INFLUENCE OF MINING-INDUCED SEISMICITY ON POTENTIAL FOR ROCK BURSTING

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ABSTRACT

Relationships between the locations of mining-induced seismic events, local fault structures, and mine geometry were examined by the U.S. Bureau of Mines in the Galena Mine, a deep hard-rock mine in northern Idaho. Stopes in the Galena Mine experiencing rock bursts and other large seismic events were found to fall into two structural regimes: the Silver vein and the N. 48° W. trend. The latter is a steeply dipping plane of seismic activity that is subparallel to major, locally steeply dipping faults that bound blocky structures. The N. 48° W. trend also intersects a shaft that was seriously damaged when fault gouge was expelled into the opening during a 3-month period of high seismic energy release. Models of stress interaction were developed to support the hypothesis that mining-induced deformation was mobilized along a 1.5-km length of the N. 48° W. trend. Specifically, numerical models were used to simulate rupture of seismic events and estimate induced changes in the quasistatic stress field. A Coulomb failure criterion was used with these results to estimate spatial variations in the potential for slip on planes parallel to local faults. Increases in the potential for slip on fault planes subparallel to the N. 48° W. trend were consistent with activation of deformation along the trend's 1.5-km length.

INTRODUCTION

Certain mine geometries and geologic structures play critical roles in the generation of rock bursts and other large mining-induced seismic events (Cook and others, 1966). To develop effective strategies for the reduction of rock-burst hazards at a particular mine site, the underlying mechanisms, whether controlled by mine geometry, geology, or both, must first be identified. Toward this end, the relationships among large seismic events, mining geometry, and local fault structures were examined in a burst-prone mine (Galena) in the Coeur d'Alene Mining District of northern Idaho.

Rock bursts in deep hard-rock mines have been classified into two groups: those associated with high stresses induced by mine geometry and those linked to the interaction of these stresses with preexisting geologic structures, such as faults and dikes (e.g., Gibowicz, 1990). The high-stress-induced events occurring in the immediate vicinity of mine workings and pillars are often considered to be less damaging (i.e., result in a smaller area of damage) and of lower magnitude than those associated with large-scale slip along faults (Gay and others, 1984; Brummer and Rorke, 1990). Nevertheless, fault-slip events can be triggered far out in the host rock without significant, or any, in-mine damage.

Rock bursts in the Coeur d'Alene district are often triggered during mining into remnant (sill) pillars produced by the commonly used overhand cut-and-fill mining method (Blake, 1972). In this case, both geology and mine geometry influence rock bursting; fault structures are present in the immediate vicinity of mining and are subjected to the high stresses present in the pillars. An attempt to reduce rock bursting by eliminating pillars in an experimental underhand longwall cut-and-fill mining operation is in progress at one mine in the district (Williams and

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Cuvelier, 1990). Eliminating pillars, however, does not reduce the frequency of encounters with faults. Studies of rock bursts in the Coeur d'Alene district show that many are consistent with slip along faults and other planar geologic structures (Jenkins and others, 1990; Williams and others, 1992; Boler and Swanson, 1993; Lourence and others, 1993).

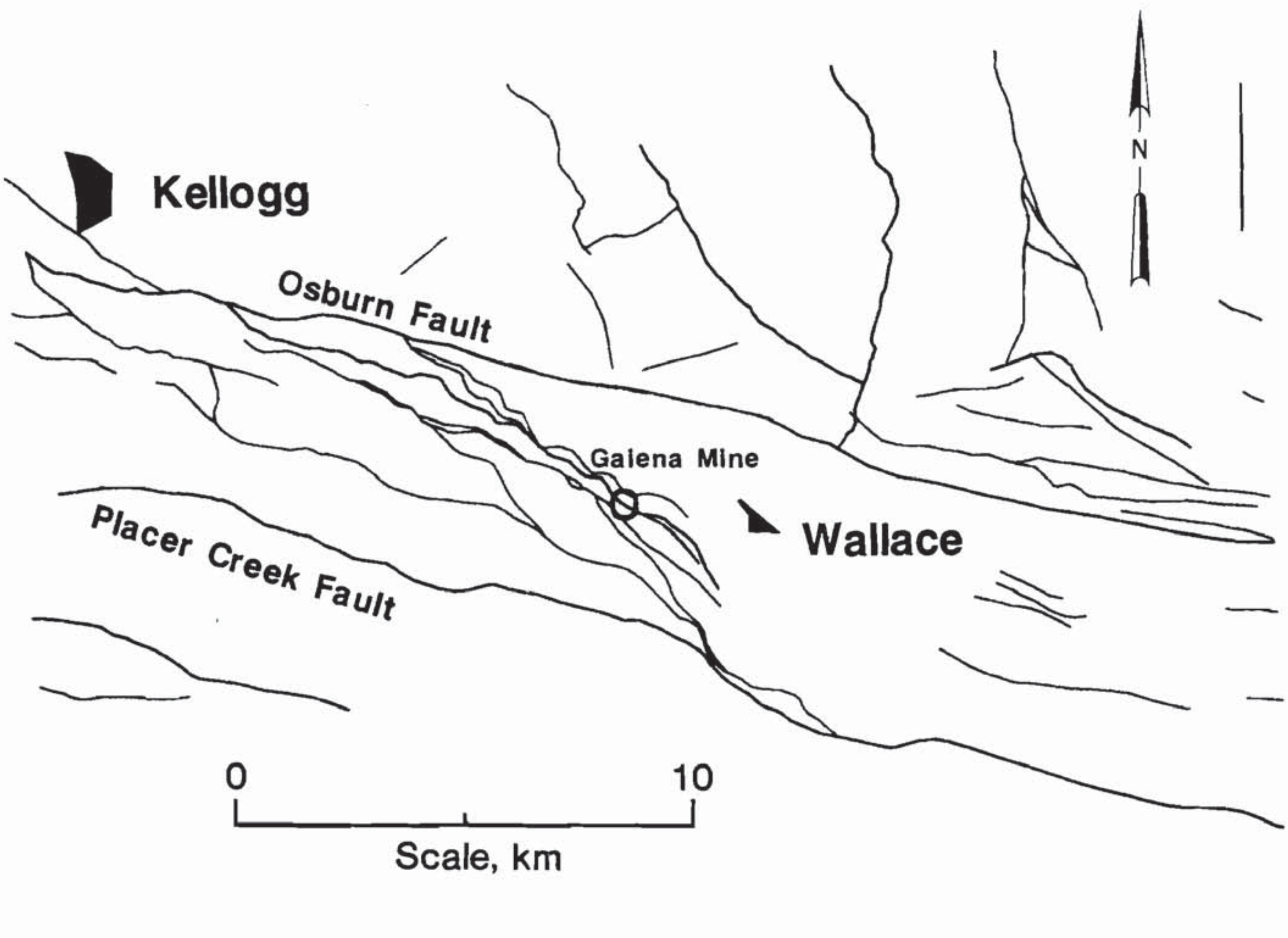
This study was initiated by researchers at the U.S. Bureau of Mines (USBM) after a 3-month sequence of large seismic events occurred in six separate stopes that fell along a well-defined plane. This 1.5- by 0.5-km near-vertical plane, hereafter referred to as the N. 48° W. trend, was generally parallel to the trend of, and approximately coincident with, major local faults. During the same time period, the main entry shaft, which intersects the N. 48° W. trend, experienced significant ground control problems, resulting in a 3-month shutdown. Evidence is presented here that suggests that deformation was mobilized over the entire length of the mine along the N. 48° W. trend in a series of Richter-magnitude (M_L) 1 to 3 seismic events. A stress-interaction mechanism for this mobilization is investigated.

