Mining-Induced Seismicity at the Lucky Friday Mine.

Seismic Events, $M > 2.5$, 1989–1994

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Foreword

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Mining-Induced Seismicity at the Lucky Friday Mine: Seismic Events of Magnitude > 2.5, 1989-1994

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ABSTRACT

An understanding of the types of seismic events that occur in a deep mine provides a foundation for assessing the seismic characteristics of these events and the degree to which initiation of these events can be anticipated or controlled. This study is a first step toward developing such an understanding of seismic events generated by mining in the Coeur d'Alene Mining District of northern Idaho. It is based on information developed in the course of a long-standing rock burst research effort undertaken by the U. S. Bureau of Mines in cooperation with Coeur d'Alene Mining District mines and regional universities. This information was collected for 39 seismic events with local magnitudes greater than 2.5 that occurred between 1989 and 1994. One of these events occurred, on average, every 8 weeks during the study period. Five major types of characteristic events were developed from the data; these five types describe all but two of the 39 events that were studied. The most common types of events occurred, on average, once every 30 weeks. The characteristic mechanisms, first-motion patterns, damage patterns, and relationships to mining and major geologic structures were defined for each type of event. These five types of events need to be studied further to assess their ability to camouflage clandestine nuclear tests as well as the degree to which they can be anticipated and controlled.

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INTRODUCTION

Mining activity throughout the world routinely creates large seismic events with local magnitudes as large as 5.2. These events continue to be produced despite the best efforts of mining science and engineering to reduce their number and severity. The potential for using these events to camouflage nuclear tests has been raised by workers investigating nuclear test detection techniques (Heuze, 1994). The technical feasibility of designing a large mining induced seismic event with desirable seismic characteristics is receiving considerable attention. This report supports those efforts by (1) collecting and organizing information on large mining induced seismic events having local magnitudes greater than 2.5 at a seismically active mine and (2) attempting to define types of events with similar seismic characteristics and similar relationships to geologic structures and mining activity. The potential for purposeful, controlled initiation of these various types of events is the subject of ongoing work.

This study examines seismic activity at the Lucky Friday Mine, Mullan, ID, which is owned and operated by Hecla Mining Co. The Lucky Friday Mine is considered to be the most seismically active mine in the Coeur d'Alene Mining District and among the most seismically active mines in North America (Jenkins and others, 1990). Seismicity at this mine has been the subject of considerable study by the Spokane Research Center (recently transferred from the U.S. Bureau of Mines [USBM] to the National Institute for Occupational Safety and Health).

The intensity of seismic activity at the Lucky Friday Mine has made the mine an ideal laboratory for monitoring mining-induced seismicity. Various seismic systems installed and maintained by the USBM, University of Idaho, and Hecla Mining Co. have created a large seismic database. A number of case studies from this database has been published (e.g., Jenkins and others, 1990; Jung and others, 1995; Williams and others, 1993, 1995). This investigation goes beyond many of these case studies by examining a complete set of large mining-induced seismic events having local magnitudes greater than 2.5 in an attempt to identify their common characteristics. Classes of events with similar seismic characteristics and similar relationships to geologic structures and mining activity are defined.

LUCKY FRIDAY MINE

The Lucky Friday Mine is located on the eastern edge of the Coeur d'Alene Mining District of northern Idaho near Mullan, ID. The first claims were filed in 1889; however, it wasn't until 1941 that the first commercial-grade ore was found. Mining has progressed ever deeper to the present mining horizon below the 5500-ft-level (650 m below sea level). The Lucky Friday Mine used a traditional overhand cut-and-fill method until 1986, when the mine was converted to a mechanized underhand longwall method of cut-and-fill mining that eliminated burst-prone pillars.

The change in mining method was the result of a major cooperative research effort by the USBM, the University of Idaho, and Hecla Mining Co. in the 1980's (Hautala and others, 1996; Whyatt and others, 1992). The underhand cut-and-fill method is proving to be a much safer way to mine in seismically active ground (Poada and others, 1995). Many of the large seismic events caused by pillar recovery are being eliminated as the primary stopes progress away from previously mined areas and pillar mining is eliminated. Reinforced, cemented backfill provides a reliable and competent roof above the miners. The full impact of this change of mining method on mining-induced seismicity is the subject of continuing studies.

Control of rock bursts at the Lucky Friday Mine has also been pursued through improved ground control systems (Blake and Cuvelier, 1990, 1992) and pillar preconditioning. Recent work on the state of stress at the Lucky Friday Mine has found that seismicity produced by driving development openings is associated with hard stratigraphic subunits. In situ stress measurements have shown that these hard subunits concentrate in situ stress (Whyatt and others, 1995a). Related work has examined the geologic structures associated with strain rock bursts (White and others, 1995).

GEOLOGY

The Lucky Friday vein at 1,600 m (1 mile) below the surface forms an S-shape in plan view and extends horizontally about 490 m (1,600 ft). Splits off the Main vein extend potential stope length to over 610 m (2,000 ft) along strike. Mineralogically, the vein is composed of galena, sphalerite, and tetrahedrite in a quartz and siderite gangue. The vein is 0.6 to 9 m (2 to 30 ft) wide and averages about 1.5 m (5 ft) wide. The vein is in the Precambrian Revett Formation, which hosts most of the silver- and lead-producing mines in the Coeur d'Alene Mining District.

Because the vein itself dips at a steeper angle than bedding (70° to 90° versus 60°) to the south and east, it comes into contact with progressively older rocks with depth (figure 1). Presently, mining intersects Precambrian Superbelt rocks of the lower member of the Revett Formation.

Numerous faults and secondary folds are apparent, and some of these also intersect the vein structure. The most pronounced faults are the North and South Control Faults that delineate the ends of the 460-m (1,500-ft) long Lucky Friday vein. The rock mass surrounding the vein is made up of vitreous quartzite and sericitic quartzite beds from 30 to 91 cm (12 to 36 in) thick with soft interbeds of argillite generally less than 2.5 cm (1 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).⁵ Whyatt and others (1996) have estimated strength and deformational properties for these rock types, and combinations of these rock types that form various subunits, units and formations.

The in situ stress regime at the Lucky Friday Mine has been extensively investigated (Whyatt and others, 1995b). The maximum principal stress is oriented to the northwest and is considerably greater than the vertical stress (approximately 2:1). Furthermore, large structural stresses were found associated with variations in rock properties between strata and near locked sections of faults. Whyatt and others (1995a) reported intense seismic activity associated with a stress concentration that was confirmed with an overcore measurement.

SEISMIC SYSTEMS

Seismic systems vary widely in the quality and information content of data they produce. Many seismic monitoring systems are designed merely to provide a rough location and intensity measure of events for use in managing mine operations, while whereas research systems are designed to capture precise digital records of an event from a number of stations. Mining-induced seismicity at the Lucky Friday Mine has been monitored by three systems. The oldest, operated since 1973, is an analog

⁵This information is based on work being conducted by B. G. White of the Spokane Research Center to be published in a Report of Investigations.

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

microseismic system that determines the location of seismic events. It includes a surface seismograph for estimating relative magnitudes of these events. The development of powerful digital systems based on personal computers (PC's) provided an opportunity to supplement the microseismic system with full-waveform monitoring systems to support USBM research efforts. A mine-wide "macroseismic" digital system was installed in 1989 (Girard and others, 1995), and the district-wide North Idaho Seismic Network (NISN) began operation in March 1992 (Lourence and others, 1993). Williams and others (1995) provide a more detailed summary of system components, geophone networks, and the types and format of data produced by these systems.

MICROSEISMIC SYSTEM

The Lucky Friday Mine analog microseismic system has been maintained and operated by Hecla Mining Co. since 1973 (Langstaff, 1974; McLaughlin and others, 1976). The system has been upgraded a number of times and the geophone net is continually modified to follow mining progress. The system monitors signals from a network of geophones distributed throughout the operating portion of the mine. Seismic events within the bounds of the net occur within 30 m (100 ft) of a geophone. The signals are monitored by an Electrolab MP250 system and, if five or more geophones report an event within a 100-ms time window, arrival and energy data are sent to a PC. The PC computes event location and estimates a relative energy level. Larger events are monitored by a surface seismograph as well, which allows empirical estimation of event energy from the shape of the seismograph trace. The energy of the largest events is also estimated by a calibrated seismograph operated by the Montana Bureau of Mines.⁶

The capability of the microseismic system to locate events at the Lucky Friday Mine has been the subject of some study. Botts⁷ surveyed error estimates produced by the microseismic system solution algorithm and found that these errors were much greater for the smallest events monitored by the system. Dodge and Sprenke (1992), in a more detailed study, found similar problems and traced errors to the voltage threshold method of finding first arrivals in the MP250 system. Dodge and Sprenke also examined consequences of the constant seismic velocity model assumed in computing locations. They found only minor errors in computed hypocenters (10 to 20 m) for sources well enclosed by the array. However, for source outside the array, they found that errors were much greater. Both of these studies looked at data sets arising from only a day or two of seismic activity, and thus they paid considerable attention to small events. While recognizing the variability of accuracy with location, system operators use ± 15 m (50 ft) as a rule of thumb for location accuracy of events occurring within the sensor net. For comparison, Gray estimated the approximate radius of slip for a 2.5 local magnitude event at the Lucky Friday Mine at 46 m.⁸ Mining moved ahead of the sensor net toward the end of the study period, and greater location errors are expected for events that occurred below the 5480 level.

⁶Mike C. Stickney, Earthquake Studies Office, Montana Bureau of Mines, Montana College of Mineral Science and Technology, Butte, MT 59701.

⁷Tom Botts, Evaluation of the Lucky Friday Rock Burst Monitoring System, Montana Tech. internal report, April 30, 1989, 45 pp.

⁸Don Gray, Bursting Mechanism Report, Hecla Mining Co. internal memo, December, 1984, 5 pp.

MACROSEISMIC SYSTEM

The first modern seismic monitoring system in the district was developed by the USBM and installed at the Galena Mine. Development of this experimental system began in the late 1960's (Blake and others, 1974), and modernization continued through closure of the mine in 1992 (Swanson and others, 1992; Boler and Swanson, 1990). In its mature state, the workstation-based system provided close-in digital monitoring of small microseismic events generated around individual stopes, as well as mine-wide monitoring of major events. This research system has been used to search for precursory patterns that might warn of impending rock bursts (Estey, 1995).

Success of the experimental Galena system demonstrated the advantages of digital monitoring, but the high cost of these systems was an impediment to their use in routine mine monitoring. Advances in PC-based seismic monitoring systems, particularly the International Association of Seismology and Physics of the Earth's Interior (IASPEI) system developed by the U.S. Geological Survey in the late 1980's (Lee and others, 1988) resulted in a dramatic reduction in system costs. The USBM adapted the IASPEI system to rock-burst monitoring conditions and installed the first system at the Lucky Friday Mine in 1989. Girard and others (1995) provide a comprehensive description of the modified IASPEI system, known as the "macroseismic" system. The USBM has installed macroseismic systems at the Lucky Friday, Sunshine and Homestake Mines in cooperation with mine operators. These systems are typically set up to monitor the largest rock bursts and use a sparser geophone array than microseismic systems.

The Lucky Friday macroseismic system was specifically designed to monitor events with local magnitudes (M_L) from 0.5 to 2.5 (Jenkins and others, 1990) with an array of five three-dimensional velocity geophones. Events smaller than 0.5 have not been recorded until recently. Events larger than 2.5 M_L were recorded, but system electronics were overdriven, causing clipping of waveform records at the upper and lower bounds of the waveform trace.

An inspection of the macroseismic system in December of 1990 revealed that the common return lines on the macroseismic system geophones were not hooked up correctly. Although the system had appeared to perform satisfactorily during its initial period of operation, this discovery cast some doubt on early system performance. This problem was quickly corrected.

The original 16-channel system was then expanded to 32 channels in January of 1991, and a greater reliance was placed on single-axis geophones. The second part of the system was set up to monitor 11 vertically oriented single-axis geophones, including the vertical components of the three-dimensional geophones and the seismograph geophone. In designing this part of the system, a greater emphasis was placed on providing good coverage of the mine for location and first-motion solutions at the expense of triaxial waveform information. The triaxial portion of the system was taken out of operation early in 1994. The uniaxial geophone portion of the system remains in operation.

The macroseismic system monitors a larger portion of the mine but coverage is sparser than coverage by the microseismic system. This is particularly the case in the bottom portion of the mine, which is covered by a macroseismic system geophone installed on the 5900 level. Within the core of this net, most events occur within 50 m (160 ft) of a geophone (Williams and others, 1995), suggesting less location accuracy than the microseismic system for events within both nets. However, improved picking of first-arrival times with more sophisticated algorithms and, for selected events, by manual inspection, can create superior location estimates for some events (Dodge and Sprenke, 1992). The macroseismic system provides better or equivalent locations for events occurring below the 5480 level.

However, even with careful picking of first arrivals, a solution with a large location error may be calculated. Often, factors such as line noise and blasting make accurate picking of the first arrival difficult if not altogether impossible. In addition, mine openings and complex geology affect wave travel and create a nonuniform velocity structure. In addition, when events occur outside the geophone array, location accuracy is diminished. Finally, an inferior solution from one or the other system is often created by operational difficulties with failed or noisy geophones, delays in moving geophones to keep pace with mining, etc. In most cases, solutions from the two systems and the location of any underground damage are used to estimate a probable location.

The digital seismic records created by the macroseismic system also allow analysis of the first-motion pattern of seismic events (e.g., Aki and Richards, 1980). These patterns identify whether the event begins predominantly as shear movement, collapse, or a combination of these motions. If shear is indicated, a set of conjugate shear planes are also identified. The accuracy of first-motion results from the Lucky Friday Mine has not been considered analytically. However, as will be discussed later in this report, Lucky Friday Mine first-motion results based on as few as six geophones have been generally consistent with geologic structures, known stress fields, and, in a few cases, observations of fault movement.

NORTH IDAHO SEISMIC NETWORK

A third system, the NISN, began monitoring district-wide seismicity with a three-geophone surface array in 1983. The system was expanded to 16 channels and converted to a modified IASPEI system with USBM funding (Lourence and others, 1993). Stickney and Sprenke (1992) describe the NISN design study which used a portable monitoring system for a one week trial period. The NISN system provides far-field digital records of Coeur d'Alene Mining District seismicity. The loss of funding for this system has meant loss of geophone channels through attrition and more recently, complete shutdown of the system. Records are available for most rock bursts at the Lucky Friday Mine from March 1992 to June 1994.⁹

The accuracy of locations provided by NISN is comparatively poor, as would be expected considering the district-wide area covered by this 16-channel system. Locations are generally good enough to indicate which mine produced a given event, or whether the seismic event occurred in unmined ground, independent of mining. The system has been focused on smaller events than the macroseismic system, clipping waveform records for events with magnitudes greater than 1.

The system is useful, however, for supplementing first-motion information provided by the mine macroseismic system, particularly for events occurring outside of the mine geophone arrays and along faults that intersect mined vein. The near-field mine systems are more sensitive to location errors than the NISN and records higher frequency components that are attenuated before reaching the far-field NISN sensors. Published comparisons of results from the two systems have shown good agreement (e.g., Williams and others, 1995).

⁹Records are available from Kenneth Sprenke, College of Mines and Earth Resources, University of Idaho, Moscow, ID 83843.

CLASSIFICATION OF LARGE SEISMIC EVENTS

The foundation for determining the feasibility of purposefully initiating a seismic event with mining can be established by determining whether sequences of seismic events with similar characteristics and mechanisms are being initiated by current mining. Definition of series of events would provide a sound basis for back-calculation of event energies and triggering mechanisms, if any. This section reviews an attempt to classify the 39 large seismic events addressed by this study into a few groups and describes typical characteristics for each group.

Seismic, mining, geologic and damage information were collected for events with estimated local magnitudes of 2.5 or greater that occurred between 1989 and 1994.¹⁰ Thirty-nine events were identified as meeting this criterion, an average of one event every 8 weeks during the study period.

The quantity and quality of information available to support analyses of these events varied widely, but was generally sufficient to identify five major types that described 37 of the 39 large events occurring during the study period. These types of events are summarized in table 1 and figure 2. The following sections provide an overview by type of event and briefly review some of the events in each class. A complete analysis of each event is provided in the appendixes to this report.

Table 1.—Summary of characteristics of event types

Type	No. of events	Range of magnitude	Typical first-motion and structure	Range of damage	
				Stope	Development
Southern bedding plane	10	2.4-3.3	Normal dip-slip movement on bedding plane.	None to moderate.	None to extensive.
Central shear zone	6	2.5-3.0	Right-lateral strike-slip on vertical faults.	None to minor.	None to extensive.
South Control Fault .	8	2.5-3.0	Strike-slip on fault. Some indications of shear implosion. ¹	None to extensive.	None.
Vein	4	2.4-3.7	Vertical slip on fault with footwall block downthrown.	Minor to extensive.	None to minor.
North Control Fault .	10	2.5-4.1	Right-lateral and left-lateral strike-slip, and normal dip-slip movement on fault. Shear and general implosion indicated for some events. ¹	None to extensive.	None.

¹Shear implosion (S-I) is similar to a double-couple or shearing first-motion pattern but has three of the four quadrants showing implosion.

¹⁰An additional event, which had a magnitude of 2.4, was added to the study because it occurred almost simultaneously with a larger event. Both events had to be studied to differentiate between them.

Figure 2.—Overview of five major types of rock bursts by typical location and sense of motion.

SOUTHERN BEDDING PLANE SLIP

Ten of the events were caused by slip on bedding planes in the southern limb of the mine (table 2). A plot of bedding plane slip events with time (figure 3A) shows that these events were particularly prevalent in the first half of the study period (1989 through 1991) and, with one exception, absent in the second half of the study period (1992 through 1994). By comparison, the 5300-95 pillar was 15 m (50 ft) high in June 1991 and was completely removed by the end of May 1992. The steady increase in slip activity along beds in the 5300-95 pillar (one event in 1989, two in 1990, and four in 1991) was likely related to progressive reduction of this pillar.

Table 2.—Southern bedding plane slip

No.	Date of occurrence	Magnitude	Damage	Movement	Notes
2	3/2/89	3.3	250 st 5300-95.	On footwall near top of subunit C.	First few stope cuts.
3	4/4/89	2.8	100+ st to west end 4900-93 in subunit A.	On footwall bedding.	Destress drilling 4900-93 pillar.
7	4/11/90	2.5	75 st footwall rib 49/93/ 95 stope, access slot.	On footwall bedding.	I-dripping into pillar.
8	6/12/90	2.6	100 st 5150-95 footwall west.	On footwall bedding.	
9	7/31/90	2.6	Minor damage to east side of 5150-95 slot.	Normal on foot-wall bedding.	Movement into filled stope.
13	3/27/91	2.6	Extensive damage to 5300-95 stope, cross-cut, and raise.	Thrust on hanging wall bedding opposite pillar.	
16	5/23/91	2.5	Extensive damage to 200 ft of 5300 lateral.	Normal and right-lateral on foot-wall bedding.	Related to 95/101 dip pillar.
22	11/11/91	2.5	Minor damage 95 development.	Normal on foot-wall bedding.	Low stress drop, soft sub-unit.
23b	12/11/91	2.4		Normal on foot-wall bedding.	5100-95 foot-wall stope filled.
37	5/19/94	2.6		Normal on foot-wall bedding.	Movement into filled stope.

Figure 3.—Time lines showing (A) bedding plane slip event, (B) events along South Control Fault, and (C) events along North Control Fault.

Most bedding plane slip events occurred as normal slip along bedding planes in the southern portion of the mine along the western limb of the Hook Anticline and were preferentially located in the footwall of the vein (figure 4). The occurrence of these events in the footwall is related to the orientation of bedding planes, which dip into the vein from the footwall and form a ramp for sliding footwall blocks. Mining releases the normal load on bedding planes in the footwall, substantially reducing shear resistance. Board (1994) addresses this mechanism in his modeling of Lucky Friday Mine seismicity. Dip-slip movement may also be associated with buckling of axially loaded strata into the mined vein where confinement has been removed by mining. Thrust and strike-slip movements are also possible on these bedding planes. However, thrust and significant strike-slip movements were only evident in one event each.

The amount of damage to development openings and stopes varied widely. The degree of damage did not correlate with magnitude, and one of the largest events caused no damage at all. The most severe damage reported was to development openings that crossed the event slip plane. In these cases, entire sections of haulageway were obliterated. However, in other instances, development openings were undamaged by events of similar or even greater magnitude. It appears that, in the latter cases, the slip plane did not cross development openings. However, it is possible that variations in stress drop could have led to variations in peak particle velocities, which could also explain some of the variations in degree of damage.

Damage to mine stopes was moderate by comparison. This contrast can be attributed to the location of the slip planes below and to the footwall side of the stopes. Thus, slip planes did not appear to intersect the stopes as they occasionally do in development openings.

Figure 4.—Bedding plane slip events plotted in (A) plan view and (B) longitudinal view.

Figure 4 (continued).—Bedding plane slip events plotted in (A) plan view and (B) longitudinal

CENTRAL SHEAR ZONE (HOOK AXIAL PLANE TO NORTH CONTROL FAULT)

Six events occurred near the vein along a set of near-vertical faults that form the central shear zone (table 3). This zone lies between the North Control Fault and the axial plane of the Hook Anticline. This group included events with local magnitudes from 2.5 to 3.0.

These events involved strike-slip movement along nearly vertical faults and occurred mainly on the footwall side of the vein (figure 5). Initial events in 1989 and 1990 occurred in the vein footwall during mining of the 5100-106 pillar. Destress blasting of this pillar in December 1990 coincided with the beginning of a 2-year lull in central shear zone events. The first event after this lull occurred as right-lateral, strike-slip movement deep in the hanging wall near the active longwall stope elevation. The final two events occurred in 1993 and 1994 with right-lateral, strike-slip movement in the vein footwall. The first was located at the active longwall mining elevation, and the second was much higher in a remnant pillar.

