

TRANSACTIONS OF THE INSTITUTION  
OF MINING AND METALLURGY  
SECTION A

# Mining industry

September-December 1997

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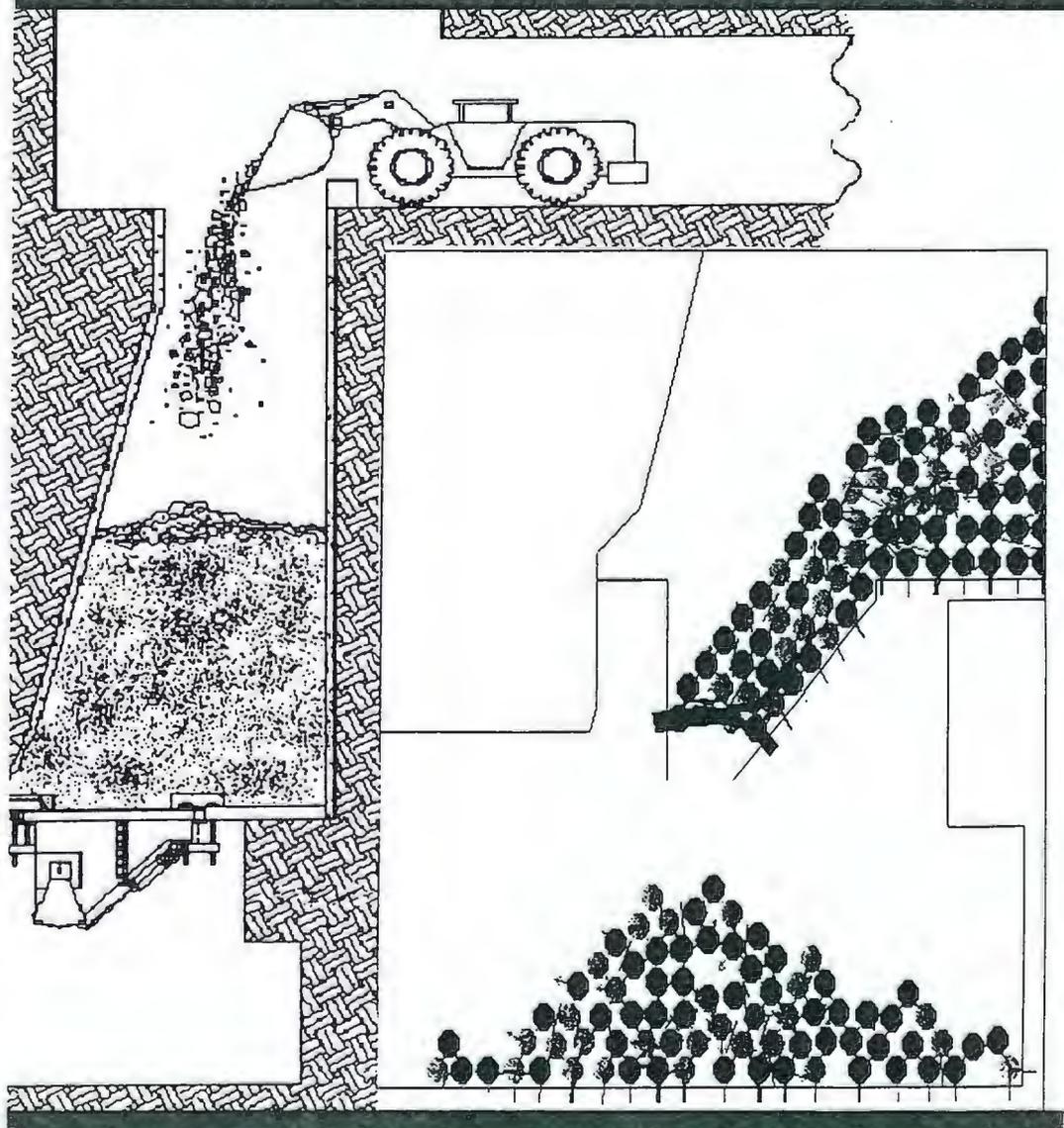
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# Classification of large seismic events at Lucky Friday mine

J. K. Whyatt, W. Blake and T. J. Williams

## Synopsis

A study of large seismic events at the Lucky Friday mine in northern Idaho, U.S.A., revealed that, despite apparent randomness, there were common characteristics that could be used to define five types of recurring events. These common characteristics included slipping geological structure, first-motion pattern and the location and intensity of damage resulting from the seismic events. In all these events damage was concentrated at intersections between slipping structures and mine openings. The study was based on information collected in the course of a long-standing rockburst research programme conducted by the U.S. Bureau of Mines in cooperation with mines in the Coeur d'Alene mining district and regional universities. Data were collected on 39 seismic events having local magnitudes greater than 2.5 that occurred between 1989 and 1994. The study provides a foundation for the design of measures to reduce further the potential for damage arising from these events and to assess whether changes in mining activity aimed at reducing one type of rockburst will increase the incidence of other types.

As mines have gone deeper the number of seismic events and, correspondingly, the potential for damaging rockbursts have increased. (A rockburst is defined here as a mining-induced seismic event that causes damage to mine openings.) The potential for catastrophic injury and loss of life is of continuing concern. Improved mining methods, mining sequences and ground control measures have been used to control the problem, but have not eliminated it. Further progress will require an even greater understanding of rock-mass deformation mechanisms that produce large seismic events.

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.<sup>1</sup> For instance, Sprenke *et al.*<sup>2</sup> reported that the mine experienced a magnitude 2.5 or larger event every 15 weeks (while mine production was less than 900 t/day). The intensity of such seismic activity has made the mine an ideal laboratory for the monitoring of mining-induced seismicity. Personnel from the U.S. Bureau of Mines (USBM) have been involved in rockburst research in the Coeur d'Alene mining district of northern Idaho since the 1970s. This work is being continued by the National Institute for Occupational Safety and Health (NIOSH) following transfer of the health and safety functions of the USBM to NIOSH.

Various seismic systems installed and maintained at the Lucky Friday mine by the USBM, University of Idaho and Hecla Mining Co. have led to the creation of a large seismic database. A number of case studies from this database have been published.<sup>1,3,4,5</sup> The current investigation goes beyond

many of these case studies by examining a complete set of mining-induced seismic events having local magnitudes ( $M_L$ ) greater than 2.5 in an attempt to identify common characteristics of these events, including their relationship to geological structures and mining activity and the resulting level and distribution of damage.

## Lucky Friday mine

The Lucky Friday mine, owned and operated by Hecla Mining Co., Coeur d'Alene, is located on the eastern edge of the Coeur d'Alene mining district of northern Idaho near Mullan. The first claims were filed in 1889; however, it was not until 1941 that the first commercial ore was found. Mining has progressed ever deeper to the present mining horizon below the 5500 level (650 m below sea-level). The Lucky Friday mine used a traditional overhand cut-and-fill method until 1986, when the mine 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 1980s.<sup>6,7</sup> The underhand cut-and-fill method is proving to be a much safer way to mine in seismically active ground.<sup>8</sup> 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 rockbursts at the Lucky Friday mine has also been pursued through improved ground control systems<sup>9,10</sup> and pillar preconditioning. Recent investigations at the Lucky Friday mine have revealed that seismicity produced by the driving of development openings has been associated with hard stratigraphic subunits. *In-situ* stress measurements have shown that these hard subunits concentrate *in-situ* stress.<sup>11</sup> Related work has investigated the geological structures associated with strain rockbursts.<sup>12</sup>

## Geology

The Lucky Friday vein at 1600 m below the surface forms an S-shape in plan view, extending horizontally about 490 m. Splits off the main vein extend the potential stope length to more than 610 m along strike. Mineralogically, the vein is composed of galena, sphalerite and tetrahedrite in a quartz and siderite gangue. The vein is 0.6–9 m wide, averaging about 1.5 m. The vein is in the Precambrian Revett Formation, which hosts most of the silver- and lead-producing mines in the Coeur d'Alene district.

Because the vein dips at a steeper angle than bedding (70–90° versus 60°) to the south and east, it comes into contact with progressively older rocks with depth (Fig. 1). At present, 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, which lies between the

Manuscript first received by the Institution of Mining and Metallurgy on 27 September, 1996; revised manuscript received on 1 September, 1997. Paper published in *Trans. Instn Min. Metall. (Sect. A: Mining industry)*, 106, September–December 1997.