In this paper, the structural geology typical of the region is described, followed by descriptions of the stress field and vein geometry. Then, the N. 48° W. trend is identified along with other structures known to be associated with rock bursting. The paper then focuses on a short period of high seismic energy release along the N. 48° W. trend. Using seismic source size and stress-drop estimates and calculations of induced fault-slip potential, a case for stress interaction among these large seismic events is argued.

STRUCTURAL GEOLOGY

The Coeur d'Alene Mining District has been described as being located in an intensely faulted and sheared structural knot (Hobbs and others, 1965; Wallace and Morris, 1986). The slightly metamorphosed Precambrian rocks were compressed into a series of folds having varying amplitudes and wavelengths (synclinorium) and were subsequently faulted. Figure 1 shows that portion of the district surrounding the Galena Mine. Two locally dominant structural features, the right-lateral, strike-slip

Figure 1
Silver Valley Near Galena Mine Showing Major Faults.



Osburn and Placer Creek Faults, can be traced for over 100 km and make up part of the extensive Lewis and Clark lineament (Wallace and others, 1990). These two faults are connected by a dense concentration of lesser faults (e.g., Polaris, Silver Standard, Killbuck, Argentine) that are found in the vicinity of the mine along a line that trends approximately N. 50° to 60° W. Most of these faults dip steeply to the southwest, and some approach near-vertical in the vicinity of the Galena Mine. Segmentation into complex strands is common. The following discussion refers to the geologic structure in the vicinity of the Galena Mine.

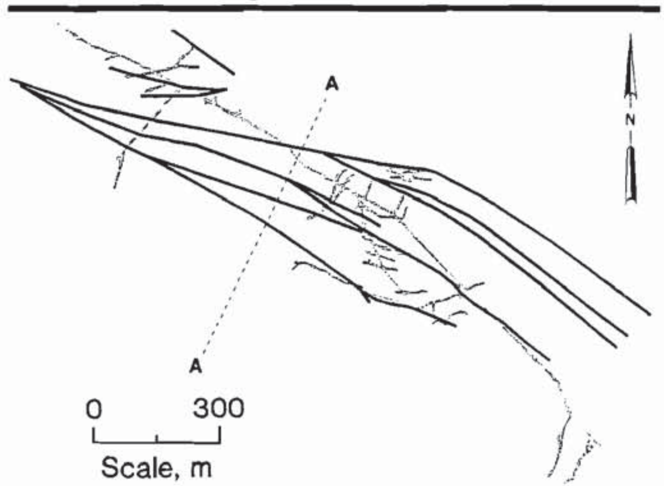
Figures 2 and 3 are maps of fault structure at depth. Only faults that can be traced with certainty across mine levels, diamond-drill holes, and sequential vertical cross sections (250-m spacing) are shown in figure 2. Many other faults are observed in mine openings (figure 3) but, because of their vast numbers and the fact that they can end abruptly, they have not been traced between levels. The northwest-trend of faulting persists down to the scale of a few meters.

The country rock surrounding the mine workings in figure 3 is the Revett Formation. The Revett is locally made up of 0.2- to 1.0-m-thick beds of brittle, high-strength, high-modulus quartzite interbedded with thin beds of argillite (typically <2 cm thick, with rare zones up to 0.7 m thick). In the vicinity of much of the present mining activity, the beds strike northwest and dip steeply (~75° to 80°) to the northeast. Bedding plane faults are ubiquitous, with typical spacings of a few meters. Bedding plane fault offsets average well under 5 m. Many other faults and joints with various orientations are present, producing a complex blocky structure. Throughout the mine, the maximum size block that is free of visible faults is estimated to be only 5 to 7 m on a side.

