3.0 MINING SEISMICITY AND “GROUND TRUTH”—AN UPDATE

Mining seismicity generally includes both seismic events induced by underground mining and mine blasts at surface mines. Our attention here is restricted to the former and primarily focuses on the Wasatch Plateau (WP)-Book Cliffs (BC) coal-mining districts of east-central Utah—with secondary attention to the trona-mining district of southwestern Wyoming (see upper right-hand corner of Figure 1-1). “Ground truth” in the context of mining seismicity simply means information on what actually happened in or near a mine at the time of some discrete event that produced observable seismic signals.

We use the term mine tremor as synonymous with a seismic event induced by mining, and we restrict the term rockburst or “coal bump” to those seismic events associated with damage in accessible areas of a mine due to violent failure of rock (see Arabasz et al., 1997). One of the major challenges in studying mining seismicity in the WP-BC area is the ability to determine unambiguously the primary source of seismic energy release when material suddenly fails at a mining opening. The failure can be caused either by local static stresses in the direct vicinity of mining openings or by dynamic effects from seismic slip on a fault hundreds to thousands of meters away (e.g., Gibowicz, 1990; Knoll and Kuhnt, 1990).

An overview of mining seismicity in the WP-BC area was given by Arabasz et al. (1997), including a description of available seismological data, the correlation of seismicity and mining, and outstanding issues and seismological challenges. Arabasz and Wyss (1999) reported a follow-up study on spatial variations in b-value (the slope of the frequency-magnitude distribution) in the WP-BC area. General issues posed by mine seismicity for mining engineers and seismologists, chiefly based on examples in the Utah region, were recently summarized by Arabasz and McCarter (2000).

Our chief purpose in the remainder of this section is to extend and update the information summarized by Arabasz et al. (1997) for mining seismicity in the WP-BC area in order to provide a useful reference for LLNL researchers. First, we describe the University of Utah’s current monitoring capabilities, and we summarize incident reports communicated to LLNL during the course of this project (section 3.1). Second, we provide background information necessary to understand our approach to developing a homogeneous catalog of mining seismicity for the period January 1, 1978-June 30, 2000 (section 3.2). Third, we update information on coal production in the WP-BC area and compare the data to observed seismicity (section 3.3). Fourth, we describe “ground truth” information to which we were able to gain access for significant mine tremors (section 3.4)—referring the reader to Appendix C for documentation.

3.1 CONTINUOUS MONITORING AND INCIDENT REPORTS TO LLNL

The University of Utah Seismograph Stations (UUSS) operates a regional seismic network, with 105 stations in July 2000 (Figure 3-1), that has continuously monitored the Utah region, with progressively evolving instrumentation, since 1962. Telemetered data from the network have been centrally recorded on the University of Utah campus in Salt Lake City since 1974. Digital triggered recording of the UUSS network dates from 1981.

As evident in Figure 3-1, short-period, analog-telemetry stations predominate in the UUSS regional seismic network. Broadband stations in Utah include five UUSS stations installed and calibrated during 1997 and 1998 (Pechmann et al., 1999) that strategically complement six broadband stations of the U.S. National Seismograph Network (USNSN) in and near Utah, currently resulting in a broadband station spacing of 100 to 200 km or better.

UUSS network operations are cooperatively funded by the U.S. Geological Survey, the state of Utah, the U.S. Bureau of Reclamation, and (for the Yellowstone National Park area) the U.S. National Park Service. For additional details regarding the regional seismic network, see <www.quake.utah.edu>.

Figure 3-2 (from Arabasz et al., 1997) shows the WP-BC study area in relation to the regional seismic network. The post-1978 distribution of stations allows fair to good map locations of seismic events in the vicinity of mines within the study area, but focal-depth control for shallow events is poor. Epicentral precision (95% bounds), on average, is about ±3 km for the post-1978 data. This does not apply, however, to the eastern Book Cliffs area where poor azimuthal station control results in greater epicentral errors. Analysis of the UUSS catalog indicates that seismic monitoring of the mining areas shown in Figure 3-2 has been complete above about magnitude 1.8 since 1978 (Arabasz et al., 1997).