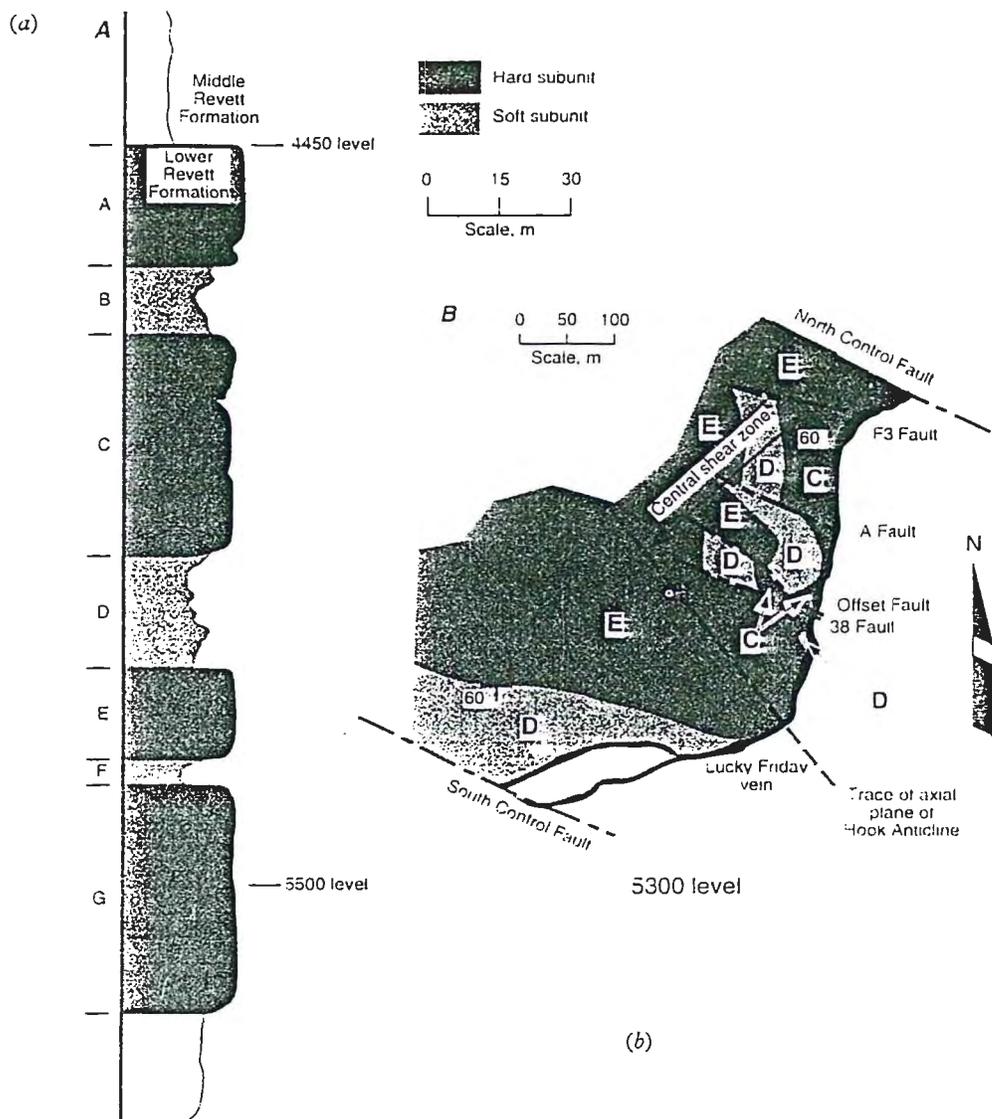


Fig. 1 (a) Stratigraphy and (b) structure, Lucky Friday mine

North and South Control Faults. The rock mass surrounding the vein is made up of vitreous quartzite and sericitic quartzite beds from 30 to 91 cm thick with soft interbeds of argillite generally less than 2.5 cm thick. These beds have been grouped into 15–45 m thick subunits of predominantly hard, brittle, vitreous quartzite and relatively soft, plastic argillite and sericitic quartzite (Fig. 1). Wyatt and co-workers<sup>13</sup> 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.<sup>14</sup> The maximum principal stress is orientated to the northwest and is approximately twice the vertical stress. Furthermore, large structural stresses were found associated with variations in rock properties between strata. Wyatt and co-workers<sup>11</sup> reported intense seismic activity associated with a stress concentration confirmed with an overcore measurement.

### Seismic monitoring systems

Seismic systems vary widely in the quality and types of information that they produce. Many seismic monitoring systems are designed merely to provide a rough estimate of event location and magnitude for use in the management of mine operations, whereas research systems are designed to capture

precise digital records of an event. Mining-induced seismicity at the Lucky Friday mine has been monitored by the three systems described below. The oldest is an analog microseismic\* system that determines the location of seismic events. A surface seismograph estimates the magnitudes of these events. The development of powerful digital systems based on personal computers (PCs) 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,<sup>15</sup> and the district-wide North Idaho Seismic Network (NISN) began operation in March, 1992.<sup>16</sup> Williams *et al.*<sup>5</sup> have published details of the 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.<sup>17,18</sup> The system has been upgraded a number of times and the geophone network is modified systematically to fol-

\*'Microseismic' refers to the capability of a system to detect very low-magnitude seismic (microseismic) events. The term 'macroseismic' is used to differentiate from such systems digital systems that are tuned to collect data on relatively large events.

low the progress of mining.

The system uses an Electrolab MP250 to monitor signals from a network of geophones distributed throughout the operating portion of the mine. Any seismic event that occurs within the bounds of this network will lie within 30 m of a geophone. 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 the location of the event and estimates a relative energy level. Larger events are monitored by a surface seismograph as well, which allows empirical estimates of event energy to be determined 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.\*

The capability of the microseismic system to locate events at the Lucky Friday mine has been the subject of some study. Botts 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.<sup>19</sup> Dodge and Sprenke,<sup>20</sup> 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 the consequences of the constant seismic velocity model assumed when computing locations. They found only minor errors in computed hypocentres (10–20 m) for sources well enclosed by the array. For sources outside the array, however, they found that errors were much greater. Both these studies considered data sets arising from only a day or two of seismic activity, and thus considerable attention was paid to small events.

While recognizing the variability of accuracy with location, the system operators use  $\pm 15$  m (50 ft) as a rule of thumb for the location accuracy of events that occur within the sensor network. For comparison, Gray estimated the approximate radius of slip for a 2.5 local magnitude event at the Lucky Friday mine at 46 m.<sup>21</sup>

### 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 1960s,<sup>22</sup> and modernization continued until closure of the mine in 1992.<sup>23,24</sup> In its mature state the workstation-based system provided close-in digital monitoring of microseismic events generated around individual stopes, as well as mine-wide monitoring of major events. This research system was also used to search for precursory patterns that might warn of impending rockbursts.<sup>25</sup>

The success of the experimental Galena system demonstrated the advantages of digital monitoring, but the high cost of these systems was an impediment to their routine use in 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 1980s,<sup>26</sup> resulted in a dramatic reduction in system costs. The USBM adapted the IASPEI system to rockburst monitoring conditions and installed the first version of this system at the Lucky Friday mine in 1989. Girard *et al.*<sup>15</sup> have provided a comprehensive description of the modified IASPEI system, which became known as the 'macroseismic' system. The USBM 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 rockbursts and use a sparser geophone array than microseismic systems.

The Lucky Friday macroseismic system was specifically designed to monitor events having local magnitudes from 0.5 to 2.5<sup>1</sup> with an array of five three-dimensional velocity geophones. Events smaller than 0.5 were not recorded until recently. Events larger than 2.5  $M_L$  were recorded, but the system electronics were overloaded, causing clipping of waveform records at the upper and lower bounds of the waveform trace.

The original 16-channel system was expanded to 32 channels in January, 1991, and a greater reliance was placed on single-axis geophones. The array was augmented with 11 vertically orientated single-axis geophones. In this expansion good coverage of the mine to locate seismic events and obtain first-motion solutions was given priority at the expense of triaxial waveform information. The triaxial geophones were taken out of operation early in 1994, but the uniaxial geophones are still in operation.

The macroseismic system monitors a larger portion of the mine, but coverage is sparser than coverage by the microseismic system. Any seismic event that occurs within the bounds of this network will lie within 50 m of a geophone,<sup>5</sup> suggesting less location accuracy than was obtained with the microseismic system. However, digital records can support better location estimates by replacing the voltage threshold first-arrival logic imbedded in the microseismic system with more sophisticated algorithms and, for important events, visual inspection.<sup>20</sup>

Even with careful picking of first arrivals, however, a solution with a large location error may be calculated. Often, such factors as line noise and blasting make accurate picking of the first arrival difficult, if not altogether impossible. Mine openings and complex geology affect wave travel and create a non-uniform velocity structure. When events occur outside the geophone array the location accuracy is further dimin-

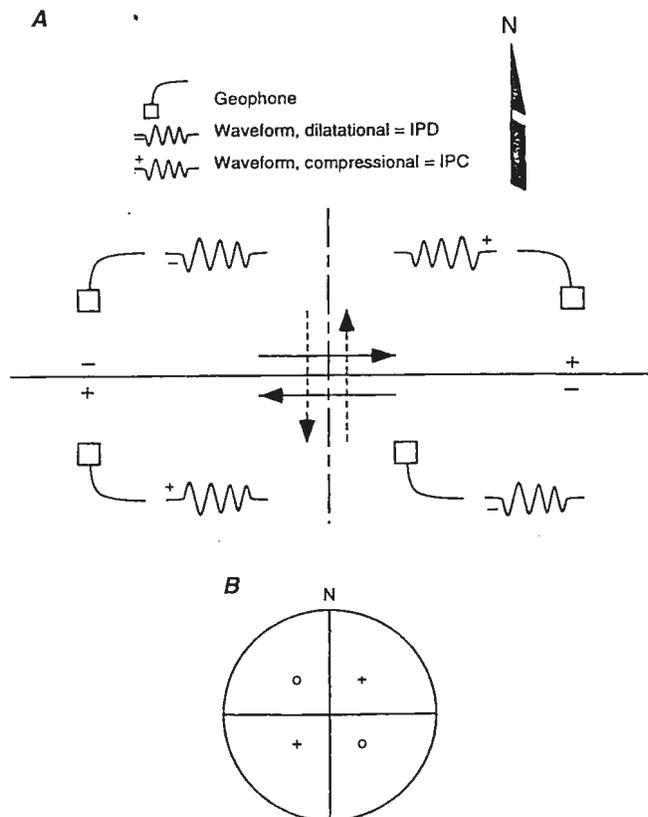


Fig. 2 Representation of fault-slip first motion: (a) sensing first motions on fault; (b) Schmidt net representation

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

ished. 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 support analyses of the first-motion patterns of seismic events.<sup>27</sup> These patterns identify whether the event begins predominantly as shear movement or collapse or a combination of these motions. If dominant shear (double-couple) movement has occurred, dilatational and implosional first motions are produced that alternate between four quadrants (Fig. 2(a)). Mapping of these first motions on a Schmidt net is a convenient way to identify a set of possible conjugate shear planes that could produce the observed first motions (Fig. 2(b)). Implosions are characterized by uniformly dilatational first motions. A number of events in this study showed dilatational first motions in three of the four Schmidt net quadrants, the remaining quadrant showing a

compressional first motion. This pattern is described here as 'shear-implosional', presumably combining shear movement along a geological feature, such as a fault, with closure of a mine opening. It is not well understood.

