In the aftermath of the Crandall Canyon mine tragedy, a key issue is how to improve and use information from seismic monitoring more effectively for mining safety—recognizing that such monitoring has fundamental value but is not a magic solution. My purpose here is to suggest how to enhance seismic monitoring and its use in the Wasatch Plateau (WP)-Book Cliffs (BC) coalfields in a sensible and cost-conscious way.

Unlike the situation in most other mining areas in the U.S., local seismographs in the WP-BC area are an integral part of a modern real-time earthquake information system. The regional system was developed in Utah by the University of Utah Seismograph Stations (UUSS), with federal and state funds, for earthquake emergency management, engineering, and science (see http://www.seis.utah.edu/). My suggested framework has four parts (I–IV). Parts I–III deal with data acquisition, starting with an infrastructure for seismic monitoring “throughout the neighborhood” of the WP-BC coalfields and progressing to individual mine sites. Part IV deals with data processing and the effective use of resulting seismic information.

PART I. Regional-Scale Monitoring of the Wasatch Plateau-Book Cliffs Coalfields

Goal — Basic infrastructure that ensures effective regional-scale seismic monitoring (above a magnitude threshold of ~1.6–1.8) of all areas of active coal mining, both present and planned, in the WP-BC area and that includes a minimal number of modern broadband digital seismographs.

Background — Figure 1 illustrates some simple requirements for the spatial distribution of seismographs to reliably determine the source location of seismic events. Figure 2 points out the limitations of outdated analog seismographs versus modern digital instruments. Figure 3 shows the distribution of existing seismic stations by type in the WP-BC coal-mining area.

Requirements — (1) Filling in gaps in coverage of the WP-BC area, including the southern Wasatch Plateau (SUFCO) and the easternmost Book Cliffs (Lila Canyon, planned). (2) Addition of a minimal number of broadband digital seismographs.

Recommended — Take advantage of a one-time opportunity to purchase and “adopt” three high-quality broadband stations of USArray (see Figure 3), temporarily operating in the WP-BC area since July 2007 and scheduled for removal in late 2008 or early 2009. The opportunity is described at http://www.iris.edu/USArray/researchers/adopt.html#adopt2. In order of priority, the three most useful stations are P17A, Q16A, and Q18A.

Estimated Cost — Approximately $110,000 for the cost-effective “adoption” of instrumentation, power, and communications equipment at three USArray stations. Funds might be used by UUSS in a slightly modified way—for example, purchasing stations P17A and Q16A and perhaps installing an equivalent of station Q18A closer to the eastern extremity of mining seismicity.

Funding Source — One-time state funds (could be added to existing state line-item appropriation to UUSS). Estimated ongoing costs = $5,000/year.
Figure 1. Sketches showing geometric requirements for reliably determining the location of a seismic event, both in map view (top) and depth (bottom). In simple terms, one needs to have recording stations reasonably surrounding a seismic event to fix its epicenter (map location). In order to resolve the focal depth of the seismic source, the distance to the nearest recording station must be comparable to the depth of the source. In the top panel, the dashed ellipse shows the confidence bounds on the computed epicenter—a measure of its precision, which is model-dependent. Lateral changes in seismic velocities can cause a computed epicenter to be systematically displaced from its true location (as shown in the top panel)—a measure of its accuracy. In such cases, special study is needed to make appropriate corrections to improve the absolute accuracy of the location (for example, to see what was done with the relocation of seismic events at Crandall Canyon, click on the link below:

