REMOTE MONITORING OF MINE SEISMICITY AND EARTHQUAKES USING RADIO TELEMETRY, COMPUTERS, AND THE INTERNET

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ABSTRACT

The National Institute for Occupational Safety and Health and the Stillwater Mining Company worked cooperatively with the Montana Bureau of Mines and Geology to develop a system that would collect seismic data at the Stillwater and East Boulder mines. The purpose was to obtain baseline information on the magnitude and location of mining-induced seismicity to determine if the mines needed multi-channel in-mine monitoring systems. Seismic data recorded at field sites near the mines are being telemetered via FM radio through a series of repeaters to a central recording site where the seismic signals are digitized using an Earthworm data acquisition system. The Earthworm system performs several data analysis tasks in near-real time and places raw seismic data, preliminary hypocenter locations, and magnitudes on a Website within 5 min of a seismic event. Such rapid access to seismic data allows personnel at the Stillwater Mine, Spokane Research Laboratory, and Earthquake Studies Office to evaluate seismic events quickly and respond in ways that may improve the safety of mine personnel underground. Installation of the system also broadened earthquake coverage to south-central Montana, a region previously not covered by the seismograph network.

1. INTRODUCTION

The Stillwater and East Boulder mines in south-central Montana are underground mines that produce palladium and platinum from a geologic structure known as the JM Reef. The JM Reef is part of the Stillwater complex, a 42-km (26-mile) long, layered stratiform, mafic-to-ultramafic igneous intrusion approximately 2.7 billion years old (Czamanske and Zeintek, 1985; Hess, 1960). Currently, the Stillwater Mine produces ore using variations on horizontal cut-and-fill mining, but longhole stoping practices are playing an increasingly important role. The East Boulder Mine uses longhole stoping for most of its extraction.

Engineers at the Stillwater Mining Company and at the National Institute for Occupational Safety and Health (NIOSH) have become concerned about the potential for hazardous rockbursts as mining proceeds deeper into the highly stressed, hard, brittle rock (Johnson et al., 2003). Rockbursts are defined as "a sudden and violent failure of overstressed rock resulting in an instantaneous release of large amounts of accumulated energy," according to the regulatory definition (30 CFR 57.3000) applicable to U. S. mines. Rockbursts are a common problem in many mines throughout the world, some of which have hard, brittle rock similar to that found at the Stillwater Mine (Whyatt et al., 2002).

Many rockburst-prone mines have sophisticated and expensive in-mine monitoring systems to determine the locations and magnitudes of mining-induced seismic events (Girard et al., 1995). The purpose of this study was to determine the amount of seismicity at the Stillwater and East Boulder mines before the mines decided whether to install expensive in-mine seismic systems. Therefore, NIOSH researchers installed relatively inexpensive surface seismic stations as a first step in identifying the level of the seismic activity near the mines. The problem was how to measure frequency-of-occurrence and event-magnitude data from mining-induced seismicity in a timely manner and get this information to rock mechanics engineers responsible for the mine sites and to researchers at NIOSH's Spokane Research Laboratory in Spokane, WA, 960 km (600 miles) from the mines.

NIOSH approached the Earthquake Studies Office (ESO) of the Montana Bureau of Mines and Geology in Butte about expanding the regional seismic network in the vicinity of the mines. Much of western Montana was already being monitored by ESO. The agency was also experienced in using radio telemetry to retrieve seismic signals from remote sites. Adding monitoring sites near the mines would benefit ESO by including south-central Montana in Montana's seismograph network. Fortuitously, the U.S. Geologic Survey (USGS) had recently developed the

Earthworm[1] data acquisition and analysis system, and ESO had installed this system in June 1999 for its Montana seismic monitoring program. Not only does the Earthworm system dramatically improve seismic analysis capabilities, but its use has led to better cooperation and data-sharing among ESO, USGS, and other regional seismic monitoring centers.

This paper describes the hardware and software needed to transfer mine seismicity data into the Earthworm system and provides examples of data display.