Figure 3-3 gives a current and future view of the location of seismographic stations in the WP-BC area, updating beyond 1994 the depiction shown in Figure 3-2. Comparing with Figure 3-2, Figure 3-3 indicates: (1) the continued operation of stations EMU, which dates from October 1986, and SRU, dating from November 1990; (2) the operation of station SRU as a broadband, digitally-telemetered station (see section 2.0) beginning in September 1998; (3) the recent addition of station DBD, which earlier operated on a temporary basis in 1995 for a four-month period; (4) the location of four planned short-period vertical-component stations (open triangles); and (5) the location of a temporary special-study array of accelerographs and short-period stations (installed in late 2000) for ground-motion studies of mining-induced seismic events in the Trail Mountain area. Station SKYM (not shown on Fig. 3-3), operated at 39°41.63'N, 111°12.27'W, from June 29, 1995, until June 22, 1999.

Based on continuous monitoring with the UUSS regional seismic network, the following incident reports were made by e-mail and/or telephone to William Walter of LLNL during the project period:

1. February 5, 1998 — Report of an M_L 3.7 (later revised to M_L 3.8) seismic event that occurred the previous night in the vicinity of the Willow Creek Mine in the WP-BC area. (On July 14, 1998, a detailed follow-up report was made summarizing available information on ground truth for the February 5 seismic event.)

2. April 13, 1999 — Confirmation that an M_L 4.5 seismic event in south-central Wyoming on April 6, 1999 (UTC date) was a tectonic earthquake and not a mining-related event.

3. December 22, 1999 — Report of an M_L 3.9 seismic event in central Utah earlier in the day and confirmation that the event was a tectonic earthquake and not a mining-related event.

4. January 30, 2000 — Report of an M_L 4.4 (later revised to M_L 4.3) seismic event earlier that morning near the Solvay Trona Mine in southwestern Wyoming—and confirmation that this was a mining-related event.

5. March 6, 2000 — Report of an M_L 4.1 (later revised to M_L 4.2) seismic event that occurred less than two hours earlier that evening close to the Willow Creek Mine in the WP-BC area. (Subsequent communications reported on available ground-truth information, the precise hypocentral location, a velocity model for the source, and a focal mechanism for the source.)

6. July 19, 2000 — Report of an M_L 3.2 (later revised to M_L 3.0) seismic event three days earlier on July 16 in the trona mining district of southwestern Wyoming, west of Green River, Wyoming. Report included a refined epicentral location placing the event in the vicinity of the TG Soda Ash and FMC mines, but local observations gave no indication of a simple association with either mine. P-wave first-motion information was also reported indicating the event did not appear to be of a collapse type.

7. August 22, 2000 — Report of an M_L 3.3 (later revised to M_L 3.1) seismic event that occurred five days earlier on August 17 in the trona mining district of southwestern Wyoming. Report included a refined epicentral location and a brief summary of waveform and first-motion information suggestive of a collapse-type mechanism. However, no information was available to confirm that the event was associated with a specific mine.

3.2 DEVELOPING A HOMOGENEOUS CATALOG

Most earthquake catalogs are heterogeneous in time, particularly in terms of non-uniform estimates of event size (e.g., Habermann, 1995; Zuniga and Wyss, 1995). Arabasz et al. (1997) made a major effort to address this issue in the case of the University of Utah's earthquake catalog, and they determined homogeneous magnitudes for mining-related seismic events in the WP-BC area for the period July 1962 through March 1996. Here we extend their revised catalog through June 2000.

For review, magnitude is reported in the University of Utah's earthquake catalog as either local Richter magnitude, M_L, based on amplitude measurements of standard Wood-Anderson (W-A) seismograms, or coda-duration magnitude, M_C, an empirical estimate of M_L typically made for events smaller than about magnitude 3. Inadvertent temporal changes in the M_C scale can arise variously from factors such as changes in network configuration, the type of instrumentation and its ground-motion magnification, or analysis software and procedures (Pechmann et al., 2000; Wiemer and Wyss, 1994, and references therein).

3.21 Methodology

Arabasz et al. (1997) did two basic things to achieve a catalog of homogeneous magnitudes for the WP-BC area. First, they used quantitative tools available in the interactive software package ZMAP (Wiemer et al., 1995) to derive time-varying correction terms for values of M_C in the catalog between January 1, 1978, and March 31, 1996, designating the corrected values as M_C'. Their correction terms are given in Table 3-1 here. Second, in order to develop robust estimates of size anchored to the University of Utah's Wood-Anderson-based M_L for the larger events in the catalog since 1962, they used empirical relations to convert all available magnitudes to an M_L equivalent and then calculated a weighted average, designated M_L'. The practical reason for doing this was that prior to 1994, only a few W-A seismographs were in operation in the Utah region.

