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Composite source mechanism solutions for rockbursts at the Lucky Friday Mine, Mullan, Idaho

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ABSTRACT: U.S. Bureau of Mines researchers have analyzed full-waveform digital seismic records from moderate-to-large rockburst events at the Lucky Friday Mine, Mullan, ID. The goal of this work is to characterize source mechanisms for rockburst events. Because the seismometer array used for the recordings usually consists of fewer than 10 instruments, a method of obtaining composite source solutions has been developed. These solutions are determined by selecting events with similar arrival patterns at the seismometer array and with hypocentral locations in the same general region of the mine. Some events have all-dilatational first arrivals, while others display arrival patterns with both compressional and dilatational arrivals. There are at least three types of events in the mine. Some of the more complex arrival patterns seem to be associated with right-lateral, strike-slip motion, while others seem to be associated with left-lateral or dip-slip movement.

The type of event seems to be independent of source location, although geologic conditions in different regions vary. Even though there is a fundamental difference in the geometry of the mining environment, the three types of events are still recognizable.

This work is continuing, and data from all large events (Richter magnitude, $m_L > 2.0$) at the mine are being analyzed and added to a database.

1 INTRODUCTION

The complex geologic setting of the Lucky Friday Mine, Mullan, ID, and the interaction of mine-induced changes in the regional stress field present a unique opportunity for rockburst research. The mine is located in a region of intense folding and faulting, and there is some evidence that tectonic deformation continues at the present time (Sprenke et al. 1991).

Full waveform recording of seismic events and the use of three-component seismometers were initiated in 1989 and were described by Jenkins et al. (1990). The original data were obtained by five seismometers placed at strategic positions in the mine. The original array, although minimal, demonstrated the usefulness and desirability of a more complete seismic data collection system. The receiver array was modified in January 1991 and now includes a mixed array of three-component and single-component seismometers. The number of receivers was increased to 11, and this new array has operated successfully ever since.

Because of the limited number of geophones available for analyzing individual rock-burst events, U.S. Bureau of Mines (USBM) researchers adapted a method used in studies of earthquake seismology—composite source solutions. Composite solutions are used to analyze events occurring in the same general region of the mine and having the same general first-motion arrival patterns. Composite solutions do not represent a particular source mechanism, but instead represent classes of source mechanisms occurring throughout the mine. This paper outlines a method for creating composite source solutions for digitally recorded events from the Lucky Friday Mine.

1.1 *Geologic Setting*

Figure 1 shows a plan view of the 5100 level of the Lucky Friday Mine and three major regions in the mine (labeled A, B, and C in Figure 1). In general, the trend of the mine workings is northeast-southwest; however, Figure 1 shows that some mine workings trend north-south or east-west.

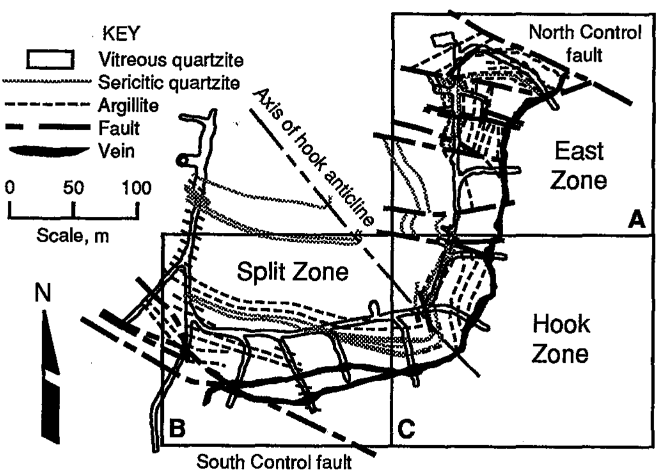

Figure 1. Plan view of 5100 level, Lucky Friday Mine.

There are also abrupt major changes in orientations of geologic formations throughout the mine. In the northeast portion of the mine, bedding trends north-south and dips steeply to the east. However, close to the North Control Fault (NCF), strikes and dips change rapidly. The NCF is a major tectonic feature that strikes northwest and dips at a near-vertical angle. Offset on the fault is believed to be left-lateral (Blake 1989), and near the fault the strike of the bedding can change by as much as 90°.

In the southwest portion of the mine (region B in Figure 1), the general strike of the bedding is approximately east-west and dips are to the south. Another major tectonic feature, the South Control Fault (SCF), is located in this region of the mine. The intersection between bedding and faults in region B is not as complex as that in region A. Because trends of bedding and faulting are similar and because some tectonic separation is thought to have occurred through slip along bedding planes, the identification of faulting in the southwest portion of the mine is somewhat difficult (Scott et al. 1993).