2. SEISMIC MONITORING

NIOSH purchased and helped install the seismic monitoring equipment specified by ESO. At each monitoring site, ground movement is detected using a model L4 moving-coil seismometer. These seismometers have a natural period of 1 sec and respond to ground velocity rather than to acceleration or displacement. The seismometers are typically buried less than 0.5 m (2 ft) below the ground surface on or near bedrock and are connected to an electronics package with a 15-m- (50-ft-) long, direct burial cable.

The electronics package consists of a preamplifier, a voltage-controlled oscillator (VCO), a dc power supply, and a signal multiplexer. It also contains a voltage regulator/power supply that regulates the output of a solar panel and charges a 12-V deep-cycle battery. The battery, in turn, powers the VCO and the telemetry radio. The preamplifier amplifies and filters the signal from the seismometer. The VCO uses the amplified seismic signal to modulate the carrier frequencies up to a maximum of ±125 Hz. Eight standard audio carrier frequencies range from 680 to 3060 Hz in 340-Hz steps. The signal multiplexer in the electronics package allows multiple VCO signals to be mixed together (either multiple seismic channels from a single site or signals from different sites) for telemetry on a single communications channel. In this manner, as many as eight different seismic signals can be transmitted on one communications channel (either an FM radio link or a voice-grade telephone circuit).

Figure 1. Seismic monitoring electronics

The telemetry radios are small FM radios that operate in the VHF band (162 to 171 MHz) with power outputs typically below 0.25 W. The low output power of the radio transmitter requires that all telemetry paths be line-of-sight, requiring placement of most seismic stations and repeater sites on ridges or mountaintops.

The electronics package, telemetry radio, and battery are housed in a sealed, 200-L (55-gal) drum (Figure 1). A 50-W solar panel and YAGI (directional) radio antenna are mounted on a 50-mm (2-in) in diameter steel pole near the drum. The seismometer is placed as far as possible from the pole to minimize recording wind-generated pole vibrations. The seismic stations are designed to operate under severe weather conditions, including high winds, deep snow, and bitter cold, and will run for at least 20 days without solar input. The seismic data from both mine seismographs are telemetered by radio through a series of repeater stations to ESO, located on the campus of Montana Tech of the University of Montana in Butte, a distance of approximately 320 km (200 miles) from the mine.

In addition to the seismograph stations at the mines, each repeater location also includes a seismograph to supplement seismic coverage

[1] Mention of specific products and manufacturers does not imply endorsement by the National Institute for Occupational Safety and Health.

Figure 2. Mission Creek repeater station

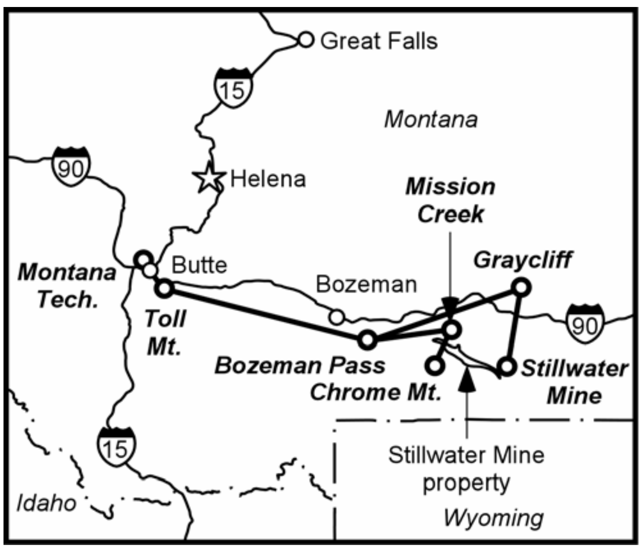

Figure 3. Radio telemetry path to Butte

near the mines and also to improve regional seismic monitoring coverage. In all, five sites are monitored within 60 km (40 miles) of the mines. Figure 2 shows the Mission Creek repeater station with the Chrome Mountain seismograph site above the East Boulder Mine (background). The radio telemetry path from the mines to ESO is shown in Figure 3. Collecting usable data telemetered through the six relay links is possible because meticulous attention is paid to matching signal levels at each relay point. At the ESO central recording facility in Butte, the radio telemetry signal is received, and individual analog seismic signals are recovered from the audio carrier frequencies by means of an FM discriminator (essentially a narrow-band audio filter and a frequency-to-voltage converter).