Table 3.—Central shear zone slip

No.	Date of occurrence	Magnitude	Damage	Movement	Notes
5	11/2/89	2.6	No damage.	Normal or implanational; footwall, Offset Fault.	4900 level.
10	8/3/90	2.5	No damage.	Right-lateral; footwall, F-series fault.	51-106 pillar.
11	10/19/90	2.5	60 st south end of 5100-106.		Occurred during destress drilling in 5100- 06 pillar.
12/90		<i>Destress blast in 5100-106 pillar</i>			
27	8/4/92	3.0	250 st 5400-101 slot.	Right-lateral with some normal; NE of Offset Fault in hanging wall.	Battelle Northwest, MT Bur. Mines.
4/93		<i>Last mining in 5100-106 pillar</i>			
32	10/22/93	2.5	750 st, 5480-107 slot, 5570-107 ramp.	Right-lateral; footwall, F-series fault.	
35	4/1/94	2.5	Minor damage.	Right-lateral; footwall near 38-Offset Fault.

Figure 5.—Location of large events in central shear zone. A, Plan view; B, longitudinal view

Figure 5 (continued).—Location of large events in central shear zone. *A*, Plan view; *B*, longitudinal view.

The driving force for these events is not well understood, particularly given the change in slip direction that occurred during the study period. In fact, the existence of these events was not indicated in the recent modeling study by Board (1994). An in situ stress measurement reported by Whyatt and others (1995b) found locally concentrated stresses consistent with left-lateral slip on these faults. Mine stress analyses conducted to date have failed to account for this stress concentration, which was apparently formed naturally rather than as a result of mining. The stress concentration was centered on a portion of the 38-Offset Fault portion of the central shear zone where hard subunits C and E had shifted to come into contact with each other (figure 1). Left-lateral movement was also consistent with closure of the mined vein south of the 5100-106 pillar.

The regional in situ stress field is oriented north of the strike of faults in the central shear zone, which would drive right-lateral slip on these features. The sense of slip of later events, which are located above, below, and to the east of the left-lateral events, reverts to right-lateral movement, in line with the regional in situ stress field. Additional work is needed to develop a full understanding of the physical mechanisms driving these events.

These events resulted in little or no damage to stopes, but occasionally caused extensive damage to development openings. The degree to which development openings were damaged appears to have depended largely on whether the opening intersected the area of slip. The orientation and location of local geologic structures, particularly faults and bedding, also affected the degree of damage. For example, hidden faults in and parallel to ramp ribs have been associated with particularly severe but localized damage arising even from very small seismic events.

SOUTH CONTROL FAULT STRIKE-SLIP

Eight strike-slip events (magnitudes from 2.5 to 3.0) occurred along the South Control Fault, which forms the southwestern boundary of the mine (table 4). A plot of South Control Fault slip events with time (figure 3B) shows no large-event activity until the 5300-95 stope was mined down to a height of 15 m (50 ft) in the first half of 1991. A flurry of four large events followed in the next 6 months, three of which occurred in June and July. The direction of slip indicated was consistent with closure of the mined vein, and all occurred above the mining front. Three occurred in the hanging wall and one in the footwall (figure 6). The hanging wall events were probably linked to the reduction in normal or "clamping" forces on the fault caused by mining.

The next three events were located above the mining front in the vein footwall. These events differed from previous South Control Fault events in that they showed a shear-implosional first-motion pattern on both the macroseismic and NISN systems. While this first-motion pattern is not fully understood and is the subject of continuing investigations, it implies movement of the footwall block into the mined-out vein, probably in association with slip on bedding planes, as opposed to the more symmetrical release of shear strain energy implied by a double-couple mechanism. The final event in this series was the first to occur below the mining front and showed right-lateral movement in the hanging wall. This event was likely driven by the northwest-trending, maximum horizontal principal stress, which is concentrated in the abutment.

Damage caused by these events occurred entirely in stopes, in marked contrast to damage associated with the southern bedding plane and central shear zone sets discussed earlier. In fact, damage to development openings was not reported for any of these events. Damage to stopes, on the other hand, particularly stopes that included portions of the South Control Fault, was occasionally severe. In this case, there does appear to be some relationship between degree of damage and event

Figure 6.—Location of South Control Fault strike-slip events. A, Plan view; B, longitudinal view.

Figure 6 (continued).—Location of South Control Fault strike-slip events. *A*, Plan view; *B*, longitudinal view.

magnitude. Two of these events (local magnitudes of 3.0) caused 90 mt (100 short tons) and 635 mt (700 short tons) of damage. In contrast, only one of four smaller events (local magnitudes of 2.5 to 2.6) caused minor [23 mt (25 short tons)] damage.

This set of events has been recognized in a number of studies and is one of the best understood. For example, Lourence and others (1993) and Jung and others (1995) provide case studies and a simple two-dimensional, boundary-element analysis. The detailed three-dimensional study by Board (1994) has clearly been the most comprehensive.

Table 4.—South Control Fault strike-slip

No.	Date of occurrence	Magnitude	Damage	Movement	Notes
17	6/12/91	3.0	Minor spalling at footwall.	Left-lateral, hanging wall, 5100 level.	
18	7/20/91	2.6		Right-lateral footwall, 4900 level.	
19	7/31/91	2.6	25 st 5210-95 east on hanging wall.	Left-lateral, hanging wall, 5100 level	
23a	12/11/91	3.0	Minor damage 4900-93/95 and 5300-95 Main vein.	Left-lateral, hanging wall, 5130 level.	
28	8/12/92	3.0	700 st 5210-95 and 5400-94 Main vein.	Footwall, right-lateral below 5300 level.	NISN S-I: conflicting seismic and damage data. ¹
31	10/17/93	3.0	100 st 5100-94/96, widespread minor damage.	Right-lateral footwall and vein below 5100 level.	S-I first-motion: both macro and NISN.
33	1/5/94	2.5		Footwall, right-lateral.	S-I first-motion: both macro and NISN
36	5/13/94	2.5		Footwall, right-lateral below longwall front.	Deep abutment strike-slip.

¹S-I: A shear implosional first-motion pattern defined by three quadrants of dilation and one of compression.

VEIN SLIP

Four events (table 5) occurred on the vein itself, including a very large event (local magnitude 4.1). These events were fairly evenly distributed throughout the study period. Spatially, they appeared to be concentrated in remnants of the vein abutted by subunit C in the footwall (figure 7).

In these events, slip forced the hanging wall of the vein up with respect to the footwall. The slip surface typically followed the vein, but cut through wall rock locally to cross minor jogs in the vein. Reverse movement on the steeply dipping vein was consistent with the inclined orientation of the major principal stress (Whyatt and others, 1995a). Stress appeared to be concentrated in (and oriented parallel to) hard subunits. The vertical component of stress in these subunits has been measured locally at up to twice overburden loading. The shear stress on the vein created by these "lithopillars" was concentrated on smaller and smaller areas as mining progressed, leading to shear failure with thrust movement as more of the vein abutting the hard subunit was extracted. A case study describing this mechanism has been published (Jenkins and others, 1990). However, a full mechanical analysis has not been conducted, and this mechanism was not reflected in the analysis by Board (1994). The foundation for such an analysis has only recently been laid with mapping of subunits and estimation of their physical properties (Whyatt and others, 1996).

All of these events damaged stopes, particularly those within and closely parallel to slipping portions of the vein. Damage to development openings was nonexistent to minor, despite the large magnitudes of some of the events. Damage to the ramp-stope intersections of was reported as stope damage.

Table 5.—Vein slip

No.	Date of occurrence	Magnitude	Damage	Movement	Notes
14	7/6/891	3.1-3.7	1,000 st south limb of mine.	Minor right-lateral with vertical slip, footwall down.	Event detected by Battelle Northwest.
20	8/17/91	2.9	200 st to both ribs, 5100-106	Vertical slip with footwall down.	Failure of pillar section missed in destress blast.
24	1/30/92	2.5	150 st west end of 5300-95.	Vertical slip, footwall down.	Pillar reduced to 20 to 30 ft. Failed destress. Damage in subunit C, not D.
31	10/17/93	3.0	100 st 5100-94/95, widespread minor damage.	Right-lateral foot-wall and vein below 5100 level.	S-I first-motion, both macro and NISN. ¹

¹S-I: A shear implosional first-motion pattern defined by three quadrants of dilation and one of compression

Figure 7.—Location of vein slip events. A, Plan view; B, longitudinal view.

Figure 7 (continued).—Location of vein slip events. *A*, Plan view; *B*, longitudinal view.

SLIP ON NORTH CONTROL FAULT

Ten events of magnitudes 2.5 to 4.1 occurred with strike-slip and/or normal dip-slip along the North Control Fault, which forms the northeastern boundary of the mine (table 6) (figure 8). A plot of these events over time shows an initial quiet period similar to the initial quiet period on the South Control Fault, but with an earlier and less decisive ending in April of 1990 (figure 3C). However, four large events in 7 months, including two events in only 8 days, followed destress blasting in the 5100-106 stope. This concentrated activity was caused by double-couple, strike-slip movement on both sides of the vein around the 5100-106 pillar, although most activity was located in the hanging wall. Two subsequent events occurred in the hanging wall of this area during a 6-week period in 1992. These events show a transition from double-couple to implosional behavior. The first event registered as a double-couple event on NISN, but the in-mine system suggested a shear implosional pattern. The second event showed up on NISN as entirely implosional, while the in-mine system suggested a shear implosional motion.

Slip movement associated with these events was consistent with closure of the mined vein southwest of the fault, with right-lateral movement in the hanging wall predominating. Release of normal stress on the fault and the coincidence of mining-induced and in situ stress orientations drove hanging wall events. An interesting difference in activity between the North and South Control Faults was the presence of normal movement in many of the events on the North Control Fault. The southerly dip of the two faults (and strata outside of the "kink" represented by the Lucky Friday vein between the control faults) allows downward movement into the mined block on the North Control Fault but not on the South Control Fault.

The damage caused by these events varied widely from no or minor damage (five events) to the September 19, 1991, event that caused 1,800 mt (2,000 short tons) of damage. Stopes have borne the brunt of this damage, while development openings have generally been unscathed. The exception is the September 19 event, which caused moderate damage in the 4660-level haulageway. This haulageway had already been weakened by earlier seismic events.

This set of events has been analyzed previously, generally in conjunction with South Control Fault events, and is one of the best understood. For example, Lourence and others (1993) and Jung and others (1995) present case studies and results from a simple two-dimensional, boundary-element analysis. The detailed three-dimensional study by Board (1994) has been the most comprehensive.

Table 6—North Control Fault strike-slip

No.	Date of occurrence	Magnitude	Damage	Movement	Notes
6	4/10/90	2.5		Hanging wall, right-lateral on 5100 level.	
	12/90		Destress blast in 5100-106 pillar		
12	2/28/91	2.8	Minor damage.	Footwall, left-lateral, 5100 level.	
14	5/9/91	2.8	Minor damage.	Footwall, left-lateral, 5130 level.	
15	5/17/91	2.7	Minor damage 5100-106.	Probably hanging wall.	Poor location northeast of fault.
21	9/19/91	3.6	2,000 st, 5100-106 and 4660 lateral.	Hanging wall, right-lateral, 5100 level.	
25	6/27/92	2.8	No damage.	Right-lateral and normal, hanging wall, 5100 level.	S-l, macro.
26	7/30/92	2.5	No damage.	Right-lateral, footwall, S-l. ¹	NISN general implosion, macro, S-l.
29	11/3/92	3.0	500 st 5100-106 east.	Hanging wall, right lateral, 5100 level.	Only 2-3 cuts left in 5100-106 pillar.
	4/93		Last mining in 5100-106 pillar		
30	5/28/93	2.8	50 st 5100-107.	Normal, hanging wall.	5100-106 pillar mined out.
38	8/16/94	4.1	500 st, 5100-106 and 5570-107.	Hanging wall, right-lateral, below 5100 level.	

¹S-l: A shear implosional first-motion pattern defined by three quadrants of dilation and one of compression.

Figure 8.—Location of North Control Fault slip events. A, Plan view; B, longitudinal view

Figure 8 (continued).—Location of North Control Fault slip events. *A*, Plan view; *B*, longitudinal view.

MISCELLANEOUS MECHANISMS

Two of the events examined in this study depart sufficiently from the five major groups that they must be considered separately (table 7). The first was similar to slip events in the southern bedding plane zone considered earlier, but occurred in one of the larger blocks in the central shear zone. The second event was a poorly located right-lateral slip located well below the mining front (but not so deep as to be unrelated to mining). The late dates of both of these events suggest that they may be related to changing mining and/or geologic conditions. For instance, longwall mining and extraction of remnant pillars was creating a true longwall geometry by 1994. Further study of these events is probably not warranted until further, similar events are identified, perhaps in 1995 activity.

Table 7—Miscellaneous

No.	Date of occurrence	Magnitude	Damage	Movement	Notes
1	2/24/89	2.8	Widespread shakedown.		Destress blast in 5100-100/104 pillar.
34	3/29/94	2.7		Normal on bedding.	Central shear zone bedding slip.

CONCLUSIONS

This study has demonstrated that five types of events produced over 90% of the seismic events having a local magnitude greater than 2.5 at the Lucky Friday Mine between 1989 and 1994. First-motion patterns, locations, associated structural features, magnitude ranges, and underground damage characteristics have been identified for these five types of events. The events examined in this study were generally not triggered by specific mining activities, although mining certainly created the conditions required for their initiation. The same holds true for destress blasts. These types of events may be amenable to development of composite first-motion solutions that use first-motion information from a number of events to improve constraints on the fault plane solution (Wideman and others, 1994).

Most of these events show double-couple first-motion patterns, but two groups include events that show shear-implosional or implosional patterns. Events that produce these patterns may be of particular interest for the development of nuclear test ban treaty evasion scenarios.

The apparent stratigraphic control of vein slip events may also be useful. This factor could be used as a design tool for controlling the timing and magnitude of a desired event. Changes in the rate at which various types of seismic events occurred as mine geometry evolved from large pillars to small pillars to a longwall configuration also suggests that modest changes in mining activity can influence mining-induced seismicity.

Damage to various mine openings caused by these events was highly variable and appeared to depend primarily on whether the opening intersected the event's radius of slip. Many seismic events cause little or no damage to mine openings. Thus, the economic cost and safety hazard of a seismic

event appear to depend much more on whether the event's radius of slip intersects a mine opening rather than on the magnitude of the event. This result suggests that the damage caused by an intentionally initiated event may be minimal and may be as controllable as the event. That is, placement of the slip plane relative to mine openings in the event design will largely control the degree of resulting damage.

Unfortunately, full and unclipped digital waveform records suitable for detailed seismological analysis of these events are rare. Further seismological studies of large events in the Coeur d'Alene Mining District should consider deployment of additional instruments. A few new stations are being deployed in the region through a cooperative arrangement between the University of Idaho (Dr. Ken Sprenke) and the Montana Bureau of Mines (Dr. Mike Stickney). However, they are not specifically designed to monitor mining-induced seismicity. Moreover, the NISN, which has provided valuable data to this study, has lost funding and has been shut down.

DISCUSSION

This study was undertaken as a first step toward testing the engineering feasibility of camouflaging a nuclear test with seismic events similar to those routinely created in the course of mining (Heuze, 1994). If these events prove to have camouflaging characteristics, they would have three advantages for development of an evasion scenario. First, since they are routinely produced in the course of mining, their occurrence is expected and routine. Second, a base of experience is available to support calibration of event design models. Third, ongoing experiments can be conducted in the guise of evolving mining practices to improve the reliability and camouflage capability of events.

An alternative approach would be to design a camouflaging operation independent of ongoing mining operations. The camouflaging characteristics of an event created in this way would be at least as good as the mine-based scenarios developed in the first approach. The lack of a base of experience would, however, increase the number of events that would have to be produced to establish reliability. In addition, such a project would require a substantial operational base, increasing the probability that the purpose of the excavation would be discovered. This approach would also be substantially more expensive.

The purposeful initiation of a large-magnitude seismic event by mining would be complicated by generally incomplete geologic information at the initiation site and the immature state of our understanding of rock burst mechanisms. However, production of large-magnitude seismic events is often affected by changes in mining practices. Alterations in mining practices aimed at minimizing rock-burst hazards are often implemented in continuing mine operations and are based on experience with local rock mass conditions and active rock-burst mechanisms. This base of experience makes up for deficiencies in our understanding of rock-burst mechanisms and helps to identify key geologic features. Thus, it seems reasonable to expect that a similar evolution of mining practices could be applied to purposeful initiation of a seismic event. It also appears that some characteristics of the resulting event should be controllable.

Thus, the following approach is proposed for studying the feasibility of purposeful initiation of large seismic events. Briefly, the major elements of this approach, in approximate order of execution, would be—

1. Compile information on seismic events that meet minimum criteria for seismic energy release (addressed in this study).

2. Identify series of recurring seismic events having common characteristics, mechanisms, and relationships to geologic structures (addressed in this study).
3. Assess the ability of each series of events to provide the desired seismic camouflage and prioritize further studies accordingly.
4. Study each type of events to ascertain whether various event characteristics are controlled by mining and geology. The success of these studies will depend on the availability of basic geomechanical information on in situ stress, seismic closure of mine openings, and rock mass and fault properties.
5. Construct and analyze scenarios for producing the desired events. Triggering requirements will play a large role in scenario design. The degree to which a test trigger could recognize that a camouflaging event has started and then initiate the test before cessation of the event would greatly influence the feasibility of evasion. In fact, having such a trigger might allow the test to be held up until an appropriate event occurred without any alteration in mining activity. If this capability is lacking, initiation of an event through carefully designed blasting at a precise time is the best alternative.

Some attention should be paid to mechanisms that are advantageous for camouflage but that are not generated through normal mining practice. For example, an implosional mechanism caused by widespread pillar collapse is intentionally suppressed in contemporary deep mines through widespread use of backfill and manipulation of the mining sequences. Design models for these scenarios would be developed in a similar manner, but these models would have to be based on old mining records and experience in other mining situations (primarily shallow room-and-pillar mines). An added complication is that carrying out such a scenario in a deep mine would necessitate employing unconventional and dangerous excavation plans.

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APPENDIX A: CATALOG OF LARGE SEISMIC EVENTS, 1989

Five seismic events having estimated local magnitudes of 2.5 or greater occurred during 1989. The locations of these events were plotted on a longitudinal section of the vein (figure A-1) and a plan view map of the 5100 level (figure A-2). The available information on each event is reviewed on a case-by-case basis in the remainder of this appendix.

Figure A-1.—Location of major seismic events during 1989, Lucky Friday vein. This longitudinal view shows the true area of the vein and rotates from a point south of the vein in the western portion of the mine to a point east of the vein in the northern portion of the mine.

Figure A-2.—Location of major seismic events during 1989, plan view, 5100 level.

Event 1 2/24/89 23:11:22 80 mm 2.8 M_L

This event was a large destress blast shot in the 5100-100 and 5100-104 stopes. Over 5000 lb of explosives was shot in a number of boreholes with 1-ms delays between blasts. Widespread shakedown of loose rock and cratering of a portion of the destressed vein were observed after the blast. Given the large magnitude of the event, it is possible that the blast was augmented by a seismic event or events triggered by, and occurring during, blasting.

This destress blast initiated a period of heightened seismic activity that persisted for a couple of weeks and included several significant events, including event 2. The estimated event location (20412, 20214, -1553) was in the footwall of the vein and to the west of the central 5100-101/104 pillar. The vertical coordinate was consistent with the position of this highly stressed pillar (figure A-1). The horizontal coordinate placed the event approximately 50 ft into the vein footwall, indicating the level of location error associated with event locations in this area of the mine (figure A-2).

Wall rock of the 5100-101/104 pillar is in upper third of subunit C. This subunit extends throughout all of the 4900-101/104 pillar east to the Offset Fault. Stratigraphy in the central shear zone proper, northeast of the 38 Fault, is more confused.

This event was clearly a destress blast, although it might have included a limited amount of triggered seismicity. Thus it was not assigned to any of the major sets of rock bursts.

Destress Blast.

The best estimate of event location was 20412, 20214, -1553. The quality of the location is fair and no first-motion information is available.

Event 2 3/2/89 14:05:42 79 mm 3.3 M_i

This event occurred in the 5300-95 Lucky Friday underhand longwall (LFUL) stope block. The microseismic system was used to develop an estimated location of 19990, 20043, -1695. The event occurred with normal production blasting.

The event caused 250 short tons of damage to the footwall side of the 5300-95 longwall stope (figures A-3 and A-4), which is being mined down from the 5100 level. This stope is on its first few cuts and has 200-ft pillars above and below. Mining in the 5300-93 overhand stope was halted after completion of the I-drift and two cuts. Damage was not apparent in footwall development openings.

The 5300-95 LFUL stope was being mined downward in the lower part of subunit C. The bottom of subunit C crosses the vein just below the 5300 level in this part of the mine.

Figure A-3—Thin argillite bed uncovered during repair of 5300-95 stope. It is not clear whether slip occurred on this plane or whether it was just a convenient structural bound for damage. Models of the bed slip mechanism suggest that slip was initiated below the stope floor and farther into the footwall.

In addition to mining, a number of destress blasts had been conducted in the area. A destress blast the previous Friday evening near the 4900-101 crosscut may have shifted stress into this area. Previously, destress blasts had been conducted out of the 5100-96 crosscut to the west and out of the 5100-94 crosscut to the east. The 5100-94 crosscut had subsequently been filled. An inspection of this crosscut showed no evidence of damage to the back above the fill.

The mine report ascribed the event to "slip on a bedding plane fault in the footwall of the main vein in the 96 crosscut area at about rail elevation."