http://www.seis.utah.edu/MONRESEARCH/CM/CM_images/CCM_AGU_poster_07.pdf

Figure 2. Not all seismographs are equal—as shown by this comparison of seismic recordings from a modern digital instrument and an outdated analog instrument (from USGS Fact Sheet 075-00 [http://pubs.usgs.gov/fs/2000/fs075-00/]). Many of the instruments relied on by the UUSS for seismic monitoring of the WP-BC area are the old analog type. Recordings on broadband digital seismographs were critical for determining the source mechanism of the magnitude 3.9 Crandall Canyon seismic event. Digital instruments are essential for modern mining seismology.
Figure 3. Map of existing seismic stations in the Wasatch Plateau-Book Cliffs coal-mining area. Dashed polygons outline areas of mining-induced seismicity (including allowance for location errors for older seismic events). For more information about the UUSS stations, see http://www.seis.utah.edu/STATION_MAP/web_station_table.html. For the USAArray stations, see http://www.iris.edu/earthscope/usarray/US-TA-OpStationList.htm.
PART II. “Minimalist” Approach to Enhanced Seismic Monitoring at Individual Mines

Goal — Enhancement of seismic monitoring (beyond the capabilities of the UUSS regional seismic network) at individual bump-prone active mines through a “minimalist” approach of adding one above-mine digital accelerograph, linked by continuous telemetry to the UUSS, at each target mine. (Installing a companion in-mine accelerograph would be desirable but goes beyond the “minimalist” approach considered here and can be considered as one possible scenario of Part III.)

Background — In Figure 3, the blue triangles labeled BCW, DCM, and BCE indicate three mine sites in the Book Cliffs area where UUSS has had partnering arrangements with the mine for the last three to four years. Under the terms of these partnerships (described in Attachment A), UUSS has installed a three-component digital accelerograph together with a vertical-component short-period sensor at a surface rock site above the mine workings. The instrument package is fully integrated into our UUSS earthquake information system and enables: (1) a continuous 24-hour visible recording of seismic activity recorded by the local station, accessible on the Web (see, for example, http://www.quake.utah.edu/helicorder/); (2) improved UUSS event locations in the vicinity of the mine; and (3) on-scale ground-motion data for events of special interest. [Note: Attachment A indicates that locations and magnitudes of local shocks of magnitude 2.5 or larger are automatically processed and posted to the Web; the actual current threshold is magnitude 3.0, but a customized lower threshold is feasible.]

Requirements — For each candidate mine, the installation would require a multi-channel digital accelerograph, a companion short-period vertical sensor, communications hardware, and continuous telemetry to UUSS (typically achieved by radio telemetry to an Internet connection at the mine site or to a UUSS communications node in the region). A site-use permit for the surface installation is also required.

Estimated Cost — For each mine, approximately $15,000 for seismographic equipment and accessory hardware, plus installation/implementation costs of a few thousand dollars. Ongoing costs, including continuous telemetry and maintenance and operation of the seismographic equipment would also be of the order of a few thousand dollars.

Funding Source(s) — State or federal funds conceivably could be sought to help capitalize the necessary equipment for the likely candidate mine sites. Otherwise, these costs would have to be borne by the mine owner/operator. Ongoing costs would appropriately be the responsibility of the mine owner/operator. Terms could be negotiated with UUSS as part of a partnering agreement similar to that described in Attachment A. Because of its public funding, UUSS is reluctant to undertake any “contract for services” with an individual mine.
PART III. High-Resolution Seismic Monitoring at an Individual Mine

Goal — High-resolution seismic monitoring at an individual mine involving both in-mine and surface instruments to achieve specific performance goals typically achievable only with significant investment in technology and human resources.

Background — To my awareness, this kind of seismic monitoring has been carried out at only one mine in Utah—the now-closed Willow Creek mine, where NIOSH researchers installed and operated a three-dimensional microseismic system in 1999–2000. Although aggressively pursued in South Africa, Canada, Australia, eastern Europe, and China, among other places, intensive seismic monitoring in mines is not common in the U.S. As practiced in these other countries, seismic recording is an integral part of continuous monitoring of rock deformation in the mine and in the surrounding rockmass.

Requirements — Variable, depending on desired performance goals, but typically requiring multi-element sensor arrays, digital instrumentation, and sophisticated systems for automated data processing and near-real-time data display.

