EXECUTIVE SUMMARY

Underground coal mining (down to ~0.75 km depth) in the contiguous Wasatch Plateau (WP) and Book Cliffs (BC) mining districts of east-central Utah induces abundant seismicity that is monitored by the University of Utah regional seismic network. This report presents the results of a systematic characterization of mining seismicity (magnitude ≤ 4.2) in the WP-BC region from January 1978 to June 2000—together with an evaluation of three seismic events (magnitude ≤ 4.3) associated with underground trona mining in southwestern Wyoming during January-August 2000. (Unless specified otherwise, magnitude implies Richter local magnitude, M_L.)

The University of Utah Seismograph Stations (UUSS) undertook this cooperative project to assist the University of California Lawrence Livermore National Laboratory (LLNL) in research and development relating to monitoring the Comprehensive Test Ban Treaty (CTBT). The project, which formally began February 28, 1998, and ended September 1, 2000, had three basic objectives:

1. Strategically install a three-component broadband digital seismic station in the WP-BC region to ensure the continuous recording of high-quality waveform data to meet the long-term needs of LLNL, UUSS, and other interested parties, including the international CTBT community.

2. Determine source mechanisms—to the extent that available source data and resources allowed—for comparative seismic characterization of stress release in mines versus earthquakes in the WP-BC study region.

3. Gather and report to LLNL local information on mine operations and associated seismicity, including "ground truth" for significant events.

Following guidance from LLNL's Technical Representative, the focus of Objective 2 was changed slightly to place emphasis on three mining-related events that occurred in and near the study area after the original work plan had been made, thus posing new targets of opportunity. These included: a magnitude 3.8 shock that occurred close to the Willow Creek coal mine in the Book Cliffs area on February 5, 1998 (UTC date), just prior to the start of this project; a magnitude 4.2 shock on March 7, 2000 (UTC date), in the same area as the February 5 event; and a magnitude 4.3 shock that occurred on January 30, 2000 (UTC and local date), associated with a panel collapse at the Solvay trona mine in southwestern Wyoming. This is the same mine in which an earlier collapse event of magnitude 5.2 occurred in February 1995, attracting considerable attention from the CTBT community.

Objective 1

Objective 1 was successfully met with the completed installation (described in detail in section 2) of a high-quality, three-component, broadband digitally telemetered seismograph station in the San Rafael Swell, Utah (SRU) on September 9, 1998. Station SRU (39° 6.65′ N, 110° 31.43′ W, 1804 m elevation) is located at a roughly uniform distance of 70 ± 20 km from the active mines in the arcuate WP-BC coal-mining region. This distance enables good recordings of larger mine tremors (magnitude ≥ 3.0), which are of primary interest, with minimal interference from more frequent smaller-magnitude events (hundreds per day) that occur in the coal fields.

Seismographic equipment at station SRU includes a Guralp CMG-3T broadband seismometer, with a flat velocity response from .01 to 50 Hz, and a 24-bit REF TEK 72A-07 data logger. The signal from the seismometer is digitized at 100 samples/sec and is continuously transmitted to the UUSS central recording laboratory in Salt Lake City where data are recorded using an Earthworm data-acquisition system. Instrumental response to ground motion was carefully calibrated, and calibration details are described in section 2.

Waveform data from station SRU are made publicly available in two ways. First, the UUSS Earthworm system routinely exports triggered 40 sample/sec waveform data from station SRU and other selected stations via an Internet link to the U.S. National Seismograph Network (USNSN) data center in Golden, Colorado. These data are available from the data center via the USNSN AutoDRM system. Second, since June 19, 2000, continuous data files from station SRU and other selected UUSS stations have been converted to SEED format and sent daily via FTP to the IRIS Data Management Center in Seattle, Washington, where the data are permanently archived and made available to all interested users.

Objective 3 (Background for Objective 2)

Information on seismic monitoring and mining seismicity in the WP-BC region is presented in section 3. We extend and update information earlier summarized by Arabasz et al. (1997) in order to provide a useful reference for LLNL researchers as well as other interested parties. We describe the University of Utah's current monitoring capabilities and summarize incident reports communicated to LLNL during the course of this project. These reports concerned seven seismic events of magnitude 3 or larger that occurred between February 1998 and August 2000.