The accuracy of first-motion results from the Lucky Friday mine has not been considered analytically. As discussed later, however, results based on as few as six geophones have been generally consistent with geological structures, known stress fields and, in a few cases, observations of fault movement. In this study direct evidence of offset in four instances confirmed seismic first motions. Indirect evidence of offset from patterns of damage confirmed a number of other seismic first motions.

#### North Idaho Seismic Network

A third system, the NISN, began monitoring seismicity district-wide 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.<sup>16</sup> Stickney and Sprenke<sup>28</sup> have described the NISN design study, which

Table 1 Summary of characteristics of event types

Type	Number 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- or left-lateral strike-slip on vertical fault	None to minor		None to extensive
South Control Fault	8	2.5-3.0	Strike-slip on fault. Some indications of shear implosion*	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*	None to extensive		None

\*Shear implosion is similar to a double-couple or shearing first-motion pattern, but has three of the four quadrants showing implosion.

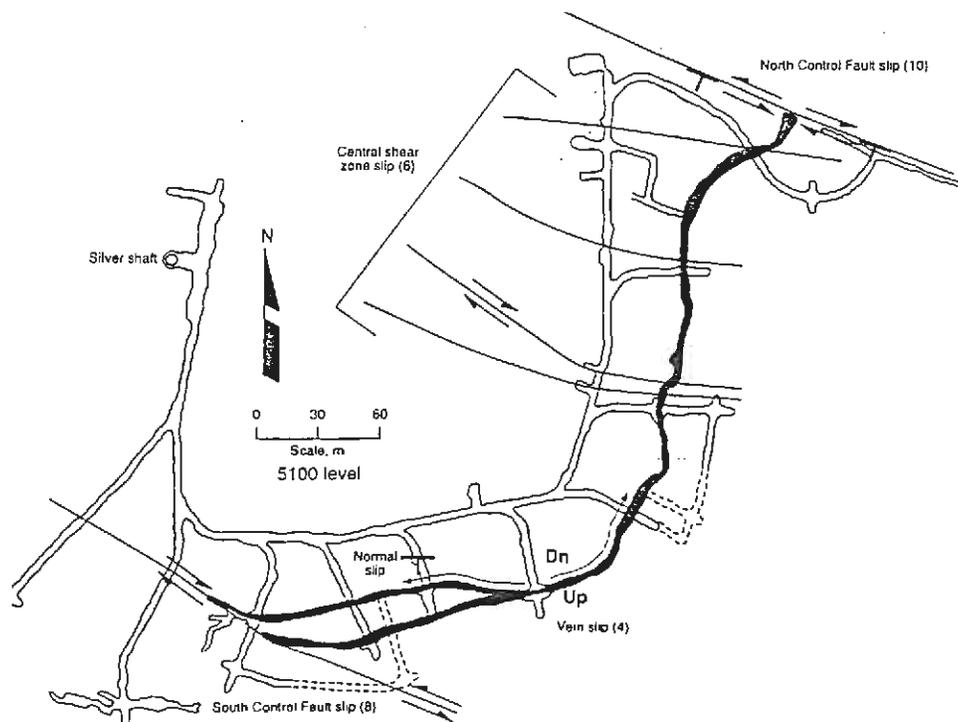


Fig. 3 Overview of five major types of rockbursts by typical location and sense of motion

used a portable monitoring system in a one-week trial. The NISN system provided 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 wear and tear and, more recently, complete shutdown of the system. Records are available for most rockbursts at the Lucky Friday mine from March, 1992, to June, 1994.\*

The accuracy of locations provided by the NISN was comparatively poor—as would be expected, considering the wide geographical area covered. The location accuracy was generally good enough to indicate which mine had produced a given event or whether it had occurred in unmined ground, independently of mining. The system was operated with a lower threshold than the macroseismic system, resulting in clipped waveform records for events with magnitudes greater than 1.

The system proved to be a useful supplement to the first-motion information provided by the mine macroseismic system, particularly for events occurring outside the mine geophone arrays and along faults that intersect the mined vein. The near-field mine systems are more sensitive to location errors than the NISN and record higher-frequency components that are attenuated before reaching the far-field NISN sensors. Comparisons of results from the two systems have shown good agreement.<sup>5</sup>

### Classification of large seismic events

Seismic, mining, geological and damage information was collected for events having estimated local magnitudes of 2.5 or greater that occurred between 1989 and 1994. Thirty-nine events were identified as meeting this criterion, an average of one event every eight weeks during the study period. The quantity and quality of information available to support

\*Records are available from Dr. Kenneth Sprende, College of Mines and Earth Resources, University of Idaho, Moscow, ID 83843.

Table 2 Southern bedding-plane slip events

No.	Date of occurrence	Magnitude	Damage	Movement	Notes
2	2/3/89	3.3	227 t, 5300-95	On footwall near top of subunit C	
3	4/4/89	2.8	>90 t, to west end 4900-93 in subunit A	On footwall bedding	Destress drilling 4900-93 pillar
7	11/4/90	2.5	68 t, footwall rib 49/93/95 stope, access slot	On footwall bedding	I-drifting into pillar
8	12/6/90	2.6	90 t, 5150-95 footwall west	On footwall bedding	
9	31/7/90	2.6	Minor damage to east side of 5150-95 slot	Normal on footwall bedding	
13	27/3/91	2.6	Extensive damage to 5300-95 stope, crosscut and raise	Thrust on hanging-wall bedding opposite pillar	
16	23/5/91	2.5	Extensive damage to 60 m of 5300 lateral	Normal and right-lateral on footwall bedding	
22	11/11/91	2.5	Minor damage, 95 development	Normal on footwall bedding	
23b	11/12/91	2.4		Normal on footwall bedding	
37	19/5/94	2.6		Normal on footwall bedding	

Fig. 5 (Opposite) (Top) Location of bedding-plane slip events plotted in plan view; (bottom) location of bedding-plane slip events plotted in longitudinal view

analyses of these events varied widely, but were sufficient for the identification of five major types that describe 37 of the 39 large events that occurred during the study period. These types of events are summarized in Table 1 and Fig. 3. The following sections provide a review of these events by type. A complete set of individual event analyses has been reported by Whyatt *et al.*<sup>29</sup>

### Southern bedding-plane slip events

Ten of the events were caused by slip on bedding planes in the southern limb of the mine. A plot of bedding-plane slip events with time (Fig. 4(a)) shows that these events were particularly prevalent in the first half of the study period (1989-91) and, with one exception, absent in the second half of the study period (1992-94). The reduced rate of bedding-plane slip activity appears to be related to completion of pillar mining. For instance, the final pillar to be mined in this part of the mine, the 5300-95, was 15 m high in June, 1991, and was completely removed by the end of May, 1992. Reduction of the pillar was accompanied by an increase in bed slip activity.