Rock bursting is prevalent in the Revett Quartzite throughout the Coeur d'Alene Mining District. The Polaris Fault separates the Revett Quartzite from the St. Regis argillites in certain parts of the mine (figure 4). A layer of gouge and sheared rock (0.3 to 10 m thick, with 1 m being typical) is commonly observed in mine openings driven through the Polaris Fault. Such crossings indicate the weak and highly permeable nature of these larger faults, as do the obvious signs of moisture, and enlarged (eroded) mine openings that often need timbered support. Until it dries out following exposure to air circulated by the mine's ventilation system, the soft plastic gouge can be molded by hand.

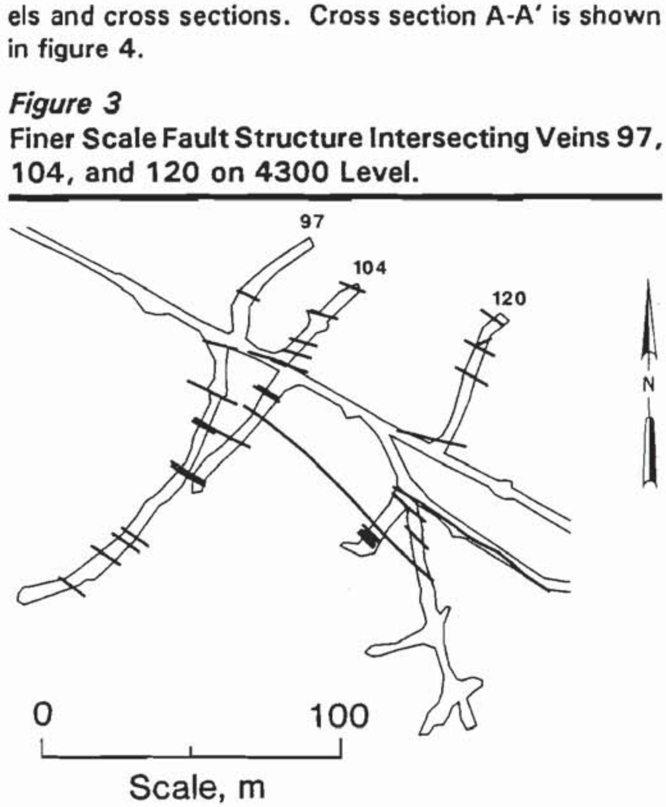
Mine workings that penetrate the Polaris Fault, and those in the St. Regis Formation, often experience considerable "squeeze" (obvious deformation without significant seismic activity, i.e., $M_L < -1$), but few, if any, rockbursting problems. Apparently, the St. Regis argillites consume strain energy by deforming plastically, thus reducing the severity of rock bursts.

Figure 2
Faults Intersecting 4300 Level of Galena Mine.



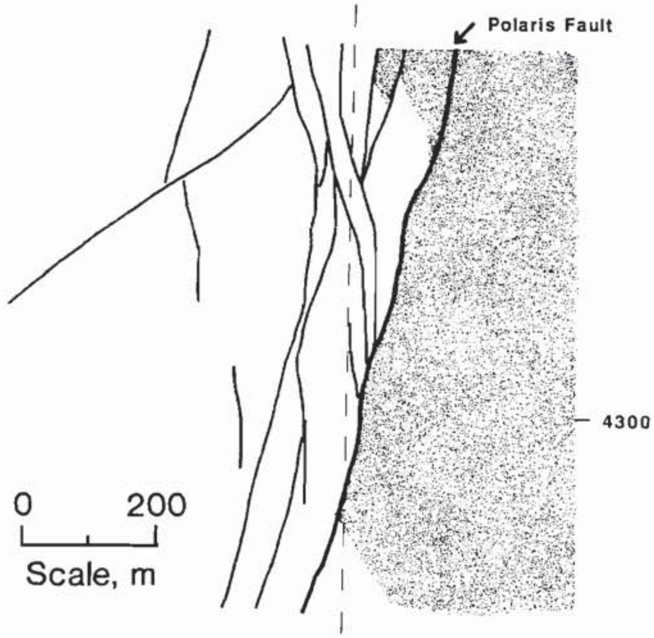
These faults (heavy lines) can be traced between levels and cross sections. Cross section A-A' is shown in figure 4.

Figure 3
Finer Scale Fault Structure Intersecting Veins 97, 104, and 120 on 4300 Level.



Faults range from a few grains in width, with clean, discrete surfaces, to the larger shear zones exhibited by the Polaris Fault, with cataclasis and gouge. In general, fault zones in the quartzite are narrower than in the argillites. The width, however, may depend upon the scale at which observations are made; a single discrete interface may represent one small facet of a large, complex, anastomosing shear zone involving many structural blocks. The blocky nature of the rock mass found at the scale of individual stopes may be interpreted, in certain instances, as

Figure 4
Vertical Cross Section Through Galena Mine as Depicted in Figure 2.



Shading indicates St. Regis argillites. Dashed line is approximate trace of N. 48° W. trend.

representing deformable elements that belong to much larger fault structures.

In summary, stiff quartzite blocks are bounded by compliant fault structures and argillites and are elongated parallel to these structures. As these structures are commonplace in the Galena Mine, mining-induced deformation may be strongly influenced by rigid-block mechanics.

IN SITU STRESS, VEIN GEOMETRY, AND SLIP POTENTIAL

Studies of in situ stress in the district (Board and Beus, 1984; Whyatt, 1986; Sprenke and others, 1991) indicate that the predominant direction of maximum horizontal compressive stress is N. 45° W. ±15°. In the vicinity of the Galena Mine, this direction is parallel to the strike of local faulting and the near-vertical bedding. Limited observations of borehole breakouts in the Galena Mine are consistent with a maximum principal stress direction of N. 45° W. Based on empirical relationships fit to in situ stress data collected throughout the district (Whyatt, 1986), the vertical, maximum, and minimum horizontal principal stresses in the central part of the mine are estimated to be 38, 51, and 39 MPa, respectively.

