Investigation of a rock-burst site, Sunshine Mine, Kellogg, Idaho

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ABSTRACT: Rock masses in deep-level mines are subject to high stresses, which can result in unexpected failure of rock into mined-out openings. Historically, various independent methods have been used to discern the causes of rock bursts and to evaluate stress conditions in rock masses susceptible to violent failure. Personnel from two research centers of the former U.S. Bureau of Mines, Spokane and Twin Cities, investigated a rock burst that occurred in May of 1994 in a rock mass between the 4400 and the 4600 levels of the Sunshine Mine, Kellogg, ID. The team evaluated the current state of stress in the pillar and the most likely cause of the rock burst by studying the seismic history of the pillar, examining the geology, analyzing the available in situ stress data, calculating possible fault-plane solutions for the burst, and performing a seismic velocity tomographic survey. The results of the study showed that post-rock-burst seismicity was concentrated about 15 to 30 m west of and about 15 m above the rock-burst location. The pillar is composed of a very hard sericitic-to-vitreous quartzite of a type rarely found in the mine, but that is often found in other district mines having a history of seismic activity. In situ stress analysis of the pillar and the surrounding rock mass showed a probable stress rotation from northwest-southeast to east-west. Of four fault plane solutions, the most probable was either a left-lateral, strike-slip movement with a compressive principal stress oriented nearly north-south, or a right-lateral, strike-slip movement oriented east-west. Finally, tomographic images showed low-velocity areas (interpreted as areas of low stress) associated with the crosscuts and haulageways, and high-velocity areas (interpreted as areas of high stress) associated with the rock-burst location. High velocities were also found in a planar area oriented in an elongate northeast-southwest direction.

1 INTRODUCTION

On May 13, 1994, one miner was killed and another injured in a rock fall resulting from a rock burst at the Sunshine Mine, Kellogg, ID (figure 1). The Sunshine Mining Co. and the former U.S. Bureau of Mines (USBM) agreed to conduct research to determine the cause and then-current state of stress of the rock mass above and around the rock-burst site.

The rock burst occurred in a raise 18.3 m above track level on the 4600 level in the Chance vein footwall. The area studied was a pillar (CFO2) between the 4400 and 4600 levels (-1344 and -1392 m below the collar of the Jewel shaft, respectively) and between 73500E and 74500E, and 79600S and 80300S (figure 2). The pillar was approximately 52 m high, 183 m long, and 152 m wide. Above the pillar, a 6-m-high, 91-m-long, and 2.4-m-wide stope had been excavated. Intact rock surrounded the remaining portions of the pillar. Other than development openings on the

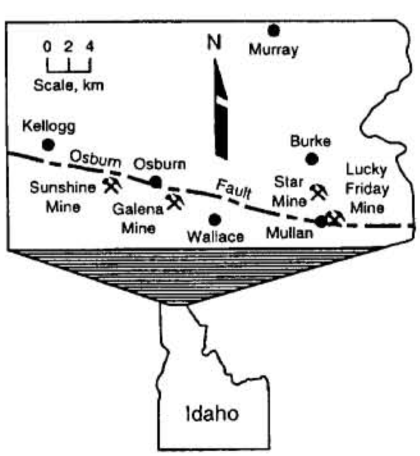

Figure 1.—Location of Sunshine Mine, Kellogg, ID

4400 and 4600 levels, the only other opening was the 18-m-high, 2.7-m-wide, and 4.6-m-long raise where the rock burst occurred.

This study involved combining several types of assessments, including seismicity, geologic, in situ stress measurements, fault plane solutions, and seismic tomography results to determine relative stress at the rock-burst site.

2 SEISMICITY

For the purposes of this paper, a seismic event is defined as the initial appearance of seismic energy on a seismic record. Seismic events include microseismic events, rock bursts, and earthquakes. Only microseismic events and rock bursts associated with mining will be discussed here. Microseismic events are defined as events that usually displace less than 1 to 2 m^3 of material into a mine opening, are less than 0.5 Richter magnitude, or result in less than 30 mm of displacement on a seismograph. Accuracy of locating a microseismic event is confined to a radius of about 8 m, depending on its magnitude. Determining the location of larger events is less accurate because a larger volume of rock is involved; conversely, the location of smaller events is more accurate. Microseismic events are detected with underground geophones, but are normally not measured on a surface seismograph because of the small amount of energy released. They generally occur near drifts, haulageways, or stopes and cause popping, spitting, and spalling of the surrounding rock mass.