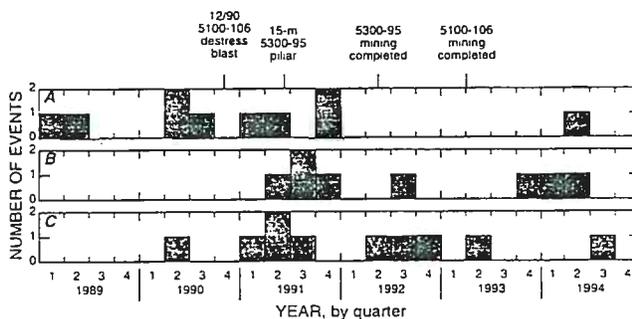
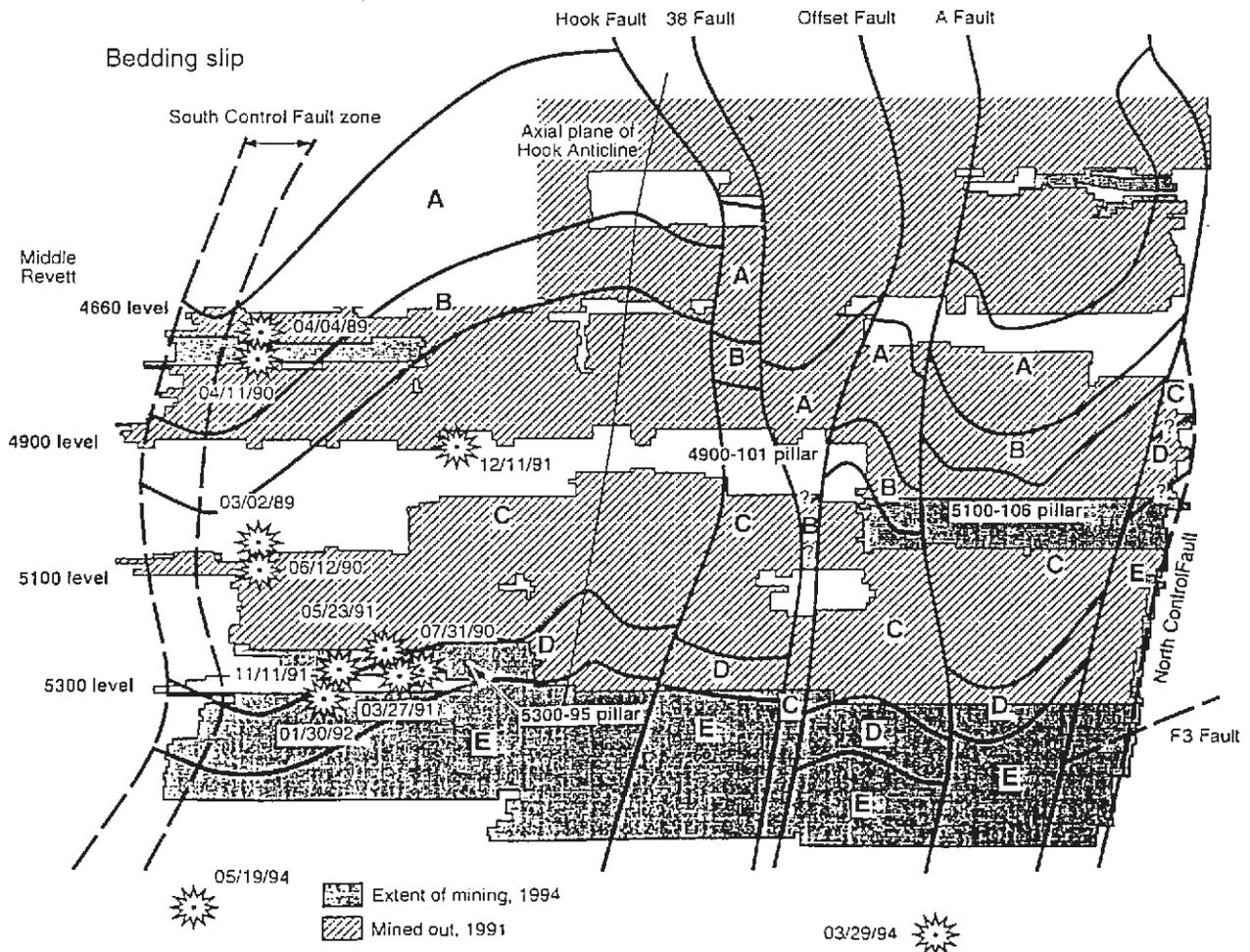
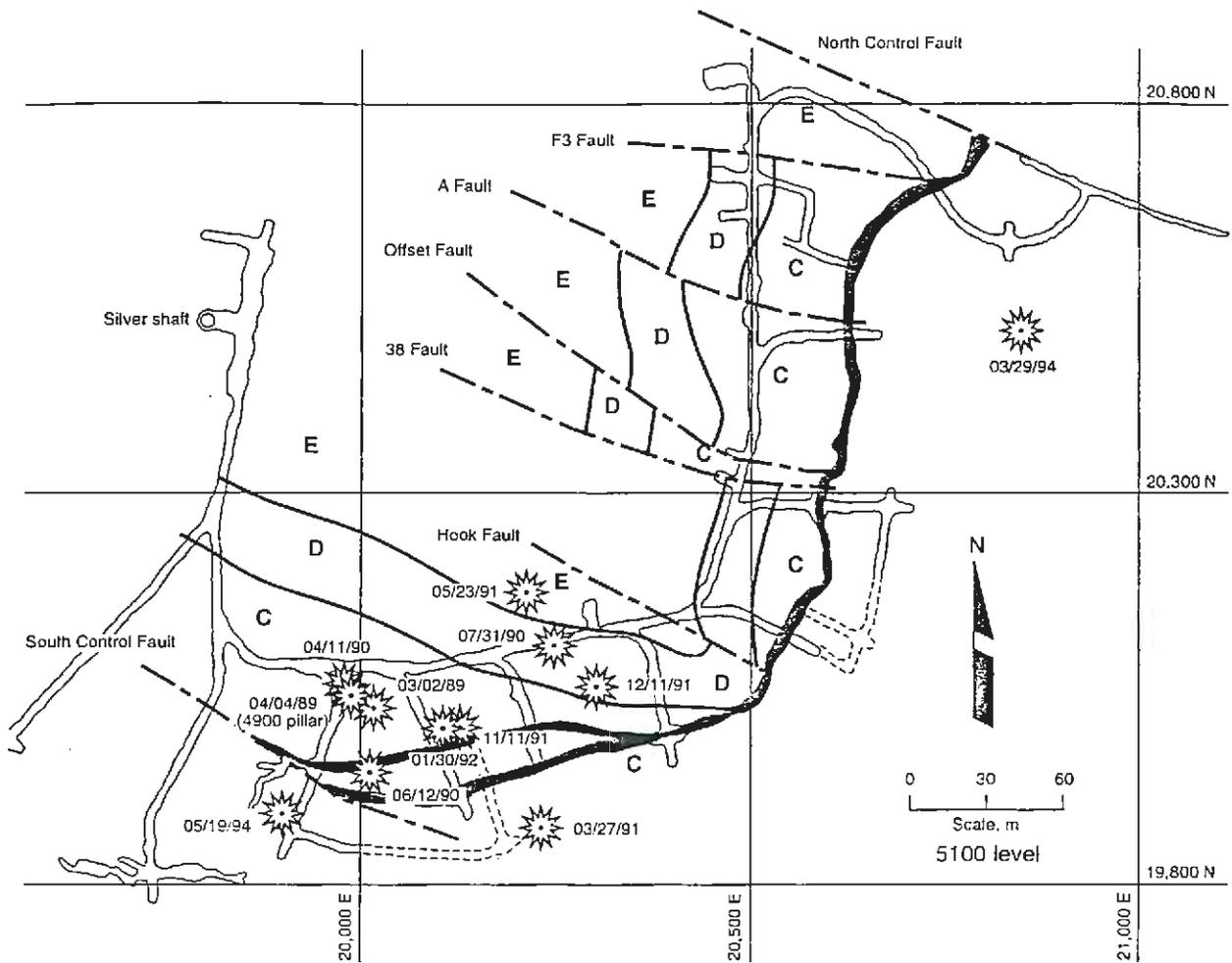


Fig. 4 Time lines by calendar quarter showing (a) bedding-plane slip events, (b) events along South Control Fault, and (c) events along North Control Fault



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 (Fig. 5 and Table 2). The occurrence of these events in the footwall was 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<sup>30</sup> addressed this mechanism in his modelling 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 a significant strike-slip movement were evident in only 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. Development openings that crossed the event slip plane suffered the most damage. In these cases entire sections of haulage way were obliterated. 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. It is possible, however, 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. Unfortunately, these large events often overloaded the monitoring system, preventing calculation of the stress drop.

Damage to the 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 although they occasionally intersect development openings.

#### Central shear-zone events

Six events occurred near the vein along a set of near-vertical faults that form the central shear zone, which lies between the axial plane of the Hook Anticline and the North Control

Fault. The events had 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 (Fig. 6) (Table 3). The first identifiable slip direction in 1990 showed left-lateral movement 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 two-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.

The driving force for these events is not well understood, particularly given the apparent change in slip direction that occurred during the study period. In fact, the existence of these events was not predicted in the recent modelling by Board.<sup>30</sup> An *in-situ* stress measurement reported by Whyatt and co-workers<sup>14</sup> found locally concentrated stresses consistent with left-lateral slip on a central shear zone fault below the mining front. Mine stress analyses conducted to date have failed to account for this stress concentration, which apparently formed naturally rather than as a result of mining. The stress concentration was centred on part 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 (Fig. 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 orientated 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 that drive these events.

These events resulted in little or no damage to stopes, but damage to development openings was occasionally extensive. The degree to which development openings were damaged

Table 3 Central shear-zone slip events

No.	Date of occurrence	Magnitude	Damage	Movement	Notes
5	2/11/89	2.6	No damage	Footwall, Offset Fault. Poorly constrained first motion	
10	3/8/90	2.5	No damage	Left-lateral; footwall, near A-fault	
11	19/10/90	2.5	55 t south end of 5100-106		Occurred during destress drilling in 5100-06 pillar
	12/90				Destress blast in 5100-106 pillar
27	4/8/92	3.0	227 t 5400-101 slot	Right-lateral with some normal; northeast of Offset Fault in hanging-wall	
	4/93				Last mining in 5100-106 pillar
32	22/10/93	2.5	680 t 5480-107 slot, 5570-107 ramp	Right-lateral; footwall, near F3-fault	
35	1/4/94	2.5	Minor damage	Right-lateral; footwall near 38-Offset Fault	

Fig. 6 (Opposite) (Top) Location of central shear-zone events plotted in plan view; (bottom) location of central shear-zone events plotted in longitudinal view