All but one of the steeply dipping burst-prone veins strike N. 35° E. to N. 65° E., or roughly perpendicular to both the N. 48° W. trend and the maximum horizontal stress direction (see, for example, figure 3). Faults that intersect these veins strike between N. 45° W. and N. 80° W. (e.g., figure 2) with most clustering between N. 50° W. and N. 65° W. Thus the faults generally strike perpendicular to the veins and subparallel to the N. 48° W. trend.

The vein-normal maximum horizontal stress orientation gives rise to local stress distributions similar to those found in gravity-loaded horizontal tabular deposits with large end lobes where shear stress is high (e.g., Jaeger and Cook, 1976). Alignment of these lobes with preexisting fault surfaces and argillite (and other) beds provides optimum conditions for aiding stope closure through both stable and unstable right-lateral and left-lateral slip. These conditions for slip can be illustrated by examining changes in normal and shear stresses across such beds upon mining a vein. The Coulomb failure criterion (e.g., Jaeger and Cook, 1976) is considered in a form that describes the difference between the shear stress required for slip on a surface and the actual stress on that surface. In this paper, this quantity is called the slip potential and is expressed by the equation,

$$\text{Slip potential} = |\tau| - s_o - \mu\sigma_n, \qquad (1)$$

where $|\tau|$ = shear stress on the surface in question,

$s_o + \mu\sigma_n$ = Coulomb stress required for slip,

s_o = cohesive shear strength,

μ = coefficient of friction (internal friction for intact rock),

and σ_n = normal stress acting on the plane.

Equation 1 is identical to the excess shear stress (ESS) parameter of Ryder (1988) and other researchers in which the difference between static shear stress prior to slip and the dynamic strength of the plane is expressed when μ is the dynamic coefficient of friction.

Figure 5 is a schematic showing one excavated vein intersecting the N. 48° W. trend at nearly 90°. Absolute values of slip potential are shown for slip on planes trending N. 48° W. The direction of σ_1 in figure 5 was taken to be N. 30° W., representing one end of the reported range of the maximum principal stress direction (i.e., N. 45° W. ±15°). Symmetry of contour lobe size and orientation occurs when σ_1 is oriented N. 45° W. The elevated slip-potential lobes are thus elongated to the northwest over the reported range of σ_1 orientation. Localized fault structures (figures 1-4) and bedding planes parallel to these elevated slip-potential lobes are prime candidates for seismic and aseismic slip (both right- and left-lateral) that accommodate closure.

SPATIAL DISTRIBUTION OF ROCK BURSTS

At a depth of 1 to 1.7 km, the silver ore vein deposits of the Galena Mine are extracted using the overhand cut-and-fill method. There are more than 40 near-vertical veins that are distributed, in subparallel fashion, over a horizontal distance of 1.5 km. Up to 20 different stopes are mined at any one time. Of these, 10 may be prone to rock bursting.

The seismicity data described in this paper were initially examined to constrain the design of a full seismic waveform recording system. Richter magnitudes were estimated from a calibrated short-period vertical seismometer operating on the surface. Seismic events were located (Swanson and Sines, 1991) using one of eight 16-channel accelerometer arrays in a networked microseismic monitoring system (Steblay and others, 1990; Estey, 1995). This system provides real-time hypocenter locations for events with magnitudes greater than approximately -5. Each array is roughly 150 m on a side and is centered around individual rock-burst-prone stopes. Location errors for events falling within an individual array, where the detection and location sensitivity are greatest, are ±10 m at best (Swanson and others, 1992).

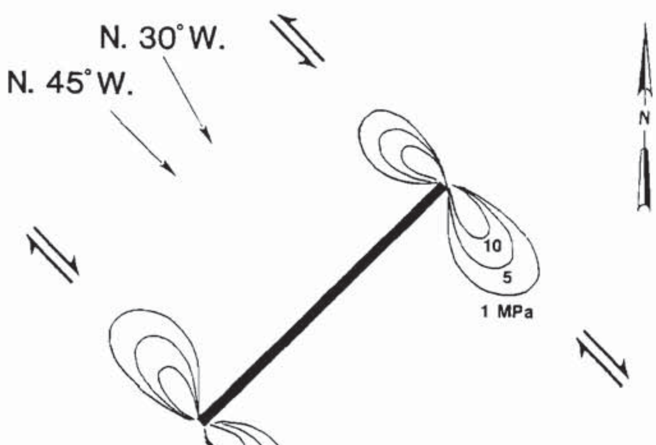
Approximately 200 of the largest mining-induced seismic events with M_L ranging from 0.0 to +3.0 were located. Figure 6 is a histogram showing all located seismic events and a subset of damaging seismic events. A damaging seismic event is defined here as one that requires at least one-half day of stope cleanup and/or repair.

Ten rock-burst-prone stopes fell into two different structural regimes: the Silver vein and the N. 48° W. trend (figure 7). Figure 7 illustrates the two structural regimes and the 4300 level at a depth of approximately 1.3 km. The Silver vein is the largest vein in the mine and has been associated with rock bursts since the 1950's. It extends at least 1 km vertically and as much as 400 m horizontally. The mined horizontal extent of more typical veins is 80 to 120 m. The near-vertical veins have a height that is typically two to four times their breadth and an excavation width of 2 to 5 m.

Six stopes with recurring seismic activity plus the damaged shaft define the N. 48° W. trend. In one 11-month period, 30 of 32 events having an M_L >1.0 occurred exclusively along the N. 48° W. trend despite the fact that mining was progressing in at least 25 different stope and development headings that were not aligned with this trend. Several particularly large seismic events (M_L >2.5)

Figure 5

Absolute Slip-Potential Contours for Slip on N.48°W.-Oriented Planes.



Contours (in MPa) are calculated near vicinity of mined-out vein on N.30°W. trend. Direction of σ_1 is N.30° W. Perfect contour symmetry occurs for σ_1 oriented at N.45°W.