In this study, a rock burst is defined as the sudden and sometimes violent release of accumulated energy expressed when a volume of rock is strained beyond its elastic limit. Rock bursts can be classified as strain, crush, or slip. Strain bursts are small and localized, while crush and slip bursts can cause extensive damage to drifts and stopes. Events exceeding 0.5 Richter magnitude or greater than 30 mm displacement on a seismograph are classified as rock bursts.

The May 13 rock burst was located by a macroseismic system and was calculated to have originated at about 73775E, 80021S,

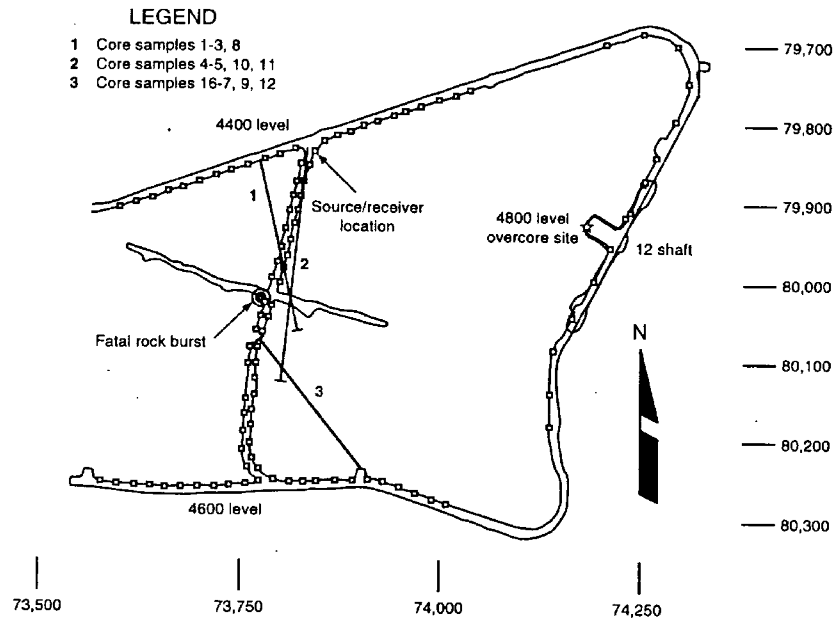

Figure 2.—Location of fatal rock burst and source and receiver sites for seismic tomography survey