Analysis

The microseismic location, damage pattern, and lack of displacement in accessible openings suggest that the event occurred on the footwall side of the 5300-95 longwall stope. Thus this event was assigned, in accordance with the mine staff's explanation of the event mechanism, to the

Southern Bedding Plane Slip Set.

The best estimate of event location is 19990, 20043, -1695. The quality of the location is poor and no first-motion information is available.

Figure A-4. —Location of damage to 5300-95 stope caused by March 2, 1989, event

Event 3 4/4/89 03:42:59 78 mm 2.8 M_i

This event occurred in the 4900-93 overhand stope block. The microseismic system was used to develop an estimated location of 20012, 20018, -1369.

The event caused over 100 short tons of damage to west end of the 4900-93 overhand stope and some damage to the north (footwall) side of the raise. This stope is being mined up into a 90-ft-high pillar. The west end of the stope abuts the South Control Fault. Inspection of accessible portions of this fault (primarily the 4660 haulageway and the 4660-94 crosscut) failed to reveal any evidence of movement. The stope has been mined up through 120 ft of the ore block and lies above a 190-ft-high pillar. Mining on the west (South Control Fault) end was nearly complete and destress drilling was being carried out from the raise. Damage was relatively minor for a major burst and was not typical of a pillar burst. Mine staff attributed the burst to "increased stress in the pillar that likely resulted in movement on the South Control Fault." While the mine staff felt that this burst likely destressed the zone, the drilled destress holes were loaded and blasted for added security.

The west third of the stope, roughly the portion of the stope that was damaged (except possibly the raise), had penetrated into subunit A, and the remainder of the stope was in the softer subunit B. Initiation of destress drilling is typically a response to heightened seismic activity, as would be the cause as mining moves from sericitic to vitreous quartzite (subunit B to A).

Analysis

This event was located in the footwall of the stope, a location that is typical to locations of normal bed slip events that occur in the footwalls of underhand stopes. The footwall location was also indicated by damage to the north side of the raise and damage along a long section of stope, which is typical of bedding plane bursts. Thus, this event was assigned to the

Southern Bedding Plane Slip Set

The best estimate of event location is 20012, 20018, -1369. The quality of the location is fair and no first-motion information is available.

Event 4 7/6/89 00:07:57 76 mm 3.1 - 3.7 M_i

This event was reported from the 5100-100 stope block. Mining in a number of stopes on the 4900, 5100, and 5300 levels had created a network of pillars of various shapes (figure A-1). The event was recorded by the newly installed macroseismic system (file 89070600.wvm), which provided a location estimate far south-southeast of the mine between the 5100 and 5300 levels. A wider-than-usual range of magnitude estimates were reported for this event, with the largest (3.7) reported by Sprenke and others (1991). This event was also monitored by the Battelle Northwest seismic net.

Damage from this event was very extensive in the west end of the mine on the 4900 and 5100 levels (figure A-5). Some 1000 short tons of rock was displaced and a number of timbered raises were damaged (figure A-6). Extensive repair of crosscut walls was required, particularly on the heavily damaged east walls (figure A-7). Damage along the 4900 level appeared to be associated with movement along the footwall vein where the northern (footwall) block moved down and to the east relative to the southern (hanging wall) block. The most severe damage occurred in the 4900-99 access and stope, which was consistent with a pillar burst. However, damage on the 4900 level to the west of this area and on the 5100 level appears to be the result of movement along the footwall vein.

In the 4900-99 stope, which bore the worst of the damage, the 5100-100 crown pillar was being mined from the 4900 level. Mining in this stope had been halted for at least a year before the burst. The 5100-100 crown pillar was the subject of the February 24, 1989, destress blast recorded as event 1 (and that possibly created conditions for event 2). The occurrence of this event suggests that the February 24, 1989, destress blast was not entirely successful.

In previous analyses (Blake, 1980; Jenkins and others, 1990), the burst was judged to have originated about 60 ft below the 4900 sill in the 5100-100 remnant pillar, which was actively being mined. However, a number of locations have been proposed on the basis of data from the microseismic and macroseismic systems and the location of damage.

Solutions

1. A first-motion pattern reported by Jenkins and others (1990) for the microseismic system location (20450, 20169, -1640) shows vertical slip, with the southern block moving upward on a plane striking N 56° E and dipping 76° to the southeast. This plane is nearly parallel to the footwall vein in the damaged portion of the mine (figure A-8A).
2. A subsequent first-motion pattern developed for this location shows similar vertical slip but on a plane striking north-northeast, which is parallel to the vein east of the Hook Anticline (figure A-8B). A minor right-lateral slip component is also included in this solution. The geophone locations on this stereonet are essentially the same as those reported by Jenkins and others (1990).
3. A first-motion pattern developed for the centroid of damage (20230, 19900, -1580) as reported by Jenkins and others (1990) shows vertical slip, with the eastern block moving up on a steeply dipping plane striking north-northeast (figure A-8C).
4. A first-motion pattern was also developed for the location reported in mine records (20111, 18885, -1867), presumably on the basis of macroseismic system data. The resulting pattern shows vertical slip on a vertical north-northeast-striking plane with the eastern block moving upward and

LEGEND

	Distressed		Damage
- 1 Timber damage from vertical movement
 - 2 Footwall rib damage, floor unaffected
 - 3 Some minor footwall rib damage
 - 4 Damage along South Control Fault and footwall raise. 10 tons displaced from east rib and floor
 - 5 Major damage in footwall raise, minor damage in Main vein raise. 20 tons displaced from east rib and floor
 - 6 Major damage in footwall raise, minor damage in Main vein raise. 30 tons displaced from east rib and floor
 - 7 Major damage in footwall raise, 0.3-m of track heave at footwall vein, minor damage in Main vein raise, total 75 tons displaced from east rib and floor
 - 8 Major damage in stope. Stope choked with broken rock. 500 tons displaced from floor and ribs
 - 9 Minor damage to South Control Fault area. 5 tons displaced from back and west rib
 - 10 Minor damage in raise. 10+ tons damage from back of stope
 - 11 Major damage in Main vein. 250 tons from footwall stope rib.
 - 12 Very minor damage in Main vein stope, loose rock from ribs and sand back bagged behind wire mesh

Figure A-5—Damage caused by July 6, 1989, event. A, Longitudinal section along vein; B, plan view, 4900 level; C, plan view, 5100 level.

Figure A-6—Damage to chutes at bottom of timbered raise caused by July 6, 1989, event.

Figure A-7—Damage in cut 2 of 5300-95 Main vein stope caused by July 6, 1989, event. North (downward moving) wall is on the right.

Figure A-8.—First-motion patterns, July 6, 1989, event. A, Microseismic system location (Jenkins and others, 1990); B, microseismic system location (subsequent solution); C, centroid of damage (after Jenkins and others, 1990); D, mine macroseismic system location; E, automatic macroseismic system location; F, inferred location

minor left-lateral slip (figure A-8D). This location was much further south than is usual for damaging seismic events.

5. A first-motion pattern developed on the basis of a location automatically calculated by the macro-seismic system (21184, 19114, -1797), which was too far from mining to be realistic, shows vertical slip on a north-south plane with the eastern block moving upward (figure A-8E). This location was much further south than is usual for damaging seismic events.
6. The pillar configuration and damage pattern suggest that the event was associated in some way with the upper portion (C1) of subunit C. C1 is increasingly mined out toward the east, suggesting that stress may be concentrated most severely on the eastern end of C1 near the bend in the vein. Based on this reasoning, a location of (20400, 20000, -1570) was inferred. The first-motion pattern developed for this location (figure A-8F) suggests that the event actually originated east of the Hook Anticline where structures, including the vein, line up with the first-motion slip plane.

Analysis

The damage pattern was clearly correlated with the C1 portion of the hard C subunit and was concentrated in the southwestern limb of the mine. The most severe damage was reported in an I-drift on the 4900 level (note 8, figure A-4B).

The downward and eastward (right-lateral) movement of the footwall side of the vein appears to be consistent with preexisting and mining induced stresses. Downward movement would release shear forces on the vein created by natural axial loading of the hard subunit C (Whyatt and others, 1995b, discuss an overcore measurement of this natural stress concentration). Right-lateral movement was consistent with closure of mined areas in the northeastern limb, which was likely reflected by severe damage in the 4900 I-drift east of the bend (severe I-drift damage limited access to this area, which has never been re-entered).

The first-motion pattern reported by Jenkins and others (1990), and the first-motion patterns generated here all show the hanging wall of the vein moving upward in relation to the footwall. However, they do not reflect the observed right-lateral movement. Such a pattern would require that the 590 geophone arrival be dilational instead of compressional. While there is no evidence that the 590 geophone performed poorly during this early period of system operation, this possibility cannot be ruled out. It is also possible that the right-lateral movement absent from initial movement occurred later in the event.

The first-motion patterns generated here differ from the previous interpretation (figure A-8A) in that they suggest slip initiating just east of the bend in the vein rather than on the western limb. The robustness of this result through the range of locations contrasts with the marginal and somewhat forced nature of first-motion patterns reported earlier.

It appears that this event was initiated near the inferred location and northeast of the bend in the vein and propagated around the bend toward the west. This interpretation has slip being initiated in the distressed 5300-100 pillar, which was supporting a large portion of subunit C. Stress drops, and hence damage, likely increased as the slip propagated around the bend, into the western limb of the vein, and out of the distressed pillar.

Fracturing and movement were likely governed by stress concentrated in the plane of the hard C subunit (particularly in C1), which acted as a "lithopillar." Mining caused these steeply dipping stresses to be carried through the ever-decreasing cross section of the remaining vein (figure A-4) until the shear strength of the remaining vein was overcome. The appearance of vertical slip is consistent with driving forces acting along the plane of subunit C. The presence of stress concentrations within the plane of hard strata is consistent with, and suggested by, in situ stress measurements in this area (Whyatt and others, 1995a, 1995b).

Thus, this event is attributed to slip on the vein. Slip was likely dominated by vertical movement that initiated east of the vein bend and propagated westward. Some right-lateral movement likely accompanied propagation of slip. It is also possible that the 590 geophone was not entirely accurate and right-lateral slip was associated with event initiation as well. This event was assigned to the

Vein Slip Set

The best location estimate for the initiation of this event is 20400, 20000, -1570, while the damage was centered on 20230, 19900, -1580. The double-couple, first-motion pattern has values of 210°, 25°, and 10° for dip direction, dip, and rake, respectively. The location quality is poor and the quality of first-motion information is fair.

Event 5 11/2/89 22:31:00 76 mm 2.6 M_i

This event was reported as occurring 20 ft below the 4900 level on the Offset Fault. The microseismic system did not locate the event, although it was recorded by the macroseismic system (file 89110203.WVM). This event did not damage the mine, not even the 5100-106 or 4900 107/109 underhand stopes, both of which had a complete cut open at the time of the event. Underground inspections also failed to reveal displacements that would identify the slip plane. There was no active mining in the immediate area at the time of the event. Mine reports attribute this event to "continual loading of the ore block from the combination of mining 101 LFUL, 107 LFUL and 106 stopes." Estimated locations are a problem, since neither the microseismic system nor mine damage can be used to pinpoint the event.

Mining in this area had formed a remnant pillar about 100 ft high that was not being actively mined. The Offset Fault is located in the northern third of the pillar. The pillar was destressed earlier (recall the February 24, 1989, distress blast event). The 5100-106 pillar to the east was being actively mined.

Solutions

Digital event records show poorly defined first arrivals. Locating the event was also complicated by blasting. The records were interpreted to show an implosional first-motion on all channels. The sparse array allows development of double-couple solutions in which compressional first motions are inferred in unsampled quadrants. The following locations and resulting solutions were examined.

1. The location automatically calculated by the macroseismic system (24772, 22961, -2582) lies a good distance to the northeast and down from active mining. It is unrealistic.
2. The mine reported a location for this event at the intersection of the Offset Fault and the vein on the 4900 level at 20600, 20300, -1500. The first-motion pattern for this location indicates an implosion (figure A-9). Sampling is sufficiently sparse to also allow normal movement on the Offset Fault.
3. A series of arbitrary locations were used to test the stability of the first-motion pattern. These included a location on the Offset Fault in the 4900 level hanging wall (20750, 20250, -1520), a location on the Offset Fault in the footwall at a deeper horizon (5040 level, at the bottom of the pillar) (20600, 20350, -1640), and a location on the Offset Fault deep in the 4900 level footwall (20400, 20400, -1520). First-motion patterns developed for these locations shifted only slightly, suggesting that the first-motion information in figure A-9 is relatively insensitive to location error.

Analysis

The mine reported that this event occurred on the Offset Fault. The first-motion information is generally consistent with normal movement on the Offset Fault. A general crushing or implosion of the pillar area is also consistent with the sparse information available. However, closure of mine openings, which would be expected in association with an implosion, was not noted. Thus, the slip interpretation is preferred. This event was assigned to the

Central Shear Zone Set

The best estimate of event location is 20400, 20400, -1520. The quality of the location and the first-motion information are poor. The first-motion solution for dip-slip movement is dip direction = 130° dip = 40° , and rake = -130° .

Figure A-9. — First-motion pattern, November 2, 1989, event.

APPENDIX B: CATALOG OF LARGE SEISMIC EVENTS, 1990

Six seismic events having estimated local magnitudes of 2.5 or greater occurred during 1990. The locations of these events were plotted on a longitudinal section of the vein (figure B-1) and plan view maps of the levels (figures B-2 and B-3). The available information on each event is reviewed on a case-by-case basis in the remainder of this appendix.

Figure B-1.—Location of major seismic events during 1990, Lucky Friday vein. This longitudinal view shows the true area of the vein and rotates from a point south of the vein in the western portion of the mine to a point east of the vein in the northern portion of the mine.

Figure B-2—Location of major seismic events during 1990, plan view, 5100 level.

Figure B-3.—Location of major seismic events during 1990, plan view, 5300 level.

Event 6 4/10/90 21:22:44 80 mm 2.5 M_i

This event was reported to have occurred in the 5100-112 east stope block near the North Control Fault. This location was toward the bottom of the 5100-106 pillar, which had been reduced to about 100 ft vertically. Mining of a single underhand stope across the entire pillar was continuing to reduce this height. The event did not damage mine openings.

The 5100-106 pillar lies outside the boundary between subunits B and C (figure B-1). Subunit B dominates the center of the pillar with subunit C more prevalent at either end of the pillar. The 5100-106 pillar is also cut by the A and F3 Faults.

Solutions

1. A first-motion pattern developed for the microseismic system location (20807, 20684, -1682) was consistent with right-lateral slip on the North Control Fault (figure B-4).
2. The location automatically calculated by the macroseismic system (22754, 19564, -2461) was too far east of the mine to be reasonable.

Analysis

This event was most likely caused by right-lateral slip on the North Control Fault in the hanging wall of the vein. The event was located near the bottom of the 5100-106 pillar, approximately 100 ft below the nearest mining face. It was assigned to the

North Control Fault Slip Set

The best estimate of event location is 20807, 20684, -1682. The quality of the location is fair and the quality of the first-motion information is fair. The first-motion solution is dip direction = 15°, dip = 85°, rake = -170°.

Figure B-4. — First-motion pattern, April 10, 1990, event.

Event 7 4/11/90 06:04:57 86 mm 2.5 M_i

Mine records place this event in the 4900-93/95 stope block at mine coordinates 19983, 20061, -1418. The macroseismic system did not record this event.

The damaged stope was I-drifting into the 4900-93/95 pillar, splitting off a 20-ft-high pillar from the main portion of the pillar (figure B-5A). The major portion of the pillar was reduced to about 80 ft and lay above the 5100 and 5300 pillars at this end of the mine. Mining was active on the bottom of these three pillars (5300-95) but not the middle (5100-95).

The event blew the footwall rib out midway in the 4900-93/95 Main vein stope for a length of 130 ft, displacing 75 short tons (figure B-5B). It occurred in proximity to two previous smaller events. The damage pattern and the lack of damage in the stope back suggest that all of the energy came out of the floor and footwall.

The eastern portion of the stope lies in subunit A, which gives way to softer rock of the middle Revett Formation in the west. The exact location of the subunit boundary is not known.

Analysis

The location and damage pattern suggest that the event was caused by slip on a bedding plane. It was assigned to the

Southern Bedding Plane Slip Set

The best estimate of event location is 19983, 20061, -1418. The quality of the location is fair. First-motion information is not available.

Figure B-5.—Location of damage caused by April 11, 1990, event. *A*, Longitudinal section; *B*, plan view, 4660 level.

Event 8 6/12/90 14:04:56 81 mm 2.6 M_L

Mine records place this event in the west block of the 5150-95 footwall stope. Both the microseismic and macroseismic systems appear to have missed this event.

The event caused 100 short tons of damage to stope face, floor and footwall rib at mine coordinates 20025, 19950, -1750. The worst damage created a pocket 15 by 9 by 3 ft deep in the footwall rib 20 ft from the face. Miners also noticed a foot of floor heave that extended 40 ft from the face. Williams (1990) ascribed the event to vertical slip on the vein, with upward motion on the foot wall side of the vein. A microseismic location was not available for this event.

The 5100-95 foot wall stope was being mined from the bottom of three pillars (vertically) on the west end of the mine (the 5300-95 pillar). Mining was active in the upper pillar (4900-94 and 97/99) but not in the middle pillar (5100-95). Active mining in the 5300-95 stope was in the lower portion of subunit C.

Analysis

The sense of slip proposed by Williams (1990) was opposite the sense of vein shear stress inferred from concentration of stress in hard subunits and the sense of slip observed in the July 6, 1989, event. Moreover, the stope foot wall location of the event and the pattern of damage were typical of bedding plane slip events. Thus, this event was assigned to the

Southern Bedding Plane Slip Set

The best estimate of event location is 20025, 19950, -1750. The quality of the location is poor and first-motion information is not available.

Event 9 7/31/90 06:01:01 78 mm 2.6 M_L

Mine records place this event near the 5150 95 stope cut 6 slot. The macroseismic system monitored this event (file 90073100.wvm). Mine records report a local magnitude of 2.6, but a subsequent investigation estimated the magnitude at 1.5.

The event damaged 60 ft of the east rib of the 5150-95 slot for stope cut 6 (mining the 5300-95 block). Damage to the floor of the left rib of the slot was observed from the corner of the stope to 60 ft into the footwall. Wire mesh in the back was bagged with collapsed material in two spots (figure B-6). This event is interesting in that damage was limited to the slot with no damage to the stope itself. The slot was on its second cut, opening up to a height of 20 ft near the stope (where the damage occurred), while the stope was developed to a length of only 40 ft (10 ft west and 20 ft east of the slot). Records do not indicate if the upper part of the slot was backfilled, but stulls placed across the slot were displaced by the event. In this geometry, the slot may be more vulnerable to seismic loading than the stope, although the relative location and mechanism of the event would also have had an influence.

This event was located in the same pillar as the June 12, 1990, event, but damage was reported in the east side of the slot rather than the west side of the stope. This pillar (the 5300-95 pillar) is the bottom of three pillars that were being mined on the west end of the mine. Mining was active in the upper pillar (4900-94 and 97/99), but not in the middle pillar (5100-95).

This stope lies above the lower boundary of subunit C. The boundary with subunit D lies just below and within the footwall of the stope. The damaged section of the slot lies in subunit C.

Figure B-6. — Location of damage caused by July 31, 1990, event.

Solutions

The macroseismic system indicated an implosional first motion on all channels. The sparse array allows development of double-couple solutions in which compressional first motions are inferred in unsampled quadrants. A number of first-motion patterns were developed for this event, including the following.

1. The microseismic location (20091, 19855, -1807) lies on the Main vein, whereas the damage was recorded on the footwall side of the footwall vein. The first-motion pattern for this location fit a normal slip pattern roughly consistent with footwall bedding (figure B-7A).
2. The macroseismic system produced a location (20372, 19634, -1840) about 300 ft south-east of the microseismic system and close to South Control Fault in the hanging wall. A first-motion pattern for this location can be constructed that with equal parts right-lateral and thrust movement on an east-west-striking plane

(figure B-7B). Although this strike is subparallel to the South Control Fault, the sense of movement would widen rather than close the mined vein.

3. The apparent movement for the macroseismic location would be appropriate for the footwall side of the South Control Fault. A first-motion solution for such a location (19750, 19900, -1800) suggests right-lateral movement on a steep, north-south to northwest-striking plane, consistent with closure of the mined vein (figure B-7C). However, this location was situated west of the slot while the east side was damaged.

Figure B-7.—First-motion patterns, July 31, 1990, event. A, Microseismic system location; B, macroseismic system location; C, hypothetical location on the South Control Fault in vein footwall; D, hypothetical location in vein footwall east of slot.

4. Considering the damage pattern, an event location in the footwall east of the slot (20250, 20100, -1900) would be reasonable (see figure B-3). The first-motion pattern for this location (figure B-7D) was consistent with a bedding plane slip motion essentially identical to the first-motion pattern suggested for the microseismic location (figure B-7A).

Analysis

Three types of movement are commonly encountered in this area of the mine—bedding slip, vein slip and South Control Fault slip. The sense of slip on the South Control Fault in the hanging wall does not agree with the general tendency to close mined areas. A location in the footwall is more plausible but requires a more substantial location error. Also, both of these mechanisms fail to account for preferential damage to the east wall of the access ramp. Vein slip was clearly not consistent with the first-motion patterns and would call for a different damage pattern (damage in the stope on the slip plane rather than in one side of the access ramp). Likewise, a general implosion caused by failure of the vein would be expected to result in floor heave and damage consistent with closure of the stope.