Figure 6

Distribution of Seismic Magnitudes for January 1989 Through June 1991.

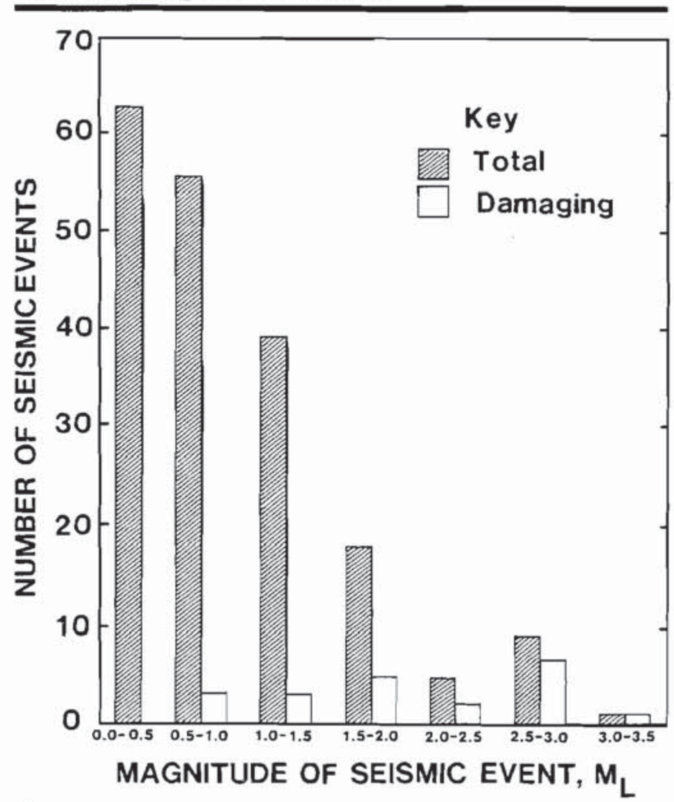
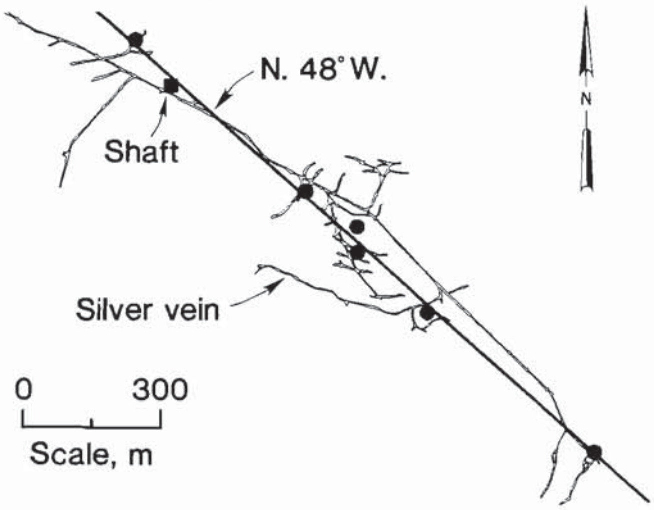


Figure 7

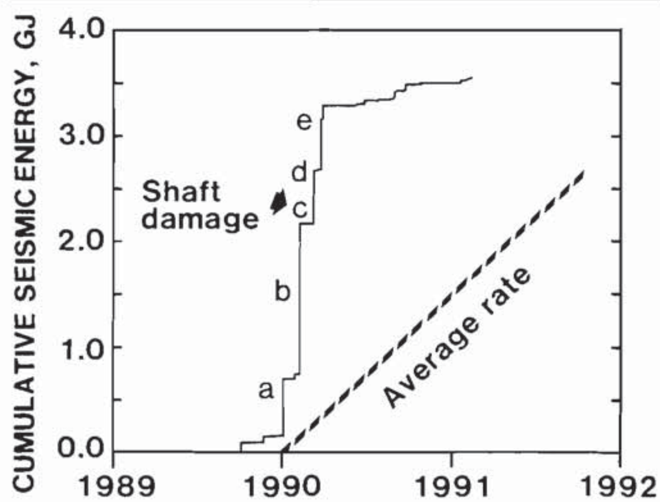
N.48°W. Trend of Stopes (Solid Circles) Experiencing Rock Bursting and Other Large Seismic Events.



Rock-burst-prone stopes on Silver vein are omitted for clarity. Plan view shows 4300 level at a depth of 1.3 km.

Figure 8

Cumulative Seismic Energy Released Along N.48°W. Trend.



Periods of energy release a, b, d, and e are associated with events shown in figure 10. Time of fault-gouge expulsion into main entry shaft is denoted by c. Dashed line shows long-term average energy release rate.

occurred in the last 3 months of this 11-month period. The remainder of this paper focuses on this short period of high seismic activity along the N. 48° W. trend.

CONCENTRATED RELEASE OF SEISMIC ENERGY

Periods of elevated rock-burst activity, or rock-burst "seasons", have long been recognized by old-time Galena miners. One such period of elevated activity occurred in the first 3 months of 1990 (figure 8). Over 90 pct of the seismic energy released from the mine in 1990 was released during this time. Seismic energy E (in ergs) was estimated using Gutenberg and Richter's (1956) relation log E = 11.8 + 1.5 M, with M_L as magnitude M. The seismic energy emitted along the N. 48° W. trend occurred in a series of 11 events having an M_L of 1.1 to 2.9. Four events, ranging from M_L 2.6 to M_L 2.9, dominated the periods of energy release, labeled a, b, d, and e in figure 8. The main entry shaft damage at c occurred shortly after the largest event of the sequence at b. Following this short period of high seismic energy release, the rate remained below the average long-term rate, which is indicated by the slope of the dashed line in figure 8, for 10 months. Mining productivity was nearly constant during this entire period.