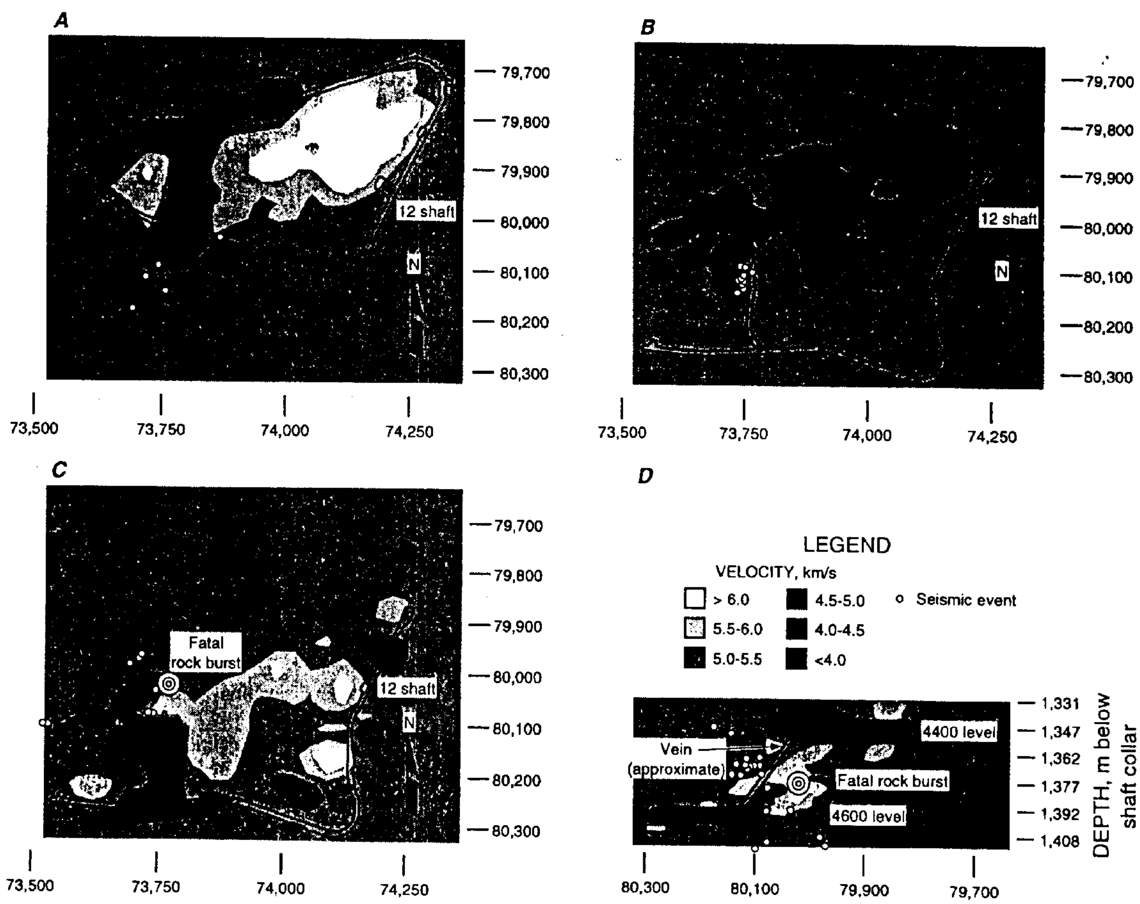

Figure 3.—Velocity tomograms showing locations of seismic events. *A*, Depth = -1330 to -1360 m; *B*, depth = - 1360 to -1373 m; *C*, depth = -1373 to -1403 m; *D*, cross section 73,759E.

and -1373 m below the collar of the Jewel shaft (figure 2). The macroseismic system is designed to record digitized waveforms sensed by triaxial geophones and to target mining-induced events large enough to cause damage to mine structures. These events range from Richter magnitude 0.5 to 2.5 and have frequencies between 1 and 500 Hz. Accuracy is about plus or minus a 30-m radius.

Because this area of the mine had not been fully developed, it was not adequately monitored by a seismic array at the time of the fatal rock burst; however, the array has subsequently been expanded to include the area of the May fatality. Records of seismic events in the CF02 pillar were collected and evaluated for the months of October through December 1994 and correlated with the results of the three-dimensional seismic tomographic survey conducted in December 1994. Thirty-one events were recorded by the system for the 3-month period. These events had magnitudes ranging from 0 to 10 mm as measured by displacement by the surface seismograph needle. Figure 3 is a set of tomograms that shows seismic activity between the 4400 and 4600 levels. Table 1 shows the number of seismic events associated with each depth range.

Table 1.—Seismic activity

Elevation range, m	No. of events	Figure
-506 to -536 . . .	8	3*A*
-536 to -549 . . .	10	3*B*
-549 to -547 . . .	13	3*C*

In plan view, most of the events occurred just west of the CF02 crosscut (figure 3*A*-*C*). In cross section, looking west (figure 3*D*), the events form an X with the vein. This indicates that the seismic events were probably related to the geometry of the vein as most events occurred in the hanging wall above the top of the raise.

3 GEOLOGY

Hard, vitreous, white-to-tan quartzite of the lower part of the upper Revett Formation constitutes most of the pillar rock mass.

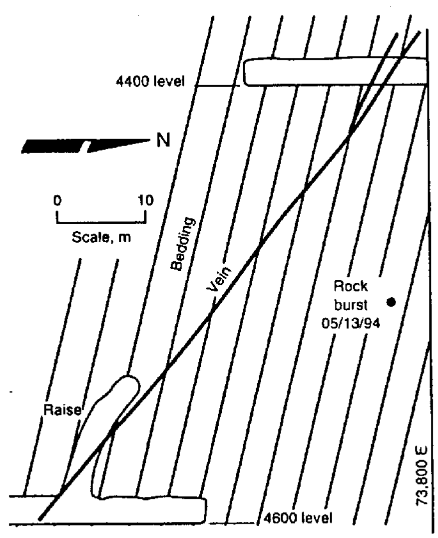

Figure 4.—Geologic cross section looking west and showing relationship of bedding to vein and mine workings

In the Coeur d'Alene Mining District, this formation has a history of increased rock-burst activity relative to other stratigraphic units. Soft argillite is interlayered randomly throughout the quartzite. The average strike of the Revett in the pillar is nearly east and average dip of bedding is about 77° to the south. The vein, which consists of tetrahedrite, galena, and gangue, strikes about N 80° W and dips about 55° to the southwest. On the 4400 level, 6 m east of the top of the projected raise from the 4600 level, a right-lateral, strike-slip fault strikes nearly north and dips 35° to the east, offsetting the vein by 1.2 m. Figure 4 is a cross section looking west and shows the relationship of bedding to the vein and workings.