3. EARTHWORM SEISMIC DATA ACQUISITION AND ANALYSIS SYSTEM

The Earthworm seismic system consists of computer software modules that perform specific tasks with seismic data. These tasks include digitizing analog waveforms, picking seismic phase arrivals in real time, determining hypocenter locations and event magnitudes, and posting information to Websites. Earthworm software will run on either Unix or Windows 2000 operating systems. The USGS Earthworm Website, http://gldbrick.cr.usgs.gov/ew-doc/, describes the Earthworm system in detail and provides links and instructions for downloading this free software package.

At ESO, the Earthworm system is divided into two general parts—an automatic, real-time portion that collects and processes seismic data, and an interactive portion that allows users to view, and in some cases edit, seismic data. The automatic portion includes a National Instruments PCI-6040E multifunction I/O board installed on a PC running Windows 2000. This digitizer samples 22 analog data streams (including the two mines' seismographs and three repeater site seismographs) at a rate of 100 samples per second and stores the resulting digital data on large hard drives. Other modules scan the seismic data streams and pick seismic phase arrivals, associate these arrivals into coherent events, determine hypocenter locations and magnitudes, and report these data to a database and a Website.

The interactive portion of the Earthworm system includes a Website where preliminary hypocenter locations and magnitudes are listed within 5 min of their occurrence (http://mbmgquake.mtech.edu/earthworm/). The Butte Earthworm system introduces reasonable preliminary hypocenter locations for most seismic events of magnitude 2.0 or greater within the Montana regional seismic network, but on occasion, it also produces spurious events caused by large distant earthquakes or radio telemetry noise glitches. After review by a seismologist, updated earthquake hypocenters and magnitudes are listed at http://mbmgquake.mtech.edu/reviewed_events.html.

The ESO Website (Figure 4) also includes graphic representations of the raw seismic data from all stations in the network. These images, known as webicorders, are designed to resemble paper seismograms recorded by analog seismic drum recorders. Two sizes of webicorder images are generated, a smaller version (http://mbmgquake.mtech.edu/earthworm/wavef_disp/welcome.html) that shows 24 hours of seismic data in a 200- by 290-mm (8- by 11½-in) page format for all 35 stations in the Montana network, plus selected regional stations, and a larger 280- by 965-mm (11- by 38-in) version (http://mbmgquake.mtech.edu/earthworm/large_wavef_disp/welcome.html) that closely resembles the old paper seismograms produced by a drum recorder. The larger images are only generated for 19 of the better-quality seismograph stations in the network. All webicorder images are automatically updated every 5 min and are available on-line for the period covering the past 14 days. The mine webicorder images are available in both size formats by selecting either CRMT EHZ MB for the Chrome Mountain station or STMT EHZ MB for the Stillwater Mine station.

