Rock Bursting and Seismicity During Ramp Development, Lucky Friday Mine, Mullan, Idaho

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ABSTRACT

A comprehensive survey of mine seismicity and rock bursting during development of two sublevels at the Lucky Friday Mine, Mullan, ID, USA, was conducted to better define rock failure mechanisms and sources of ground control hazards. Survey data included rock burst damage reports, seismic event locations and magnitudes and, for the most energetic events, first-motion information. Several subsets of this database, including large seismic events, rock bursts, and microseismic activity near the face, were analyzed. Elements of the large-event and rock burst data sets were nearly independent. That is, there was no relationship between the risk posed by a seismic event and its energy, although such a relationship is well established for the mine as a whole. All data sets showed that certain geologic features appear to control the spatial distribution of events and the spatial distribution of rock burst risk. The data also suggest that, within the scope of this study, the greatest risk of injury occurs when a pocket of heightened rock burst risk is first encountered and that this risk is controlled when miners adapt their practices to these conditions. Recognition of the role of particular geologic features in the spatial distribution of rock burst hazards provides an opportunity for anticipating, rather than only reacting to, a changing level of rock burst hazard. However, much work will be required to make good on this promise.

INTRODUCTION

Ground falls can be attributed to a number of failure mechanisms. Of these, rock bursting[1] is an unusually hazardous failure mechanism. Persistent mining-induced seismicity is a feature of many deep mines in the United States, and events with Richter magnitudes of 2 to 4 are not unusual. Catastrophic rock bursts may also occur in mines with sparse records of mining-induced seismicity. The 5.2-Richter-magnitude event at the Solvay Mine in which three-quarters of a square mile of the mine suddenly collapsed is a recent example.

Despite a long history of rock burst research, much remains to be learned. Substantial efforts have been made to understand rock burst mechanisms, alter mine designs to reduce rock bursting, improve the effectiveness of ground support, and anticipate (and even predict) the occurrence of rock bursts. However, the occurrence of any particular mining-induced seismic event is still a surprise, and the consequences of a particular event are difficult to ascertain without inspection of affected areas of a mine.

This National Institute for Occupational Safety and Health (NIOSH) study was designed to address the hypothesis that geologic structures, independently and in conjunction with mining-induced stresses, control the spatial distribution of rock burst hazards. This hypothesis implies that the level of hazard can be anticipated, providing an opportunity to control and/or avoid the hazard. This hypothesis was suggested by recent studies that found variations in the premining stress field that were associated with particular geologic structures (Whyatt et al., 1995d), and that these stresses promote some types of the largest (Richter magnitude greater than 2.5) rock bursts (Whyatt et al., 1996b).

This study examines ramp development history in a portion of the Lucky Friday Mine for possible links between (1) geologic structures and (2) patterns of rock burst hazards and mining-induced seismicity. The authors examined a large population of seismic events, defined groups of events with similar characteristics, and explored the essential, repeatable characteristics of these groups. This approach serves to provide a balanced picture of overall seismic activity while de-emphasizing the effect of errors, data deficiencies, and random aspects of individual events.

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[1] A rock burst is defined as damage to an excavation that occurs in a sudden or violent manner and is associated with a seismic event (Kaiser et al.,1998).

An intense seismic response to mining; exceptional cooperation by the mine operator; and a wealth of geomechanical, operational, and seismic data made the Lucky Friday Mine a particularly useful laboratory for this study. The Lucky Friday is considered to be the most seismically active mine in the Coeur d'Alene Mining District and among the most seismically active (in terms of seismic energy per ton of ore mined) mines in North America (Jenkins et al., 1990). Whyatt et al. (1996b) found that events with local magnitudes greater than 2.5 occurred, on the average, at a rate of one every 2 months over a 6-year period. This study addresses only a portion of the seismicity that occurred from mid-1990 through mid-1993 and focuses on seismicity associated with development of the 5400 and 5480 sublevels. The selection of study dates and sublevels was based primarily on the relative quality and availability of seismic, in situ stress, geologic, and damage data.

This report begins with an overview of Lucky Friday Mine geology and its geomechanical setting, then discusses development and screening of the seismic event data set. Whyatt and White (in progress) provide detailed data on individual events. Various groups of seismic events are identified, evaluated for degree of rock burst hazard, and investigated for links to various geologic features and mining progress. Finally, the study discusses the potential for integrating these results into planning future development openings in rock-burst-prone mines.