4 IN SITU STRESS

Several lines of evidence point to significant levels of maximum horizontal stress. At the Sunshine Mine, a stress measurement obtained using an experimental U.S. Geological Survey (USGS) solid inclusion gage (Beus and Chan, 1980) indicated that the orientation of maximum horizontal stress was N 80° E. A raisebore at the site corroborated this direction, indicating a similar orientation of the maximum principal stress. Beus and Chan reported core disking in holes oriented perpendicular to maximum horizontal stress and to bedding. The number of breakouts produced during boring of a 1.2-m-diam raise at the measurement site also suggested high stress levels (Beus, 1995, personal communication) and confirmed an east-west orientation.

Development openings in the vicinity of this site experienced unusually concentrated rock burst and other seismic activity and were probably associated with the elevated stress levels. The in situ stress field in the vicinity of the Sunshine Mine is most likely variable. However, the raisebore breakout observed by Beus and Chan near the site of the tomographic survey offers evidence that the stress field has been rotated to almost east-west.

5 FAULT-PLANE SOLUTIONS

Fault-plane solutions (also known as source mechanisms, focal mechanisms, or first-motion studies) are a visual representation of possible failure planes that correspond to the shear movement responsible for a given seismic event. When a seismic event occurs, shock waves radiate out in a spherical pattern from the source. In general, the first wave to reach the recording geophones is a primary, or P, wave followed by a secondary, or S, wave. By studying the relative upward or downward motion of the P-wave at each geophone (i.e., whether the first motion was compressional or dilatational), fault-plane solutions for the event can be computed.

The solution presented is one of four possible solutions and was generated by FPFIT/FPPLOT software (Reasenberg and Oppenheimer, 1986) developed by USGS. Since the event occurred outside the geophone array and at approximately the same level as some of the geophones, the solutions are not well constrained. The surviving miner's account of rock motion during the event indicates that a shock wave was generated from the north and struck him in the back as he was facing south. Based on the miner's account of the motion and knowledge of typical regional stress distributions, a left-lateral, strike-slip movement oriented N 15° W, or a right-lateral, strike-slip movement oriented N 78° E seems to be a probable fault-plane solution (figure 5).

6 TOMOGRAPHIC STUDY

Several researchers have investigated the use of seismic tomography to evaluate stress in underground mines. Friedel et.

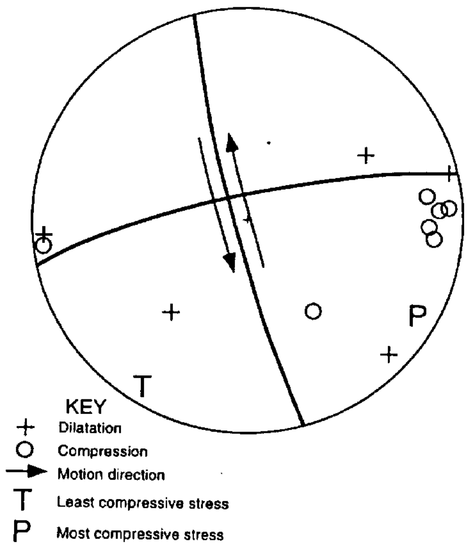

Figure 5.—Fault-plane solution for fatal rock burst.

al. (1995a, 1995b) and Young and Maxwell (1992) used seismic tomography to evaluate mechanical conditions in metal/nonmetal mines. Maxwell and Young (1992) were among the first to initiate a simultaneous linear inversion of both source and velocity structure to generate a three-dimensional analysis of a mine.

Seismic tomography is a noninvasive geophysical technique in which seismic waves are used to penetrate a rock mass and, based on apparent velocities, generate stress gradient contours (tomograms). Successive surveys can be used to compare changes over time.