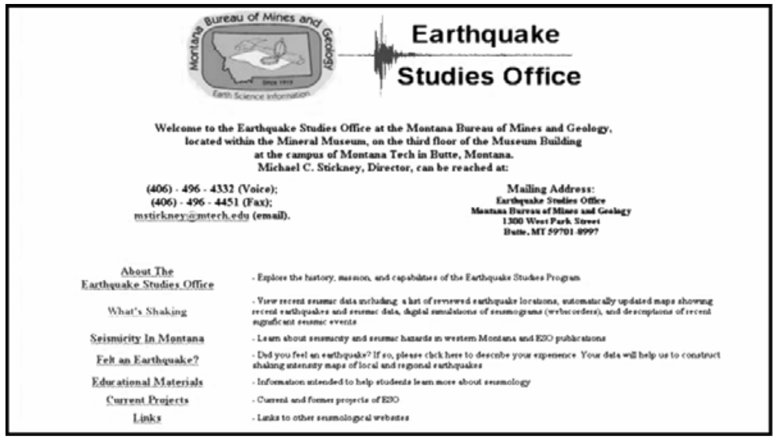

Figure 4. Earthquake Studies Office main Web page

The interactive portion of the Earthworm system includes an Oracle database that stores the original seismic trace as well as the hypocenter locations and other information produced by the Earthworm system. The Oracle database is also available on a Website, but it is password-protected to prevent system overload by multiple users (particularly following a significant earthquake) and unauthorized editing of seismic data by the public. Posting raw seismic data and preliminary event information on the Website within 5 min makes the data rapidly available to a wide variety of users, including mine managers, health and safety experts, and seismologists.

Another tool for viewing seismic data collected on an Earthworm system is a software package called Waveviewer. Waveviewer connects to the wavetanks of an Earthworm computer through a network connection and displays time-series seismic trace data for groups of stations selected by the user. It is useful for quickly observing the arrival sequence of P-waves on the seismic network and for zooming in to check first-arrival polarities from a given seismic station. However, public use of Waveviewer is not allowed because of the potential for overloading the Earthworm computer and its network connections.

4. DATA ANALYSIS

Documenting seismicity rates and characteristics of mining-related seismicity at the two mines motivated this project. An objective is to identify changes in seismic trends before seismic events become a problem at the mine. Each day, the seismic data are reviewed to determine the number of mine blasts and mining-related seismic events.

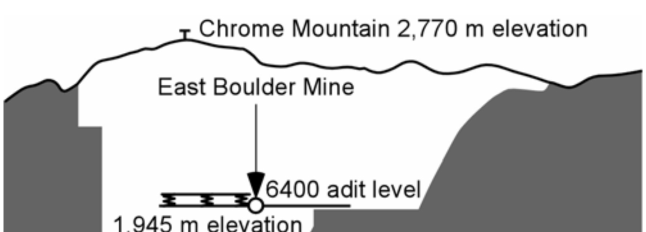

Figure 5. Chrome Mountain site in relation to East Boulder Mine workings.

The East Boulder Mine detonates production rounds at approximately 6:00 in the morning and evening local time, and these blasts show up well on the Chrome Mountain seismograph located approximately 900 m (3,000 ft) above the active mine workings (Figure 5). Production blasts consist of a series of drill holes loaded with high explosives and detonated in a specific sequence via time-delayed blasting caps. The seismic recordings clearly show multiple holes fired over 6 to 10 sec. Figure 6 is a portion of a large-