The temporal coincidence of a rapid sequence of large seismic events and shaft damage (all occurring on the N. 48° W. trend), followed by a significant quiet period, suggests large-scale release of stored elastic strain energy through activation of fault-slip along one of the major northwest-trending faults. However, a single major discontinuity surface cannot be traced through the N. 48° W. trend. It should be reemphasized that faults on the scale of the mine in the Coeur d'Alene Mining District are not simple planar structures, but are complex, multiple, anastomosing surfaces that can vary rapidly in character over very short distances (Wallace and Morris, 1986). Therefore, even if one envisaged a complex 3-month-long propagation of a shear-slip event that was periodically triggered by mining activity, the presence of a single, continuous discontinuity surface does not seem to be required for fault structure and fault movement at this scale. An alternate interpretation involves the transmission of seismicity-induced changes in stress by relatively rigid quartzite blocks that are elongated parallel to the dominant northwest fault structures. The latter view is consistent with the expected mechanical response of the local geologic structure.

RELATIONSHIP BETWEEN SEISMIC SOURCE SIZE AND EVENT MAGNITUDE

To evaluate the degree to which ruptures generated in a particular stope affect the stress field in adjacent stopes, an approximate measure of rupture size is required (figure 8). Such interaction may promote stope closure and release of stored energy along the N. 48° W. trend. Earthquake seismologists routinely estimate fault-slip areas and resulting stress drops through quantitative analyses of seismic waveforms (Gibowicz, 1990). Numerous estimates of rupture dimensions and shear stress drop have been reported for mining-induced seismicity in hard-rock mines (Spottiswoode and McGarr, 1975; McGarr and others, 1981; Spottiswoode, 1984; McGarr and others, 1990). These published values were fit to an equation relating seismic magnitude to the logarithm of seismic source dimension r, where r is the radius of a circular rupture area.

$$M_L = 2.4 * \log r(m) - 2.7. \quad (2)$$

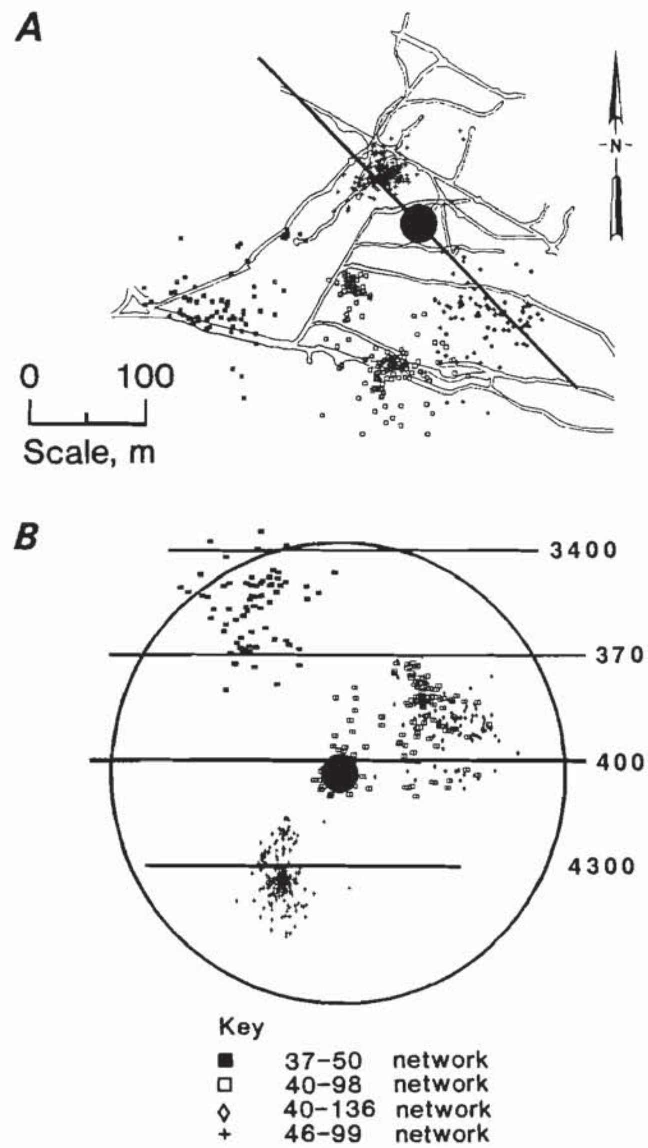
The best fit occurs for a stress drop of 2.2 MPa (319 psi), which is consistent with the typically small values (1 to 10 MPa) reported for mining-induced seismicity (Gibowicz, 1990).

As a check on the assumed relationship between magnitude and source dimension, the mine volume exhibiting microseismicity ($M_L \geq -5$) following a M_L 2.9 event was estimated using the data collected by the microseismic monitoring system. The event occurred in the country rock between the stopes covered by four separate arrays of the monitoring system (figure 9). Damage was restricted to rock falls on several levels and one M_L 0.9 aftershock on the 4300 level that lifted a train track a few centimeters. The observed volume of aftershock microseismicity was a minimum due to the extremely low detection sensitivity beyond individual accelerometer arrays.

Nearly 4,000 microseismic events were detected during the 10½ hours following the M_L 2.9 event. Less than 700 events were actually located; the remainder did not meet the location criteria used in the routine monitoring system (Swanson and others, 1992).

An order of magnitude fewer events are typically located with these four arrays when there have been no large rock bursts. Figure 9 is a graphic representation of the seismic source estimated from equation 2 (r = 201 m). Both estimates of source dimension (equation 2 and figure 6) are of the same order of magnitude.

Figure 9
Source Dimension Estimate for M_L2.9 Event.