Since early 1994, UUSS has routinely determined values of M_L using synthetic W-A seismograms from several USNSN stations in the region and from five UUSS broadband digital telemetry stations in Utah installed during 1997 and 1998 (see section 3.1 and Figure 3-1). This has greatly increased the fraction of earthquakes for which M_L can be robustly determined using recordings from multiple stations. With these new data in hand, a major project is under way at UUSS to review and revise, as appropriate, all magnitude estimates in the UUSS catalog since January 1981 when digital triggered recording of our network began. Here we continue the approach taken by Arabasz et al. (1997), and demonstrate its validity, but we caution that future revisions of the UUSS catalog may result in minor differences with the corrected magnitudes presented here.

The revised catalog of Arabasz et al. (1997) for mining seismicity in the WP-BC area was extended from March 31, 1996, to October 31, 1999, by Arabasz and Wyss (1999) as part of a special topical study. Their correction terms, given in Table 3-2, reflect the following: First, they justified the extension of equation (4) in Table 3-1 beyond March 1996, and we have lengthened the extension from October 1999 to June 2000. Second, when they analyzed the whole revised catalog from 1978 through October 1999 using ZMAP, they discovered a small bias of 0.1 unit for values of M_C prior to 1995, and they subtracted 0.1 to correct for this. (Note: Recognizing that M_C also factored into some of the weighted-average estimates of M_L' made by Arabasz et al. [1997], those values of M_L' were recalculated to be consistent with the adjustment of 0.1 in Mc for events before 1995. Consequently, some of the values of M_L' reported herein may differ from those of Arabasz et al. [1997] by 0.1 unit or less.)

To test the validity of their corrected values of M_C' as reliable estimators of M_L, Arabasz and Wyss (1999) compared M_C' with M_L for 85 events in the WP-BC area for which an estimate of M_L was available. With one exception, all estimates of M_L prior to 1994 were based on one station; those for 1994 and later, on two or more stations. The results of the comparison are shown in Figure 3-4. (Note: The sample includes eight tectonic earthquakes with M_L values in the range 2.5 to 4.4.) The lower panel of Figure 3-4 shows a plot of M_C' versus M_L and the line for perfect agreement. The mean residual for the 85 data points is -0.002 ± 0.273 (one standard deviation), indicating very good correlation. The upper panel is a plot of differences between $M_C'$and M_L as a function of time. The running average indicates random rather than systematic differences with time about the mean of -0.002. Thus, we believe that the revised coda magnitudes, M_C', together with available values of M_L, provide reliable, homogeneous estimates of size for mining seismicity in the WP-BC area.

3.22 Revised Catalog

Figure 3-5 shows an epicenter map of 6,851 seismic events in our revised catalog for the WP-BC area for the period January 1978 through June 2000. The events are restricted to two polygons, following Arabasz et al. (1997), which bound what is judged to be almost entirely mining-related seismicity located within (1) an arcuate crescent encompassing the Wasatch Plateau and Book Cliffs coal fields and (2) an isolated area of mining in the southern Wasatch Plateau. In Figure 3-5, the locations of the three largest seismic events are indicated by large stars. These include a shock of M_L 4.2 on March 7, 2000, one of M_L 3.8 on February 5, 1998, and another of M_L' 3.8 on May 14, 1981. Coincidentally, these three shocks are the largest not only since 1978 but also since systematic instrumental monitoring in this region began in July 1962.

A listing of all events of magnitude 2.5 and greater (N=148) in the revised catalog for 1978-2000 is presented in Appendix A. For special reference, a listing of all events in the revised catalog of magnitude 3.0 or greater, ordered by decreasing size, is presented in Table 3-3. We refer the reader to Table 1 of Arabasz et al. (1997) for the identification of larger mining-related seismic events in the WP-BC area that occurred after July 1962 but before January 1978, when the revised catalog here begins. The largest event in the 1962-1977 period was one of magnitude (M_L') 3.7 that occurred in April 1966.

3.23 Focal Depths

We emphasized earlier that focal-depth control in the WP-BC area based on the UUSS regional seismic network is generally poor because of the large station spacing, and computed focal depths such as included in Appendix A are not reliable. As part of the study reported by Arabasz and Wyss (1999), Arabasz investigated focal-depth control for events in the polygonal areas of Figure 3-5 to determine whether there might be a mixed sample of mining seismicity and deeper tectonic seismicity.

Of 5,063 events between January 1978 and October 1999, Arabasz was able to find only 15 for which the data arguably supported a focal depth greater than 6 km. None of these events was larger than magnitude 2.1. The results, combined with those of local studies (Williams and Arabasz, 1989; Wong et al., 1989) allow and suggest that virtually all the events clustering in the vicinity of the active coal mines in the WP-BC area are relatively shallow events occurring less than 6 km in depth. Because of the close spatial and temporal association of the seismicity with active mining (elaborated in section 3.3), we believe that nearly all this seismicity probably occurs at or within hundreds of meters above or below mine level and is mining-related.