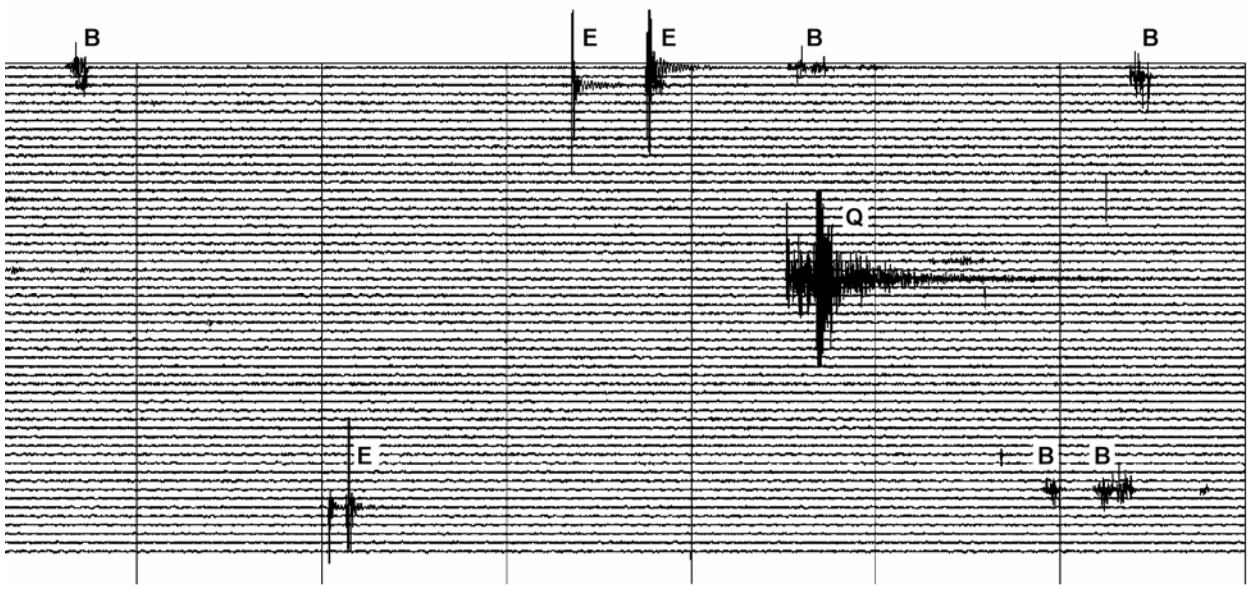

Figure 6. Web page showing large waveform display. B = mine blasts, E = mine seismic events, and Q = a local earthquake.

format webicorder image for the Chrome Mountain seismograph recorded on May 15, 2003, showing production blasts (B), mining-related seismic events (E), and a regional earthquake from Yellowstone Park (Q). Figure 7 shows a seismic record from Chrome Mountain using Waveviewer to show a single production blast at the East Boulder Mine lasting 7 sec. The P-wave arrival for this event is positive, indicating a compressional wave.

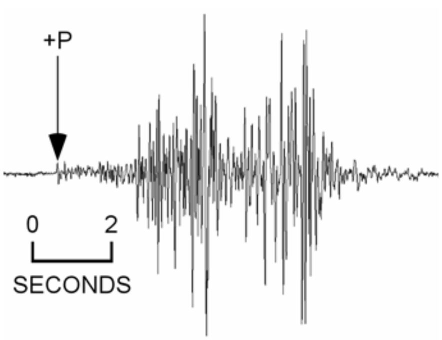

Figure 7. Waveviewer image of typical production blast at East Boulder Mine showing compressional P-wave (positive) arrival for first hole fired.

In contrast to blasts, mining-related seismic events are single events of short duration, typically lasting less than 1 sec. From November 2002 through April 2003 the Chrome Mountain seismograph recorded an average of 2.4 mining-related seismic events each day. Measured S-P intervals for 232 of these events ranged from 0.11 up to 0.62 sec with a mean of 0.24 sec (Figure 8). These S-P intervals indicate that most events occurred within 6,500 feet of the seismograph station. Mining-related seismic events were clearly related to production blasting; 84% of the mining-related events occurred between 5:20 p.m. and 7:00 p.m. (Figure 9) during the afternoon blasting period. Only 7.6% of the mining-related events occurred during the early morning blasting period. The remaining 8.5% of the events occurred at other times throughout the day.

The P-wave onset for most mining-related events (about 81%) was very impulsive, and the P-wave first motion is clearly recorded on the seismogram (Figure 10). About 47% of the mining-related seismic events had downward (dilatational) impulsive P-wave first

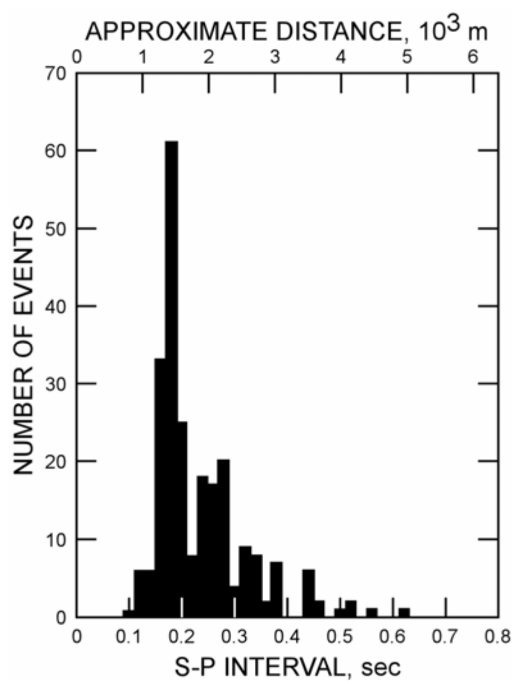

Figure 8. S-P intervals for 239 mining-related seismic events recorded at Chrome Mountain station.