The remaining alternative was bedding plane slip. Usually, this mechanism causes damage to the stope. However, only a short section of stope had been mined, and it is possible that the slip occurred east of this small section. Such a location produces a first-motion pattern consistent with bedding plane slip and is not too far from the location identified by the microseismic system. Moreover, this sense of slip is essentially identical to the pattern developed for the location identified by the microseismic system. Thus, this event was most likely caused by normal bedding plane slip of a footwall block into a mined and filled portion of the vein east of the damaged crosscut. This event was assigned to the—

Southern Bedding Plane Slip Set

The best estimate of event location is 20250, 20100, -1900. The quality of the location is poor and the quality of the first-motion information is fair. The first-motion solution is dip direction = 170° , dip = 60° , and rake = -80° .

Event 10 8/3/90 09:39:13 81 mm 2.5 M_L

Mine records place this event in the 5100-106 pillar at mine coordinates 20572, 20462, -1663. The macroseismic system monitored this event (file 90080300.wvm). The event caused minor damage to the 5100-95 stope at the crosscut entry. No other damage was reported, not even to the 5100-106 stope.

The 5100-106 pillar is located astride the boundary between the Offset Fault and the North Control Fault. Some subunit B strata can be found between the Offset and 38 Faults immediately to the west of the stope. The pillar is cut by the A and F3 Faults. Mining had reduced the 5100-106 pillar to 110 ft.

Solutions

1. The first-motion pattern developed for the microseismic system location (20572, 20462, -1663) shows right-lateral, strike-slip movement on an east-west-striking plane (figure B-8). The sparse data set also allows a shear implosional interpretation.
2. The location automatically identified by the macroseismic system (21967, 19250, -2121) was too far southeast of the mine to be useful.

Figure B-8.—First-motion pattern, August 3, 1990, event.

Analysis

The most likely mechanism was right-lateral, strike-slip in the vein footwall, most likely on an F-series fault, halfway between the top and bottom of the 110-ft-high 5100-106 pillar. Normal stress was likely reduced slightly by mining in the 95 stopes and the July 31st burst. The in situ stress field is oriented to provide the driving force required for this event. This event was assigned by virtue of its location, lack of damage, and first-motion pattern to the

Central Shear Zone Set

The best estimate of event location is 20572, 20462, -1663. The quality of the location and the first-motion information are fair. The first-motion solution has dip direction = 250°, dip = 80°, and rake = -10°.

Event 11 10/19/90 13:34:46 80 mm 2.5 M_i

Mine records place this event in the 5100-106 stope block at mine coordinates 20607, 20609, -1719. The event caused 60 short tons of damage to the west end of the stope and included heaving of the floor. The event appears to have been triggered by distress drilling and ruined a number of these holes. Damage, including kinked rails observed in the last, unfilled cut of the 4900-106 underhand stope, suggest movement on the F1 Fault. The direction of slip indicated by kinking of the rails was either not evident or not recorded.

The event was located by the microseismic system about 20 ft below the bottom of the 5100-106 pillar (100 ft high). The macroseismic system did not record this event. This pillar lies astride the boundary between subunits B and C. The pillar is cut by the A and F3 Faults.

This event was assigned by virtue of its location, limited damage, and apparent movement on the F1 Fault to the—

Central Shear Zone Set

The best estimate of event location is 20607, 20609, -1719. The quality of the location is fair and no first-motion information is available.

APPENDIX C: CATALOG OF LARGE SEISMIC EVENTS, 1991

Twelve seismic events having estimated local magnitudes of 2.5 or greater occurred during 1991. The locations of these events were plotted on a longitudinal section of the vein (figure C-1) and plan view maps of the levels (figures C-2 and C-3). The available information on each event is reviewed on a case-by-case basis in the remainder of this appendix.

An error in wiring the ground return lines to the macroseismic system geophones was discovered December 20, 1990, during a review of system components. The error was corrected quickly and its impact is not apparent.

Figure C-1.—Location of major seismic events during 1991, Lucky Friday vein. This longitudinal view shows the true area of the vein and rotates from a point south of the vein in the western portion of the mine to a point east of the vein in the northern portion of the mine.

Figure C-2.—Location of major seismic events during 1991, plan view, 5100 level.

Figure C-3.—Location of major seismic events during 1991, plan view, 5300 level.

Event 12 2/28/91 20:09:23 78 mm 2.8 M_i

Mine records and event locations placed this event in the hanging wall portion of the 5100-106 block along the North Control Fault near the elevation of the 5100-106 pillar. The macroseismic system monitored this event (file 91022804.wvm). The 2.8 M_i estimate was developed by the Montana Bureau of Mines. The event caused minor shakedown damage in the 5100-106 stope (spalling of loose rock in stope ribs and the north face). There was no damage to the 5300-106 stope below.

Recent mining activity included a 5100-106 pillar destress blast that was shot in December of 1990. The entire 5100-106 pillar lies astride the boundary between subunits B and C. The pillar is also cut by the A and F3 Faults. However, rock types along the North Control Fault are difficult to project and, particularly in the northeast wall of the fault, are essentially unknown.

Solutions

1. First-motion patterns developed for the location identified by the microseismic system (20861, 20621, -1642) showed a variety of mechanisms, including the left-lateral strike-slip shown in figure C-4A, all with at least one discrepant geophone. This plane is suggestive of the North Control Fault, but has a more northerly strike.
2. The first-motion pattern developed for the location developed by the mine using macroseismic system data (20944, 20784, -1741) also shows left-lateral slip with some downward movement of the southern block (figure C-4B).
3. The first-motion pattern developed for the location automatically calculated by the macroseismic system (21542, 20756, -2208) showed left-lateral slip on a plane parallel to the North Control Fault (figure C-4C). However, this pattern included two marginally discrepant geophones. The absence of damage in the 5300-106 stope and the location of the pattern much much farther into the hanging wall than was usual suggested that the elevation of this location was too deep.
4. The left-lateral sense of slip suggested by first-motion patterns at the preceding locations indicates slip occurred on the North Control Fault in the vein footwall. An arbitrary location (20700, 20800, -1800) was chosen to allow this interpretation to be examined further. The resulting first-motion pattern can be interpreted as a North Control Fault double-couple pattern with the 440 geophone discrepant (figure C-4D) or a shear implosional pattern on a plane subparallel to the North Control Fault (figure C-4E).

Analysis

The concentration of damage at the north end of the 5100-106 stope as well as seismic system locations indicated that the event occurred along the North Control Fault. There was a contradiction, however, between the reported hanging wall locations and the left-lateral sense of movement, which was consistent with a footwall location. An arbitrary footwall location confirmed that right-lateral movement was maintained for a footwall location, implying either for a double-couple movement with a single discrepant geophone or a shear-implosional first-motion pattern. The 440 geophone, which is discrepant in the double-couple interpretation, lies across the mined vein and above the footwall location. All other channels (except 520) had a direct path (figure C-5). The effect of filled stopes on the validity of first-motion information and the feasibility of a shear-implosional first-motion pattern

Figure C-4.—First-motion patterns, February 28, 1991, event. *A*, Macroseismic system location; *B*, macroseismic system location; *C*, automatic macroseismic system location; *D*, hypothetical location on North Control Fault in vein footwall assuming double-couple pattern; *E*, hypothetical location on North Control Fault in vein footwall assuming shear-implosional pattern.

Figure C-5.—Event location and travel paths to geophones.

are not well known. However, either interpretation confirms a footwall location and left-lateral slip. The position of this event at the edge of the geophone array resulted in degradation of location accuracy that, combined with travel paths crossing filled portions of the vein, could easily have shifted the event location from the footwall to the hanging wall. In addition, the location identified by the microseismic system, which generally provides the best location accuracy, was closest to the footwall, lying within a couple hundred feet.

Thus, this event is best explained as left-lateral slip on the footwall portion of the North Control Fault just below the 5100 level. This event was assigned to the-

North Control Fault Slip Set

The best estimate of event location is 20700, 20800, -1800, and the best double-couple first-motion estimate has dip direction = 200° , dip = 70° , and rake = 0° . The quality of the location is fair and the quality of the first-motion information is fair.

Event 13 3/27/91 04:58:50 > 50 mm 2.6 M_i

Mine records place this event in the hanging wall of the vein near the 5300-93/95 stope crosscut. The microseismic system missed this event, but the macroseismic system placed the event at mine coordinates 20225, 19925, -2000. A subsequent analysis with a variable velocity model produced a location of 20225, 19850, -1925. Waveform records for this event are missing. The 2.6 M_i estimate for this event was developed by the Montana Bureau of Mines. The event caused extensive damage to the 5300-93 crosscut near the vein and the footwall stope raise. The 5300-95 overhand cut-and-fill stope might have been damaged as well, but the stope has not been inspected.

The 5300-95 pillar is split by the boundary between subunits C above and D below. The interface was projected to encounter the east half of the stope first. As the pillar had been reduced to a height of about 70 ft by past mining of the bottom of the pillar by the 5300-95 overhand stope and continuing mining at the top of the pillar in the 5300-95 underhand stope. The stope footwall rib had almost certainly passed from subunit C to D in the eastern half of the stope. The D-E subunit interface crosses the 5300 lateral at the 95 crosscut, the western edge of damage reported for this event. Thus, the damaged section of the lateral lay predominantly within subunit E in vitreous quartzite strata.

Analysis

Slip on bedding planes and the South Control Fault are both active in this area, and both of these structural features are present at the event location. The concentration of damage in the 5300-93 overhand stope crosscut, raise, and probably the stope, although the stope was not inspected for damage, was generally consistent with both explanations. However, damage to the 5300-95 overhand crosscut suggests a bedding plane slip event since this type of event typically causes damage farther into footwall development than South Control Fault events. The lack of damage in the 5300-95 underhand stope suggests a location toward the bottom of the pillar.

The pillar configuration suggests that concentrated horizontal stresses might have created thrust movements on bedding adjacent to the pillar in addition to the normal movement commonly encountered above the pillar. Stress is being concentrated in this area as a result of mining various pillars above the 5300-95 stope. Progress in the lead 5300-101 stope would also increase pillar loading. In addition, current mining in the 5300-95 longwall stope would release normal stress along footwall bedding planes that are carrying the stresses being funneled through the pillar. High horizontal stresses coupled with a reduction in bed clamping forces could easily have caused this event.

The alternative to bedding plane slip, slip along the South Control Fault, has generally been associated with closure of the mined vein and is much less likely to occur opposite relatively unmined portions of the vein, such as the I-drift and the two cuts mined in the 5300-95 overhand stope, than after extensive mining.

Thus, this event was probably caused by thrust movement on a bedding plane driven by stress concentrated in the pillar above the 5300-95 overhand stope. This event was assigned to the-

Southern Bedding Plane Slip Set.

The best estimate of event location is 20225, 19850, -1925. The quality of the location is fair and no first-motion information is available.

Event 14 5/9/91 12:18:06 82 mm 2.8 M_l

Mine records place this event in the 5100-106 stope block. Flyrock damage associated with this event was reported on the 5100 lateral, but no damage was reported in the 5100-106 stope. The estimated magnitude of 2.8 was reported by the Montana Bureau of Mines. The microseismic system located the event deep in the hanging wall southwest of the North Control Fault and above active mining in the 5100-106 underhand stope. Various macroseismic location estimates were developed deeper into the hanging wall, but most of these estimates were clearly unreasonable.

Mining in this area had cut the 5100 level off from much of the hanging wall. The exception was the 5100-106 pillar, which had started a couple of cuts above the 5100 level. However, the only damage reported was shakedown on the 5100 level. There was no damage in the stopes. The shakedown suggests that the event must have been at or above the 5100 level in order for the shock waves to travel through the pillar. It also suggests that the stopes had better ground support than the lateral.

Solutions

1. One of the solutions developed for the microseismic system location (21000, 20342, -1556) produced a good first-motion pattern showing purely right-lateral slip on a steeply dipping, west-northwest-striking plane. This pattern included a single discrepant channel (figure C-6A). The other pattern suggested vertical slip on the vein with the hanging wall moving downward (figure C-6B) and one marginally discrepant geophone.
2. The various locations identified by the macroseismic and combined macroseismic systems (mine macroseismic location 21450, 20650, -1850; automatic macroseismic location 20507, 19925, -1294; automatic combined macroseismic location 20646, 19955, -1412) failed to provide good first-motion solutions.
3. From the seismic results, and assuming that the event did occur on the North Control Fault, it appears that splitting the difference between the microseismic system and mine macroseismic system locations might provide a reasonable compromise. This compromise location lies on the North Control Fault at the elevation of the bottom of the 5100-106 pillar. The first-motion pattern developed for this location shows right-lateral movement on a plane subparallel to the North Control Fault with a single marginally discrepant geophone (figure C-6C).

Analysis

The inferred North Control Fault location provided the best solution; showing right-lateral slip on the North Control Fault in the vein hanging wall. A better guess for the actual location of this event would likely bring the pattern further into focus. This event was classified as part of the—

North Control Fault Slip Set.

The best estimate of event location is 21250, 20500, -1700. The quality of the location and the first-motion information are poor. The first-motion solution is dip direction = 90° dip = 80°, and rake = -40°.

Figure C-6.—First-motion patterns, May 9, 1991, event. *A-B*, Alternate first-motion interpretations for microseismic system location; *C*, compromise location.

Event 15	5/17/91	00:34:18	80 mm	2.7 M _L
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Event magnitude was estimated by the mine at 2.0, while the Montana Bureau of Mines reported a magnitude of 2.7.

This event was poorly located. While the location elevation suggests that it was in line with the lower 5300-107 stope, minor amounts of flyrock and lower rib damage were reported in the 5100-106 stope instead. The location identified by the microseismic system was sufficiently northeast of the mine that, given the rapid deterioration in location accuracy with distance from the net, it could have occurred virtually anywhere. However, the most likely location was somewhere on the North Control Fault. Thus, it was assigned to the

North Control Fault Slip Set

The best estimate of event location is 21175, 20975, -2125. The quality of the location is poor and no first-motion information is available.

Event 16 5/23/91 00:36:40 80 mm 2.5 M_i

Mine records place this event in the 5300 lateral near the 95/97 crosscut. The microseismic system did not record a location, but the macroseismic system did monitor the event (files 91052300.wvb, 91052300.wvm).

This was the second of two large events (the first was a 2.4 M_i event on May 22) that caused extensive damage to a 200-ft section of the 5300-level lateral between the 5300-95 and 5300-97 crosscuts (figures C-7 and C-8). A section of the 5210-95 ramp directly above the damaged portion of the 5300 lateral also suffered minor damage. Slickensides and offsets in rock bolt holes were observed, indicating normal movement on bedding in the damaged portion of the 5210 sublevel. It is not clear how much of the offset was associated with this event.

The closest active mining was in the 5300-95 stope, which was being mined down through the 5300-95 pillar. This pillar was located in the block of vein immediately above the 5300 level. As of the end of May, the pillar had been reduced to a height of about 50 ft from its original 200 ft. Mining in this block included three overhand cuts (30 ft) mined upward from floor level on the 5300 level. The central 5300-101 stope was ahead of the 95 stope and was completely filled. A gap between the 95 footwall and 101 pillars created a 65-ft-wide pillar that connected the 5300-95 pillar to the abutment (figure C-1).

The eastern portion of the 5300-95 pillar is split by the boundary between subunits C above and D below. As the pillar was reduced to a height of about 50 ft, the stope footwall rib almost certainly passed from subunit C to D in the eastern end of the stope. Subunit C is projected to disappear entirely from the stope footwall somewhere below the 5400 level. The D-E subunit interface crosses the 5300 lateral at the 95 crosscut, which was the western edge of damage reported for this event. Thus, the damaged section of the lateral lay entirely within subunit E in predominantly vitreous quartzite strata. The D-E interface extends eastward to the southern end of the 101 stope on the 5300 level.

Intense seismicity was also experienced during initial driving of the 5300-95 crosscut through this same stratum. Six 4-in. in diameter, 100-ft-long destress holes were shot to reduce rock burst hazards in driving the crosscut.

Solutions

1. The microseismic system missed this event.
2. A location of 20200, 20170, -1860 developed by the mine from macroseismic system data lies in the vein footwall at the active stope horizon and above the intersection of the 97 crosscut with the 5300 haulageway. At this location, all but one of the geophones show an implosional first motion. However, a shear first-motion pattern could also be constructed. The pattern shows predominantly right-lateral movement on a plane essentially parallel to bedding with a minor normal component (figure C-9).
3. The location identified automatically by the macroseismic system (19912, 20223, -1406) was shifted up and west from the mine-derived location. This location was also much higher than the damaged lateral. This solution shows slip on a surface with strike matching bedding, but with a shallow dip.

Figure C-7.—Damage caused by May 23, 1991 event. A, Plan view showing relative location of 5210-95 ramp and 5300 lateral; B, damage to 5300 lateral; C, damage to 5210-95 ramp.

A

B

Figure C-8.—Damage to 5300-level lateral between 5300-95 and 5300-97 crosscuts caused by May 23, 1991, event. *A*, Looking northeast; *B*, damage to back.

Figure C-9.—First-motion pattern, May 23, 1991, event

abutment of subunit C. In addition, intense seismicity was also encountered in driving the 5300-95 crosscut. This seismic activity is indicative of a highly stressed portion of the rock mass, which was borne out by rock-burst experience and an in situ overcore stress measurement in the 5300-101 crosscut stub (Whyatt and others, 1995b).

The first-motion pattern was primarily implosional. However, it is not clear what mined area would have imploded. While damage to the haulageway was significant, the additional cavities developed were comparable to the cavities mapped for nearby strain bursts with magnitudes of 1.0 and less. An alternative explanation might involve a strain burst at a pillar or an abutment, particularly one in the same stratum that intersects the damaged section of the main haulageway. However, the absence of damage in the 5300-95 stope suggests that the event source was somewhat removed from the stope.

The shear interpretation of the first-motion pattern suggests that slip on a bedding plane is most likely. However, this event was unusually deep into the footwall for a bedding plane slip event and had an unusually strong strike-slip component. Thus, this event was likely associated with the unusual pillar geometry created by the 5300-95 pillar and the gap between the 95 footwall and 101 stopes. In fact, a vertical section of this gap constructed perpendicular to the maximum horizontal principal stress (figure C-10) shows that the damaged sections of the 5300 level and the 5210 sublevel were loaded by the pillar. Furthermore, the first-motion pattern provides for shortening in the northwest direction of the pillar, with minor vertical shortening driven by overburden loading. Lengthening is indicated in the southwest-northeast direction where mining had progressed on either side of the gap pillar (figure C-11).

The deep footwall location and right-lateral component of this event are unusual for bed slip events in this part of the mine and appear to reflect a unique pillar geometry. This event was assigned to the—

4. A location automatically calculated by the macroseismic system based on data from both macro-seismic files (20163, 20618, -2184) provided a good first-motion solution with normal movement on bedding, but the location was far removed from the site of damage, from mining, and from south-dipping bedding.

Analysis

This was the second major event to damage this portion of the 5300 level (May 22 = 2.4 M_L , and May 23 = 2.5 M_L) and followed a pair of events that also damaged 5300 93 development (crosscut and raise) at the vein (March 21 = 1.5 M_L , and March 27 = 2.6 M_L). The concentration of activity accompanied mining of only three cuts in the 5300-95 stope, but these cuts had eliminated the bottom pillar

Southern Bedding Plane Slip Set

The best estimate of event location is 20200, 20170, -1860. The quality of the location is fair and the quality of the first-motion information is fair. The first-motion solution is dip direction = 210° , dip = 55° , and rake = -140° .

Figure C-10.—Vertical section showing damaged sections of 5300 level and 5210 sublevel as seen through 95-101 gap pillar

Figure C-11.—Plan view showing location of May 23, 1991, event and view through vein gap.

Event 17 6/12/91 22:03:39 80 mm 3.0 M_i

Mine records place this event in the 5300-87 stope block just above the 5300 level. The macroseismic system did record the event (files 91061203.wvm and .wvb). The magnitude was estimated by the mine at 3.0 M_i, while the Montana Bureau of Mines reported a magnitude of 2.95. The event occurred at the end of the Lucky Friday vein where it meets the South Control Fault. The range of location elevations generally associate the event with the 53-95 pillar horizon.

Reported damage was limited to spalling in vein footwall areas where the South Control Fault crosses 5100- and 5300-level development openings. However, there were no indications of shear movement associated with this event, even in areas where spalling was observed.

The 5300-95 pillar had been reduced to about 70 ft in height. The western portions of the stope were being mined down through the bottom portion of subunit C. The east end of the stope had just passed from subunit C to D. The distribution of rock types along the South Control Fault is not known.

First-Motion Patterns

A wide range of locations have been proposed for this event. They are summarized in figure C-12. First-motion patterns developed for the various proposed locations follow.

1. A first-motion pattern generated for the microseismic system location (20008, 19906, -1778) failed to line up with local structure. However, this location is just above the horizon of the 510 geophone. A small change in elevation, for example, to -1725, would reverse the apparent polarity of this geophone and create a strike-slip first-motion pattern (figure C-13A) that implies left-lateral slip on an east-west striking plane subparallel to the South Control Fault. This sense of movement is consistent with the location on the hanging wall side of the vein on the South Control Fault.
2. The location developed automatically by the macroseismic system (19781, 19813, -1488) was both higher and southwest of the location developed by the microseismic system. It shows a pattern of slip on a vertical plane with the northeastern block moving downward (figure C-13B). This vertical plane is nearly parallel to the South Control Fault.
3. The location developed for the combined macroseismic files (19628, 19600, -1424) shows vertical slip on a northeasterly striking, steeply dipping plane with the northwestern block moving down (figure C-13C).
4. A location developed by the mine from the full set of macroseismic data (19900, 19980, -1860) lies just north of the confluence of the footwall vein and South Control Fault. The first-motion solution for the full data set shows vertical offset on a steeply dipping plane with a east-northeasterly strike, which is similar to the previous solution. However, a small change in elevation, for example, to -1725, would move this event above the 5100 level and would produce a left-lateral, double-couple-pattern (figure C-13D).
5. A second location (19900, 19740, -1935) was developed by the mine from macroseismic system data) without the 510 geophone, which had shown the largest error in the previous location. The modest southwestern movement of the location estimate resulted in a significant change in the

Figure C-12.—Various locations proposed for June 12, 1991, event. A, Plan view, 5100 level; B, longitudinal section along vein.