LUCKY FRIDAY MINE: BACKGROUND

The Lucky Friday Mine is located in the eastern portion of the Coeur d'Alene Mining District of northern Idaho. The mine used a traditional overhand cut-and-fill method until a temporary closure of the mine in 1986. A mechanized underhand longwall mining method, which eliminated burst-prone pillars, was introduced when the mine was reopened. A sublevel ramp system was developed to provide rubber-tired vehicles with access to these stopes. The 5400 sublevel was the first to use the current ramp configuration. The change in mining method was supported by a cooperative research effort by Hecla Mining Co., the U.S. Bureau of Mines (USBM), and the University of Idaho (Poad et al., 1995; Whyatt et al., 1992). The underhand cut-and-fill method is proving to be a much safer way to mine in rock-burst-prone ground (Poad et al., 1995). Ground control systems were also substantially improved during this period (Blake and Cuvellier, 1990, 1992). These measures contributed to a remarkable six-fold reduction in Mine Safety and Health Administration (MSHA) reportable accidents at the Lucky Friday (Wilson, 1997).

Geology

The Lucky Friday vein forms an S-shape in plan view and extends horizontally about 460 m (1,500 ft). Splits off this vein extend potential stope length to over 610 m (2,000 ft). The vein is composed primarily of galena, with lesser amounts of quartz, siderite, and sphalerite. The vein ranges from 0.6 to 9 m (2 to 30 ft) wide, but averages about 1.5 m (5 ft) wide. The Revett Formation, which has hosted most historic production in the Coeur d'Alene Mining District, forms the wall rock. Because the vein itself dips steeply (70° to 90°) to the south and east, it comes into contact with progressively older rocks with depth (figure 1*B*). Presently, mining is active within the quartzitic lower member of the Revett Formation under 1.5 km (1 mile) of overburden.

Numerous faults and folds are apparent, and many of these intersect the vein structure. The most pronounced faults are the North and South Control faults that delineate the ends of the Lucky Friday vein. The most pronounced fold, the Hook Anticline, divides the mine into southern and eastern limbs. A minor fault approximately traces the axial plane of this fold. The rock mass surrounding the vein is made up of thick vitreous and sericitic quartzite beds with soft interbeds of argillite generally less than 5 cm (2 in) thick. These beds have been grouped into 15- to 46-m (50- to 150-ft) thick subunits of predominantly hard, brittle, vitreous quartzite and relatively soft, plastic argillite and sericitic quartzite (figure 1*A*). An in-depth study of rock and rock mass properties was recently conducted for each of these three rock types and their various combinations as found in formations and stratigraphic subunits of the Coeur d'Alene district (Whyatt et al., 1996a).

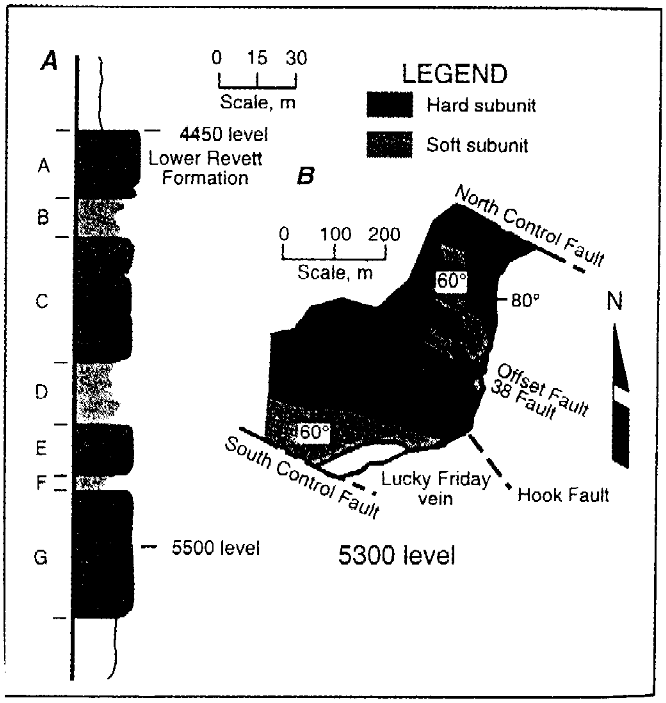

Figure 1.—Stratigraphy (*A*) and structure (*B*), Lucky Friday Mine.

In Situ Stress

The in situ stress regime at the Lucky Friday Mine was the subject of a recent in-depth investigation (Whyatt et al., 1995a-1995d). Considerable variation in the in situ stress field was observed among overcore cells and sites. Unusual stress conditions, including a rotation of horizontal principal stresses and a vertical stress component double that of overburden loading, were measured at a site on the 5300 level of the mine directly above the ramp sublevels examined in this study. Stress conditions were confirmed by unusually intense and concentrated seismicity and rock bursting encountered during subsequent excavation in this area. Raisebore breakouts observed in a number of locations from the 5100 through the 5700 levels of the mine were mapped to establish bounds to the spatial extent of the stress field rotation. These results are plotted on a map of the 5300 level on the basis of lithology (figure 2). Breakouts in softer subunits showed the maximum horizontal principal stress oriented uniformly to the northwest. Breakouts and stress measurements in the harder subunits showed similar results, except in a service raise on the 5400 level and at the overcore measurement site on the 5300 level, both of which are adjacent to the Offset Fault. Thus, this stress perturbation appears to be limited in extent, but likely extends into a portion of the study area along the Offset Fault.