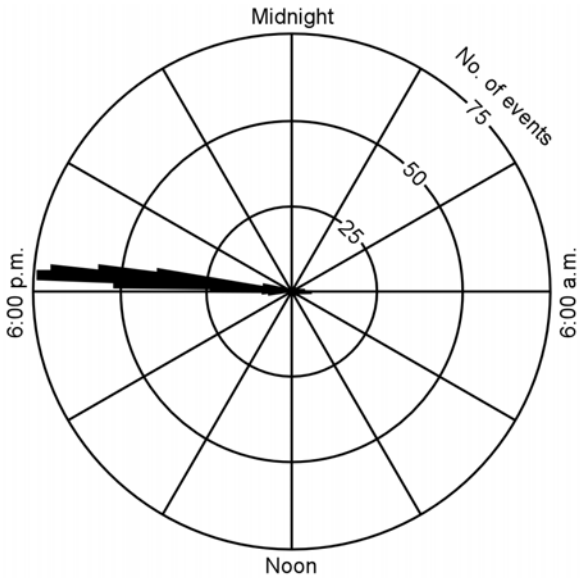

Figure 9. Mining-related seismic events as a function of time of day. Four-hundred forty-six nonblast events were binned in 10-min intervals and plotted as a polar histogram.

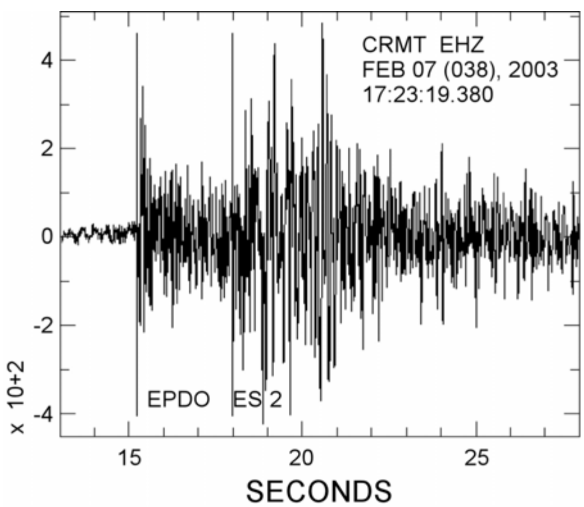

Figure 11. Local 1.0-M earthquake centered 11.9 miles from Chrome Mountain seismograph. S-P interval was 2.75 sec.

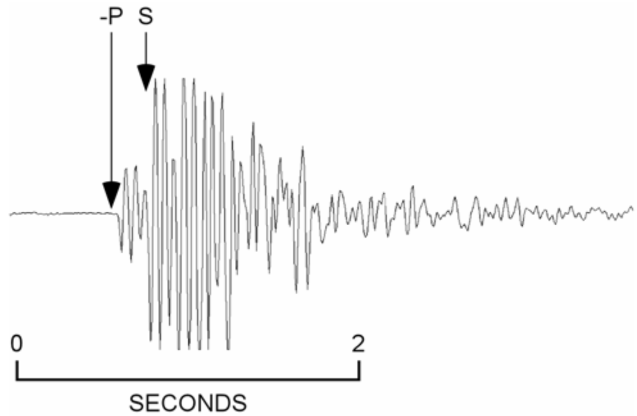

Figure 10. Mining-related seismic event at East Boulder Mine showing negative P-wave arrival. The 0.18-sec S-P interval indicates a source distance of about 4,700 ft.

motions. Blasts generate a P-wave first motion that is a push away from the source, and if recorded at a surface seismograph station, this first motion will be compressional, an upward movement of the ground. Thus the mining-related events with dilatational first motions cannot possibly result from blasting. Mining-related seismic events with dilatational first motions are well known in the Coeur d'Alene Mining District of north Idaho (Stickney and Sprenke, 1993) and are related to closure of mine openings at depth (Sprenke et al., 2002). To date, none of the mining-related seismic events has been large enough to be recorded at more than one seismograph station. Richter magnitude estimates of these events using signal duration measurements range from –1.0 to slightly more than 0.0.