3.3 ASSOCIATION OF SEISMICITY WITH MINING

In this section, we present and briefly discuss data and information relevant to the spatial and temporal association of seismicity with underground coal mining in the WP-BC area. In order to provide a useful "bridge" between results reported by Arabasz et al. (1997) for 1978-1994 and this report, data are presented here for an 8.5-year period beginning in January 1992 and ending in June 2000. While detailed analyses are beyond the scope of this project, the data summaries alone provide abundant information that (1) gives a useful overview and (2) can guide future studies relating to the correlation of mining activity and associated seismicity on a mine-by-mine basis.

Because the seismicity data inherently lack fine spatial resolution, we purposely make only general observations. Causal relationships between mining operations and seismic energy release are highly complex, and more detailed data are needed to confidently attribute specific seismic events to a particular mining operation.

3.31 Spatial Association

Figures 3-6 through 3-14 show the epicentral distribution, on an annual basis, for seismicity located within the WP-BC coal mining region using the University of Utah's regional seismic network. Also shown are the portal locations of all mines active in this region since 1978. Thus, each figure includes not only active mines but inactive ones as well, which in some cases may be associated with seismic failures.

Because distal parts of an active mine may commonly be 5 km or more from the portal, epicentral clustering may not coincide with the plotted location of an associated mine. Another consideration in comparing observed seismicity with locations of mining, separate from epicentral precision (i.e., the relative location of one event compared to another), is the possibility of systematic bias due to network configuration and non-uniform seismic velocities. Our experience suggests, for example, that computed epicenters in the Wasatch Plateau coal field tend to lie a few kilometers westward of their true locations.

A first-order feature of the annual epicenter maps, at their plotted regional scale, is the spatial clustering of seismicity in known areas of active mining. In general, one observes tighter clustering in the Wasatch Plateau coal field than in the Book Cliffs field, due in part to better epicentral control. In the Sunnyside area of the eastern Book Cliffs, an area marginal to the seismic network, there is an apparent scattering of epicenters in an ENE-WSW direction (see Figures 3-6 and 3-7) due to inadequate azimuthal station control. Higher rates of seismic activity in the Wasatch Plateau coal field during the sample period generally reflect higher extraction rates compared to the Book Cliffs coal field (see, for example, Appendix B).

Inspecting the series of annual epicenter maps from 1992 to 2000 (Figures 3-6 through 3-16), one can observe distinct clusters of seismic events in the vicinity of mines known to be active at the time. Temporal variations in the observed seismic clustering correlate in some cases with the start or completion of mining; in other cases, where extraction was relatively continuous over several years, seismic clustering has occurred in distinct episodes. We proceed to examine such changes with time.

3.32 Temporal Association

Arabasz et al. (1997) cross-correlated time series of observed seismicity with tons of extracted coal, on a quarterly basis from 1978 through 1994, for nine local areas in the WP-BC region. Seismicity was measured both in terms of counts of seismic events above a threshold magnitude and seismic energy release. In order to gain an updated view, we did the following.

First, we extended our database for quarterly coal mine production in the WP-BC region with tabulations for 1995 through 1998, the last year for which data were available. These data, which give a representative view of contemporary mining activity in the study area, were compiled by J. D. McKenzie and are presented in Appendix B.

Second, we plotted all seismic events in our revised catalog above magnitude 1.8 for the period January 1992-June 2000. The resulting map, shown in Figure 3-15 allowed twelve areas of clustered seismicity to be isolated for special analysis, following the approach of Arabasz et al. (1997). Index data for these twelve sample areas are summarized in Table 3-4.

Third, for each sample area and for the period January 1992-June 2000, we constructed composite time-series plots that show: (a) reported quarterly coal production within the sample area, (b) quarterly counts of seismic events above a magnitude threshold of uniform detection, and (c) magnitude versus time of occurrence. For (b) and (c), a magnitude threshold of 1.75 was generally adopted, except for areas 1, 8, 11, and 12 where a threshold of 1.85 was used.

The resulting composite plots for the twelve sample areas are shown in Figures 3-16 through 3-21 (note changes in the vertical scales from plot to plot). Referring to the plots sequentially, we make these observations:

- S. Wasatch Plateau area (Figure 3-16): Production throughout the sample period was from longwall mining. Annual tonnage progressively increased with time, but seismicity was variable with some notably quiet periods—longer than a few weeks duration typical of a longwall move—that are not due to gaps in seismic recording.