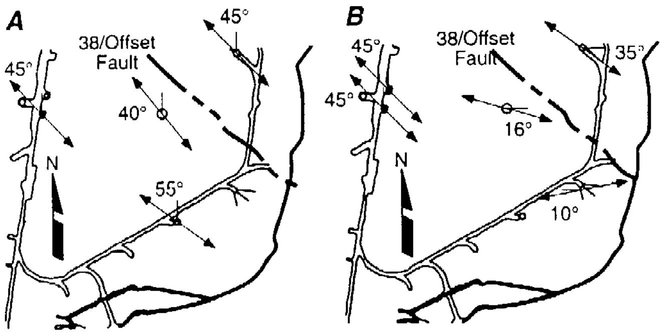

Figure 2.—Orientation of horizontal maximum principal stress at various locations projected onto 5300 level plan. *A*, Locations in relatively soft subunits; *B*, locations in relatively stiff subunits.

Seismic Monitoring Systems

Seismic activity was monitored by three seismic networks during the study period. The oldest of these systems, operated since 1973, is an analog microseismic system that determines the location of seismic events and includes a surface seismograph for estimating relative magnitudes of events. The development of powerful digital systems based on the personal computer (PC) provided an opportunity to supplement the microseismic system with full-waveform monitoring systems. The mine-wide digital seismic monitoring system (macroseismic system) was installed in 1989 (Girard et al., 1995), and the district-wide North Idaho Seismic Network (NISN) began operation in March 1992 (Lourence et al., 1993). Williams et al. (1995) provide a detailed summary of system components, geophone networks, and the types and format of data produced by these systems.

Data Screening and Sorting

The present study was based on a database containing records provided by the USBM, the University of Idaho, and Hecla Mining Co. Data was collected for events that occurred from mid-1990 through the first half of 1993. These data included records from all three seismic systems discussed above, rock burst damage reports, and the progress of stope and development headings. Reports included, wherever possible, eye-witness accounts and on-site inspection of rock burst damage. This database grew to include information on several thousand events. Detailed event records and seismic first-motion data are too voluminous to be included here, but are available in a related paper (Whyatt and White, in progress).

The database was screened using a number of criteria to define sets of events of interest to this study. Data on events occurring outside the physical or temporal limits of this study were eliminated, and then the remaining data were sorted into three sets of events for further analysis. The first of these sets consists of events with the largest seismic magnitudes located within 91 m (300 ft) of a development face. A second set was defined to include events of all magnitudes but required a location within 30 m (100 ft) of a development face. A third set was defined to contain the 20 events with reported damage. These data sets are examined in the following sections.

DATA SET 1: LARGE SEISMIC EVENTS

The seismic energy released by large mining-induced seismic events has always attracted attention. These events have been associated with many large-scale failures, like the 5.2-magnitude event produced by the collapse of a portion of the Solvay Mine in Wyoming. As such, they are generally perceived as posing a great risk to miners. The seismic signals from these events can be detected at great distances, providing seismologists and ground control engineers with abundant information on event energy, location, and mechanism that is often not available for smaller events. Thus, the largest events, defined as events registering 30 mm or more on the surface seismograph trace (approximately 0.5 M_l), were chosen for the first group of events addressed in this study. The mine has found the 30-mm threshold to be useful for identifying the events most likely to damage the mine. Thirty millimeters roughly corresponds to the threshold for collection of digital seismic records as well. This set was also limited to events occurring within 91 m (300 ft) of a development face. Large events occurring farther than 91 m from the ramp face were considered unlikely to damage the ramp, and their occurrence would be unrelated to ramp progress.

Groups of Large Events

Twenty-nine large events were sorted into a number of groups with common characteristics, including location, activated geologic feature, and failure mechanism (figure 3). Damage to mine workings was reported for only six of these events, but for three of the six, the relationship proved to be only coincidental. Overall, these events accounted for surprisingly little damage and appear to be part of the rock mass response to mining rather than to development.