1.2 *Seismic Monitoring*

Data from three types of seismic monitoring systems have been collected from the Lucky Friday Mine. A seismometer on the surface near the mine workings was used to determine event magnitudes. Approximate average distance between events and the surface seismometer was 1.5 km, and event magnitude (M_L) was estimated by measuring millimeters of displacement recorded on a drum. An event that displaces 50 mm on the seismometer is approximately an $M_L = 1$ event.

Event locations are determined by a mine-wide microseismic monitoring system consisting of single-component seismometers and accelerometers. In this system, approximately 40 detectors are placed about 60 m apart. The microseismic network is an event detection-and-location system that records only first-arrival information.

Event locations are also calculated by the USBM macroseismic network and a least-squares inversion program implemented by Girard (1990b). The distinction between the microseismic and macroseismic systems is the ability of the latter to record full waveform data. With the macroseismic array, the distance between event and detector can range from 50 m to as much as 2 km.

Events detected by the macroseismic system are recorded by an IBM-compatible computer[1] modified by the installation of an Atlab analog-to-digital board. The system is controlled by the XDETECT software developed by the International Association of Seismology and Physics of the Earth's Interior (IASPEI), with sample rates for each detector set as high as 1,290 samples per second. For data analysis, a batch file entitled GOFPS, developed by Girard (1990a), is used. GOFPS calls two USBM programs, RBURST and RPEAK (Nichols 1990) that allow P-wave and S-wave picking and spectral analysis. Nichols patterned his programs after the IASPEI program PCEQ, but the former programs differ from PCEQ primarily in their ability to output arrival time information to 0.1-ms accuracy rather than the 0.01-s limitation of PCEQ. The RBURST program is used for analysis of single-component data and the RPEAK program is used for analysis of three-component data. Figure 2 is an example of the computer screen display for RPEAK.

After the arrival times of the phases are picked, the GOFPS program puts arrival times and event location data in the correct format to be input to the FPFIT and FPPLOT programs described by Lee et al. (1988) and modified by Wong (1990). The resulting output is a double-couple source mechanism solution that best fits the data. Oppenheimer (1991) has suggested that some minimal number of seismometers is required for good source mechanism determinations and that the number may be as high as 32. Because the macroseismic system was originally very limited, the GOFPS

[1]Reference to specific equipment or tradenames does not imply endorsement by the U.S. Bureau of Mines.

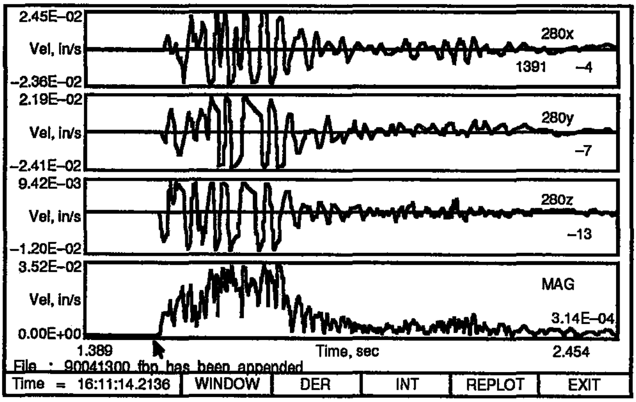

Figure 2. Computer screen display of program RPEAK.

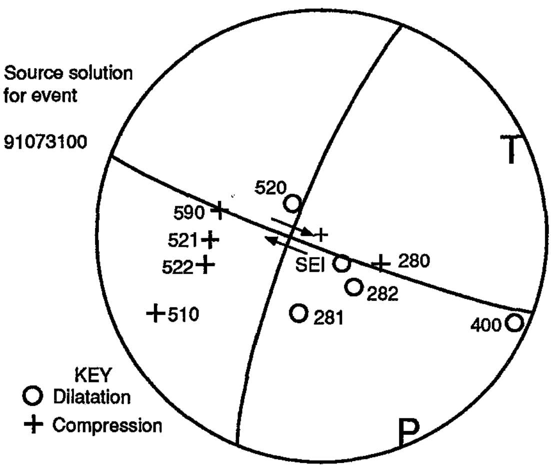

Figure 3. Source solution for a single event showing possible right-lateral, strike-slip motion on a northwest-trending fault.

program allows a researcher to use as few as six receivers before being warned of possible problems. Figure 3 is a typical source mechanism solution for a single event.