Estimate is based on volume distribution of microseismicity recorded for 10-1/2 hours by four arrays of networked monitoring system. Hypocenter is shown as large solid dot. Apparent clustering is due largely to low detection sensitivity in regions between the four arrays. Source dimension estimate from equation 2 (text) shown as 201-m-radius circle in (*A*) plan view and (*B*) vertical section looking northeast.

HYPOTHESIS: MOBILIZATION OF DEFORMATION ALONG LENGTH OF MINE

The relationship between magnitude and source size (equation 2) is now used to illustrate what portion of the N. 48° W. trend could be occupied by a slipped area if all events had a N. 48° W. orientation. The case for making this assumption rests not on seismic waveform data and analyses (for no such data are available), but rather on structural geology, compatibility between N. 48° W. slip and stope closure, and alignment of observed events. Figure 10 shows a vertical section of the plane of induced seismic activity, looking northeast. Estimated sizes and positions of rupture planes correspond to individual events (M >1) occurring during periods of energy release (a-e) shown in figure 8. A significant fraction of the 1.5- by 0.5-km plane of seismic activity is covered by the rupture sources.

To investigate the degree of stress interaction among these events, elementary two-dimensional elastic stress analyses were used to calculate quasistatic stress changes resulting from simple shear rupture sources. In particular, the increase in the potential for slip along the N. 48° W. trend resulting from simple shear rupture at other positions on this plane is examined.

When geologic and/or mine structures are stressed almost to the point of failure, minute perturbations in the stress field may trigger instability. The change in the potential for slip [also called change in the Coulomb failure function (Oppenheimer and others, 1988; Reasenberg and Simpson, 1992)] resulting from stress-altering events is given by equation 3.

$$\Delta(\text{slip potential}) = \Delta\tau + \mu\Delta\sigma_n, \qquad (3)$$

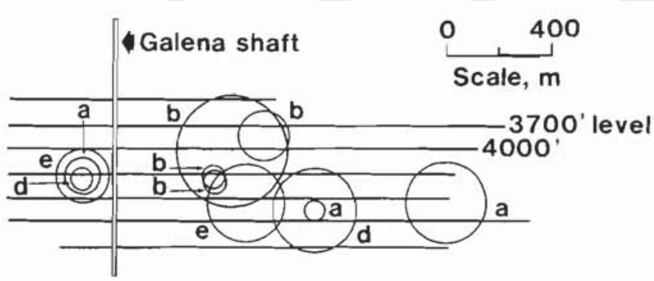
where $\Delta\tau$ = change in shear stress and $\Delta\sigma_n$ = change in normal stress (positive for increased tension).

Stress changes associated with the first three events (a) in the sequence of figure 10 are estimated. These events occurred within a 24-h period. The boundary-element method of Crouch and Starfield (1983) was modified to maintain contact between crack surfaces. The ruptures are represented by elements placed at each event location and oriented N. 48° W. Rupture dimensions are scaled by the appropriate event magnitude. A right-lateral shear stress of 2.2 MPa, corresponding to the stress drop determined from the fit to seismic data in equation 2, is applied across each slip plane, and field stresses are calculated. μ and s_o (see equation 1) are taken to be 0.6 and 0.3 MPa, respectively.

For simplicity, a homogeneous isotropic medium is first considered. This example neglects two influences. First, a nonuniform stress distribution is expected in a deforming faulted block medium. However, at the present time, there is not sufficient information to determine which of the ubiquitous potential slip planes should be included in a tractable model. Appropriate constitutive relations and initial boundary conditions are also unknown. Second, the stress-concentrating effect of stope geometry is neglected. In these initial calculations, the intent is to estimate the distance over which significant stress *changes* occur because of simple rupture. Neglect of the lower elastic modulus of the sandfill in adjacent stopes results in lower bound estimates of induced stress.

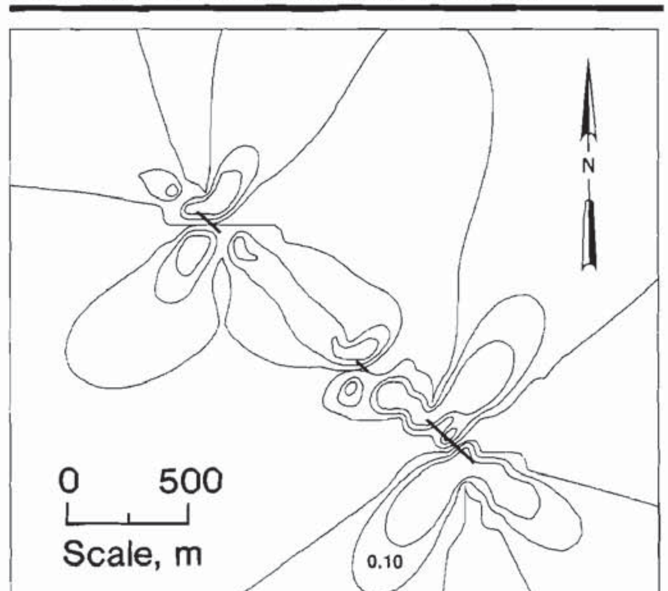
Figure 11 shows contours of increased slip potential (equation 3) resulting from slip on the first three ruptures (a events) for planes oriented N. 48° W. For clarity, contours are shown for only the positive changes in slip potential. If desired, contour maps of decreased slip potential can also be constructed. A band of elevated slip potential encompasses the N. 48° W. trend and beyond. Similar results are found for planes oriented parallel to the strike of most major faults (N. 45° W. to N. 65° W.) near stopes along the N. 48° W. trend. Imposing higher stress drops increases the magnitude of the change in the slip potential along the N. 48° W. trend. When the stress drops for the three events do not all have the same sign, slip potential along the N. 48° W. trend is decreased relative to figure 11.

Figure 10
Vertical Section View of N.48°W. Plane of Seismic Activity (Looking Northeast).