Vertical Slip Events: Macroseismic first-motion patterns showed that this set of six seismic events was generated by dip-slip movement, north block down, on two east-west-striking vertical fracture zones in the footwall of the 05 and 06 stopes. The district-wide NISN consistently detected implosional first motions. These events occurred over a single 45-day period and

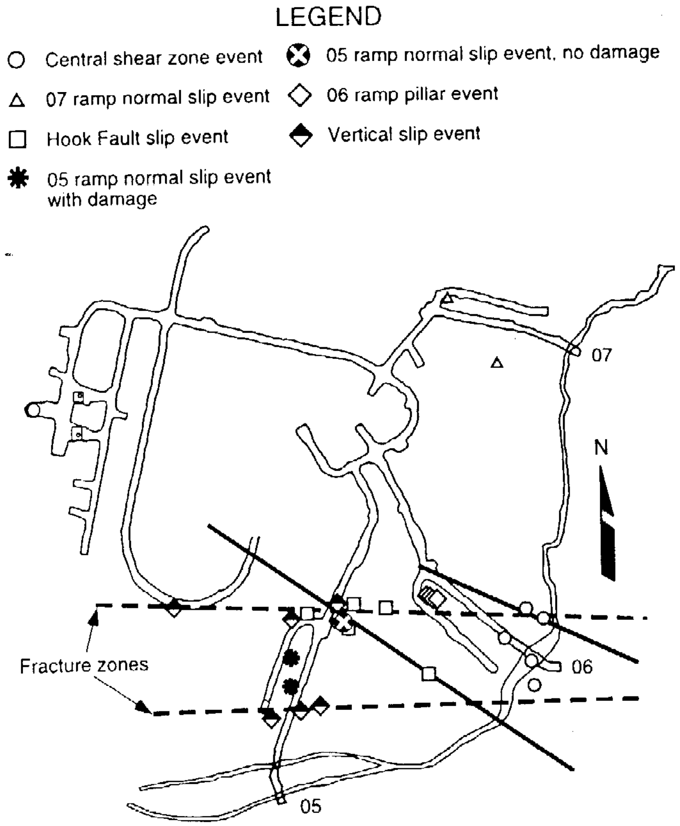

Figure 3.—Locations of large events assigned to various groups.

showed remarkable consistency in first-motion attributes. The discrepancy between systems can be interpreted as showing vertical shear on a plane of weakness with net deformations that significantly close (implode) the stope. The vertical relative movement (northern block down) of these events is the same as the offset observed between walls of the Lucky Friday vein. This sense of movement also matches the first-motion pattern observed in a series of very large (2.5+ M_l) vertical shear seismic events (Whyatt et al., 1996b) that occurred on the vein.

Central Shear Zone Events: This group of five seismic events occurred in a cluster near the vein at the southern margin of the central shear zone between the Hook and Offset faults. The group appears to be bounded to the north by the northernmost vertical shear zone. Macroseismic first motions for these events were primarily dilational, and the one event captured by the NISN appeared as an implosion. However, compressional first motions measured on a few macroseismic system geophones suggest left-lateral first motions for three of these events. Left-lateral movement is consistent with closure of the vein. Moreover, these movements are consistent with the stress field measured directly above these events on the 5300 level (Whyatt et al., 1995d). However, this sense of movement (and stresses measured at the 5300 level) is inconsistent with the northwest orientation of the regional stress field. Vertical slip on a plane parallel to the vein is indicated for another event, and a confused pattern was developed for the fifth.

Hook Fault Slip Events: This group of five seismic events occurred over a period of 60 days and is the first evidence that the Hook Fault, which is nearly coincident with the axial plane of the Hook Anticline, plays a role in the generation of seismic events. The macroseismic system and NISN both reported first-motion patterns dominated by right-lateral motion. The first event is interpreted as having occurred on the Hook Fault between the two vertical shear zones, while all four subsequent events were concentrated around the intersection of the Hook Fault with the northernmost shear zone.

05 Ramp Normal Slip Events: This group of four events occurred throughout the study period in two separate areas of the 05 ramp. First-motion information for these events was somewhat sparse, but generally indicated normal slip on bedding planes, which is a well-established mechanism for seismic events in the southern limb of the mine (Whyatt et al., 1996b). Spatially, the first two events, each of which damaged the ramp, occurred between the up and down ramps midway between the vertical shear zones. The second set of two events occurred at the same location near the intersection of the ramp with the northern-most vertical shear zone within three weeks of each other and did not damage the ramp.

06 Ramp Pillar Normal Slip Events: The first event in this group damaged the development face. Repair required removal of 100 mt of broken rock. While the magnitude of this event was measured, the seismic systems failed to provide a location or first-motion pattern. Three additional events occurred close to the first during the following 5 months. The events were located in a single 6 m (20 ft) diameter cluster in the vicinity of damage from the first event. This cluster was located just to the north of the northernmost vertical shear zone and just above the pillar between 5480-06 up and down ramps. The macroseismic system showed normal slip first-motion patterns, but not on any known plane of weakness. NISN reported implosional first-motion patterns for these same events, suggesting some reduction in excavated volume. The repeated occurrence of these events at the same location in the 06 ramp pillar suggests that some feature, or set of features, probably including the ramp pillar, contributed to this concentration of activity. It also suggests that the hazard posed by the first of these events at the unsupported face was fully controlled by ground support measures installed prior to the subsequent large events.