2 DATA ANALYSIS

Several hundred events were detected and recorded during the first 2 years of system operation. Individual events were analyzed for location and source mechanism. Several operating characteristics were established during this time: (1) The array geometry was such that some detectors were in the "near field" and some were in the "far field." (2) Because some of the seismometers were near the same level as rockburst events, placement of the hypocentral location in the vertical direction controlled the source mechanism solution. Small changes in source location estimates often had correspondingly large changes in source solutions. (3) Only a few compressional events have been detected by the surface seismometer. (4) Some source mechanism solutions were compatible with right-lateral, strike-slip motion; some were compatible with left-lateral, strike-slip motion, and others were compatible with dip-slip motion.

Before the macroseismic system was installed, there was a tendency to lump events from the same general area of the mine and assume that these events had similar source mechanisms. However, after computing several source mechanism, it became apparent that each region of the mine had a variety of source mechanisms. Because of the mine's geologic complexity, this finding was not unexpected, but this was the first time instruments had verified the complexities of the source mechanisms.

Because the small number of detectors placed severe limitations on determining source mechanisms, a method of making composite solutions was adapted. Of particular concern was that the layout of the seismometer array had caused certain events to be recorded as all-dilatational events having arrivals from the same stereonet quadrant. Such events have source solutions that would not be uniquely determined.

As source solutions were obtained, they were inspected to determine the general patterns of first-motion arrivals. If, for instance, the geophones of the array all plotted within the southwest quadrant of the focal sphere, and all the arrivals were dilatational, the focal mechanism solution was obviously poorly constrained. This was one of the problems encountered during the data analysis and probably represents a worst-case scenario. Usually the receiver array, although constrained by mine geometry, was deployed so that arrivals would be plotted in at least three quadrants, if not all four, of the focal sphere. Events from region A that had similar allowable source solutions were grouped together as a single event, and the composite solution, as shown in Figure 4, was obtained.

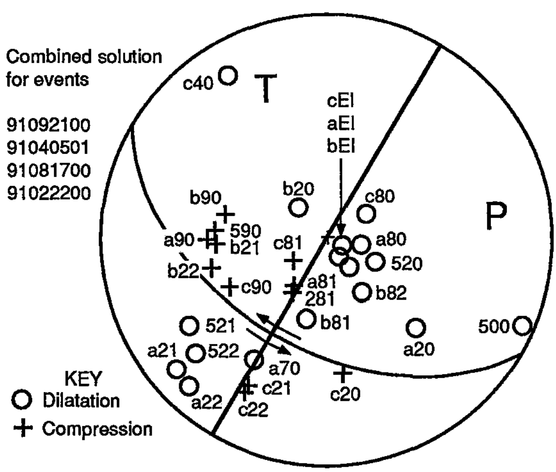

Figure 4. Composite source solution showing possible left-lateral, strike-slip motion on a northwest-trending fault.

As a result of grouping events into composite solutions, at least three distinct classes of events were determined. Figures 4 and 5 illustrate the types of source mechanism solutions obtained by combining the recordings for selected events. Each of the events selected originated in the northeast part of the mine. The actual events used for the composite source mechanisms are indicated on the figures. Because the major faults of the area trend northwest-southeast, the source mechanism classification was related to the sense of motion that could have occurred on these faults. Some source mechanisms were right lateral, some were left lateral, and some were dip slip.

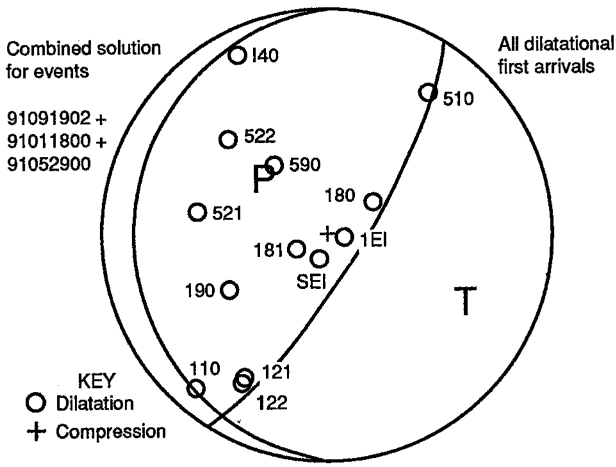

Figure 5. Composite source solution generated from events having all-dilatational first arrivals.