Estimated Cost — Variable, but usually involving costs of several tens to hundreds of thousands of dollars.

Funding Source(s) — The primary burden of funding this type of seismic monitoring appropriately lies with the mine owner/operator, and the monitoring is often achieved through a private-sector contract for services. Nevertheless, there clearly is precedent for the involvement of publicly-funded research where the goal is to serve broader interests and not just to benefit the individual mine. NIOSH is one possible source of funding for a collaborative undertaking of this type for research to benefit mining safety.
Part IV. Data Processing and the Effective Use of Seismic Information

Goals — Real-time data processing and availability of information products (automated notifications, event locations/magnitudes, maps, graphs, and other visual displays) from seismic monitoring in near-real-time. Awareness and use of available seismic data and information as part of routine mining operations.

Background — Automated processing of seismic data for event locations and magnitudes is non-trivial, and human review by a trained professional is generally necessary for quality control and to eliminate false alarms. Such processing and review—and the automated creation of near-real-time information products—are routinely provided by UUSS seismologists and staff for data flowing through UUSS’s regional network. Additional data streams from Parts I and II described here could be incorporated straightforwardly into the UUSS system, provided that the magnitude thresholds for reporting were comparable to present ones.

Where the numbers of mining-induced seismic events increased greatly—say in a case where multiple sensors were installed at a mine, markedly lowering the local threshold of detection—the UUSS system would not be able to provide data-processing services for an individual mine as part of its public-service operations. This evolves into Part III, in which responsibilities for detailed seismic monitoring at an individual mine shift to the mine owner/operator, possibly in partnership with researchers. Ideally, expanded seismic monitoring at an individual mine should be coordinated with UUSS’s regional system.

Requirements — Among others: real-time data processing capabilities, including seismological expertise; ongoing attention to mining-induced seismicity in the WP-BC area, particularly its spatial and temporal correlation with mining activities in individual mines; development of automated notification schemes for seismic events above specified thresholds at individual mines; training of mining professionals to understand and use available mine-seismicity data.

Recommended — The engagement of trained personnel in the Price area to serve an “intermediary” role (to be determined by future discussion) between UUSS and individual mines in the WP-BC area. One desirable outcome is timely, ongoing attention by stakeholders to mining-induced seismicity in the WP-BC area, particularly its spatial and temporal correlation with mining activities in individual mines.

Estimated Costs and Funding source(s) — Undetermined. Primary responsibility of stakeholders interested in these types of services.

Afterword — It remains to be seen whether, and to what extent, individual mines may want to engage customized private-sector services for enhanced seismic monitoring. Conceivably, a cooperative approach might be considered whereby multiple mines could explore how specialized processing of mine-specific seismic data could be developed, say at a common facility in the Price area, for their mutual benefit.

My ideas relating to Part IV here are incompletely formed, but I and my UUSS colleagues will gladly offer to be involved in any user-driven discussions about how to effectively use existing and improved mine-seismicity data to advance mining safety. — Walter Arabasz
EXAMPLE AGREEMENT THAT UUSS INITIATED IN 2003 WITH SELECTED MINES IN THE BOOK CLIFFS AREA

Attachment A

Monitoring Coal-Mining Seismicity in Utah—Informal Partnership With the University of Utah Seismograph Stations (UUSS)

Motivation

- To create an informal partnership—as opposed to a contract for services—between UUSS and an individual mine operator aimed at a better understanding of mining seismicity associated with underground coal mining.
- To provide a relatively low-cost option for continuous seismic monitoring at an active mine that—despite a "minimalist" approach—can yield valuable near-real-time information to the mine operator.
- To provide mine operators with more precise information about mining seismicity originating in the vicinity of their mines than would otherwise be available from UUSS's regional network data.

Background

UUSS is a research, educational, and public service unit within the University's Department of Geology and Geophysics. UUSS operates a regional seismic network which has continuously recorded seismicity associated with underground mining in the Wasatch Plateau–Book Cliffs coal mining region since 1978. Working together with the University of Utah's Department of Mining Engineering, UUSS seismologists have ongoing interests in studying and gaining a better understanding of coal-mining seismicity in Utah.