07 Ramp Normal Slip Events: This group of two events occurred during a 10-day period. The events were located above the 5480-07 ramp and above the mining horizon. The in-mine macroseismic system generated a first-motion pattern showing normal slip on bedding planes for the first event, but missed the second. The regional NISN network reported an implosional first-motion pattern for the first event, but the pattern for the second event was confused. This discrepancy between near-field and far-field readings is similar to that observed in other sets of events and likely reflects initiation of movement along bedding combined with significant closure of the 07 stope. The proximity of event locations to the ramp suggests that the ramp might have had some influence on event initiation, even though the first motions appear to be unrelated to the ramp.

Interaction of Large Events with Excavation

The link between a mining-induced seismic event and excavation at a particular location is not always clear. However, it is reasonable to expect that if an excavation truly triggers a seismic event, that event should be located in a region that undergoes a nontrivial change in stress field as a result of excavation. Only three of the 29 large events were located within 10 m (30 ft) (three diameters) of the ramp face, where ramp excavation could conceivably play a role in triggering these events. Damage to the ramp was reported with two of these events. First-motion information from the third event was characteristic of other events occurring at much greater distances from the ramp face, suggesting that the event was independent of the ramp and was only coincidentally located near the ramp face. The two damaging events, on the other hand, displayed normal first-motion patterns consistent with movement of rock into the ramp. Moreover, since both of these events were located beneath the mining horizon, the ramps were the only voids that could be closed by normal movement. These two events and, possibly, the unlocated event that damaged the 06 pillar, are the only cases in which ramp excavation appeared to trigger a large seismic event.

The relationship between large seismic events and mining can be examined by plotting the location of these events relative to the mining front (figure 4*A*). Each type of event appears to maintain a fairly constant position with respect to the mining front, and the first-motion patterns reported for these sets of events are consistent with the influence of mining-induced stresses (figure 4*B-D*). The deepest events were located at the southern end of the central shear zone, and relieved concentrated horizontal stresses below the 06 stope. The next major set of events, right-lateral events along the Hook Fault, was driven by relief of east-west horizontal stresses by mining in the 06 and 07 stopes and concentration of north-south stresses under the lagging 05 stope. Concentration of stress in the dipping beds was relieved through vertical shearing (figure 5), and vertical stress on bedding planes above the stope floor was relieved by normal movement toward the stope.

DATA SET 2: EVENTS AT THE FACE

A second set of events was formed from the large number of nondamaging seismic events detected during development of the ramps. Events were considered only if they occurred within a distance of 30 m (100 ft) of the development face. Detection by the seismograph was defined as the minimum seismic energy threshold. The rationale for examining these events was twofold. First, although these events did not cause damage, many occurred in similar locations and with similar levels of seismic energy