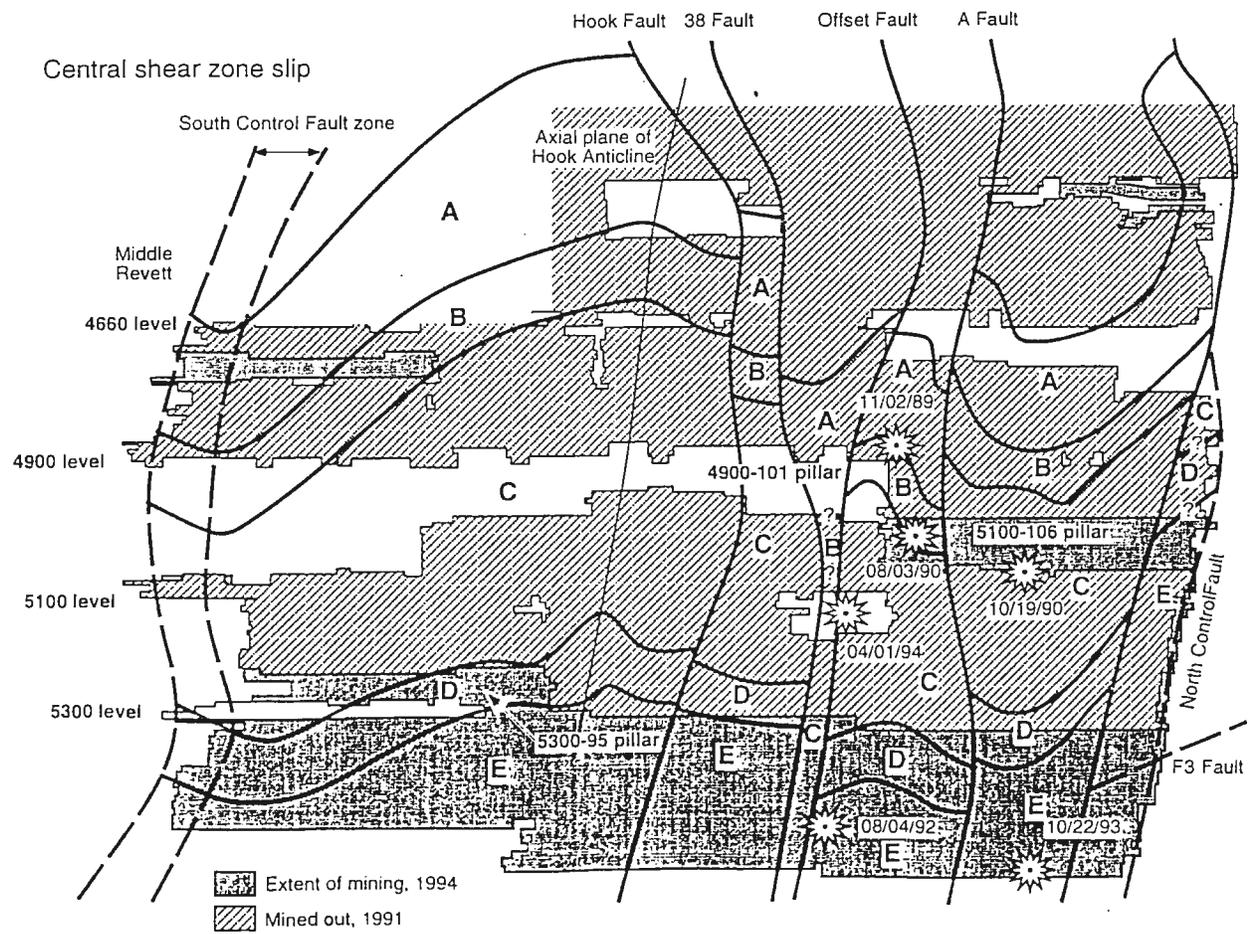
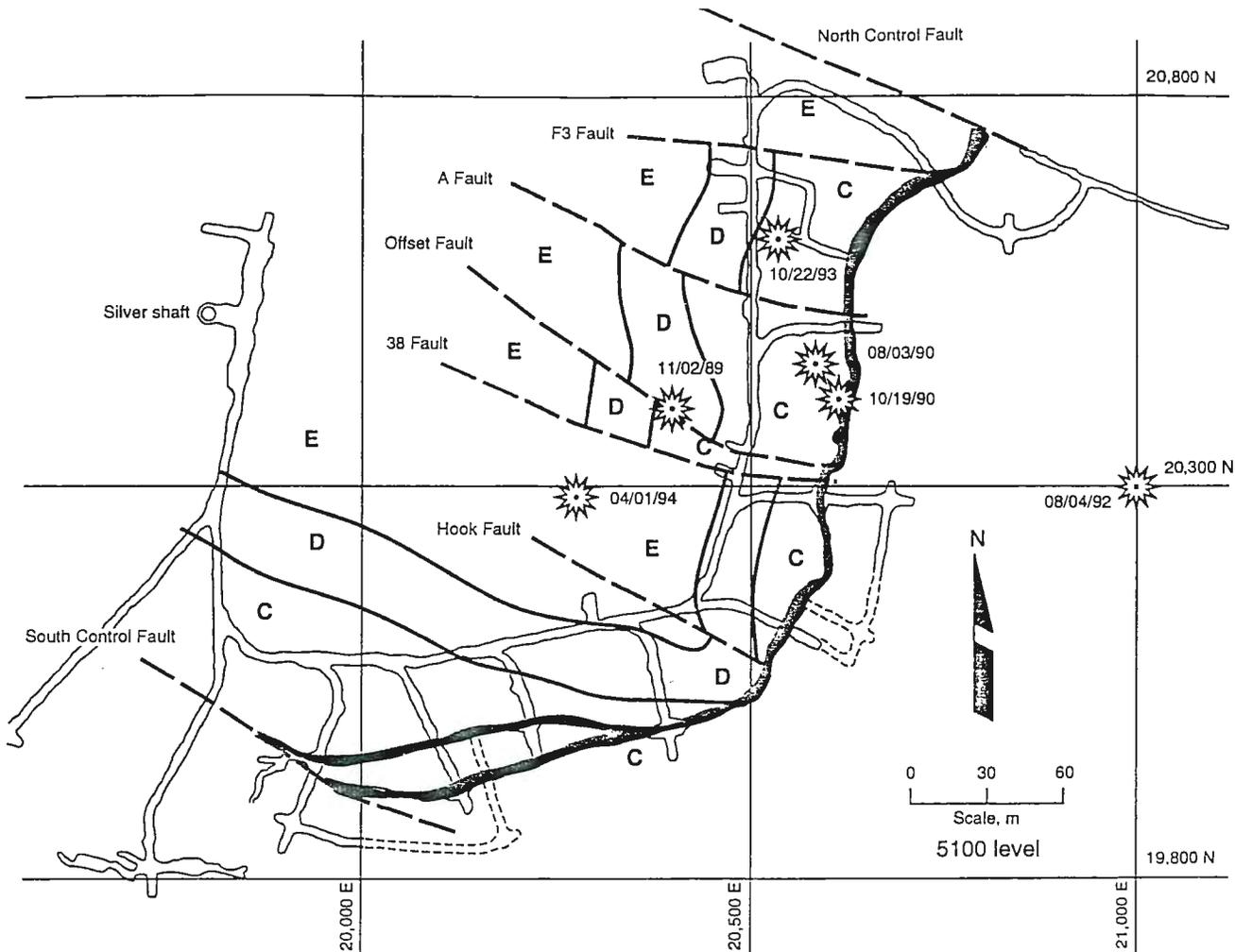


Table 4 South Control Fault strike-slip events

No.	Date of occurrence	Magnitude	Damage	Movement	Notes
17	12/6/91	3.0	Minor spalling at footwall	Left-lateral, hanging-wall, 5100 level	
18	20/7/91	2.6		Right-lateral footwall, 4900 level	
19	31/7/91	2.6	23 t, 5210–95 east on hanging-wall	Left-lateral, hanging wall, 5100 level	
23a	11/12/91	3.0	Minor damage, 4900–93/95 5300–95 main vein	Left-lateral, hanging wall, 5130 level	
28	12/8/92	3.0	635 t, 5210–95 and 5400–94 main vein	Footwall, right-lateral below 5300 level	NISN SI:* conflicting seismic and damage data
31	17/10/93	3.0	90 t, 5100–94/96, widespread minor damage	Right-lateral footwall and vein below 5100 level	SI first motion, both macro and NISN
33	5/1/94	2.5		Footwall, right-lateral	SI first motion, both macro and NISN
36	13/5/94	2.5		Footwall, right-lateral below longwall front	Deep abutment strike-slip

\*SI, a shear-implosional first-motion pattern defined by three quadrants of dilatation and one of compression.

appears to have depended largely on whether the opening intersected the area of slip. The orientation and location of local geological structures—in particular, 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 events

Eight strike-slip events (magnitudes 2.5–3.0) occurred along the South Control Fault, which forms the southwestern boundary of the mine. A plot of South Control Fault slip events with time (Fig. 4(b) and Table 4) shows no large-event activity until the 5300–95 stope was mined down to a height of 15 m in the first half of 1991. A flurry of four large events followed in the next six months, three of which occurred in June and July. The direction of slip indicated by seismicity was consistent with closure of the mined vein. Physical evidence (observed fault offset, patterns of damage) confirmed this direction of slip in two instances. All these events occurred above the mining front, three in the hanging-wall and one in the footwall (Fig. 7). The predominance of hanging-wall events is 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. Although this first-motion pattern is not fully understood, 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 with 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 probably driven by the north-west-trending maximum horizontal principal stress, which is

concentrated in the abutment.

The damage caused by these events was concentrated 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 magnitude. Two of these events with local magnitudes of 3.0 caused 90 t and 635 t of damage. In contrast, only one of the four events with local magnitudes of 2.5–2.6 caused minor damage (23 t). Overall, damage was reported from five of these eight events.

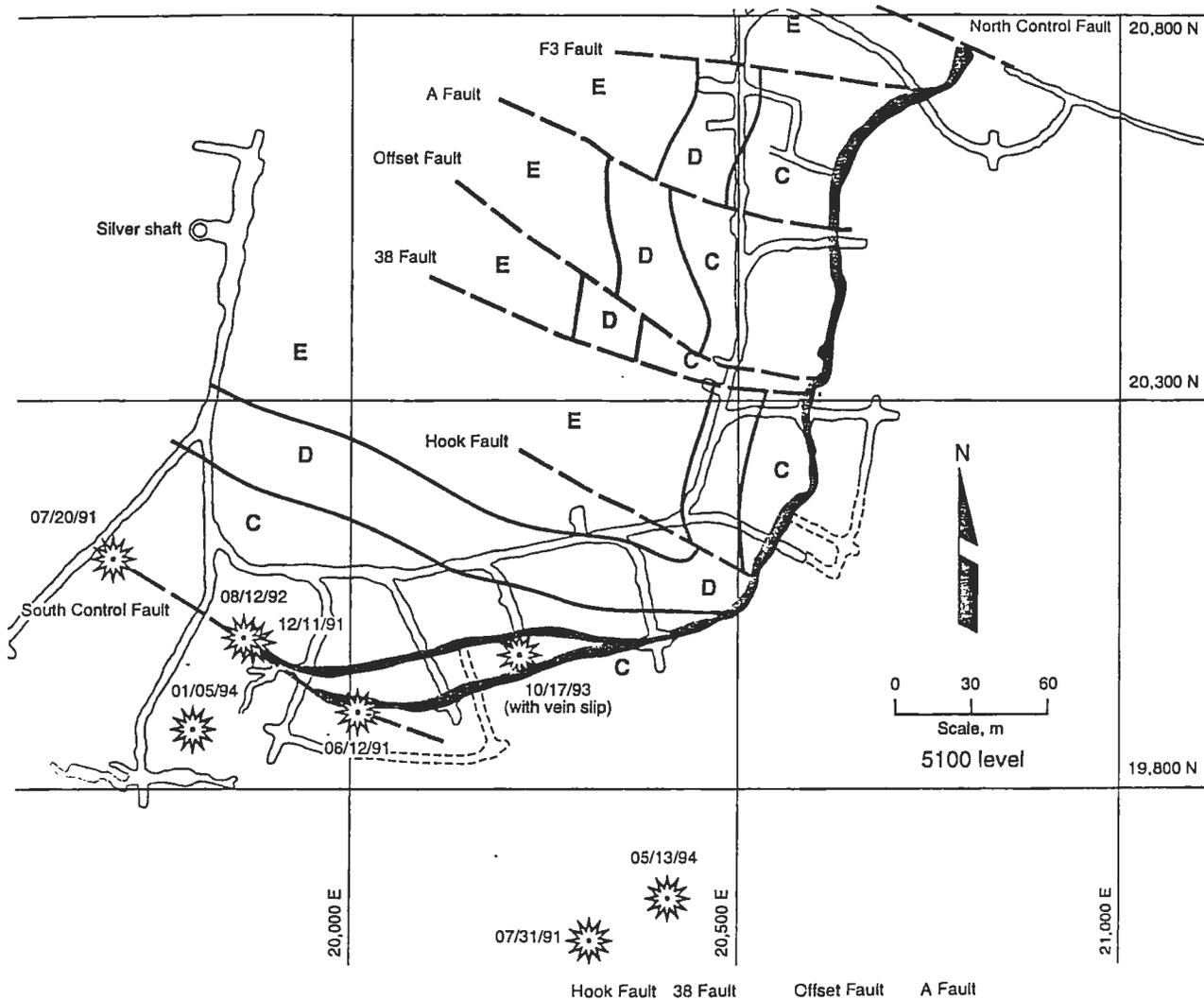
This set of events has been recognized in a number of studies and is one of the best understood. For example, Jung and co-workers<sup>3</sup> and Lourence and co-workers<sup>16</sup> have published case studies and a simple, two-dimensional, boundary-element analysis. The detailed three-dimensional study by Board<sup>30</sup> has been the most comprehensive.