The methodology used at the Sunshine Mine was identical to four earlier tomographic surveys conducted by USBM personnel, two at the Lucky Friday Mine (March and November 1993) and two at the Homestake Mine (July and October 1993). Results of these surveys, along with a detailed description of the methods used, are summarized in Friedel et al. (1995a, 1995b) and Scott et al. (1995).

The most important consideration when designing a seismic tomography survey is to include the greatest number of crossing ray paths at a variety of angles through the rock mass. Forty-seven source receivers were installed on the 4600 level and 56 source receivers were installed on the 4400 level of the Sunshine Mine. A total of 4,333 seismic ray paths were analyzed.

Seismic resolution is related to the wavelength of the propagating energy. Higher frequencies (seismic energy with shorter wavelengths) provide better resolution. The computed wavelength for this survey was 7.2 m (average velocity of 5.19 km/s divided by a frequency of 720 Hz) and provides an estimate of the smallest feature that can be recognized. Low-velocity areas will have less resolution than high-velocity areas (Wielandt, 1987). Installing geophones along the drifts enhances resolution of fractured, low-velocity areas.

The nonuniqueness of transmission tomography is a concern. Because viewing angles tend to be limited, starting models based on velocities ranging from 4.6 to 6.0 were used. Although this may be subjective, it is roughly equal to the random velocity distribution.

Inversion of the data was completed with the software package 3DTOM (Jackson and Tweeton, 1996), which can be used on a personal computer (PC). Inversion is a model-fitting process that is based on travel-time residual error (calculated travel time minus measured travel time). Ray tracing in the models begins with five straight ray paths and finishes with 10 curved ray paths. The curved ray method is described by Um and Thurber (1987) and is used to perturb a trial ray path until travel time is minimized.

A two-dimensional survey was completed on the 4400 and 4600 levels. The third dimension of the survey was between levels, where the geophones were located on one level and signals were generated on the other (figure 2).

Figure 3 is a set of tomograms based on travel-time velocities through the pillar. Figure *3A* and *3D* show good correlation between development (haulageways and crosscuts) and lower velocities, indicating fractured rock in the skin around these openings. The expected loading of the pillar from mining activity correlates with the higher velocities.

7 CONCLUSIONS

Seismic activity concentrated 15 to 30 m west of and about 15 m above the rock-burst location indicate a possible destressed area, a result that correlates well with the low velocities determined by the tomographic survey. The seismic activity did not appear to be associated with the high-velocity areas shown by the tomograms, but rather with areas where there was a velocity *gradient*. Increased seismic activity in the area of 73,750E and 80,100 to 80,200S (figure *3A)* could be a result of the rock mass trying to reach equilibrium. Bedding lies against the vein and may be causing bending of softer beds and the release of energy. The rock in the pillar is a very hard, sericitic-to-vitreous quartzite not commonly found in this mine. This rock can store large amounts of energy, which can be released catastrophically. The hard vitreous quartzite strata are parallel to the east-west maximum horizontal stress, which may provide a simple mechanical explanation of the stress rotation and concentration in the strata (Whyatt, personal communication, 1995). Similar stress anomalies have been reported in association with localized rock bursting throughout the world.

An in situ stress analysis of the pillar and the surrounding rock mass shows a probable stress rotation from northwest-southeast to nearly east-west. This analysis correlates well with the tomograms and a right-lateral, strike-slip interpretation for the fault solution (oriented N 78° E). The northeast-southwest stress concentration detected by the tomographic survey and the right-lateral, strike-slip (N 78° E) solution indicated by first-motion studies suggest that the stress rotation extends through the measurement site. Core disking, concentrated seismic activity, breakouts in the raisebore, and tomographic and in situ data provide support to the hypothesis that there was a concentration of high stress and a rotated stress field near and at the rock-burst site. These factors, including the presence of a very hard and brittle rock and the buildup of stress on the east side of the vein with a destressed area on the west side of the vein, combined to cause the rock burst.

This investigation is exciting for several reasons. First, it provides a reliable case study that directly confirms the value of using seismic tomography to identify relative stress. Second, it suggests that stress anomalies may be associated with localized rock bursting throughout the district. Finally, this investigation confirms that a more comprehensive analysis of rock-burst hazards is possible by combining seismicity, geology, in situ stress measurements, fault plane solutions, and seismic tomography.

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