Estimated sizes and positions of circular rupture planes correspond to periods of energy release (a-e) shown in figure 8. The Galena shaft (c) is shown as vertical lines.

Figure 11
Plan View of Boundary-Element Model.



Model of first three ruptures (dark lines) in sequence a of figure 10, where M_L = 1.8, 1.1, and 2.6 from upper left to lower right. Contours (in MPa) indicate values of increased slip potential for N.48°W.-oriented planes as a result of 2.2-MPa, right-lateral stress drops across the three ruptures.

DISCUSSION

The changes in slip potential, or static Coulomb stress, associated with the seismic events shown in figure 10 represent only a few percent of the total stress drop that drives these events. While these stress increments are too small to cause rupture by themselves, they may be sufficient to trigger instabilities in structures that are already critically stressed. In many recent studies, small increases in slip potential have been linked to the triggering of seismic and aseismic crustal deformation on a very large scale. Increases in slip potential greater than 0.01 MPa have been identified with zones of earthquake aftershocks triggered by crustal near-vertical strike-slip faults (Oppenheimer and others, 1988; Reasenberg and Simpson, 1992; Stein and others, 1992). Stein and Lisowski (1983) have found correlations between aftershock locations and increases in slip potential of >0.03 MPa. Similarly small values are suggested for triggering reservoir-induced seismicity (Grasso, 1992; Roeloffs, 1988). Fault creep, which is one interpretation of an event producing the shaft damage, has also been observed to be accelerated by changes in slip potential of a few tenths of an MPa (Simpson and others, 1988). Models of stress transfer developed for a southern California earthquake sequence extending back for 50 years (Stein and others, 1994) show that each event increased slip potential at the site of future earthquakes. This sequence recently culminated in the damaging 1994 Northridge earthquake. Evidence is also mounting that favorable incremental stressing caused by earlier earthquakes precedes future large seismic events across the globe (Kagan, 1994).

Small stress changes that trigger local instabilities in the Galena Mine have long been inferred from observations of (1) microseismic activity occurring several hundred meters from, but concurrent with, small-volume (~10 m^3) production blasting; (2) rock bursts and other large seismic events that are occasionally triggered at significant distances from, but concurrent with, blasting (~100 m); and (3) the high occurrence rates of seismic doublets or pairs of events in space and time (Swanson and Sines, 1990; Estey, 1995). The values of increased slip potential in figure 11 are of the same order of magnitude or larger than those reported in the above-mentioned field studies and cover multiple stopes along the N. 48° W. trend. Similar results are found in models of the other large events in figure 10. This is taken as evidence that supports the idea that seismicity- and blasting-induced quasistatic stress changes may link deformation of highly stressed areas over the observed distances.

Similarity of rupture slip direction (i.e., left-lateral versus right-lateral) is not a requirement for triggered slip in adjacent working areas; the slip need only accommodate stope closure. (This is at least the case when stress resulting from closure in a preexisting stress field is the dominant local force driving rock bursts and seismic events. This may not be the case for tectonically driven events triggered by mining.) As shown in figure 5, each stope has elevated potential for both left- and right-lateral strike-slip.

Model results shown in figure 5 apply to an isolated stope. Preliminary modeling efforts, in which seismic slip surfaces and multiple mine openings are considered together, indicate that (1) significant interaction between stopes occurs under static, nonseismic loading conditions, (2) N. 48° W.-oriented seismic events further perturb the slip potential throughout multiple stopes along the N. 48° W. trend, and (3) the change in slip potential may be positive or negative depending upon the relative orientations of the slip plane, slip direction, and strike of the stope (vein), and the relative positions of the slip plane and stope. Such perturbation of slip potential represents one possible mechanism by which deformation may be mobilized in several working areas throughout the Galena Mine.

The evidence presented to support the hypothesis that mining-induced deformation was mobilized along the entire length of the mine cannot be considered as unequivocal proof of the hypothesis. It can be argued, however, that it is reasonable, that the evidence is consistent, and that these results deserve further consideration in developing hazard forecasting and destressing methods in other mines with similar conditions.

SUMMARY

The relationship among local geology, vein and stope layout, and the locations of large seismic events and rock bursts has been examined in a deep hard-rock mine in northern Idaho. Two structural regimes were found to be associated with rock bursting: (1) the Silver vein, the largest vein in the mine, which has a long history of rock bursting and (2) the N. 48° W. trend, a near-vertical plane striking N. 48° W. throughout the length of the mine. This plane is subparallel to the strikes of the major faults in the mine.

Over 90 pct of the seismic energy emanating from the mine in 1990 was released in one 3-month period in a series of large seismic events and rock bursts along the N. 48° W. trend. During this time, the main access shaft, which is coincident with the N. 48° W. trend, was damaged when fault gouge was expelled into the shaft opening. While a single, discrete fault surface cannot be traced continuously throughout the length of the plane of activity, steeply dipping fault structures trending N. 45° W. to N. 70° W. permeate the mine. These blocky structures are thought to provide preferential slip surfaces that facilitate stope closure and stress transfer between adjacent working areas.

The degree to which calculated seismic slip surfaces fill the N. 48° W. plane of activity was examined using published relationships between magnitude and source dimension. Boundary-element models of simple shear slip were used to estimate quasistatic stress changes associated with three seismic events that initiated a rapid period of energy release. Attendant changes in slip potential for planes parallel to fault structures were calculated. For stress drops greater than or approximately equal to 2.2 MPa (the average of published results), a zone of elevated slip potential extends along the entire N. 48° W. trend, and values approach and/or exceed those reported prior to large southern California earthquakes. Such values may trigger earthquake aftershock activity, fault creep, and reservoir-induced seismicity. The evidence presented here supports the hypothesis that mining-induced deformation was mobilized along the N. 48° W. trend throughout the mine.

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