- S. Joes Valley area (Figure 3-16): Tonnage and seismicity both increased after late 1995 with the beginning of a longwall operation, and the seismicity rate later increased significantly in late 1998. Prior to 1995, minor production was from room-and-pillar mining.

- East Mountain and Rilda Canyon areas (Figure 3-17): These two plots are complicated by the fact that extraction attributed to one particular mine occurred in both areas, and the partition of tonnage to each area is unclear. Thus, while we can spatially distinguish two separate clusters of seismicity in map view (Figure 3-15), we have incomplete information for reliably characterizing the time series for quarterly tonnage in each area. One of two longwalls operating in the East Mountain area ended production in late 1995, which corresponds to the timing of a marked decrease in seismicity in that area. In the plot for the Rilda Canyon area, observed seismicity increases significantly in early 1995 but does not persist continuously thereafter.

- Lower Huntington Canyon area (Figure 3-18): Relatively low production in this area came from room-and-pillar mining. Most of the observed seismicity notably occurred in two episodes, one during 1995 and the other during 1999-2000.

- Upper Huntington Canyon area (Figure 3-18): Coal production progressively increased in this area. There was a change from room-and-pillar to longwall mining about 1996, but there is no evident contrast in the observed seismicity before and after this date.

- Gentry Mountain area (Figure 3-19): The cessation of a longwall operation in 1997 was accompanied by a marked decrease in seismicity, providing a good correlation between extraction and seismicity in this area.

- Pleasant Valley area (Figure 3-19): Seismicity in this area is predominantly related to longwall mining that occurred throughout the entire sample period at relatively high levels of production. The marked decrease in observed seismicity after mid-1996, despite continued coal production, emphasizes that seismic energy release depends not only on rate of extraction but also on other mine-specific variables, including local geology and depth of cover.

- Castle Gate area (Figure 3-20): Sparse but relatively continuous seismicity occurred in this area between 1992 and 1997 while mines in this area were inactive. The start of coal production in 1996 relates to development work in a new mine in which a longwall began operating in mid-1998, but discontinuously thereafter. The two prominent seismic events of magnitude 3.8 in 1998 and 4.2 in 2000 are discussed in sections 4.22 and 4.21, respectively.

- W. Book Cliffs area (Figure 3-20): Both coal production and seismicity in this area—as generally true for mining areas in the Book Cliffs—are lower than for counterpart mining areas in the Wasatch Plateau. A change from room-and-pillar mining to longwall mining in mid-1994 is reflected by a step increase in the tonnage plot. The seismicity plots show at least one episode of increased seismicity in 1998-1999.

- Central Book Cliffs area (Figure 3-21): Relatively low levels of coal production in this area were from room-and-pillar mining. Production ceased after 1998. Perhaps the most notable aspect of the observed seismicity was the occurrence of two distinct episodes of seismic energy release, one in 1992-1993 and another in 1996-1997, each including a seismic event in the magnitude 3 range.

- E. Book Cliffs area (Figure 3-21): Longwall mining in this area ceased in early 1994, as reflected in the tonnage graph. In 1995-1996, a distinct episode of seismic events occurred after the mine had closed.

3.4 GROUND TRUTH FOR SIGNIFICANT EVENTS

Part of Objective 3 for this study was to gather and report available information on "ground truth"–what actually happened in or near a mine at the time of a discrete event that produced observable seismic signals–for significant mining-related seismic events. In section 1.1 we described guidance from LLNL's Technical Representative for this contract, William Walter, which indicated special interest in three particular mining-related events—two in the WP-BC coal-mining region in February 1998 and March 2000, respectively, and one in the trona-mining region of southwestern Wyoming in January 2000.

To help acquire and organize the ground-truth information in a systematic way, we engaged the assistance of Dr. Michael K. McCarter, chair of the University of Utah's Department of Mining Engineering. Information was successfully gathered for the three events of special interest as well as for five other events. The total of eight events includes seven events ($3.1 \leq M_L \leq 4.2$) related to underground coal mining in the WP-BC area between 1981 and 2000 and the January 2000 trona-mining-related event ($M_L = 4.3$) in southwestern Wyoming. The WP-BC data include information for the four largest seismic events listed in Table 3-3 plus three other events for which information was recoverable.

We refer the reader to Appendix C for a listing (Table C-1) of the seismic events for which ground-truth information was compiled and for data sheets that document the observations.