Figure C-12 (continued).—Various locations proposed for June 12, 1991, event.
A, Plan view, 5100 level; B, longitudinal section along vein.

Figure C-13.—First-motion patterns, June 12, 1991, event. *A*, Macroseismic system location; *B*, automated macroseismic system location; *C*, location derived from combined files; *D*, mine macroseismic system location; *E*, alternative interpretation using mine macroseismic system location and discarding 510 geophone data; *F*, alternative interpretation using mine macroseismic system location and discarding 510 geophone data; *G-H*, alternative macroseismic system locations using revised velocity model.

first-motion pattern, suggesting right-lateral slip on the South Control Fault with the mine block moving downward as well (figure C-13E). An alternative first-motion pattern for this location (figure C-13F) did not align well with either the vein, bedding, or the South Control Fault.

6. A constant, but revised, velocity model was used to construct a location at 19950, 20000, -1600. A variable-velocity model was used to construct another location at 19950, 19975, -1625. These nearly identical locations produced essentially identical first-motion patterns. The first of two alternative patterns (figure C-13G) suggested vertical movement on the vein, similar to two of the previous solutions. The second (figure C-13H) suggested left-lateral movement on the South Control Fault with the mine block moving downward. This was similar to the left-lateral movement arising from the revised microseismic system location (figure C-13A) and the pattern arising from the revised mine macroseismic system location (figure C-13D).

Analysis

Observed spalling on the South Control Fault and the lack of damage associated with this event argued against both bedding plane slip and vein slip as mechanisms and in favor of a South Control Fault slip mechanism. The various locations and their associated first-motion patterns present a confusing picture, suggesting vein slip as much as fault slip. However, minor modifications to event elevations resulted in a consistent indication of left-lateral slip on the South Control Fault. Strike-slip movement on the vein at this location was also possible. However, the pattern of mining-induced stress suggests, and other events confirm, that a right-lateral sense of movement would result.

Thus, this event was caused by left-lateral strike-slip movement on the South Control Fault in the vein hanging wall. It was assigned to the-

South Control Fault Strike Slip Set

The best estimate of event location is 20008, 19906, -1725. The quality of the location and the first-motion information are fair. The first-motion solution is dip direction = 85° , dip = 65° , and rake = -180° .

Event 18 7/20/91 08:49:19 73 mm 2.6 M_L

Mine records place this event in the footwall of the 49-93 stope block in the general area of the South Control Fault and above the 5100-95 pillar, although the reported locations varied widely. No damage was reported from this event. A number of estimated magnitudes were developed, including estimates of 1.8 and 2.6 M_L by the mine and an estimate of 2.1 M_L by the Montana Bureau of Mines.

Two events were recorded in quick succession in this area (files 91072001 and 91072002.wvm). The time differences were well within the errors expected from the unsynchronized clocks. File 02 showed the larger amplitude, suggesting it measured the large event.

Mining in the 95 panel was active in the 4900 93/95 stope on the Main vein. This stope was being mined in the shadow of previous mining of the footwall vein. The 5300-95 Main vein and footwall stopes were also active. The 5300-95 footwall stope had reduced the pillar to about 40 ft in height. The Main vein stope was being mined in the stress shadow of the footwall stope, lagging the footwall stope by about 70 ft. The 5100-95 pillar was not being mined.

Solutions

1. The first-motion pattern produced for the microseismic system location (19618, 20500, -1483) shows right-lateral slip on a vertical plane parallel to the South Control Fault (figure C-14A).
2. The first-motion pattern produced for the location automatically calculated by the macroseismic system (19987, 19672, -1309) is also right lateral, but on a more easterly striking vertical plane (figure C-14B).
3. Since the first-motion patterns appear to correspond to right-lateral slip on the South Control Fault, but the locations were not on this fault, an arbitrary location on the fault at the 4900 level was proposed at 19700, 20100, -1500. This location resulted in a good first-motion pattern showing right-lateral slip on a vertical plane striking parallel to the South Control Fault (figure C-14C).
4. Similar first-motion results were obtained for the 01 event, suggesting that it might have been a precursory slip on the South Control Fault (figure C-14D). (First-motion pattern for location 19700, 20100, -1500 is shown).

Thus, this event, although poorly located, was caused by right-lateral slip on the South Control Fault. It was assigned to the-

South Control Fault Strike-Slip Set

The best estimate of event location is 19700, 20100, -1500. The quality of the location is poor and the quality of the first-motion is fair. The first-motion solution is dip direction = 305°, dip = 80°, and rake = 20°.

Figure C-14.—First-motion patterns, July 20, 1991, event. *A*, Microseismic system location; *B*, automatic macroseismic system location; *C*, arbitrary location on South Control Fault; *D*, precursor event.

Event 19 7/31/91 12:04:28 80 mm 2.6 M_L

Mine records place this event in the 5300-95 stope block. The macroseismic system recorded the event in files 91073101.wvm and 91073102.wvb. The local magnitude of the event was estimated at 2.3 by the mine and 2.6 by the Montana Bureau of Mines.

Minor amounts of damage (less than 25 short tons) were reported in the eastern part of the 5210-95 stope in the hanging wall rib near the slot intersection.

This event was monitored by macroseismic systems A and B. Event locations from the microseismic system and the individual macroseismic files were widely scattered in the vicinity of the axial plane of the Hook Anticline but all had elevations near the 5300 level. The combined macroseismic files located the event higher and in the hanging wall close to the South Control Fault.

Mining in this area was progressing in both the 95 and 101 stopes. The 5300-95 stope was continuing to be mined down toward the 5300 level through a pillar that was about 40 ft high. The 5500-101 stope was advancing into the abutment at the -1950-ft elevation. A small pillar had also been formed on strike between the progressing 5500-101 stope and the older 5300-95 overhand stopes. These stopes had progressed three cuts before being halted, but were not mined to the 101 stope end line.

Solutions

The locations proposed for this event are plotted in figure C-15. First-motion patterns for these locations were developed as follows:

1. The first-motion pattern for the microseismic system location (20366, 20022, -1953) had no apparent relationship to geology and included a discrepant geophone.
2. Looking at the location (20583, 19908, -1986) derived from file 01.wvm gave a thrust first motion on a north-northwest-striking plane.
3. Considering the 02.wvb file in a similar fashion (20170, 20201, -1846) also suggested slip on a north-northwest-striking plane but a plane having a vertical dip.
4. The first-motion pattern for the combined files at the combined file location (20309, 19602, -1610) differed considerably from the previous results, indicating left-lateral slip on the South Control Fault with a marginally discrepant geophone (figure C-16A).
5. This solution was tested by shifting the location to an arbitrary position on the South Control Fault. A location deep into hanging wall (20500, 19600, -1810) at the 5300-level horizon produced a left-lateral, first-motion pattern on a vertical plane parallel to the South Control Fault with a marginally discrepant geophone (figure C-16B).
6. A shallower hanging wall location (20250, 19700, -1810) produced a similar first-motion pattern with no discrepant geophones (figure C-16C).

Figure C-15.—Various locations proposed for July 31, 1991, event.

Figure C-16.—First-motion patterns, July 31, 1991, event. A, Location derived from combined macroseismic files; B, arbitrary location on South Control Fault deep in vein hanging wall; C, arbitrary location on south Control Fault at shallow depths in hanging wall.

7. A first-motion pattern for an alternative location estimate (20150, 20170, -1873) developed from macroseismic system data produced various patterns with no relationship to local structures and two discrepant channels.

Thus, this event, although poorly located (possibly because of mined ground between geophones and the event), occurred on the South Control Fault near the horizon of the mining front in the 5300-101 stope. Minor damage from this event occurred in the hanging wall side of the stope, an unusual damage pattern that confirmed the hanging wall position of the event. Shifting of the event location along the South Control Fault in the hanging wall provided generally good solutions, with slip planes subparallel to the South Control Fault arising from locations deeper in the hanging wall. This was one

of the few large events that has occurred on the South Control Fault in the hanging wall. It was assigned to the—

South Control Fault Strike-Slip Set

The best estimate of event location is 20309, 19602, -1610. The quality of the location is fair and the quality of the first-motion information is poor. The first-motion solution is dip direction = 145° , dip = 85° , and rake = 170° .

Event 20 8/17/91 01:32:51 78 mm 2.9 M_L

Mine records place this event in the 4900-106 west stope block near cut 11. The local magnitude was estimated at 2.6 by the mine and 2.9 by the Montana Bureau of Mines.

Two events were measured at the approximate time recorded for this event [files 91081700.wvm at 01:32:49.336, 91081702; wvb at 01:32:51.760 (largest amplitude); 91081701.wvm at 01:34:35.250; and 91081703.wvb at 01:34:37.699]. Both events were monitored by macroseismic systems A and B, and the .wvm and .wvb files contain results from these respective systems. The first event was identified as the largest based on the relative amplitude of the recorded waveforms. Event locations from the microseismic and .wvb files clustered near the slot location in the footwall at the 5000-level horizon.

This event caused 200 short tons of damage to both ribs of cut 11 of the 5100-106 stope (figure C-17). Also, a broken cap and post were discovered in the previous slot area after the event. Sand in the back sagged (especially on the west side), suggesting that significant closure of the vein occurred. The pillar between the two access slots seemed to be very fractured. There was no evidence of offset on any other accessible structural features. The event was located in the vicinity of destress blast holes missed in the December 1990 destress blast and could have been related to incomplete destressing of this pillar area.

Figure C-17.—Location of damage to 4900-106 stope caused by January 31, 1991, event

Mining in this area had reduced the 5100-106 pillar to about 70 ft. The next pillar above (4900-106) and the abutment below were over 200 ft away. Mining was also cutting through a small neck of pillar that joined the 5100-106 pillar to the adjacent and higher (now diagonally up and west) 5100-101 pillar.

The 5100-106 pillar area lies outside the boundary between subunits B and C. Strata in this area are flatter than is typical and form a small, steeply plunging fold that roughly reflects and amplifies a bend in the vein.

Solutions

1. The first-motion pattern developed for the microseismic system location (20582, 20643, -1656) showed vertical slip on a vertical plane oriented slightly north of east, with the northern block moving down (figure C-18A). The pattern was well constrained and did not include discrepant channels. The slip plane was roughly parallel to the vein where it meets the North Control Fault.
2. Alternative first-motion patterns, each with a single discrepant channel, were also produced for the microseismic system location. Both patterns indicated normal faulting on a northeast-striking plane dipping steeply to the northwest or at a shallow angle to the southeast. They differed only in showing a small component of either right-lateral or left-lateral slip. The steeply dipping plane of these solutions was similar in strike to the vein south of the bend and matched the dip of the essentially vertical vein. In this solution, the northwestern block moved downward, as was the case in the first solution.
3. The first-motion pattern developed for a location derived from the 02.wvb file (20671, 20679, -1509) (figure C-18B) was quite similar to the location identified by the microseismic system.
4. The first-motion pattern developed for a location based only on the 00.wvm file (21495, 20850, -1483) showed a vertical slip pattern (figure C-18C) similar to the pattern shown by the microseismic system (figure C-18A). However, this location was considerably farther into the hanging wall than the other locations and was well northeast of the North Control Fault. The first-motion pattern was not consistent with any conceivable rock mass adjustment to mining that would be occurring at this location. (The accuracy of the seismic systems for locating events this deep in the hanging wall is very poor.)
5. The first-motion pattern for the combined macroseismic data files (20612, 20752, -1452) suggested vertical slip as well. In this case, slip was on a plane parallel to the damaged section of the 5210-95 stope with a steep southeast dip (figure C-18D).
6. The first-motion pattern for the combined macroseismic data files for the subsequent smaller event (located at 20779, 20274, -1737) provided a clearer first-motion picture that suggests vertical movement on a vertical, northwest-striking plane with the footwall side down (figure C-18E).

Analysis

The first-motion patterns developed for this event consistently showed vertical slip on a northeast-bearing plane with the footwall moving downward. This pattern was consistent with similar events in the 95 area. The fact that much of the vein previously in contact with hard subunit A (4900 pillar) and C (5100 pillar) had been removed was another similarity. Vertical shear movement was driven

Figure C-18.—First-motion patterns, August 17, 1991, event. **A**, Microseismic system location; **B**, macroseismic system location using only system B geophones; **C**, macroseismic system location using only system A geophones; **D**, combined macroseismic system location; **E**, combined macroseismic system location for subsequent event.

by concentrated stresses parallel to hard subunits, which have been described as acting as lithopillars. The vein slip mechanism was also evident in a smaller subsequent event. Three of the four locations developed were very close to the vein where it turns through a northeast orientation (figure 19). The location determined from the 02.wvb file (macroseismic system B) was right on the vein and provided the most northerly strike for the slip plane. This location appears to provide the best result.

The section of pillar that was missed in the destress blast likely formed an asperity that was sheared off in this event. Destress holes in this area were lost because of excessive fracturing that blocked loading of deeper sections of the holes. The upper, unblocked section of each hole was loaded and shot. Thus, the asperity would have been located toward the bottom of this pillar rather than the top. This may explain the relatively minor damage to the stope compared with other vein slip bursts. The similarity between the extent of stope damage, which suggested considerable closure of this section of the stope, and the location of the series of missed holes was also suggestive of an asperity of limited extent. This interpretation suggests that the event occurred in the pillar, somewhat below the best seismic location.

Thus, this event was assigned to the -

Vein Slip Set

The best estimate of event location is 20671, 20679, -1509. The quality of the location is good and the quality of the first-motion information is fair. The first-motion solution is dip direction = 60° , dip = 30° , and rake = -160° .

Figure C-19.—Various locations proposed for August 17, 1991, event.

Event 21 9/19/91 09:20:28 77 mm 3.6 M_L

Mine records place this event in the 4900-106 east stope block around cut 11. The local magnitudes of this event were estimated at 3.5 by the Montana Bureau of Mines and 3.6 by the mine. The event was monitored by the macroseismic system (files 91091902.wvb and 91091903.wvm) and the Battelle Northwest array. Williams and others (1993) provide an extensive description of seismic and observational evidence gathered from this event.

The locations identified by the microseismic system (20714, 20678, -1615) and macroseismic system [constant velocity, 20964, 20619, -1501; and variable velocity, 20820, 20614, -1600) clustered between the F3 and North Control Faults at elevations between the 4900 and 5000 levels. The cluster ranged from a location at the vein to locations deeper into the hanging wall (and higher in elevation).

The event caused extensive damage (approximately 2000 short tons of rock) in the 5100-106 east and west stopes and the 4660 northeast lateral. Damage in the 5100-106 stope was estimated at about 1000 short tons, most of which came from the floor, walls, and back in a 200-ft zone in the east stope. The floor was observed to have been thrown up from the hanging wall side of the stope. Damage was particularly heavy along the northeastern end of the stope where it turned and followed the North Control Fault; an LHD was buried at this corner. In addition, three caps were broken and the walls were "bagged out" in the old slot intersection. On the 4660 level, there were about 1000 short tons of damage in the northeast lateral, 108 crosscut, and 110 crosscut between the North Control Fault and the F3 Fault. Much of the damage on the 4660 level appeared to be shakedown of rock rubblized by previous bursts. There was no damage in the 4660 lateral west of the F3 Fault. Only minor damage was observed in the 4900-105/107 stope, which had one unfilled cut at the 4660 level, although a broken cap and minor falls of sand from the backfill mat indicated that some closure of the stope had occurred. Damage was limited in this area to the collapse of some rotten timber and minor amounts of fill from the back.

Mining had reduced the 5100-106 pillar to about 70 ft. The next pillar above (4900-106) and the abutment below were over 200 ft away. Mining was also cutting through a small neck of pillar that joined the 5100-106 pillar to the adjacent and higher (now diagonally up and west) 5100-101 pillar. Mining had been halted in the 4900-106 stope, leaving a remnant pillar. This pillar was 60 ft high on the west side and 100 ft on the east, with the top of the pillar even with the 4660 level. Mining of the next-to-last cut of the 4660 108/110 pillar had reduced that pillar to only 10 ft high in places with a maximum height of 30 ft. Mining in the 107 longwall stope below these pillars had reached an elevation of -1980 ft (about the 5400 level). It does not appear that the 107 longwall stope had reached the F3 Fault at the time of the burst, and the ramp system supporting the 107 longwall stope was located south of the F3 Fault.

Solutions

1. Using published first motions for each channel, first-motion solutions developed for all three proposed locations were inconclusive and showed dilation over a wedge of the stereonet smaller than a quadrant. Thus, a wide range of solutions were possible. Williams and others (1993) invoked a solution that included a slip plane striking N 25° E and dipping 55° southeast using the constant velocity result from the macroseismic system (figure C-204). However, bedding at this orientation appears to exist only west of the F3 Fault. An alternative solution resembles other vertical vein slip events. For example, a N 70° E-striking plane dipping 70° or steeper to northwest (or a more easterly plane with a steeper dip) is fully consistent with the first-motion

Figure C-20.—First-motion patterns, September 19, 1991, event. A, Location reported by Williams and others (1993); B, alternative first-motion pattern using polarities reported by Williams and others (1993); C, microseismic system location and revised polarities; D, macroseismic system location and revised polarities; E, macroseismic system location using variable velocity model and revised polarities; F, arbitrary location on North Control Fault.

pattern (figure C-20B). For comparison, the vein strikes N 45° E and dips steeply to the northwest in the 5100-106 pillar and strikes approximately N 70° E and dips steeply to the northwest on the 4660 level.

First motions for geophones 521, 522 and 590 were difficult to ascertain. If waveforms from these geophones were compressional, as interpreted in this work, instead of dilational, as reported by Williams and others (1993), then different first-motion patterns are responsible for the three locations.

1. The location identified by the microseismic system, which lay on the vein at the F3 Fault, results in a first-motion pattern that can be interpreted in two different ways (figure C-20C). The first alternative, vertical slip on north-northeasterly -striking plane, is shown. The sense of vertical slip in this interpretation is consistent with prior vein vertical slip events. In the second alternative, these channels are seen as the southern quadrants of strike-slip movement on a west-northwest- striking fault. The sense of movement for this interpretation would be right lateral, consistent with slip events that commonly occur in the hanging wall on the North Control Fault. The 510 geophone appears to be discrepant in this interpretation, but was situated at the edge of the stereonet where a modest deepening of this location to below the 5100 level would change this channel to a compressional first motion in the northeastern quadrant.
2. A location developed from a constant-velocity model and the macroseismic system produced a similar first-motion pattern. The slip plane in this pattern had a slightly more northerly orientation and a slightly shallower (but still steep) dip than the previous pattern with one marginally discrepant channel (figure C-20D).
3. The location produced by the microseismic system using a variable-velocity model was farthest from the vein and produced a first-motion pattern that was similar to previous patterns but shifted slightly more toward a northerly strike and slightly toward a shallower dip with one marginally discrepant channel (figure C-20E).
4. The possibility that this event was caused by slip on the North Control Fault was explored further by finding first-motion patterns for an arbitrary location on the North Control Fault (20900, 20700, -1800). This location was intentionally placed below the 5100 level so that the 510 geophone would be moved to the northeast quadrant. The results show a number of possible first-motion patterns, most of which did not resemble local structures. However, one of these did correspond with right-lateral slip on the North Control Fault (figure C-20F).

Analysis

Intense damage along the North Control Fault section of the 5100-106 stope and first-motion solutions suggest that this event was caused by slip along the North Control Fault in the hanging wall of, and close to, the vein. The 510 geophone strongly suggests that the event was located somewhat deeper than the 5100 level (-1750 ft) where it provides a compressional motion in the northeast quadrant of the stereonet. Thus, this event was assigned to the -

North Control Fault Slip Set.

This conclusion updates the earlier interpretation by Williams and others (1993). The best estimate of event location is 20900, 20700, -1800. The quality of the location and first-motion information are poor. The first-motion solution is dip direction = 40°, dip = 80°, and rake = 0°.

Event 22 11/11/91 03:33:50 > 50 mm 2.5 M_L

Mine records place this event in the footwall of the 5210-95 stope block. The local magnitude of 2.5 was estimated by the Montana Bureau of Mines. The event was monitored by the macroseismic system (file 91111100.wvm).

This event was located in the immediate footwall of the 5300-95 pillar. The microseismic system suggested the event occurred near the bottom of the pillar, while the macroseismic system located the event below the 53-95 overhand stopes that had been mined up into this pillar. The stope was mined overhand for only three cuts.

Mining in this area had reduced the 5300-95 stope to a height of only 30 ft. A 30-ft-high mined and filled section of vein separated the pillar from the underlying abutment. The central and western portions of the stope were being mined through the very bottom portion of subunit C. The eastern end of the stope had already passed from subunit C to D.

This event caused minor damage in the 5300-95 crosscut and the 5210-95 downramp (figure C-21). This event might also have been associated with a fluid injection experiment in which large volumes of water had been pumped at low pressure into holes intersecting the bedding planes passing through the event location (figure C-22).

Solutions

1. The location identified by the microseismic system (20125,20000,-1910) generated a first-motion pattern that indicated normal slip on footwall bedding (figure C-23). The pattern was fairly well constrained and without discrepant channels.
2. First-motion patterns developed from the macroseismic system location (20175,20100,-1975) were more confused and included a discrepant channel.
3. Two solutions were generated for a location (20200, 20000, -1875) developed from macroseismic system data with a variable-velocity model. Both solutions included a discrepant geophone. Neither solution included a slip plane that resembled the orientation of local structures.

Analysis

This event was caused by bedding plane slip in the footwall, probably within subunit D or along the boundary of C and D. The relatively low seismograph amplitude (approximately 50 mm versus a pegged 80 mm¹¹ for similar events) suggested that the event had a lower peak amplitude and hence lower stress drop than most of the other large events. This could be related to the location of the event in the softer, sericitic quartzite of subunit D. This event was assigned to the-

¹¹80 mm is the maximum amplitude of the mine seismograph.