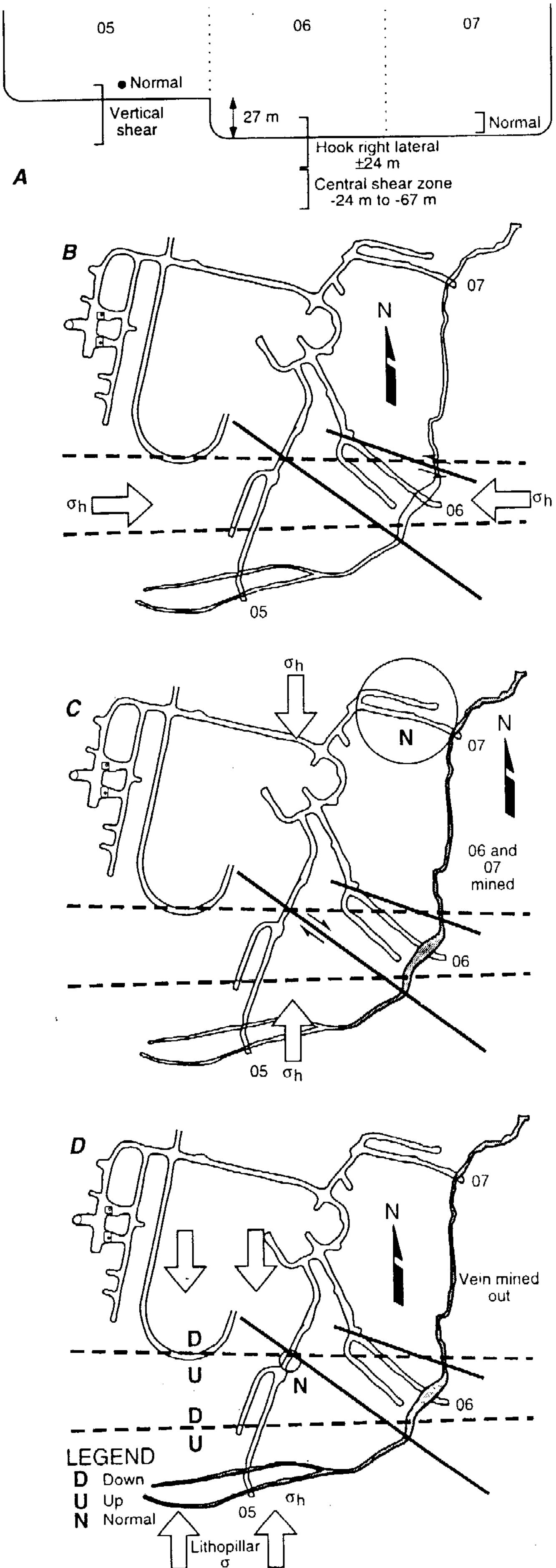

Figure 4.—Location of major groups of large events relative to mining face. *A*, Longitudinal section; *B*, deep events responding to east-west abutment stress; *C*, intermediate events responding to leading 06 and 07 stopes; *D*, uppermost events relieving stress in beds through vertical shear and vertical stresses by normal slip.

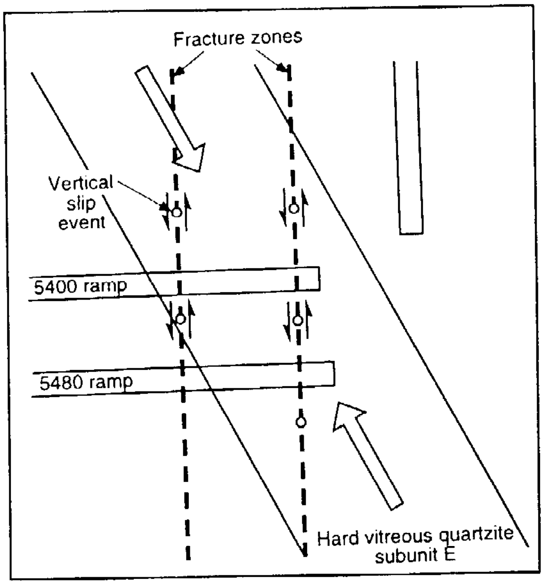

Figure 5.—Schematic showing the sense of vertical slip, stratigraphy, and stope in a vertical section.

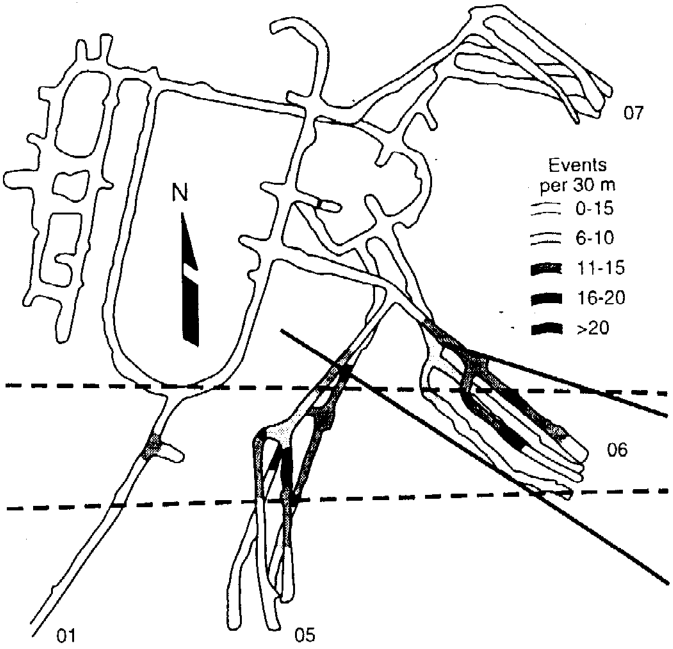

Figure 6.—Density of small seismic events

to those that did. Some of these may have been caused by mechanisms that have little potential for damage, but some, at least, would have resulted in damage if a less robust ground support system had been installed. Second, the rate at which these events were generated is likely to be indicative of local rock mass conditions.

The large number of these events precluded analysis on a case-by-case basis. Instead, the overall rate of occurrence of these events was compared to progress in developing the ramp system. The position and advance of each ramp face was determined for each of the 36 months encompassed by this study. The number of small seismic events within 30 m (100 ft) of the face during that month was ascertained and then normalized to provide the number of events per 30 m (100 ft) of advance. A plot of these results (figure 6) shows two major zones of development-induced seismic activity. The first and westernmost of the zones lies entirely within a hard lithologic subunit and is cut off rather dramatically at the Hook Fault. A similar but more gradual cutoff is evident near the vein at the subunit boundary. The second and more centrally located zone is not as clearly constrained.