#### Vein-slip events

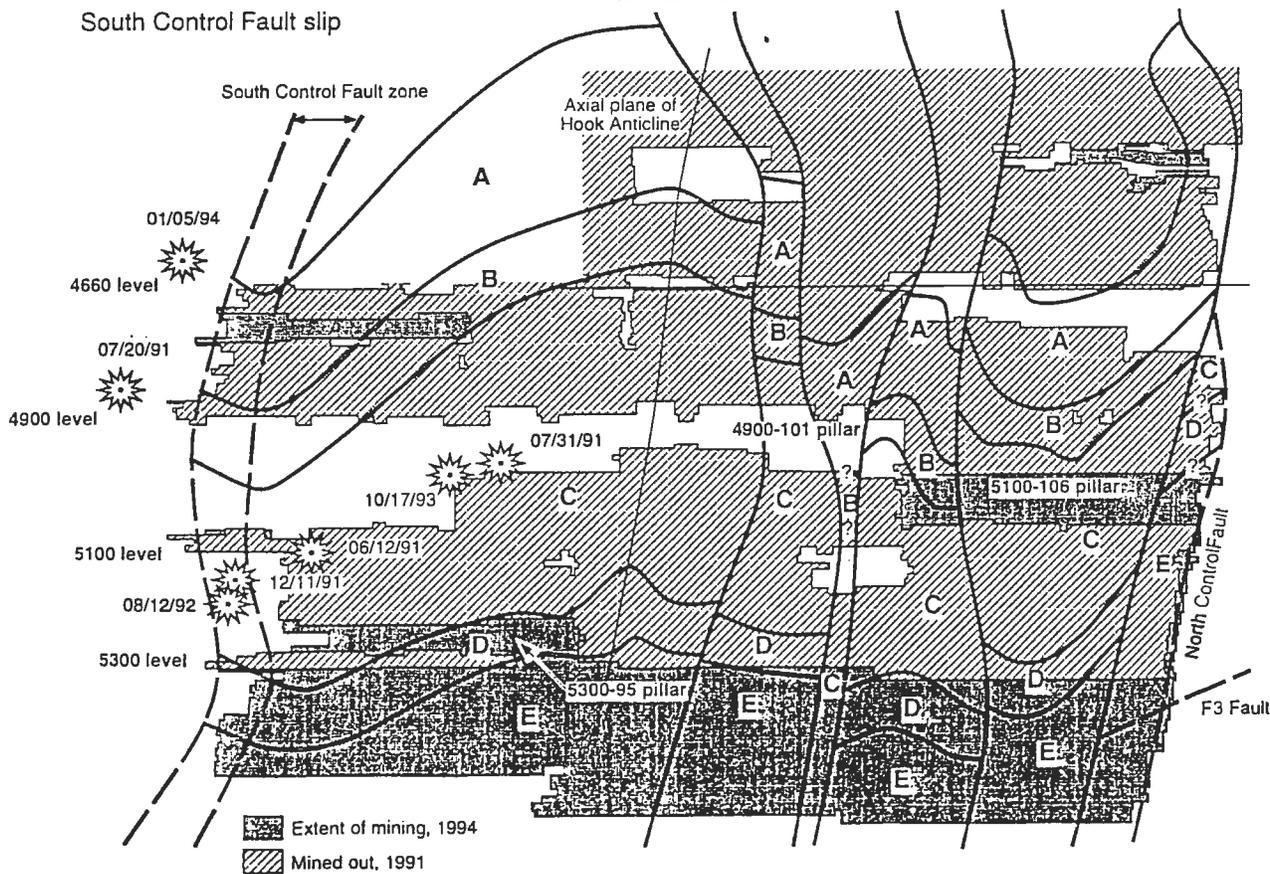
Four events occurred on the vein itself, including a very large event having a local magnitude of 4.1. These events were fairly regularly distributed over time during the study period. Spatially, they appeared to be concentrated in remnants of the vein abutted by subunit C in the footwall (Fig. 8 and Table 5).

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 wallrock 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.<sup>11</sup> Stress appeared to be concentrated in (and orientated parallel to) hard subunits. The vertical component of stress in these subunits has been measured locally at up to twice the overburden loading. The shear stress on the vein created by these 'lithopillars' was concentrated on

Fig. 7 (Opposite) (Top) Location of South Control Fault strike-slip events plotted in plan view; (bottom) location of South Control Fault strike-slip events plotted in longitudinal view



South Control Fault slip



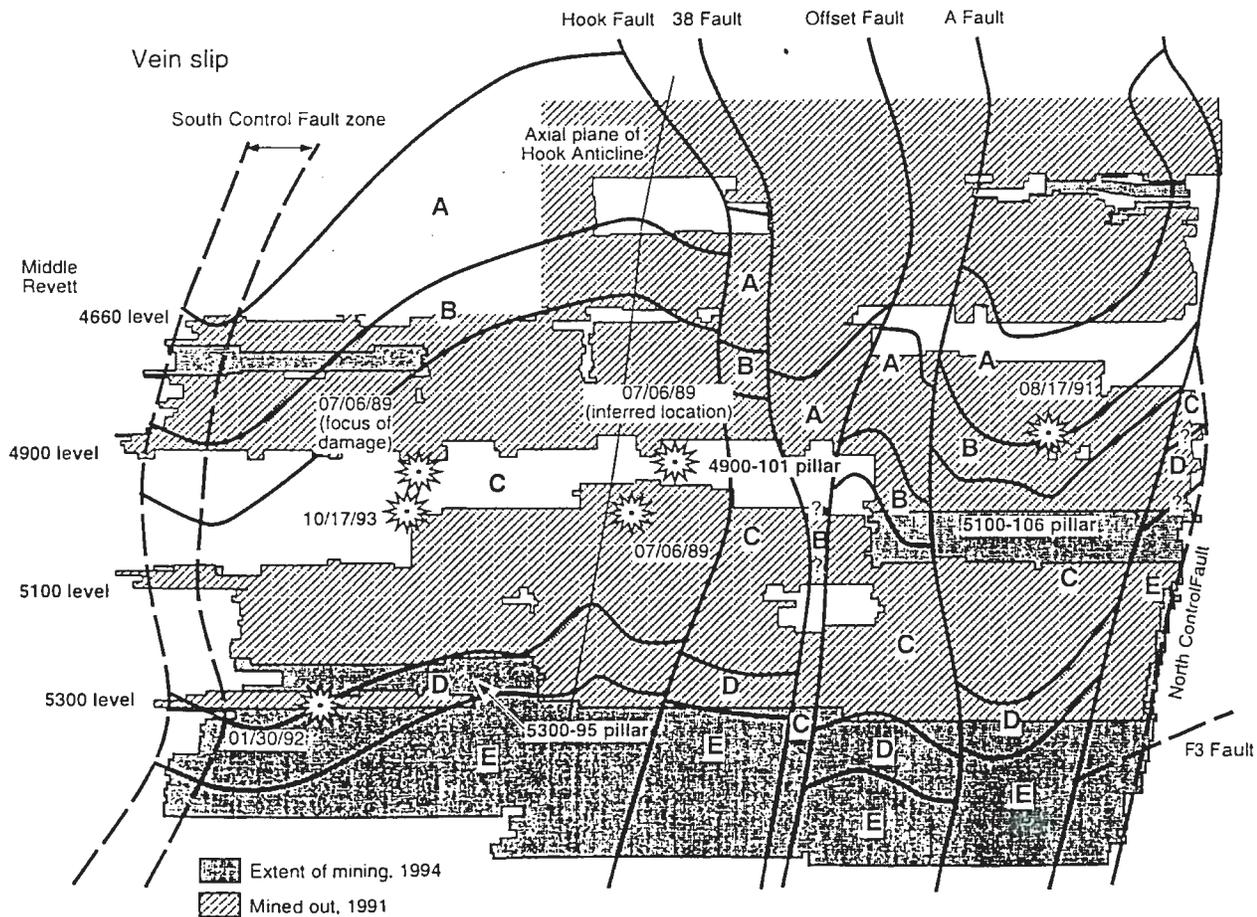
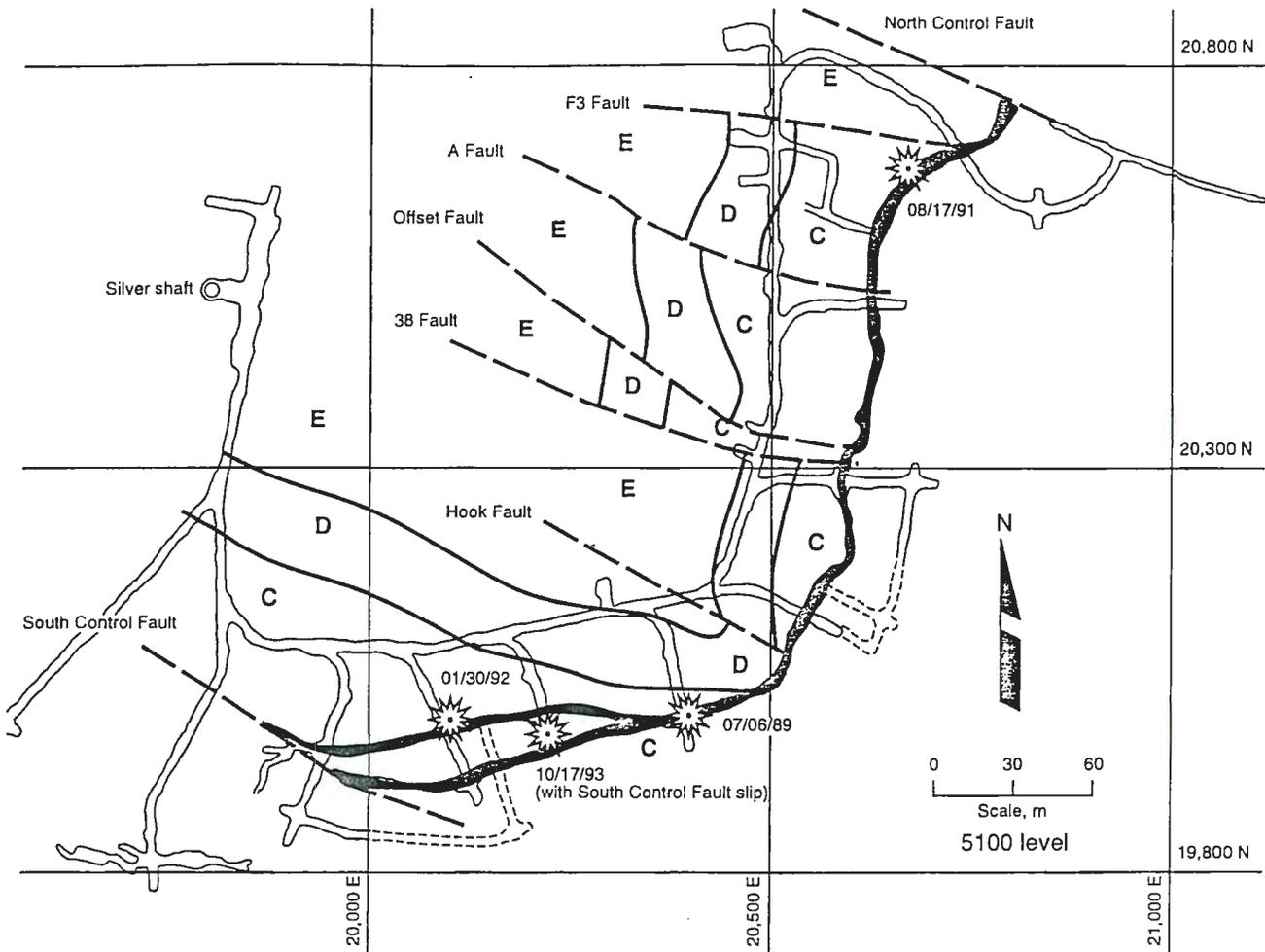


