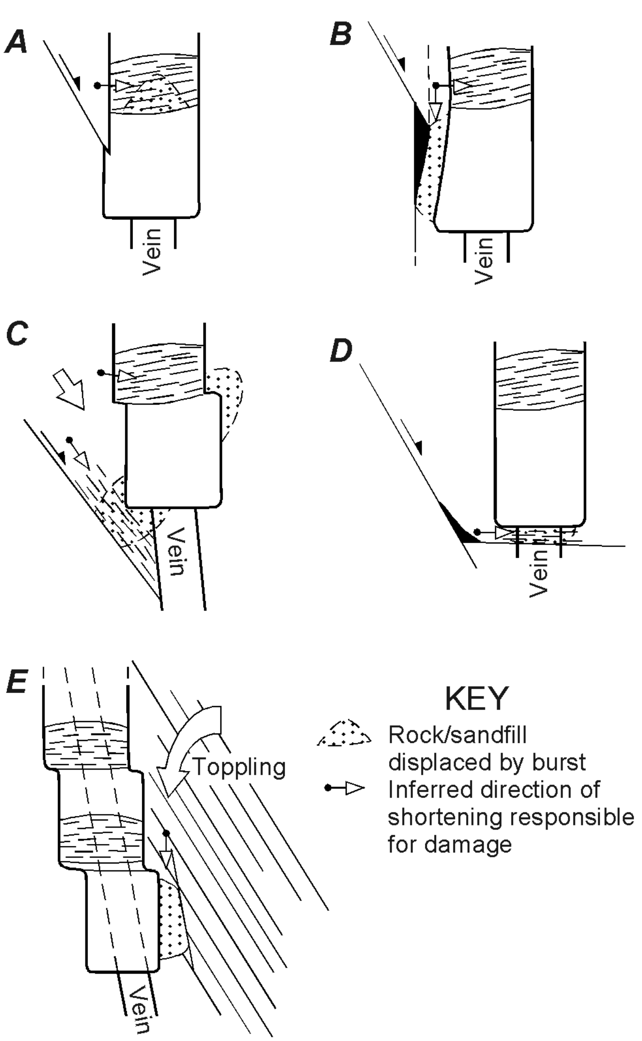

Figure 13. Interpretations of rock bursts in stopes caused by movement within the surrounding wall rock. *(A)* Sandfill damage caused by slip on bedding plane that intersects foot wall rib; *(B)* failure in footwall rib resulting from slip on bedding plane that does not truncate rock layers in rib formed by galena stringers; *(C)* damage to foot wall rib-abutment and diagonally opposite corner; *(D)* abutment damage caused by slip on mining-induced extension fractures; *(E)* damage to hanging wall rib attributed to high stress resulting from toppling of inclined strata.

Movement associated with bursts that affect the hanging wall rib has not been documented. We speculate that these bursts are promoted by high vertical stress in the hanging wall resulting from toppling of overlying strata toward the mined-out vein (Figure 13*E*).

5 COMPARISON TO WITWATERSRAND

The geometries of preexisting and mining-induced structures in Lucky Friday wall rocks bear striking resemblances to structures found in Witwatersrand gold mines as discussed by Joughin & Jager (1983), Pretorius (1966), and Adams et al. (1981) (Figure 10). The obvious differences are that the Lucky Friday vein is subvertical rather than gently dipping and cuts across strata instead of being stratabound. In each case, the direction of greatest in situ stress is nearly normal to the vein. However, some of the structures act very differently.

The mining-induced extension fractures that form in the abutment of the Lucky Friday vein and that are implicated in abutment bursts resemble the fractures most closely associated with face bursts in South African mines. In both cases, stope closure and consequent shortening of the affected stope margin apparently increases stress and promotes formation of these fractures. Slip identified along mining-induced extension fracture zones in the Lucky Friday duplicates slip along fractures seen after rock bursts in South African stopes (Joughin & Jager 1983). Shear ruptures at the Lucky Friday are virtually identical 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 (structure 3, Figure 10b). Although dilation occurs in both settings, shear is present only at the Lucky Friday Mine. Unlike in South African mines, where bursts mainly involve the face (Joughin & Jager 1983), bursts in Lucky Friday stopes affect all stope margins and several corners. However, the various planar discontinuities parallel to the affected margins in the Lucky Friday typically play a role in rock bursts similar to that of the mining-induced fractures parallel to the South African stope faces.

Planes of weakness represented by galena stringers in wall rocks parallel to the Lucky Friday vein duplicate the geometry of bedding planes in the South African mines. At the Lucky Friday, these planes are directly involved in compressive rock burst failures, whereas bedding in South African mines apparently contributes primarily to roof falls.

6 REDUCTION OF ROCK BURST HAZARDS

A limited range of measures may be considered for reducing rock burst hazards that result from shortening of stope dimensions as a result of slip on bedding. Unfortunately, some measures may aggravate other problems. Several hypothetical measures are mentioned here for the purpose of illustrating how an understanding of the mechanisms involved could be translated into practical methods of rock burst prevention.

Given the strong role of bedding slip in promoting bursts, a mining method that limits the ability of rock to slip along bedding could be considered. Mining by end-slicing the vein is a possibility, although it is likely to cause the steep, northwest-trending faults to assume a greater role in rock bursts. Using the current mining method, dip-parallel stabilizing pillars could limit bedding slip, but would eliminate some ore and might also cause burst problems associated with the pillars. Increasing the strength of sandfill, decreasing its compressibility, or increasing the percentage of fill may not be able to halt bedding slip and its effects on the stope, since stress release parallel to bedding dip as a result of mining may be concentrated at the immediate stope. Increasing the compressibility of the sandfill through installation of a layer of compressible foam within the sand may help maintain its integrity. However, if the sand actually does help reduce down-dip bedding slip, compressibility would diminish this capability. Destressing the abutment may reduce most problems resulting from bedding slip, but may also increase compression of the sandfill. A combination of compressible fill and destressing the abutment may be a reasonable compromise.

7 SUMMARY AND DISCUSSION

We have identified movement taking place in Lucky Friday wall rocks in response to mining and have interpreted mechanisms by which these movements lead to rock bursts. Our results suggest that movement in wall rock alters conditions in the stope in a way that promotes bursts. Specifically, slip movement in wall rocks causes shortening at the margins of stopes, and the shortening, in turn, increases stress and stress-induced failure.

We conclude that most seismicity originating distal from damage sites is only incidental to bursting. However, incidental seismicity identifies slip movements that have the capability of changing stress conditions that may result in bursts. Hence, while seismicity resulting from slip on bedding planes is not in itself hazardous, such seismicity is associated with the development of hazardous stress levels around stopes.

Based on these conclusions, we suggest that a clear distinction should be drawn between incidental seismicity and rock burst damage. Incidental seismicity primarily indicates that wall rocks are moving in response to mining and identifies generalized regions where such movements are taking place. However, definitive indicators of these movements and identification and mapping of active geologic or mining-induced structures are necessary to infer how incidental seismicity may be related to rock bursts.

The current research is guided by the conviction that reduction of rock burst hazards in underground metal mines can be best accomplished if the mechanical causes of rock bursts are clearly understood. The descriptions and interpretations provided here suggest plausible alternatives for reducing this hazard, thus advancing NIOSH's mission of improving the health and safety of the nation's workers.

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