Southern Bedding Plane Slip Set

The best estimate of event location is 20125, 20000, -1910. The quality of the location is good and the quality of the first-motion information is fair. The first-motion solution is dip direction = 200°, dip = 50°, and rake = -60°.

Figure C-21.—Location of damage to 5210-95 ramp caused by November 11, 1991, event.

Figure C-22.—
Location of
November 11,
1991, event
with respect
to fluid injection
holes and
bedding in
vein footwall

Figure C-23.—First-motion pattern,
November 11, 1991, event.

Event 23A, B

12/11/91

Two large seismic events that occurred with blasting in the 95 stope area were the proximate cause for 32 short tons of damage in the 4900-93/95 stope (elevation -1400) and 12 short tons in the 5300-95 Main vein stope (elevation -1900). Damage was reported in the western portions of these stopes (figure C-24) in the stress shadow of mined portions of the footwall stopes. Some evidence of slip was observed in the 5100-92 hanging wall stope ramp at the South Control Fault. Since these events occurred within a 25-min period, it is not entirely clear which caused what damage. Mine damage reports listed the larger first event as being responsible, while mine summary reports attributed the damage to the second event.

At the time of these events, there was active mining in the last fragments of the 4900-95 pillar and in the 5300-95 Main vein stope (in the stress shadow of the footwall stope). The Main vein stope was 50 ft above the bottom of mining in the footwall stope.

Event 23A 12/11/91 13:37:03 75 mm 3.0 M_i

The microseismic system located this event at 19883, 19986, -1766 in the footwall of the vein alongside a backfilled portion of the 5300-95 footwall stope. This stope lies at the western end of the Lucky Friday vein. The location was also very close to the South Control Fault. Subsequent analysis produced location estimates of 19900, 19950, -1650 for a constant velocity model and 19975, 19875, -1650 for a variable velocity model.

The macroseismic system did not collect enough usable data (too few channels) to provide an estimate of event location or first-motion pattern (file 91121103.wvm).

The mechanism of this event appears to have been slip on the South Control Fault. The location of damage required a South Control Fault event located at the end of the vein or in the hanging wall. The mix of hanging wall and footwall damage to the 5300-95 and 4900-93/95 stopes, as well as the location identified by the microseismic system, favored slip on the South Control Fault at the end of the vein. The other alternative is bedding plane slip. However, bedding plane events occur predominantly in the footwall, and usually damage the footwall rib and floor of stopes as well as development openings. Shocks waves from bedding plane events would be unlikely to cause damage to Main vein stopes after they pass through the filled footwall vein. Thus, this event was assigned to the-

South Control Fault Strike-Slip Set

The best estimate of event location is 19983, 19986, -1766. The quality of the location is fair and first-motion information is not available.

Event 23B 12/11/91 14:02:24 76 mm 2.4 M_i

The microseismic system located this event in the footwall at the eastern end of the 5100-95 remnant pillar (20297, 20061, -1544). A revised location of (20000, 19950, -1615) was also developed, which placed the event just within the footwall of the vein near the western end of the stope. These locations lay near the top of subunit C. This event was detected by regional seismographs operated by the Montana Bureau of Mines and Battelle Northwest.

A first-motion solution (91121102.dat) had all but the 522 geophone (figure C-25) showing an implosional first motion. These arrivals were generally consistent with normal bedding plane slip (the bed intersected the footwall vein), but were not consistent with strike-slip movement on the South Control Fault or vein slip.

The lack of damage from this event was likely the result of the 95-footwall stopes being filled and inactive. The first-motion solutions were compatible with a bed slip event, so this event was assigned to the —

Southern Bedding Plane Slip Set

The best estimate of event location is 20297, 20061, -1544. The quality of the location is fair and the quality of the first-motion information is poor. The first-motion solution is dip direction = 190° , dip = 40° , and rake = -40° .

Figure C-24.—Location of damage caused by December 11, 1991, event. A, 4900-93-95 Main vein stope; B, 5300-95 Main vein stope.

Figure C-25.—First-motion pattern, December 11, 1991, event

APPENDIX D: CATALOG OF LARGE SEISMIC EVENTS, 1992

Six seismic events having estimated local magnitudes of 2.5 or greater occurred during 1992. The locations of these events were plotted on a longitudinal section of the vein (figure D-1) and plan view maps by level (figures D-2 and D-3). The available information on each event is reviewed on a case-by-case basis in the remainder of this appendix.

Figure D-1.—Location of major seismic events during 1992, Lucky Friday vein. This longitudinal view shows the true area of the vein and rotates from a point south of the vein in the western portion of the mine to a point east of the vein in the northern portion of the mine.

Figure D-2.—Location of major seismic events during 1992, plan view, 5100 level.

Figure D-3.—Location of major seismic events during 1992, plan view, 5300 level.

Event 24 1/30/92 22:57:26 79 mm 2.5 M_L

Mine records place this event in the footwall of the 5210-95 stope. The event was monitored by the microseismic and macroseismic systems.

Mining in the vicinity of the event was limited to the 5300-95 stope, where the 5300-95 pillar was being cut down from three to two cuts. Mining in the adjacent 101 area was also active on the longwall front.

The event caused 150 short tons of damage to the footwall rib and floor in west end of the 5210-101 stope (figure D-4). Closure was observed throughout the entire stope.

The central and western portions of the 5210-95 footwall stope were being mined through the bottom portion of subunit C, which had been almost entirely mined out up-dip. The eastern end of the stope had already passed from subunit C to D.

Figure D-4. —Location of damage to 5210-95 stope caused by January 30, 1992, event

the pillar portion of the vein. Mining had exposed most of a hard subunit C in the footwall, another characteristic of many vein slip events. This event was assigned to the—

Vein Slip Set

The best estimate of event location is 20100, 20000, -1950. The quality of the location and first-motion information is fair. The first-motion solution has dip direction = 10°, dip = 75°, and rake = -120°.

Solutions

1. A first-motion pattern developed for the microseismic system location (20100, 20000, -1950) showed vertical movement on a plane parallel to the vein with the footwall moving downward.
2. A first-motion pattern developed for the macroseismic system location (20129, 20100, -1752) showed a very similar pattern despite being over 200 ft from the position identified by the microseismic system.

Analysis

Observed stope closure and first-motion patterns were consistent with pillar failure initiated by vertical slip on

Event 25 6/27/92 10:45:45 76 mm 2.8 M_i

Mine records place this event in the 5100-106 block near the North Control Fault. The event was monitored by the macroseismic system (files 92062707.wvb and 92062709.wva). This event did not damage the mine.

The microseismic system located this event just off the northeast end of the Lucky Friday vein across the North Control Fault on the 5150 level. The vein at this horizon had been mined and filled and lay below the 5100-106 pillar. The location identified by the automatic macroseismic system lay slightly southwest of the microseismic system location and much higher, at the 4750 level, even with the 4900-107 pillar. A location generated from the combined macroseismic files lay 400 ft farther south, in the vicinity of the Offset Fault in the hanging wall.

Mining in this area was progressing in the 5100-106 stope and had reduced the pillar to less than 50 ft high. The 4900-107 pillar was not being mined, but the final cut was being taken from the 4600-108/110 pillar. The 5400-107 underhand longwall stope was also active.

The entire 5100-106 pillar lies astride the boundary between subunits C and D. The A and F3 Faults also cut this pillar. Offset on the F3 Fault brings subunits D and E into the eastern end of the stope.

Solutions

1. The NISN reported a first-motion pattern that indicated right-lateral and normal slip (mine block down) on a steep plane striking to the northwest, which was presumed to be the North Control Fault (figure D-5A).
2. The location identified by the microseismic system (20900, 20800, -1750) suggested two interesting possibilities, both with marginally discrepant geophones. The first (figure D-5B) was very similar to the NISN solution. The other showed vertical slip on a northwest-striking plane with the mine block down (figure D-5C). The discrepant geophones in this solution suggested that a shear-implosional mechanism might more closely describe the first-motion pattern. Such a solution would also suggest entirely right-lateral movement south of the fault, which would be consistent with closure of the vein.
3. A first-motion pattern developed for a location developed from the combined macroseismic files (20716, 20323, -1350) fit the NISN solution (figure D-5D) with two discrepant 5200 level geophones.

Analysis

The first-motion solutions suggested that the event was caused by some combination of right-lateral and normal movement on the North Control Fault in the hanging wall. Right-lateral shear implosional movement on the North Control Fault best fit the in-mine data but the data were contradicted by the NISN data. The NISN is insensitive to event location and thus provides the most stable indication of first motion. General confirmation of the NISN first-motion pattern was provided by the mine-wide system with some marginally discrepant geophones. Right-lateral and normal movements at the location identified by the microseismic system were both consistent with closure of

the largely mined-out vein. This mechanism was also consistent with the absence of damage from this event.

Thus, this event was assigned to the-

North Control Fault Slip Set

The best estimate of event location is 20900, 20800, -1750. The quality of the location is fair and the quality of the first-motion information is good. The first-motion solution is dip direction = 228° , dip = 75° , and rake = -138° .

Figure D-5.—First-motion patterns, June 27, 1992, event. A, Result from NISN; B-C, alternative locations identified by microseismic system; D, combined macroseismic system location.

Event 26 7/30/92 00:38:21 80 mm 2.5 M_i

The microseismic system located this event approximately 250 ft northeast of the end of the vein and across the North Control Fault at the horizon of the remaining portion of the 5100-106 pillar. This event did not cause any damage in the mine. The event was monitored by the macroseismic system (file 92073000.wva), but the 440 geophone was unusually noisy, preventing a confident first-motion pick for this channel. The macroseismic solution located the event in the vicinity of the North Control Fault and deep into the hanging wall. This location was also deep, approximately even with the advancing longwall face in the 5300-107 stope.

Mining in this area was progressing in the 5100-106 stope, which had reduced the pillar to about 40 ft high. The 4900-107 pillar was not being mined, but the 5400-107 underhand longwall stope was active.

Solutions

1. This event was monitored by the NISN and was reported (Loureance and others, 1993) to have a generally implosional first motion with good coverage (figure D-6A).
2. The first-motion pattern generated for the microseismic system location (20998, 20844, -1669) indicated an implosional first-motion pattern (figure D-6B) except for the 590 geophone. This geophone gave a clear compressional first motion; it is the only geophone that was located beneath the event.
3. A first-motion pattern developed for the macroseismic system location (20911, 21086, -1763) showed general implosion, with the exception of the 590 and 510 geophones (figure D-6C). The small decrease in location elevation from the elevation identified by the microseismic system moved the event below the 510 geophone and flipped its polarity.
4. Moving the location south and somewhat west to an arbitrary location (21000, 20670, -1760) in the hanging wall along the North Control Fault provided a pattern having two possible interpretations. The first, which used the North Control Fault as one slip plane, generated right-lateral shear implosional movement south of the fault (figure D-6D). A double-couple interpretation implied a local reversal in North Control Fault dip and showed left-lateral motion with two unsampled quadrants (figure D-6E).

Analysis

Williams and others (1995) presented a concise description of this event and concluded that the event could have been related to collapse of a pillar along the North Control Fault or some unknown structure north of the fault. The largely implosional first-motion pattern, particularly as reported by the NISN, suggests that initiation of the event was associated with closure of the vein. Closure of the vein almost certainly involved slip along the North Control Fault, as well as possible pillar failure. The event location and absence of damage suggest that slip on the North Control Fault slip was the predominant source of seismic energy. And indeed, first-motion patterns developed for a location in the hanging wall of the North Control Fault showed movement of the hanging wall toward the stope. Depending on the local dip of the North Control Fault, the first-motion pattern could be interpreted as either a shear-implosional or double-couple motion. Thus, this event was assigned to the-

Figure D-6.—First-motion patterns, July 30, 1992, event A, Result from NISN; B, microseismic system location; C, macroseismic system location; D, location on North Control Fault assuming shear-implosional pattern; E, location on North Control Fault assuming double-couple pattern.

North Control Fault Slip Set (with implosion)

The best estimate of event location is 21000, 20670, -1760. The quality of the location is poor and the quality of the first-motion information is good. The NISN first-motion pattern was implosion. The mine macroseismic system double couple solution had dip direction = 290° , dip = 80° , and rake = 20° .

Event 27 8/4/92 02:26:29 80 mm 3.0 M_L

Mine records place this event in the hanging wall of the 5400-101 stope block in the central shear zone near the 38 Offset Fault. This event was monitored by the microseismic system, the macroseismic system (file 92080400.wva), and the Montana Bureau of Mines).

The event caused a moderate amount of damage underground. A miner driving an LHD reported that damage appeared first at his location (the LHD in figure D-7) and then progressed up the access ramp to the west. Two-hundred-fifty to three-hundred short tons of concentrated damage occurred in a short section of the slot rib. Slots access three stope cuts and are thus opened to heights as great as 30 ft. A similar rib failure occurred in the hanging wall of the 5210-101 ramp where it crossed the 38 Offset Fault.

The microseismic system located this event on the vein close to the 38 and Offset Faults in the 101 area. This location placed the event on the 5450 level, just 30 ft below the floor of the 5400-101 stope. The location identified by automatic macroseismic system was 400 ft deeper and in the vicinity of the North Control Fault in the footwall. This location was not consistent with damage reported in the 5400-101 slot. An adjusted location derived from the macroseismic data was also on the 5450 level, but was shifted northwest into the footwall and toward the Offset Fault.

Mining was active in this area in the 5400-101 longwall stope at the 5400 level and in the 107 stope to the northeast, just one cut deeper. The 5300-95 footwall stope was also active, but about 100 ft higher. The only active pillar mining was in the remnant of the 5300-106 pillar.

Strata in this area are offset by the 38 and Offset Faults, which are part of a complex set of faults. Collectively, this faulted region is called the central shear zone. South of the 38 Fault, the vein leaves the soft D subunit and enters the harder E subunit at and below the 5300 level. The D subunit is deeper north of the Offset Fault.

Solutions

1. This event was monitored by the NISN, which showed right-lateral movement (figure D-8A) consistent with the strike of central shear zone faults (including the 38 Offset Fault).
2. The first-motion pattern indicated for the location identified by the microseismic system (20600, 20175, -2050) showed right-lateral movement on a northwest-trending plane close and subparallel to central shear zone faults. There was one discrepant channel (figure D-8B).
3. The first-motion pattern indicated for the adjusted macroseismic system location (20500, 20250, -2050) supported a similar solution (figure D-8C).
4. On the basis of the damage pattern, an arbitrary location (21000, 20300, -2100) was chosen northeast of the damage on the hanging wall ramp on a projection of the A Fault at a horizon below the mining front at -2020 ft. The first-motion pattern showed right-lateral and vertical slip (southern block down) on a plane striking just north of west (figure D-8D). This result was remarkably similar to other patterns developed for this event.

Figure D-7.—Damage caused by August 4, 1992, event in (A) north rib of 5400-101 access slot and (B) 5400-95 Main vein stope.

Figure D-8.—First-motion patterns, August 4, 1992, event. *A*, Result from NISN; *B*, microseismic system location; *C*, adjusted macroseismic system location; *D*, arbitrary location on A Fault as projected northeast of damage in ramp hanging wall.

Analysis

The first-motion analyses of the macroseismic data and a first-motion analysis of data from the NISN clearly indicated that right-lateral movement occurred on a plane subparallel to the 38 and Offset Faults. The 5400-101 slot rib failure suggests that the event shock wave arrived from the northeast. Damage to the 5210 hanging wall ramp indicated that the shock wave originated deeper and farther northeast into the hanging wall. Such a deep source would be consistent with the lack of damage to the stope. The slot was somewhat more vulnerable to damage than the stope since it was open to a height of 30 ft. Failure of the stope to shield the slot from the event implies that the event occurred below the stope horizon.

Estimated event locations were farther to the southwest than implied by the damage pattern, but the hanging wall portion of the central shear zone is outside of both nets, which compromised location accuracy. In fact, the estimates showed the two locations were about 400 ft apart. In spite of this distance, however, first-motion results were remarkably stable and agreed very well with the NISN. An arbitrary location projected on the A Fault generated a first-motion pattern remarkably similar to the previous patterns and showed improved separation between channels 440 and 590, which were nearly discrepant in patterns based on seismic system locations.

Thus, this event was caused by right-lateral slip in the hanging wall northeast of the 38 Fault and probably on the A Fault. This event was assigned to the—

Central Shear Zone Set

The best estimate of event location is 21000, 20300, -2100. The quality of the location is fair and the quality of the first-motion information is good. The first-motion solution is dip direction = 115° , dip = 50° , and rake = 20° .

Event 28 8/12/92 01:30:28 80 mm 3.0 M_i

Mine records place this event in the 5210-95 stope block near the South Control Fault. The event was monitored by the macroseismic system (file 92081203.wvm).

This event caused over 700 short tons of damage in the vicinity of the South Control Fault (figure D-9). Reported damage included 500 short tons from the hanging wall in the west side of the 5210-95 stope and 40 short tons in the east side, 120 short tons in the west side of the 5400-95 stope and 50 short tons in the east side, and 20 short tons in the 5300-87 crosscut.

Mining activity had opened a full cut in the 5210-95 Main vein stope that had not been filled at the time of the event. There may also have been an open cut in the footwall vein side (the final cut). Mining on the footwall side had jumped over three overhand cuts mined in the mid-1980's from the 5300 level and had established a longwall configuration in the 5400-95 stope. The first full cut of this stope was open at the time of the event.

Figure D-9. —Location of damage caused by August 12, 1992, event.

Solutions

1. The NISN (Lourence and others, 1993) reported a first-motion pattern that indicated vertical slip on a north-south vertical plane with the eastern block moving down (figure D-10A). A reinterpretation of the data using a shear implosional model suggests right-lateral movement north of a plane parallel to the South Control Fault with general implosion to the south (figure D-10B).
2. Several first-motion patterns were suggested for the location identified by the microseismic system (19850, 20050, -1875), all with discrepant phones. These suggestions included normal movement on a north-south plane, vertical slip on a north-south plane with the eastern block moving up, and right-lateral slip on northwesterly striking plane (figure D-10C). Only the last of these corresponded with a known geologic plane of weakness, the South Control Fault (although the solution plane has a more northerly strike), and the apparent movement was consistent with closure of the mined vein. Moreover, the right-lateral movement was consistent with the footwall position of this location.
3. The adjacent location identified by the mine from macroseismic system data (19875, 20000, -1850) provided a similar set of first motions (figure D-10D). Constant and variable velocity models were used to develop very similar locations (19875, 19975, -1825 and 19925, 19975, and -1775) with very similar results.
4. The location automatically identified by the macroseismic system (20070, 19359, -1374) was higher than other estimates and much farther south. The first-motion pattern included compressional first motions in the eastern half of the stereonet similar to patterns given by the NISN, as well as some compressional channels in the western half that were unlike the NISN patterns (figure D-10E). The various solutions (each with a discrepant channel) suggested right-lateral movement on a plane parallel to the South Control Fault. However, right-lateral movement was inconsistent with the proposed location in the hanging wall.
5. In some cases, a marked contrast between NISN and in-mine macroseismic net results has been resolved by proposing alternative locations for the in-mine net. Locations derived by various means have been tried and have failed to close the gap. In an effort to see if this gap could be closed, a wide range of arbitrary locations within several hundred feet in all directions were tried. The result most closely resembling the NISN result was obtained for the location 20400, 19500, -900, which lies near the vein just southeast of the axial plane of the Hook Anticline near the 4250 level. The result (figure D-10F) still has two discrepant geophones.

Analysis

The double-couple first-motion patterns developed for this event by the NISN and the in-mine macroseismic system are not in agreement. The 400 and 440 geophones are the major obstacles to agreement. A review of both of these channels showed that while the 440 geophone data were somewhat noisy, the 400 geophone data were solid. A search for location changes that would bring the macroseismic results into line with the NISN results was not very successful. The most promising result had two discrepant geophones and was in a location that could not have been the origin point for rock burst that caused the observed damage.

The NISN double-couple solution also fails to provide a slip plane related to any local structure or mining-induced driving force. However, a shear implosional interpretation of the NISN data

Figure D-10.—First-motion patterns, August 12, 1992, event. **A**, Result from NISN; **B**, shear-implosional interpretation of NISN first motions; **C**, microseismic system location; **D**, mine macroseismic system location; **E**, automatic macroseismic system location; **F**, arbitrary location.

suggests right-lateral slip on a plane somewhat aligned to the South Control Fault, a plane that is also suggested by the double-couple macroseismic system results.

The observed damage was concentrated near the South Control Fault and was consistent with a slip event on this feature. However, during inspections of the resulting damage, stope closure was consistently attributed to movement from the south (hanging) wall. The exception was a section of the footwall rib in the 5400-95 stope that was variously described as being "blown out" or "sloughed." Movement from the hanging wall indicated by inspection of stope damage suggested a source location in the hanging wall, which is not consistent with the seismic information.

A conventional interpretation of the various sources of evidence for this event suggests three different mechanisms, including vertical slip on a north-south plane, right-lateral slip on the South Control Fault in the footwall, and left-lateral slip on the South Control Fault in the hanging wall. A shear-implosional interpretation of the NISN data brings a measure of consistency to the seismic data and focuses on right-lateral slip of the South Control Fault in the footwall. The damage pattern does confirm South Control Fault movement, but, as previously discussed, also suggests a mirror-image slip event in the hanging wall. Since observations of stope damage are difficult to check, it is difficult to determine how definitive this conclusion is.

It is possible that observers were expecting a hanging wall event, because this event was the third in a series of large events that occurred within a very few days of each other and migrated from the North Control Fault (July 30, 1992 in the hanging wall) to the shear zone (August 4, 1992, in the hanging wall), and finally to this event on the South Control Fault. It is also possible that movement on the hanging wall took place at the time of the event, but was not characteristic of event first motions. For the purposes of this study, the apparent movement on the hanging wall will be discounted in favor of information in the seismic record.