Table 5 Vein-slip events

No.	Date of occurrence	Magnitude	Damage	Movement	Notes
14	6/7/89	3.1-3.7	900 t, south limb of mine	Minor right-lateral with vertical slip, footwall down	
20	17/8/91	2.9	180 t to both ribs, 5100-106	Vertical slip with footwall down	Failure of pillar section missed in distress blast
24	30/1/92	2.5	135 t, west end of 5300-95	Vertical slip, footwall down	Pillar reduced to 6-9 m Failed distress. Damage in subunit C, not D
31	17/10/93	3.0	90 t, 5100-94/95, widespread minor damage	Right-lateral footwall and vein below 5100 level	SI first motion,* both macro and NISN

\*As defined in Table 4.

smaller and smaller areas as mining progressed, leading to shear failure with thrust movement. A case study describing this mechanism has been published,<sup>1</sup> but a full mechanical analysis has not been conducted and this mechanism was not reflected in the analysis by Board.<sup>30</sup> The foundation for such an analysis has only recently been laid with mapping of sub-units and estimates of their physical properties.<sup>13</sup>

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

#### North Control Fault slip events

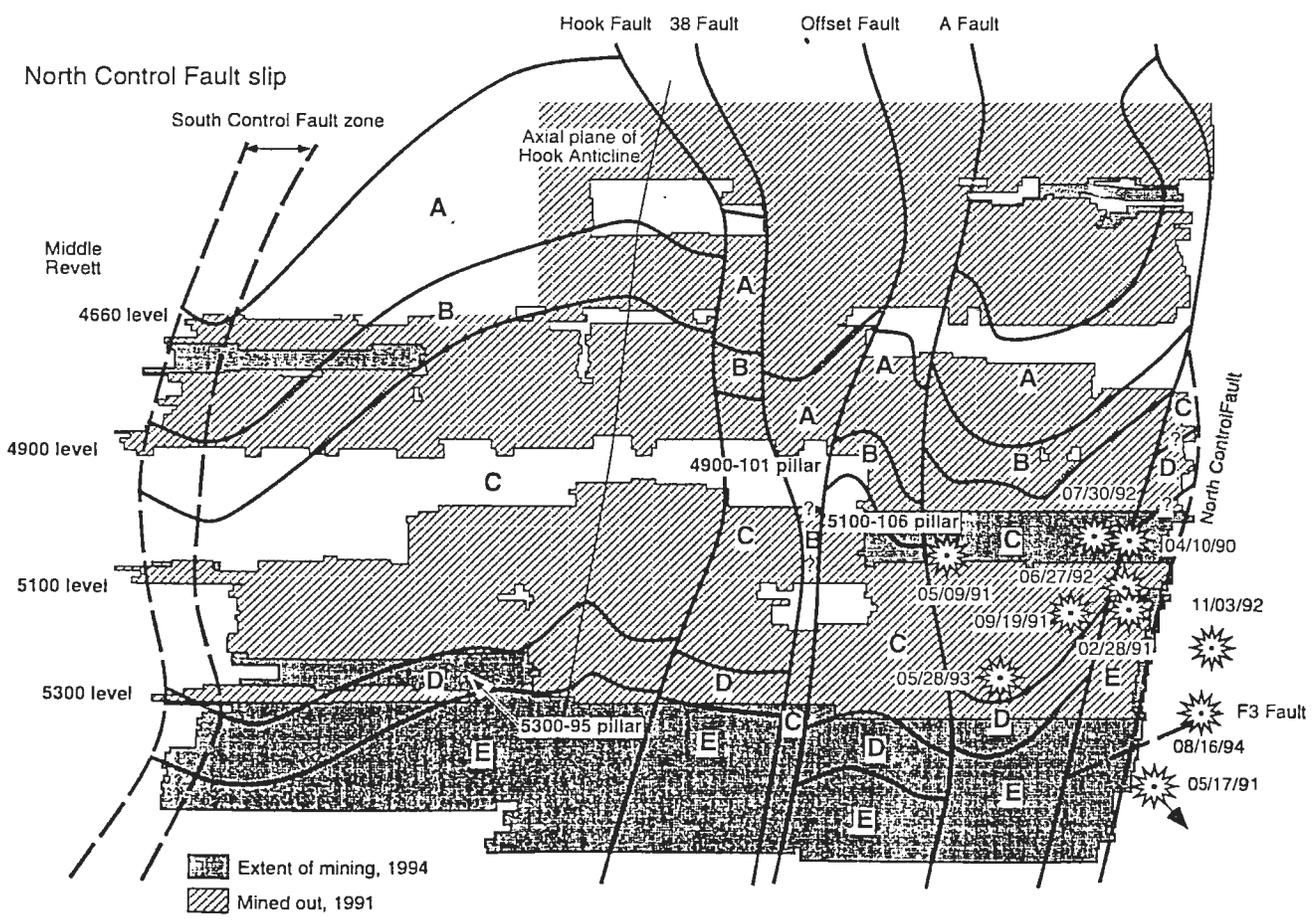
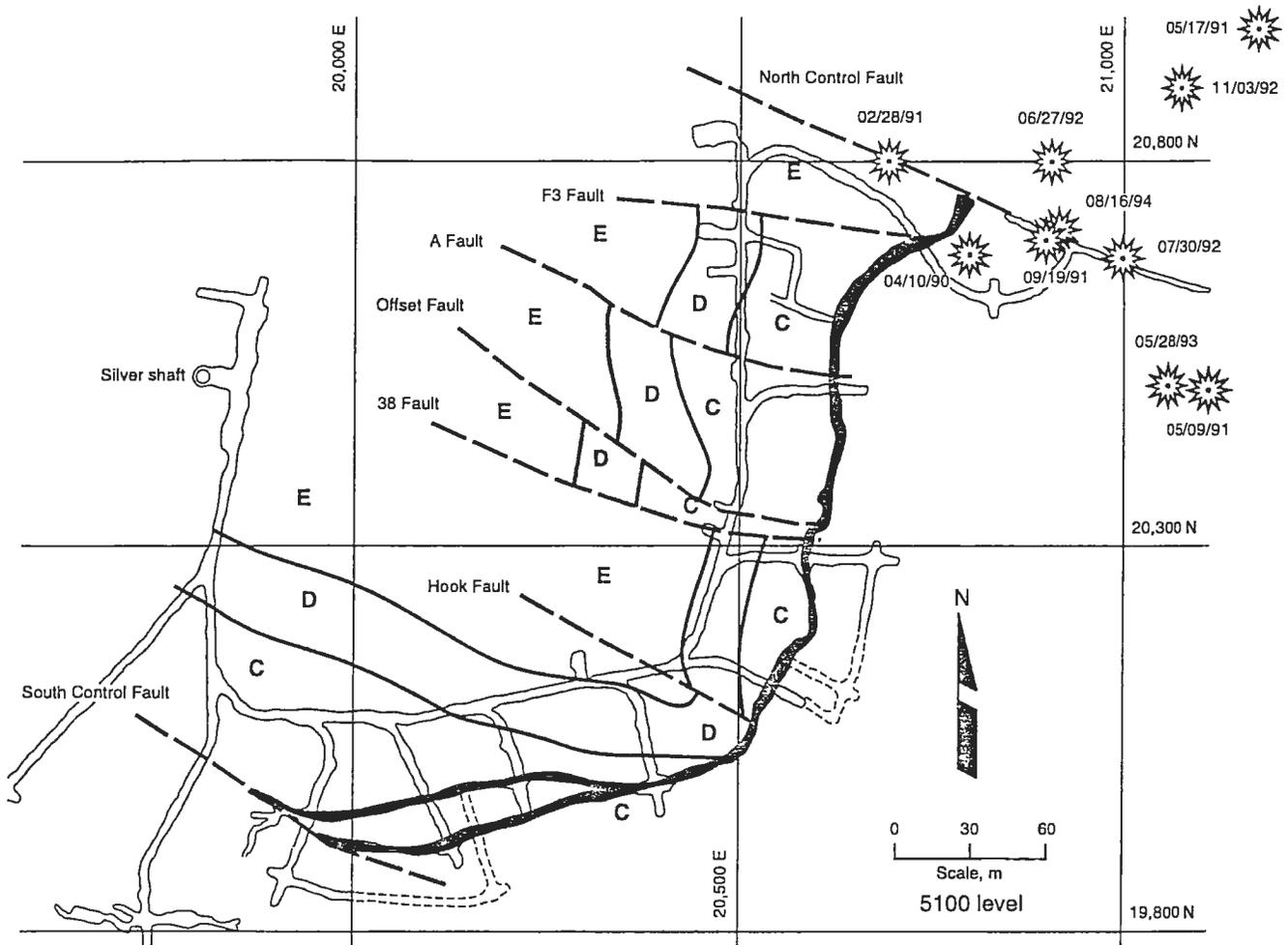
Ten events (magnitudes 2.5 to 4.1) occurred with strike-slip and/or normal dip-slip movement along the North Control Fault, which forms the northeastern boundary of the mine (Fig. 9 and Table 6). A plot of these events with time shows an initial quiet period similar to the initial quiet period on the South Control Fault, but with an earlier and less decisive ending in April, 1990 (Fig. 4(c)). The subsequent four large events occurred within a seven-month period, including two events in only eight days following distress blasting in the 5100-106 stope. This concentrated activity occurred as double-couple, strike-slip movement on both sides of the vein around the 5100-106 pillar, although most events were