The Chrome Mountain seismograph station also records local and regional tectonic earthquakes and large distant earthquakes. Figure 11 shows the seismogram of a magnitude 1.0 earthquake located 19 km (12 miles) west-northwest of the seismograph station. This microearthquake was recorded by nine stations in the Montana regional seismograph network and demonstrates that seismic events, mining-related or natural, are well recorded by the network. However, without seismograph stations installed close to the mines, low-magnitude but frequent mining-related seismic events will go undetected by the regional network.

The daily summaries of the number of mine blasts and the time, maximum amplitude, and duration of mining-induced seismic events are recorded on an Excel spreadsheet at ESO. Monthly summaries are provided to engineers at the Stillwater Mining Company and NIOSH. Monitoring shows that mining-related seismicity occurs with blasting. There are no miners in the workings at this time, so the events do not pose a danger to miners. These data show that seismicity does result from mining, but has not become an operational problem or safety hazard yet. These data are reviewed continually for changes in trends that could indicate mining-induced seismicity is becoming a hazard.

5. CONCLUSIONS

NIOSH researchers have utilized solar-powered, remote, seismic monitoring equipment; FM radio telemetry; PC's; and the Internet to provide near-real time data on mine seismicity to researchers at distant locations. This innovative technology works well and helps to ensure the safety of miners working in Montana's underground platinum/palladium mines. The cooperative project between the Stillwater Mining Company, ESO, and SRL-NIOSH has benefited all parties by providing quality seismic data for multiple uses in a timely fashion.

REFERENCES

Czamanske, G.K., and M.L. Zeintek: Stillwater Complex. Montana Bur. Mines and Geol. Spec. Pub. 92, 1985, 396 pp.

Girard, J.M., T.J. McMahon, W. Blake, and T.J. Williams: Installation of PC-Based Seismic Monitoring Systems, With Examples from the Homestake, Sunshine, and Lucky Friday Mines.. In Maleki, H, P.F. Wopat, R.C. Repshar, and R.J. Tuchman (eds.), Proceedings, Mechanics and Mitigation of Violent Failure in Coal and Hard-Rock Mines, USBM Spec. Pub. 01-95, 1995, pp. 303-312.

Hess, H.H. Hess: Stillwater Igneous Complex, Montana. Geol. Soc. Amer. Memoir 80, 1960, 225 pp.

Johnson, J., M. MacLaughlin, R. Langston, and H. Kirsten: In Situ Stress Measurements at the Stillwater Mine, Nye, Montana. Proceedings, 39th U.S. Rock Mechanics Symposium, Cambridge, MA, June 22-26, 2003, In press.

Sprenke, K.F., B.G. White, A.C Rohay., J.K. Whyatt, and M.C. Stickney: Comparison of Body Wave Displacement with Damage Observations of a Rockburst, Coeur d'Alene Mining District, Idaho. Bull. Seismol. Soc. Amer., v. 92, 2002, pp. 3321-3328.

Stickney, M.C., and K.F. Sprenke: Seismic Events with Implosional Focal Mechanisms in the Coeur d'Alene Mining District, Northern Idaho. J. Geophy. Res., v. 90, 1993, pp. 6523-6528.

Whyatt, J., W. Blake, T. Williams, and B. White: 60 Years of Rockbursting in the Coeur d'Alene District of Northern Idaho, USA: Lessons Learned and Remaining Issues. Presentation at 109th annual exhibit and meeting, Society for Mining, Metallurgy, and Exploration, Feb. 25-27, 2002, Phoenix, AZ. Preprint 02-164, 8 pp. Available on CD-ROM from SME and the author.

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