This result is one of the best-documented instances in which the in-mine network recorded a demonstrably different first-motion pattern than the NISN array. This discrepancy deserves more attention.

Based on the shear implosional interpretation of NISN data, a double-couple interpretation of in-mine data, and damage observations (only to the extent that they point to slip on the South Control Fault), this event was assigned to the—

South Control Fault Strike-Slip Set

The best estimate of event location is 19875, 20000, -1850. The quality of the location is fair and the quality of the first-motion information is fair but puzzling. The first-motion solution is dip direction = 150°, dip = 80°, and rake = 20°.

Event 29 11/3/92 21:21:44 80 mm 3.0 M_i

Mine records place this event in the 5100-106 east stope block near the North Control Fault. The macroseismic system monitored the event (files 92110300.wvb, 92110301.wva), and the magnitude was estimated by the Montana Bureau of Mines. This event caused 500 short tons of damage to the northern half of the 5100-106 stope.

Solutions

1. The NISN reported a first-motion pattern consistent with right-lateral slip on the North Control Fault (figure D-11A).
2. The location identified by the microseismic system (20818, 20789, -1685) suggests largely normal movement on a plane parallel, but north of, the North Control Fault (figure D-11B). The sense of movement had the mined block moving downward, which generally consistent with the location of this event just off the northern end of the vein at the 5100-106 stope horizon. A component of left-lateral slip was also present, which suggests a footwall location. These first motions were only somewhat consistent with the NISN results (figure D-11C). However, many of the discrepant geophones were only barely discrepant.
3. The location identified by the mine using macroseismic system data (21075, 20900, -1850) produced a different first-motion pattern with no correlation to geologic structures in the area (figure D-11D). This location was shifted down and to the northeast of the microseismic system, placing it considerably northeast of the North Control Fault. However, these first motions fit the NISN result almost as well (two instead of one discrepant systems) (figure D-11E).
4. In some cases, a marked contrast between NISN and in-mine macroseismic net results has been resolved by proposing alternative locations for the in-mine net. Locations derived by various means have been tried and have failed to close the gap. In an effort to see if this gap could be closed, a wide range of arbitrary locations within several hundred feet in all directions were tried. However, none of these locations resulted in right-lateral slip on the North Control Fault.
5. The variety of locations and first-motion results prompted a reexamination of first-arrival picks. The first-arrival polarity for the SEI geophone was particularly difficult to pick and could easily be misinterpreted. This geophone was not consistent with the rest of the NISN and also appeared to be consistently discrepant in the macroseismic system analyses. Thus, the first-motion pattern shown in figure D-11E has only one solidly discrepant geophone.

Analysis

The damage report clearly pointed to a North Control Fault event. The NISN clearly confirms this conclusion and shows right-lateral movement, suggesting a location in the hanging wall. The in-mine systems generally gave consistent locations. The first-motion results from the mine failed to agree with NISN results for a number of generated locations and a large number of arbitrary locations. However, forcing the NISN result to the first motions for macroseismic system location shows that only two geophones were discrepant. One of these, SEI, was difficult to interpret and was surrounded by contradictory geophones. This event was assigned to the-

Figure D-11.—First-motion patterns, November 3, 1992, event. *A*, Result from NISN; *B*, microseismic system location; *C*, NISN first-motion pattern superimposed on in-mine geophone data using microseismic system location; *D*, mine macroseismic system location; *E*, NISN first-motion pattern superimposed on in-mine geophone data using macroseismic system location.

North Control Fault Slip Set

The best location for this event was provided by the microseismic system is 21075, 20900, -1850. The quality of the location is fair and the quality of the NISN and direct path macroseismic first-motion information is fair. The first-motion solution is dip direction = 120° , dip = 70° , and rake = -10° .

APPENDIX E: CATALOG OF LARGE SEISMIC EVENTS, 1993

Three seismic events having estimated local magnitudes of 2.5 or greater occurred during 1993. The locations of these events were plotted on a longitudinal section of the vein (figure E-1) and plan view maps by level (figures E-2 and E-3). The available information on each event is reviewed on a case-by-case basis in the remainder of this appendix.

Figure E-1.—Location of major seismic events during 1993, Lucky Friday vein. This longitudinal view shows the true area of the vein and rotates from a point south of the vein in the western portion of the mine to a point east of the vein in the northern portion of the mine.

Figure E-2.—Location of major seismic events during 1993, plan view, 5100 level.

Figure E-3.—Location of major seismic events during 1993, plan view, 5300 level.

Event 30 5/28/93 01:55:01 80 mm 2.8 M_i

This event was located in the vicinity of the North Control Fault close to the same elevation as the 5100-106 pillar. The macroseismic system recorded the event (files 93052802.wvm and 93052803.wvm).

Mining of the 5100-106 pillar was completed in April 1993, and the final cut had been left unfilled at the time of the event. Active mining was underway in the 106/107 area on the longwall face at an elevation of -2100 ft.

This event caused 50 short tons of damage to the 5100-107 stope (the unfilled final cut that removed the last portion of the 5100-106 pillar).

Solutions

1. The first-motion pattern for the microseismic system location (20900, 20775, -1775) showed normal movement across a range of northwest-striking planes, including the strike of the North Control Fault (figure E-4A). The steep southwest dip also corresponded well with the North Control Fault and correctly showed that the mine block was moving downward.
2. The first-motion pattern for the location identified by the mine using macroseismic system data (21054, 20600, -1863) showed normal movement across a range of northwest-striking planes that included the strike of the North Control Fault (E-4B) and showed that the mine block was moving downward.
3. The location automatically calculated by the macroseismic system for the combined files (20588, 20340, -1283) was much higher in the mine than expected. The resulting first-motion pattern did not line up well with any geologic structure and included a discrepant geophone (E-4C). However, the location derived from the 03 file alone at 20927, 20637, -1815 was close to the other reported locations and indicated a similar first-motion pattern (figure E-4D).

Analysis

The first-motion pattern and location information clearly showed normal movement on the North Control Fault originating in the hanging wall of the vein. The elevation of the event (-1800, around the 5200 level) was just below the remnants of the 5100-106 pillar that had been mined out the previous month. The only damage was to the last unfilled cut of the stope that finished mining of this pillar. Thus, this event was assigned to the-

North Control Fault Slip Set

The best estimate of event location is 21054, 20600, -1863. The quality of the location is good and the quality of the first-motion information is fair. The first-motion solution is dip direction = 210°, dip = 75°, and rake = -60°.

Figure E-4.—First-motion patterns, May 28, 1993, event. *A*, Microseismic system location; *B*, mine macroseismic system location; *C*, combined file, automatic macroseismic system location; *D*, 03 file, automatic macroseismic system location.

Event 31 10/17/93 23:49:13 80 mm 3.0 M_i

This event was located in the 5100-94-96 stope block near the southwestern end of the Lucky Friday vein where it intersects the South Control Fault. The microseismic system placed the event at 20197, 20053, -1610 in the footwall of the vein and east of the South Control Fault. The location identified by the automated macroseismic system (19949, 19547, -1331) placed the event in the hanging wall of the vein and south of the South Control Fault (file 93101706.wvm). A revised macroseismic location placed the event south of the microseismic location in the hanging wall of the vein.

Active mining was underway in the 95 footwall area on the longwall face at the -2070 elevation.

Extensive but minor damage was reported throughout the 4900 level and in the western portion of the 5100 level (figure E-5). One-hundred short tons of damage was also reported in the unfilled final cut of the 5100-94/96 stope. Kinking of the track was reported where it encountered the South Control Fault (and vein; they coincide here) at the stope raise. Also, a crack was observed in cemented sandfill that had been spilled in the 5100-92 hanging wall drift. The crack was located on the South Control Fault, but suggested only a minor (1/4-in) vertical offset.

Solutions

1. The NISN reported a well-constrained shear implosional first-motion pattern that was interpreted as "an apparent gravity collapse event in the vicinity of, but not on, the South Control Fault" (figure E-6A). The first-motion pattern was also consistent with right-lateral movement on, and north of, a west-northwest-trending plane subparallel to the South Control Fault (figure E-6B).
2. A first-motion pattern developed for the location identified by the microseismic system (20197, 20053, -1610) indicated vertical slip on a northwest-striking vertical plane subparallel to the South Control Fault, with the northeast block moving downward (figure E-6C). A shear-implosional interpretation of the first-motion pattern suggested right-lateral slip on, and north of, a west- to west-northwest striking plane subparallel to either the South Control Fault or vein (figure E-6D). The location is generally consistent with a footwall origin point, but was more consistent with slip on the vein than on the South Control Fault (figure E-5).
3. The location automatically calculated by the macroseismic system (19949, 19547, -1331) resulted in a similar first-motion pattern, showing vertical slip on a northwest-trending vertical plane with the northeast block moving downward (figure E-6E). This interpretation included a discrepant geophone. A shear-implosional interpretation of the first-motion pattern was virtually identical to the shear-implosional pattern developed for the location identified by the microseismic system (figure E-6F). However, this location was much deeper into the hanging wall than suggested by any other evidence.
4. The right-lateral slip and/or northeast block downward movement suggested by the first-motion patterns were both most plausible on the South Control Fault northwest of the vein, a location not represented by the results from the various seismic systems. Manually placing a solution on this portion of the South Control Fault at (19750, 20000, -1600) resulted in a first-motion pattern showing right-lateral movement consistent with previous movement in this area (figure E-6G). A shear-implosional interpretation of this event (figure E-6H) allowed a much better match in orientation with the South Control Fault, but did not rotate sufficiently to match the vein.

Figure E-5.—Location of damage caused by October 17, 1993, event. A, Plan view, 4900 level; B, plan view, 5100 level.

Figure E-5 (continued).—Location of damage caused by October 17, 1993, event. A, Plan view, 4900 level; B, plan view, 5100 level.

Figure E-6.—First-motion patterns, October 17, 1993, event. *A*, Result from NISN; *B*, alternative interpretation of NISN first motions; *C*, microseismic system location; *D*, shear-im-plosional interpretation of first-motion pattern, microseismic system location; *E*, automatic macro-seismic system location; *F*, shear-im-plosional interpretation of first-motion pattern, automatic macroseismic system; *G*, arbitrary location on South Control Fault northwest of vein; *H*, shear-im-plosional interpretation, arbitrary location on South Control Fault northwest of vein; *I*, macroseismic system location using modified velocity model.

A shear-implosional interpretation of this event (figure E-6H) allowed a much better match in orientation with the South Control Fault, but did not rotate sufficiently to match the vein.

5. A location derived from the macroseismic data and a modified velocity model (20220, 19900, -1625) lay south and across the vein from the location identified by the microseismic system but provided very similar first-motion results (figure E-6I).

Analysis

Two movements were indicated for this event. The vertical slip solution was unlikely as vertical motion is usually down-dip toward the bottom of the saddle-shaped fold that lies south of the mine, not up-dip. The other mechanism, right-lateral slip on a west- to west-northwest striking plane, was more probable. The various locations developed showed that location accuracy in this area was not good, as would be expected in a thoroughly mined area with many travel paths forced through fill or around mined areas. The first-motion patterns, particularly the NISN pattern, suggest that this event was initiated on the South Control Fault rather than on the vein.

This event caused unusually extensive damage, reaching across the mine, in a manner similar to large vein-slip events like the event on July 6, 1989. Such a mechanism would also explain the vertical offset found in the cracked cemented sandfill at the hanging wall exposure of the South Control Fault. In addition, two of the most reliable locations (from the microseismic system and arising from the most sophisticated treatment of the macroseismic data) lie well east of the South Control Fault along the vein. However, as discussed previously, extensive mining has interfered with many geophone travel paths, casting some doubt on location accuracy.

If the event did initiate on the South Control Fault in the footwall of the vein as indicated by the NISN first-motion pattern, it could easily have propagated through the few remnant pillars that lie between the 4900 and 5100 levels. That is, where most shear slip events on the South Control Fault are arrested where the footwall block intercepts the vein, shear movement could have continued to propagate along the remnants of the vein. Movement on the vein and further compression of the pillars would allow further closure of the vein and would likely be accompanied by general slumping of the footwall and the hanging wall into the vein. Such movement could produce the vertical offset observed in the spilled cemented sandfill on the hanging portion of the South Control Fault. A second implication of significant closure is the addition of considerable implosional seismic energy to the shear energy released by slip on the South Control Fault.

The shear-implosional interpretation of the first-motion pattern suggests that eastward movement of the footwall block was accompanied by general implosional movement into the predominantly mined-out vein. The appearance of this pattern on both the district-wide and mine-wide nets suggests that these motions were simultaneous, or at least very nearly so. The relatively greater sensitivity of the mine-wide systems to true first-arrival energy, particularly the high-frequency component of this energy, suggests that initiation of the event probably occurred in a pillar rather than on the South Control Fault. The energy then immediately propagated to the South Control Fault, which released a significant portion of the seismic energy. This energy may well have dominated the first-arrival signals received by the district-wide system. These speculations deserve further attention.

Since this event included movement on two structures, it was assigned to two sets. These are the-

South Control Fault Strike-Slip and Vein Slip Sets

The best estimate of event location, assuming initiation on the vein, is 20220, 19975, -1625; which was derived by splitting the difference between the locations identified by the microseismic and revised macroseismic systems, which lie on either side of the vein. The quality of the location is fair and the quality of the first-motion information is fair. The first-motion solution, also taken for initiation of double-couple slip on the vein, is dip direction = 180° , dip = 90° , and rake = 0° .

Event 32 10/22/93 09:28:47 80 mm 2.5 M_L

This event was reported as having a local magnitude of 2.5 in mine records and by the Montana Bureau of Mines. However, internal memos written by Dr. Brian White and Dr. Wilson Blake give a magnitude of 2.0.

The event occurred in the footwall of the vein in the vicinity of F-series faults midway between the Offset and North Control Faults. The automated macroseismic system located the event closer to the Offset Fault.

The event caused 750 short tons damage in the 5480-107 slot and the 5570-107 ramp (figure E-7A and B).

The 101 and 107 stopes were at elevations of -2120 ft and -2130 ft, respectively. The 95 footwall stope was at an elevation of -2070 ft. Pillar mining had been completed.

Solutions

1. The first-motion pattern resulting from a mine location based on macroseismic system data (20530, 20625, -2151) showed downward-raking, right-lateral slip on a west-northwest-striking plane where the north block moved down and into the vein (figure E-8A). The seismograph geophone was discrepant.
2. The first-motion pattern developed for the location identified by the microseismic system (20530, 20625, -1911) showed downward-raking, right-lateral slip on a west-northwest-striking plane where the north block moved down and into the vein (figure E-8B). The seismograph geophone was discrepant.
3. The NISN reported right-lateral movement on a plane with similar orientation and having an intermediate, southerly dip (figure E-8C). The complementary solution showed left-lateral slip on the vein with the eastern (hanging wall) block moving north and downward.
4. The first-motion pattern developed using a location automatically calculated by the macroseismic system (20398, 20456, -1591) showed thrust faulting on a north-northwest-trending plane (figure E-8D).
5. The first-motion pattern developed for a revised macroseismic system location (20575, 20625, -2250) was essentially identical to those developed for the locations identified by the mine macroseismic and microseismic systems (figure E-8E).

Analysis

This event was caused by right-lateral, strike-slip movement on an F-series fault in the footwall. The footwall location was confirmed by the concentration of damage in development openings and the lack of damage to stopes. The apparent movement was consistent with the orientation of the preexisting stress field. This event was assigned to the-

Figure E-7.—Location of damage caused by October 22, 1993, event. *A*, 5480-107 downramp; *B*, 5570-107 access ramps.

Figure E-8.—First-motion patterns, October 22, 1993, event. *A*, Microseismic system location; *B*, microseismic system location; *C*, result from NISN; *D*, automated macroseismic system location; *E*, revised macroseismic system location.

Central Shear Zone Set

The best estimate of event location is 20530, 20625, -2151. The quality of the location is fair and the quality of the first-motion information is good. The first-motion solution is dip direction = 190° , dip = 75° , and rake = 140° .

APPENDIX F: CATALOG OF LARGE SEISMIC EVENTS, 1994

Six seismic events having estimated local magnitudes of 2.5 or greater occurred during 1994. The locations of these events were plotted on a longitudinal section of the vein (figure F-1) and plan view maps of the levels (figures F-2 and F-3). The available information on each event is reviewed on a case-by-case basis in the remainder of this appendix.

Figure E-1.—Location of major seismic events during 1993, Lucky Friday vein. This longitudinal view shows the true area of the vein and rotates from a point south of the vein in the western portion of the mine to a point east of the vein in the northern portion of the mine.

Figure F-2.—Location of major seismic events during 1994, plan view, 5100 level.

Event 33 1/5/94 01:00:19 80 mm 2.5 M_i

The event occurred near the South Control Fault in the vein footwall near the horizon of the lead 95 longwall stope. The 95 footwall stope was leading mining of the split vein in this part of the mine and had reached an elevation of -2070 ft. The stope was either being prepared for fill or had just been filled.

This event did not damage mine openings, and there was no evidence of movement on exposed sections of the South Control Fault in active mining areas.

Solutions

1. The NISN solution showed right-lateral slip on a flat-lying west-northwest-striking plane (figure F-4A). A shear implosional interpretation of this pattern fit right-lateral movement north of, and on, the South Control Fault (figure F-4B).
2. The solution generated for the microseismic system location (19894, 19942, -1856) provided a confused first-motion picture that suggested predominantly normal movement on a northwest-trending plane (figure F-4C).
3. The location identified by the mine based on macroseismic system data (19896, 19864, -1901) also provided a generally confused first-motion picture (figure F-4D). However, the pattern did fit a generally shear-implosion pattern consistent with right-lateral slip on, and north of, the South Control Fault. The two discrepant channels for this sense of motion were near the edge of the stereonet, meaning that a small change in location elevation might flip the polarities of these channels and relocate them to the other side of the lower hemisphere projection. Such a flip would bring the first-motion pattern more closely into line with a pure shear-implosion pattern.
4. The location automatically calculated by the macroseismic system (19800, 19876, -1287) resulted in a shear-implosional first-motion pattern with all four quadrants sampled and no discrepancies. The pattern showed right-lateral movement on, and northeast of, a steeply dipping plane striking northwest (figure F-4E).
5. Both 4400 level geophones were discrepant in a double-couple interpretation for the location identified by the automated macroseismic system. An even shallower elevation at this location (for example, at 19800, 19876, -800) would reverse these channels. The resulting first-motion pattern (figure F-4F) does fit a double-couple pattern showing right-lateral slip on a northwest-striking plane without discrepancies. This pattern fits a shear-implosional model if the unsampled quadrant is assumed to be implosional.

Analysis

This event was most likely a shear-implosional event with right-lateral slip on, and northeast of, the South Control Fault. The correlation between the NISN first-motion pattern and macroseismic system patterns developed for shallow locations suggest the event occurred well above the mining front. The lack of damage and lack of observed displacement on the South Control Fault in the vicinity of active mining also suggest the event occurred somewhere else. Finally, the apparent shear implosional first motion requires a largely mined-out section of the vein to implode into. Thus, the

Figure F-4.—First-motion patterns, January 5, 1994, event. *A*, Result from NISN; *B*, result from NISN, shear-implosional interpretation; *C*, microseismic system location; *D*, mine macroseismic system location; *E*, automated macroseismic system location; *F*, arbitrary location above automated macroseismic system location.

location identified by the macroseismic system and shear implosional movement on the South Control Fault in the footwall of the vein best describe this event. The event was assigned to the—

South Control Fault Strike-Slip Set

The best estimate of event location is 19800, 19876, -1287. The quality of the location is poor and the quality of the first-motion information is fair. The shear implosional first-motion pattern is similar to a double-couple first-motion solution with dip direction = 145° , dip = 85° , and rake = -20° .

Event 34 3/29/94 00:40:04 2.7 M_L

A local magnitude of 2.7 was estimated by the Montana Bureau of Mines, while the mine estimated a local magnitude of 2.5.

This event occurred near the North Control Fault and below the longwall front (which is at -2200 ft). The location identified by the mine macroseismic system put the event in the hanging wall of the vein, while the automated macroseismic system located the event in the footwall.

This event did not damage mine openings.

Solutions

1. The location developed by the mine from macroseismic system data (20850, 20510, -2350) produced a first-motion pattern showing normal movement on a west-northwest-striking plane and an intermediate northeast or southwest dip (figure F-5A). The dips are shallower than the local faults.
2. A first-motion solution generated for a location automatically calculated by the macroseismic system (20502, 20585, -1485) produced a similar first-motion pattern with a single discrepant geophone (figure F-5B). The first-motion pattern matched an implosional model with no discrepant geophones. This location lay just above the 4900 level, but below the 4900-107 pillar (-1310- to -1400-ft elevation).
3. The NISN produced a first-motion pattern showing normal movement on a northwest-striking plane dipping at an intermediate angle to the northeast or southwest (figure F-5C). This was a well-constrained pattern with two compressional geophones. Thus, an implosional model did not fit this pattern. NISN: dip azimuth = 205°, dip = 35°, and rake = -80°.

Analysis

This event could have been associated with normal movement on a central shear zone fault, the North Control Fault, or bedding planes. The lack of a location from the microseismic system considerably increased location uncertainty. The two proposed macroseismic system locations were nearly 1,000 ft apart. Fortunately, the macroseismic first-motion pattern appeared to be quite stable with regard to location and was in full agreement with NISN results. The dip of the slip plane in these patterns was much too shallow for the faults, but there is a minor fold in this area that contains beds with a variety of orientations. In addition, bedding north of the North Control Fault folds back to a west-northwest strike. The best match of this slip plane was obtained by the deeper mine macroseismic system, suggesting that this system provides a better estimate of the actual location as well. The normal sense of movement, however, required that the event originate at or above the mining front, which would be at least slightly above this location. It also required a location in the vein footwall, North Control Fault, or North Control Fault footwall.