Table 6 North Control Fault strike-slip events

No.	Date of occurrence	Magnitude	Damage	Movement	Notes
6	10/4/90	2.5		Hanging-wall, right-lateral on 5100 level	
	12/90				Distress blast in 5100-106 pillar
12	28/2/91	2.8	Minor damage	Footwall, left-lateral, 5100 level	
14	9/5/91	2.8	Minor damage	Footwall, left-lateral, 5130 level	
15	17/5/91	2.7	Minor damage 5100-106	Probably hanging-wall	
21	19/9/91	3.6	1800 t 5100-106 and 4660 lateral	Hanging-wall, right-lateral, 5100 level	
25	27/6/92	2.8	No damage	Right-lateral and normal, hanging-wall, 5100 level	SI,* macro
26	30/7/92	2.5	No damage	Right-lateral, footwall, SI	NISN general implosion, macro, SI
29	3/11/92	3.0	430 t 5100-106 east	Hanging-wall, right lateral, 5100 level	Only two or three cuts left in 5100-106 pillar
	4/93				Last mining in 5100-106 pillar
30	28/5/93	2.8	45 t 5100-107	Normal, hanging-wall	5100-106 pillar mined out
38	16/8/94	4.1	430 t 5100-106 and 5570-107	Hanging-wall, right-lateral, below 5100 level	

\*As defined in Table 4.

Fig. 8 (Opposite) (Top) Location of vein-slip events plotted in plan view; (bottom) location of vein-slip events plotted in longitudinal view



located in the hanging-wall. Two subsequent events occurred in the hanging-wall in this area during a six-week period in 1992. These events show a transition from double-couple to implosional behaviour. The first event registered as a double-couple event on the NISN, but the in-mine system indicated a shear-implosional pattern. The second event showed up on the NISN as entirely implosional, whereas the in-mine system indicated a shear-implosional motion.

Slip movement associated with these events was consistent with closure of the mined vein southwest of the fault, 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 as part of many North Control Fault events. The southerly dip of the two faults (and strata outside 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 heavy (1800 t damage in the event on 19 September, 1991). Stopes have borne the brunt of this damage and development openings have generally been unscathed. The exception was the 19 September event, which caused moderate damage to the 4660-level haulage way. This haulage way had already been weakened by earlier seismic events.

This set of events has been analysed previously, generally in conjunction with South Control Fault events,<sup>3,16,30</sup> and is one of the best understood.

## Discussion and conclusions

The present study has demonstrated that five types of events accounted for more than 90% of the large ( $M_L > 2.5$ ) seismic events 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. Most of these events showed double-couple first motion, but two types include events that showed shear-implosional or implosional patterns.

The damage to various mine openings caused by these events was highly variable, many large events causing little or no damage. The vulnerability of stopes and development openings to damage depended heavily on the type of event that occurred. One possible explanation for this pattern is that damage may depend on whether the active area of slip intersects an opening. Although it was difficult to ascertain the actual area of slip for these events, damaged areas were typically located at the intersection of an opening with the slipping structure and relatively close to the point at which the event initiated. Thus, the safety hazard posed by a large seismic event appears to depend not only on the relative location of the slipping structure but also on whether the slipping structure is orientated to intersect a mine opening.

Strategies for the control of mining-induced seismicity need to consider all five types of events lest a strategy that reduces one type of seismic event result in an increase in other types of events. The findings should form a sufficient basis for analyses of geomechanical conditions that produce these events, examination of interactions between different types of events and evaluation of the effect of various mining

strategies on each of the five types of events. These analyses, which will require extensive numerical modelling, will form the next step in the investigation. Future work will also address smaller (but still dangerous) strain events and generalize these results to other mines and other mining districts.

## Acknowledgement

The authors' effort has benefited from the efforts of a number of colleagues—in particular, Ken Sprende, University of Idaho, and Charles Wideman, Montana Tech.—and close cooperation between Hecla Mining Co., the University of Idaho, Montana Tech. and the USBM.

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Fig. 9 (*Opposite*) (Top) Location of North Control Fault slip events plotted in plan view; (bottom) location of North Control Fault slip events plotted in longitudinal view

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#### Authors

J. K. Whyatt is a mining engineer in the Catastrophic Failure Detection and Prevention Branch, Spokane Research Laboratory, National Institute for Occupational Safety and Health. He holds degrees of B.S. and M.S. in mining engineering from the University of Idaho and is a Ph.D. candidate in geoen지니어ing at the University of Minnesota.

Address: Spokane Research Laboratory, National Institute for Occupational Safety and Health, E 315 Montgomery, Spokane, Wa, 99207, U.S.A. E-mail: juw6@cdc.gov

Wilson Blake received a Ph.D. in mining engineering from the Colorado School of Mines. He is an independent consultant active in the area of ground control and rockbursting in deep mines and works from Hayden Lake, Idaho, U.S.A.

T. J. Williams received a B.S. degree from Montana Tech, Butte, Montana in 1972. He is a mining engineer currently working for the Spokane Research Laboratory.

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**Title:** TRANSACTIONS. SECTION A, MINING INDUSTRY / INSTITUTION OF MINING & METALLURGY.  
**Status:** Active  
**Subject:** MINES AND MINING  
**Abbrv Ttl:** Inst. Min. Metall., Trans., sect. A: Min. ind.  
**Added/Corp:** Institution of Mining and Metallurgy (Great Britain)  
**Var Form:** Transactions of the Institution of Mining and Metallurgy. Section A, Mining industry  
**Var Form:** Mining Industry  
**Date/Vol:** Vol. 75 (Jan. 1966)-  
**ISSN:** 0371-7844  
**Ser type:** Trade Publication  
**Country:** UK  
**Language:** English  
**Frequency:** Four times a year (Jan., Apr., July, Oct.)  
**Price:** £70.00  
**Publisher:** Institution of Mining and Metallurgy  
44 Portland Place, London W1N 4BR United Kingdom  
**Telephone:** 011 44 171 5803802, Fax: 011 44 171 4365388  
**Editor(s):** M. J. Jones  
**Ind/Abstr:** Coal Highlights., Current Contents. Engineering, Computing & Technology., Ei Page One.,  
Engineering Index Annual., Ergonomics Abstracts., GeoRef [Computer File]., Metals Abstracts.  
**LC Class:** TN1 .T73  
**DD Class:** 622/.05  
**UDC Class:** 62  
**CODEN:** TIMNAQ  
**CONSER:** 02401163  
**Bk Review:** Yes  
**Advertise:** Yes  
**Circulation:** 3,200  
**Circ controlled:** Yes  
**Reg CCC:** Yes  
**Descript:** These are technical notes, meetings, reports, and papers on science and technology. It includes  
other articles on the **mining industry**, mineral processing and earth science.  
**Preceding:** Transactions of the Institution of Mining and Metallurgy 0371-7836  
**Successor:** IMM Bulletin 0308-9789