3 METHODS OF DETERMINING COMPOSITE SOURCE SOLUTIONS FOR THE LUCKY FRIDAY MINE

Composite solutions developed for events at the Lucky Friday Mine are not actual fault plane solutions and should not be used to "prove" that a particular rock mass is moving along a fault or geologic formation in the direction of the double-dipole seismic solutions. The correct use of composite solutions is in showing that there are recognizable types of events and that each region of the mine is experiencing more than one type of event.

As events are analyzed, a *.FBP file is generated that contains data for each geophone used in the computation of a source solution for each event. A sample FBP file is shown as follows:

Example FBP file

```
281Z  1817  1:18:54.5220   -6
520X  1632  1:18:54.3791   -1
520Y  1632  1:18:54.3791    1
520Z  1632  1:18:54.3791   -3
400Z  1719  1:18:54.4463    4
440Z  1679  1:18:54.4154   -3
590Z  1655  1:18:54.3969   -5
521X  1611  1:18:54.3629  -23
521Y  1611  1:18:54.3629   34
521Z  1611  1:18:54.3629   19
522X  1607  1:18:54.3598  -10
522Y  1607  1:18:54.3598   -5
522Z  1607  1:18:54.3598  -27
SEIS  2010  1:18:54.6709  -18
570H  1659  1:18:54.4000   95
```

The first column is a list of geophone names and components. For example, geophone 520 has three components: the vertical Z component (+ indicates upward motion); the east-west X component (+ indicates eastward motion); and the north-south Y component (+ indicates northward motion). The next column consists of sample numbers from the waveform file for the P-wave phase pick. The third column shows the time corresponding to the sample number in column 2. The format of column 3 is hours: minutes:seconds, and times are recorded to tenths of milliseconds. Column 4 is a list of magnitudes and polarities of motions at the time the sample was recorded.

Data from the first and last columns of the file, along with event location information, are used to make source mechanism estimates by incorporating this information into *.DAT files to be input to the FPFIT program. An example DAT file is illustrated below:

EXAMPLE DAT FILE

```
1
  DATE      ORIGIN     LAT N     LONG W     DEPTH      MAG
 92062703      .00 47-26.10 115-43.09 -19.24       .30

  STN  DIST AZM AIN PRMK
  281   2.8  28 150 IPD
  521    .3 332 102 IPC
  590   1.0 312  51 IPC
  440   1.3 104 131 IPD
  520    .5  33  91 IPD
  522    .2 298 100 IPD
  SEI   5.3 352 167 IPD
  570    .9 224  40 IPD
  400   1.8 313 132 IPC
```

The information contained in the first three rows of the DAT file is required to run the source mechanism program, but includes some dummy variables. The event name (in this case, 92062703) and the event depth (in this case, -19.24 hundred feet) are real. However, LAT/LONG refers to general mine location, and the ORIGIN and MAG fields are filled only to satisfy software format requirements and are not used in the analysis. The remaining information is determined by comparing the previously calculated event hypocenter with geophone (STN) locations. The distance (DIST) between the event and the geophone is indicated, as well as the azimuth (AZM) and take-off angle (INC) for the seismic wave leaving the source and arriving at the receiver. The last column contains information about the seismic wave: IPC indicates an *I*mpulsive *P*-wave with *C*ompressional motion, while IPD indicates an *I*mpulsive *P*-wave with *D*ilational motion.

After a DAT file is created, the information is in the correct format to be input to the U.S. Geological Survey programs FPFIT and FPPLOT. These programs are used to generate fault plane solutions and to view them on lower hemisphere stereonet projections. Each solution is analyzed to see if the pattern of geophone arrivals is unique or if the pattern can be incorporated in composite solutions.

If the fault plane solution is similar to several other solutions for events in the same region of the mine, a composite solution is made. Composite solution files are obtained by concatenating FBP files for similar events. A new DAT file is computed for the concatenated data and is then used for the FPFIT and FPPLOT programs.

4 CONCLUSIONS

Conditions for inclusion of data into a composite solution is somewhat arbitrary. Composite solutions for events at the Lucky Friday Mine are obtained as follows:

1. Events are separated by region.
2. Events are chosen from similar depths and the same general area of the mine.
3. Arrival patterns are examined as they are recorded by the receivers. Groups of compressional and dilatational arrivals must be similar.

The composite solutions are not used as actual double-dipole seismic solutions, but instead represent classes of solutions. Preliminary characterization of source mechanisms has shown there are at least three types of events occurring in the mine and arrival patterns seem to be associated with right-lateral, left-lateral, or dip-slip motions. This work is continuing, and large events are being analyzed and added to the current database.

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