This combination of factors suggested a normal bedding plane slip event either in the folded vein footwall bedding or possibly in the footwall (north) of the North Control Fault. The lack of damage is probably attributable to the 107 stope having just been filled. Thus, this event was assigned to a new set, the-

Figure F-5.— First-motion patterns, March 29, 1994, event. *A*, Mine macroseismic system location; *B*, automated macroseismic system location; *C*, result from NISN.

Central Shear Zone Bedding Slip Set.

The best estimate of event location is 20850, 20510, -2350. The quality of the location is poor and the quality of the first-motion information is fair. The first-motion solution is dip direction = 190°, dip = 40°, and rake = -110°.

Event 35 4/1/94 03:31:40 74 mm 2.5 M_L

This event was poorly located, but indications are that it was located in the general vicinity of the Hook axial plane (and the Offset Fault) and in the vein footwall.

Damage was reported in the south wall of the 5480-05 stope, which was being mining at an elevation of -2100 ft. The damage was apparently associated with a structure in the south wall of the stope, probably weak bedding planes parallel to the vein. Bursting occurred frequently at this location in the cut.

Solutions

1. The NISN reported right-lateral movement on a northwest-striking, steeply dipping plane (figure F-6A). This solution included one discrepant geophone. A shear-implosional model can also be fit to the first-motion pattern, suggesting right-lateral slip on, and northeast of, a northwest-striking plane. This model fit with no discrepant geophones. (NISN: dip azimuth = 250°, dip = 15°, and rake = 40°.)
2. The location identified by the mine from macroseismic system data (20394, 19935, -2219) was very close to the last location and produced a similar result, right-lateral movement on a west-northwest-striking, steeply dipping plane subparallel to the Offset Fault (figure F-6B).
3. The macroseismic system automatically calculated a location on the vein at the split just west of the axial plane of the Hook Anticline (20308, 20210, -1600). The first-motion pattern showed vertical slip on a northeast-striking vertical plane with the southeastern block moving down (figure F-6C) with a discrepant geophone. This sense of movement was opposite the movement displayed by known vein slip events. This location was relatively close to the reported damage but lay below the mining front.
4. Raising the location above the mine macroseismic estimate to 20394, 19935, -1800 produced a dramatically different first-motion pattern that showed right-lateral slip, although the slip plane was rotated to an east-west orientation (figure F-6D).
5. A macroseismic location developed by careful first-motion picks (20281, 20289, -1746) lay very close to the Offset Fault in the vein footwall. The first-motion pattern for this location showed right-lateral movement on a west-northwest-striking, steeply dipping plane subparallel to the Offset Fault (figure F-6E). This pattern included a discrepant geophone.
6. An alternative location that would support right-lateral slip was on the South Control Fault in the footwall of the vein (19750, 20000, -2300). The first-motion pattern for this location showed right-lateral slip along a west-northwest-striking plane (figure F-6F). This pattern had a large number of compressional arrivals in the southwest quadrant in direct contradiction to the proposed shear-implosion pattern.

Analysis

Location accuracy for this event was poor, indicating only that the event occurred somewhere in the central part of the mine block between the control faults. In cases like this, the relative insensitivity of the NISN first-motion pattern is quite useful. The only vertical faults with an

Figure F-6.—First-motion patterns, April 1, 1994, event. *A*, Result from NISN; *B*, mine macroseismic system location; *C*, automatic macroseismic system location; *D*, arbitrary location above mine macroseismic system location; *E*, revised macroseismic system location; *F*, arbitrary location on South Control Fault in vein footwall.

appropriate strike within the central part of the mine are contained within the central shear zone. The right-lateral movement pattern generated for two footwall locations near the 38 Offset Fault was consistent with this interpretation. Since the reported damage was minor and commonly occurs at the reported location, it was probably related to an unusually weak structure rather than part of the zone of slip. Thus, it did not necessarily contradict this interpretation.

This event was assigned to the—

Central Shear Zone Set

The best estimate of event location is 20281, 20289, -1746. The quality of the location is poor and the quality of the first-motion information is good. The first-motion solution is dip direction = 190° , dip = 85° , and rake = -170° .

Event 36 5/13/94 22:13:43 76 mm 2.5 M_L

This event was not well located by the mine microseismic system (the 5900-level elevation is a default elevation limit used when the solver is trying to move the location deeper than is considered reasonable). The mine assigned the event to the central 06 stope (called the 101 stope in older areas), and the various locations that were developed are scattered through the portion of the area that lies southwest of the axial plane of the Hook Anticline.

This event did not damage the mine.

Solutions

1. The NISN showed right-lateral movement on a northwest-striking, steeply dipping plane (figure F-7A).
2. The microseismic location (20364, 20011, -2500) showed a confused first-motion pattern. Depending on the choice of discrepant geophones and small changes in slip plane orientation, the apparent left-lateral movement on a steep, northwest-striking plane could become right-lateral slip on a nearly parallel plane. Both interpretations would have at least one solidly discrepant geophone and one or more marginally discrepant geophone.
3. The first-motion pattern for the initial location identified by the mine from macroseismic system data (20159, 19813, -2187) showed right-lateral slip on a steep, west-northwest-striking plane with the southern block moving down as well as to the west (figure F-7B). Two geophones in this pattern were discrepant.
4. The first-motion pattern for a subsequent location identified by the mine from macroseismic system data (20414, 19660, -2346), with some modification, also showed right-lateral slip on a steep, west-northwest-striking plane (figure F-7C). One geophone was marginally discrepant in this pattern.
5. The first-motion pattern for a location automatically calculated by the macroseismic system (20241, 20122, -1372) showed right-lateral strike-slip on a steep, northeast-striking plane, or left-lateral slip on a steep, northwest-striking plane (figure F-7D). This pattern included two discrepant geophones.
6. An arbitrary location in the vein footwall on the South Control Fault (19750, 20000, -2300) showed right-lateral movement on a west-northwest vertical plane with two marginally discrepant geophones (figure F-7E).

Analysis

The NISN reported the best first-motion pattern, which clearly showed right-lateral movement on a northwest-striking, steeply dipping plane. First-motion patterns developed by the macroseismic system for a variety of locations showed that this first motion was possible, with the exception of the location identified by the automatic macroseismic system. However, the latter location was also unreasonably high in the mine. All of the mine macroseismic system patterns were plagued by discrepant geophones that muddy the results. The most plausible locations are in the range of 20150

Figure F-7.—First-motion patterns, May 13, 1994, event. *A*, Result from NISN; *B*, initial mine macroseismic system location; *C*, modified mine macroseismic system location; *D*, automatic macroseismic system location; *E*, arbitrary location in vein footwall on South Control Fault.

to 20450, 19650 to 20050, -2150 to -2500. This area is centered on the split in the Lucky Friday vein and lies at or below the mining front.

Mining-induced stress below mining are greatest perpendicular to the greatest cross section of the mined vein (that is, the greatest span). Thus, mining-induced stress on the abutment will predominantly amplify the maximum horizontal principal stress component, which is oriented to the northwest. Locally, the stress concentration will take on a more northerly orientation west of the Hook where these locations are concentrated. Thus, strike-slip is possible on a number of features, including the South Control Fault, bedding planes (particularly the D-E interface or the thin F subunit), and the 38-Offset Fault. The footwall of the South Control Fault is the most plausible based on the lack of damage and precedence. The 38-Offset Fault is less likely. Bedding planes are the most plausible based on location. Slip on the stope boundary is a particularly interesting possibility as the 101 stope leads the 95 stope by about 50 ft, and the D-E-F subunit boundaries are located in this vicinity.

Since slip on the South Control Fault was the most plausible mechanism for this event, it was assigned to the-

South Control Fault Strike-Slip Set.

The best estimate of event location is 20414, 19660, -2346. The quality of the location is poor and the quality of the first-motion information is good. The first-motion solution is dip direction = 90° , dip = 60° , and rake = -20° .

Event 37 5/19/94 00:06:24 78 mm 2.6 M_i

This event did not damage the mine.

The event occurred near the southeastern end of the vein in the vicinity of the South Control Fault. Most location estimates showed the event as near or below the longwall face (figure F-8).

Figure F-8.—Various locations proposed for May 19, 1994, event.

Solutions

1. The first-motion pattern reported by the NISN showed right-lateral movement on a west-northwest-striking vertical plane (figure F-9A). These channels also fit a normal slip first-motion pattern (figure F-9B).
2. The first-motion pattern resulting from location identified by the microseismic system (19914, 19918, -2247) showed normal movement on a northwest-striking plane with an intermediate northeast or southwest dip (figure F-9C).
3. The location automatically calculated by the macroseismic system (19897, 20151, -1293) was much higher in the mine and generated a first-motion pattern that showed vertical slip on a vertical, east-west plane with the footwall moving down (figure F-9D). A minor right-lateral component was also present.
4. The first-motion pattern from an adjusted macroseismic system location (19887, 19725, -2153) showed normal movement on a west-northwest-striking plane with an intermediate northeast or southwest dip (figure F-9E).
5. An arbitrary location in the vein footwall and on the South Control Fault (19700, 20000, -2200) showed similar results (figure F-9F).
6. Another location was proposed farther to the south on the South Shop Fault, which parallels the South Control Fault. This location (19900, 19500, -2150) showed a normal slip mechanism similar to that identified for previous events (figure F-9G).

Analysis

Nearly all of the locations developed in this analysis resulted in normal movement on a plane close to bedding (the exception was the location identified by the automatic macroseismic system). These patterns were consistent with the interpretation of normal slip by the NISN data. However, the lack of damage was somewhat unusual for a bedding slip event of this magnitude and suggested a somewhat higher location with normal movement of a footwall block into fill rather than the stope.

This event was assigned to the-

Southern Bedding Plane Slip Set

The best estimate of event location is 19914, 19918, -2247. The quality of the location is poor and the quality of the first-motion information was good. The first-motion solution is dip direction = 210° , dip = 40° , and rake = -90° .

Figure F-9.—First-motion patterns, May 19, 1994, event. A, Result from NISN; B, result from NISN, alternative interpretation; C, microseismic system location; D, automatic macroseismic system location; E, adjusted macroseismic system location; F, arbitrary location in vein footwall and on South Control Fault; G, arbitrary location on South Shop Fault.

Event 38 8/16/94 23:56:51 77 mm 4.1 M_L

This event occurred on the northeastern end of the mine in the vicinity of the North Control Fault (figure F-10). Location elevations generally placed the event above the mining face but below the mined-out 5100-106 pillar. The final cut of the 5100-106 stope was left unfilled (at an elevation of -2200 ft), but had not been mined for some time.

This event caused 500 short tons of damage to the 5100-106 and 5570-107 underhand stopes (figure F-11). There was extensive local rib failure throughout the 5570-107 stope south of the North Control Fault and in the 5100-106 stope, including the North Control Fault portion. Failed wall rock did not generally appear to have been blasted violently into the chain-link fencing but to have just fallen down. These failures were locally deep enough to release 3-ft-long Split-Set bolts. Both stopes also mine a portion of the vein that turns and follows the North Control Fault into the hanging wall (the 40 vein). This section of the 5100-106 stope showed a definite bias toward damage in the south wall. Damage to the 5570-107 stope was limited to the inside corner rib.

An 8-in vertical jog was found in the floor of the 5570-107 stope at the F-3 Fault. The ribs and sand in the back showed no corresponding offset. The shape of the floor south of the fault suggested that substantial floor heave had taken place, but this heave was not observed north of the F-3 Fault.

Figure F-10.—Various locations proposed for August 16, 1994, event.

Figure F-11.—Location of damage to 5570-107 stope caused by August 16, 1994, event.

Thus, the 8-in jog most likely represented the amount of floor heave and was not related to generation of the seismic event.

The event also disrupted water flow in the stope. Water that once entered the stope near the North Control Fault and flowed down the stope floor to the ramp before the event now flowed into the fractured floor within a few feet and disappeared.

Stope closure measurements that were being taken on a regular basis in the 5100-106 stope indicated that this event caused 2.37 in of closure. Closure in the 5570-107 stope was not monitored, but localized floor heave and squeeze of overhead sand were observed. Heave and squeeze were particularly evident south of the F-3 Fault with lesser amounts evident between the F-3 Fault and the North Control Fault. No heave or squeeze were observed in the 40 vein section of either stope. However, a closure station in the central portion of the mine where the 5210-101 ramp crosses the vein showed 0.67 in of closure, suggesting that this event caused significant and widespread closure.

Solutions

1. The first-motion pattern for the location identified by the microseismic system (20915, 20713, -1849) suggested vertical movement on a vertical plane striking west-northwest, downward movement on the southwest block, and minor right-lateral movement. The pattern also suggested that a shear-implosional solution would fit (figure F-124). The shear-implosional solution would have left-lateral slip on, and southwest of, the west-northwest-striking vertical plane. A small

change in location moves the 521 channel across the stereonet, suggesting left-lateral movement consistent with the movement implied by the shear implosional interpretation.

2. The first-motion pattern for the location developed by the mine from macroseismic system data (21070, 20660, -1975) suggested vertical slip on a west-northwest-trending vertical plane with the southwest block moving downward (figure F-12B).
3. The location calculated automatically by the macroseismic system (20678, 20791, -1318) was much higher than the other locations and lay in the footwall of the vein but generated a similar first-motion pattern. This pattern suggested vertical slip on a northwest-striking plane with the southwest block moving downward (figure F-12C). This interpretation included two discrepant channels. A shear implosional pattern can be fit to these data without discrepant channels and calls for left-lateral slip on, and southwest of, the northwest-striking plane.
4. The left-lateral slip generally indicated by the macroseismic system suggested a footwall location. The robustness of this first-motion interpretation can be checked by proposing an arbitrary source location deep in the footwall of the vein on the North Control Fault near the horizon where the microseismic system placed the location (20500, 20850, -1900). The first-motion pattern was surprisingly similar to previous patterns (figure F-12D). The double-couple interpretation suggested downward movement southwest of the North Control Fault. The shear implosional interpretation suggested left-lateral slip on, and south of, the North Control Fault with general southwestern movement of ground northeast of the North Control Fault.

Analysis

Observations of mine damage and closure measurements indicated that significant closure of the vein occurred, particularly in the northeastern third of the mine, and that this closure was accompanied by significant fracturing of the longwall abutment. The damage pattern also suggested that the F3 Fault served as some kind of northern boundary to the most severe floor heave. The orientation of the F3 Fault suggests that it connects with the North Control Fault in the hanging wall. The location of this event well above the mining front may account for the relatively minor and uniform damage experienced in the 5100-106 and 5570-107 stopes.

The macroseismic system provided a surprisingly consistent first-motion picture over a wide range of locations on the North Control Fault. However, the locations placed the event at elevations of -1300 to -2000 ft, all of which lay well above the 5570-107 front at -2200 ft. There was also a 750-ft span between the longwall front and the 4900-107 pillar. This geometry provided a large potential for further closure of the vein. It also provided a large continuous expanse of backfilled vein for first-motion signals to travel through or around. The location identified by the microseismic system had good nonfilled paths to the SEIS, 281, 282, 441, and 440 geophones. First-motion patterns consistent with only these geophones included vertical movement (as in figure F-12A) and right-lateral movement (figure F-12E). Right-lateral movement was consistent with this location in the hanging wall.

A similar exercise for the footwall location identified by the automatic macroseismic suggested that geophones SEI, 280, 281, 282, 283, 284, 400, 511, 521, and 590 had nonfilled travel paths (figure F-13). The 520, 400, and 590 geophones implied a shear-implosional pattern with left-lateral movement south of the fault. The sense of motion was consistent with this location.

Figure F-12.—First-motion patterns, August 16, 1994, event. **A**, Microseismic system location; **B**, mine macroseismic system location; **C**, automatic macroseismic system location; **D**, arbitrary location on North Control Fault in vein footwall; **E**, geophones with clear paths and microseismic system location.

Most events along the North Control Fault in this area have been right-lateral events in the hanging wall with varying degrees of normal movement. The seismic information developed for this event is consistent with the normal movement component. The most reliable event locations lie along the North Control Fault in the vein hanging wall. First motions consistent with these locations can only be obtained by neglecting information from the majority of geophones that lie in the vein footwall and whose travel paths encounter fill. This interpretation has the advantage of not requiring a shear-implosional model.

This event was assigned to the—

Slip on North Control Fault Set

The best estimate of event location was taken to be the location identified by the microseismic system (20915, 20713, -1849). The quality of the location is fair and the quality of the first-motion information is poor as it appears to be affected by travel paths that pass through filled stopes. The first-motion solution is dip direction = 210° , dip = 90° , and rake = 0° .

Figure F-13.—Geophones with intact travel paths to microseismic system location for August 16, 1994, event.

APPENDIX G: SUMMARY OF LARGE EVENT CHARACTERISTICS

Event No.	Date	Mag-nitude	Best location			Set	Quality		Dip	DD	Rake
							Location	Motion			
1 ..	2/24/89	2.8	20412	20214	-1553	Distress blast.	Fair	None	ND	ND	ND
2 ..	3/2/89	3.3	19990	20043	-1695	Southern bedding plane slip.	Poor	None	ND	ND	ND
3 ..	4/4/89	2.8	20012	20018	-1369	Southern bedding plane slip.	Fair	None	ND	ND	ND
4 ..	7/6/89	3.1-3.7	20400	20000	-1570	Vein slip.	Poor	Fair	210	25	10
5 ..	11/2/89	2.6	20400	20400	-1520	Central shear zone	Poor	Poor	130	40	-130
6 ..	4/10/90	2.5	20807	20684	-1682	North Control Fault slip.	Fair	Fair	15	85	-170
7 ..	4/11/90	2.5	19983	20061	-1418	Southern bedding plane slip.	Fair	None	ND	ND	ND
8 ..	6/12/90	2.6	20025	19950	-1750	Southern bedding plane slip.	Poor	None	ND	ND	ND
9 ..	7/31/90	2.6	20250	20100	-1900	Southern bedding plane slip.	Poor	Fair	170	60	-80
10 .	8/3/90	2.5	20572	20462	-1663	Central shear zone	Fair	Fair	250	80	-10
11 .	10/19/90	2.5	20607	20609	-1719	Central shear zone	Fair	None	ND	ND	ND
12 .	2/28/91	2.8	20700	20800	-1800	North Control Fault slip.	Fair	Fair	200	70	0
13 .	3/27/91	2.6	20225	19850	-1925	Southern bedding plane slip.	Fair	None	ND	ND	ND
14 .	5/9/91	2.8	21250	20500	-1700	North Control Fault slip.	Poor	Poor	90	80	-40
15 .	5/17/91	2.7	21175	20975	-2125	North Control Fault slip.	Poor	ND	ND	ND	ND
16 .	5/23/91	2.5	20200	20170	-1860	Southern bedding plane slip.	Fair	Fair	210	55	-140
17 .	6/21/91	3.0	20008	19906	-1725	South Control Fault slip.	Fair	Fair	85	65	-180
18 .	7/20/91	2.6	19700	20100	-1500	South Control Fault strike-slip.	Poor	Fair	305	80	20
19 .	7/31/91	2.6	20309	19602	-1610	South Control Fault strike-slip.	Fair	Poor	145	85	170
20 .	8/17/91	2.9	20671	20679	-1509	Vein slip.	Good	Fair	60	30	-160
21 .	9/19/91	3.6	20900	20700	-1800	North Control Fault slip.	Poor	Poor	40	80	0
22 .	11/11/91	2.5	20125	20000	-1910	Southern bedding plane slip.	Good	Fair	200	50	-60
23A	12/11/91	3.0	19883	19986	-1766	South Control Fault strike-slip.	Fair	None	ND	ND	ND
23B	12/11/91	2.4	20297	20061	-1544	Southern bedding plane slip.	Fair	Poor	190	40	-40
24 .	1/30/92	2.5	20100	20000	-1950	Vein slip.	Fair	Fair	10	75	-120

25 .	6/27/92	2.8	20900	20800	-1750	North Control Fault slip. ¹	Fair	Good	228	75	-138
26 .	7/30/92	2.5	21000	20670	-1760	North Control Fault slip. ¹	Poor	Good	290	80	20
27 .	8/4/92	3.0	21000	20300	-2100	Central shear zone	Fair	Good	115	50	20
28 .	8/12/92	3.0	19875	20000	-1850	South Control Fault strike-slip.	Fair	Fair	150	80	20
29 .	11/3/92	3.0	21075	20900	-1850	North Control Fault slip.	Fair	Fair	120	70	-10
30 .	5/28/93	2.8	21054	20600	-1863	North Control Fault slip.	Good	Fair	210	75	-60
31 .	10/17/93	3.0	20220	19975	-1625	South Control Fault strike-slip; vein slip. ¹	Fair	Fair	180	90	0
32 .	10/22/93	2.5	20530	20625	-2151	Central shear zone	Fair	Good	190	75	140
33 .	1/5/94	2.5	19800	19876	-1287	South Control Fault strike-slip. ¹	Poor	Fair	145	85	-20
34 .	3/29/94	2.7	20850	20510	-2350	Central shear zone bedding slip.	Poor	Fair	190	40	-110
35 .	4/1/94	2.5	20281	20289	-1746	Central shear zone	Poor	Good	190	85	-170
36 .	5/13/94	2.5	20414	19660	-2346	South Control Fault strike-slip.	Poor	Good	90	60	-20
37 .	5/19/94	2.6	19914	19918	-2247	Southern bedding plane slip.	Poor	Good	210	40	-90
38 .	8/16/94	4.1	20915	20713	-1849	North Control Fault slip.	Fair	Poor	210	90	0

¹DD = Dip direction. ND = No data.

¹Shear implosional first-motion pattern indicated by macroseismic system and/or NISN.

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