Since 2000, UUSS has modernized its regional seismic network into a real-time earthquake information system, which enables the automated processing and reporting of various types of earthquake information on our Web site at http://www.seis.utah.edu.

Opportunity

UUSS has some unique capabilities for helping mine operators in the Wasatch Plateau–Book Cliffs coal-mining region monitor mining seismicity. These capabilities arise from (a) the infrastructure of UUSS's regional seismic network, (b) modern data processing facilities at UUSS's network operations center in Salt Lake City, and (c) the availability of a limited number of spare portable digital accelerographs, each of which can be installed directly above an active mine and linked by real-time telemetry to UUSS's network center.
Proposal

In exchange for a $200 per month partnering contribution (see next page), UUSS will:

- Install and maintain a Kinematics K2 digital accelerograph (plus a vertical-component short-period velocity sensor) at a surface rock site above mine workings, located as feasible, at the participating mine.

- Implement continuous radio telemetry from the digital instrument, via a line-of-sight spread-spectrum radio link, to an Internet connection point for data transmission to UUSS's network operation center in Salt Lake City. (The Internet connection point may be provided by the mine operator or otherwise be established by UUSS personnel.)

- Provide 24-hr continuous digital seismic records on the Web (so-called "Webicorder" or "Live Seismogram" .gif images) for the above-mine seismic instrument and provide limited training in the interpretation of these seismic records. (Depending on the mine operator's choice, Internet access to the Webicorder records can be made either public or password-restricted. Because UUSS Webicorder records are maintained and posted on the Web for only seven days, mine personnel may wish to download and save the .gif images.)

- Incorporate the data streams from the above-mine instrument into routine data processing—including the location of seismic events large enough to be recorded at a sufficient number of regional-network stations.

Notes: Epicenter and magnitude information for located seismic events will be posted on our UUSS public Web site http://www.seis.utah.edu just as for other earthquake locations processed from our regional network.

For shocks of magnitude 2.5 or larger, a location and magnitude are automatically processed and posted to the Web within five minutes; for locatable shocks smaller than magnitude 2.5, data are processed by a seismic analyst and the information is generally posted to the Web within one business day following the seismic activity.

Proximity of an above-mine station will markedly improve horizontal and vertical resolution of event locations. However, locations by our regional array may still have errors up to a kilometer in some circumstances. (A single near station will not achieve fine-scale spatial resolution of the order of tens of meters or less as enabled by a costly, elaborate in-mine microseismic array.)

Waveform data processed as part of our regional network operations are routinely forwarded to a national data center and are publicly accessible, chiefly by scientists and other technical users adept at accessing the data.

- Following seismic events of special interest to mine personnel, provide corrected peak ground-motion measurements from the above-mine triaxial accelerometer
within approximately one week of the seismic event. (We anticipate that requests for this special service would ordinarily be made only a few times per month or less.)

**Partnering Contribution**

As part of the proposed partnership, we ask the participating mine to pay UUSS $200 per month (on either a monthly or quarterly basis as convenient) to help defray UUSS's costs for travel, installation, maintenance, supplies, data processing, and so on, involved in providing the data and services described on p. A-2.

For perspective, the seismographic equipment and accessory hardware to be installed at a mine has a value of approximately $15,000—and installation/implementation costs are of the order of a few thousand dollars.

The participating mine may terminate this informal arrangement at any time. Upon termination of the arrangement, UUSS will remove the seismographic instrumentation from the mine site.

*Note: While the partnership is in effect, UUSS personnel will repair field instrumentation failures as quickly as possible consistent with varied project priorities. The continuous functioning of our network’s real-time earthquake information system is always a high-priority goal. However, on occasion and without warning, hardware/software at our UUSS central recording lab may have to be taken off-line for repair or maintenance.*