DATA SET 3: ROCK BURSTS

Data set 3 was defined for events that reportedly damaged a ramp face, rib, or back within the 5400 and 5480 sublevels. The set consists of 20 events that injured four miners and required removal of 750 mt (830 st) of rock during repair of the ramp back, rib, or face (at 10 to 100 mt per burst). Rib damage, reported in 11 of these 13 events, predominated. Back damage was reported in three events, and face damage in two events. Burst damage to the floor was reported for one event. The majority of these events are best described as strain bursts, and many appear to have been driven by buckling of slabs in the ramp rib or face.

An eyewitness account of a small-magnitude rock burst in the 01 ramp on May 20, 1993, illustrates this mechanism. The burst occurred as two miners were drilling bolt holes in the rib to install bolts and chain-link fencing. One miner reported that his jackleg drill seemed to leap toward the rib, as if the drill steel had broken (it had not). In the next instant, the rib burst almost from floor to back along a 5-m (15-ft) section of the ramp to a depth of about 1 m (3 ft). A miner was bruised but not seriously injured, being protected somewhat by the fencing hanging between them and the burst.

An examination of the rib at the ends of the burst cavity revealed many closely spaced, joint-like fractures at a slight angle to the surface of the rib. These fractures had not been recorded during mapping of the rib several days earlier. Whether or not they were preexisting structures, their prominence after the burst suggests they at least opened as the burst occurred. The miner's perception that his drill leaped toward the rib suggests that quasi-static dilation of the rib occurred as a prelude to the burst. The movement was likely caused by fracturing and bending of rock layers defined by fractures prior to buckling of these slabs into the ramp.

A number of similar accounts have been gathered from other rock bursts. These accounts share the following observations:

X Sudden, intense fracturing of intact rock into coffee-cup size or smaller rubble.

X A loud, instantaneous report. The report is described as resembling an exploding charge or a sonic boom. For nearby observers, the sound seemed to originate at the immediate site of the burst. It seems likely that instantaneous fracturing of rock at the rock burst site is responsible for the sound.

X Rock rubble expelled into the mine opening before miners could react. Initial expulsion of rubble is followed by a brief interval in which rock burst debris continues to be distributed about the burst site. Miners involved in these bursts are not generally knocked down by the ejected rock. Instead, they are engulfed by a fluid-like flow of rock debris. Miners have been partially or completely buried while standing erect. Their legs have been extensively bruised but not broken from the impacts of individual rock fragments.

X A dense cloud of dust that immediately fills the air. Near a major burst, dust may be so dense for several minutes that miners have the impression that their lamps have gone out (Dolph, 1993).

X An air pressure shock wave or "air blast" that travels through the mine. The initial air blast shock may be followed by a period of burst-induced wind that varies from very brief to sustained, depending on the change in excavated volume induced by the burst.

X A concave cavity that narrows with depth. Weak discontinuities often form the back of the cavity, which is revealed when rubblized rock is removed. Damage reports examined in this study reported cavities ranging from 30 to 120 cm (1 to 4 ft) deep.

Rock bursts, like events in the first two sets, occurred in a few clusters involving only a small portion of the ramp system. Figure 7 illustrates the locations of these clusters and locations where these bursts resulted in injuries. The location of injuries within the clusters of rock bursts suggest that the level of hazard was influenced by sudden onsets of rock bursting that may have surprised miners. Adding destress holes to the round and adjusting support measures were probably responsible for the lack of subsequent injuries in these clusters, but detailed records of these measures were not obtained.

Figure 7 also indicates which rock bursts could be linked to records of a particular seismic event. This link could not be forged for a majority of reported rock bursts, including all bursts reported in the 07 ramp, and 3 of the 4 reported in the 06 ramp. Establishing a link between damage and a seismic event can be difficult, particularly when the event has little seismic energy or occurs with blasting. The time at which the ramp is damaged can be difficult to ascertain if a section of ramp is idle when the damage occurs and the seismic event is not unusually energetic. Finally, it is also possible that some of these rock bursts, particular those with minor amounts of reported damage, might have occurred independently of a seismic events and, thus, be more appropriately described as falls of ground. However, there was no correlation between amount of damage and seismic magnitude within this data set. In fact, many of the most damaging bursts could not be linked with a seismic event while while one of the least damaging bursts was included in the set of large seismic events.

Most of the rock burst clusters fell within the footwall of the southern limb of the Lucky Friday vein where both large and small seismic events were concentrated. However, bursting in the 07 ramp was a notable exception. The scarcity of both large seismic events (data set #1) and seismic events in general (data set #2) in the 07 area suggests that stress levels were lower than in burst-prone zones to the south. Steeply dipping bedding and a steeply dipping fault both cross the 07 ramp at low angles and appear to have severely weakened ramp ribs. These bursts were largely eliminated from the 07 ramp in subsequent sublevels by reorienting to cut bedding at high angles and repositioning to avoid the fault.

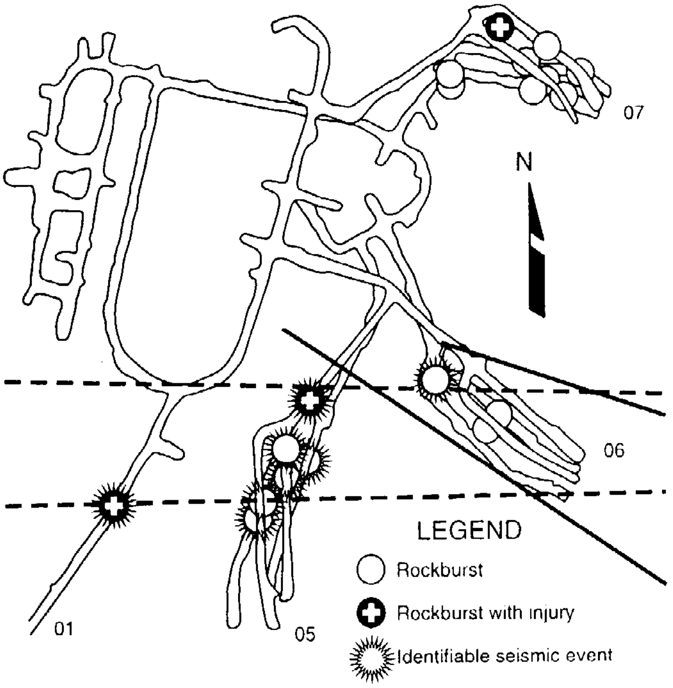

Figure 7.—Locations of rock bursts and rock burst injuries.

DISCUSSION

This study was designed to examine rock burst hazards encountered during development of just over a mile of ramp within the 5400 and 5480 sublevels of the Lucky Friday Mine.

The study examined 29 large seismic events, hundreds of microseismic events, and 20 rock bursts. Repair of damage caused by these bursts required removal of 750 mt (830 st) of broken rock. Eyewitness accounts were used to build a composite description of a typical rock burst. These accounts indicate that most of these bursts were caused by buckling of rock plates defined by preexisting or stress-induced discontinuities within the ramp rib or face. These bursts can best be described as strain bursts. They generated low levels of seismic energy and did not meet energy threshold criteria useful in other areas of the mine for identifying potentially damaging events. However, the spatial distribution of large and small seismic events did correlate with rock bursting in some areas. The 07 ramp is an exception and may reflect a difference in burst conditions. The 07 ramp bursting occurred largely as a result of location and orientation relative to weak bedding planes and a fault. Intense seismicity and rock bursting were correlated in areas that were highly stressed, as shown by the 5300 level stress measurement, and were developed at favorable orientations to structure in strong vitreous quartzite.

Nearly all of the large events examined in this study were driven by mining of the Lucky Friday vein. The relatively simple mining geometry of the underhand longwall front combined with a fairly complex geologic setting to drive a rich mix of seismic events and, potentially, rock bursts. The influence of geologic features on seismicity is clearly displayed in first-motion patterns that show slip on a number of faults, bedding planes, and fracture zones. This influence is also apparent in the bounding of seismic activity by shear zones, faults, and subunit boundaries. Mining clearly concentrates the stress available to drive many of these events, but there is a marked difference in the seismic response to the concentration of stress between the two limbs of the mine. One explanation suggested by earlier in situ stress studies is that the level of premining stress differs through the rock mass. Thus, the highly stressed, and stress concentrated, southern limb is seismically active, while the quieter east limb lacks high levels of premining stress, and the deep footwall lacks a mechanism for concentration of premining stresses. Further work is needed to discern how varying intial stress fields can be reasonably included in an assessment of the spatial distribution of rock burst risk.

The lack of damage from large events reflects well on the ground control measures that have been applied. Outside the 07 area, most damage was recorded at the unsupported face or in immediately adjacent ribs, often before or during installation of support. The 06 pillar events are a case in point. The first event caused significant damage to the face, but three subsequent events were successfully contained by the support system. It also appears that injuies tended to occur when an area of intense rock bursting was first entered and that changes in practices were successful in preventing subsequent injuries in each of these areas.

The sources of information available to this study, including conventional seismic monitoring systems, geologic mapping, damage observations, and good background information on rock mass properties and in situ stress, were sufficient to identify geologic controls that spatially concentrate seismic activity and rock bursting. Recognition of the role of particular geologic features in the spatial distribution of rock burst hazards provides an opportunity for anticipating, rather than reacting to, a changing level of rock burst hazard. However, much work will be required to make good on this promise.

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