In section 3 we also describe our methodology for creating a catalog of mining seismicity in the WP-BC region for the period January 1, 1978-June 30, 2000 with revised, homogeneous magnitudes. A complete listing of all seismic events (N=148) of magnitude 2.5 or larger in this catalog is presented in Appendix A. Using the refined catalog (6851 events; 95 percent ≥ magnitude 1.3) together with updated information on coal production (summarized in Appendix B), we present numerous plots and briefly discuss the spatial and temporal association of seismicity with mining in the WP-BC area. Figures include annual epicenter maps from 1992 through mid-2000 and composite time-series plots for 12 local areas where clustered seismicity coincides with sites of active mining. For each sample area, the time-history plots show quarterly coal production, quarterly counts of seismic events above a threshold magnitude, and the magnitudes of individual events.

A magnitude 4.2 shock that occurred in the BC district on March 7, 2000 (more below) is the largest seismic event to have originated in the WP-BC mining region since at least mid-1962, when instrumental seismic monitoring began. Mining-related seismic events in the magnitude 3 range have occurred throughout most of the WP-BC mining region, associated with sites of both longwall and room-and-pillar mining.

There is an evident spatial association of clustered epicenters with sites of active mining in the WP-BC area. Epicentral clustering in the WP mining district is generally tighter and more intense than in the BC district, due to better epicentral control and higher extraction rates at mines in the WP district during the sample period. Seismic events located in the WP-BC area by the University of Utah's regional seismic network have poorly constrained focal depths because of the relatively large station spacing. Nevertheless, combined evidence from (a) an analysis of focal-depth resolution, (b) data from local studies, and (c) the spatial and temporal association of seismicity with active mining allows and suggests that the vast majority (> 95 percent) of the observed seismicity in the WP-BC coal fields is shallow, probably occurs either at or within hundreds of meters above or below mine level, and is mining-related.

Temporal variations in observed seismic activity in the WP-BC area correlate simply in some cases with the start or completion of mining. In other cases, where extraction was relatively continuous over several years, seismic activity has occurred in distinct episodes—indicating the influence of other mine-specific factors, such as local geology and depth of cover. In the WP-BC area, longwall mining results in higher extraction rates and generally tends to be accompanied by higher rates of mining seismicity than room-and-pillar mining. But time series of longwall production and seismicity do not always correlate simply. Again, other mine-specific variables besides extraction rate appear to influence the generation of seismicity in the size range recorded by the regional seismic network.

Information on "ground truth"—what actually happened in or near a mine at the time of a discrete event that produced observable seismic signals—was gathered with the help of Dr. M. K. McCarter of the University of Utah's Department of Mining Engineering. Ground-truth information was successfully acquired for eight seismic events, for which observational data summaries and mine sketches are provided in Appendix C. These include (a) seven events of magnitude 3.1 to 4.2 related to underground coal mining in the WP-BC area between 1981 and 2000 and (b) a trona-mining-related event of magnitude 4.3 in southwestern Wyoming in January 2000. Multiple pillar failures are documented for four of the WP-BC events, and a roof collapse involving three room-and-pillar sections is documented for the trona-mining-related event.

Objective 2

Results of our investigations of source mechanisms of mining seismicity in the WP-BC region, as well as of three seismic events in the trona-mining region of southwest Wyoming, are presented in section 4. For the WP-BC mining region, we systematically investigated the 18 largest events (3.0 ≤ magnitude ≤ 4.2) since 1978. Because of the early dates and (or) relatively small size of most of the events (14 have magnitudes < 3.5), broadband waveform data at regional distances are either sparse or of marginal signal-to-noise quality. In this study we carefully refined local velocity models and then analyzed P-wave first motions for focal-mechanism information. Companion ground-truth information was successfully recovered for seven of the 18 events.

Contrary to some published interpretations and our expectation, mechanisms for only three of the 18 events are unambiguously of a shear-slip type: (1) a shallow (~0.6 km), predominantly reverse-faulting event of magnitude 4.2 near the Willow Creek Mine in the BC district on March, 7, 2000; (2) a magnitude 3.8 event on February 5, 1998, in nearly the same location as event (1) and with first motions compatible with the same mechanism; and (3) a tectonic normal-faulting earthquake (11 km deep) of magnitude 3.0 on June 2, 1996, beneath the WP district. For events (1) and (2), observations in the Willow Creek Mine (< 1 km distance) indicate isolated roof falls, interpreted for each event to be the result of shaking caused by nearby shear-slip and not as the seismic source.

For 13 of the other 15 events, coincident with sites of both longwall and room-and-pillar mining throughout the WP-BC region, only dilatational first motions were recorded by the University of Utah's regional seismic network (209 total observations). For the remaining two of the 18 events, first-motions are obscured by small preceding events. Collapses or partial closures of mine openings are documented for four of the events with all dilatational first motions. Based on varied evidence presented in section 4, including size considerations, we consider it highly likely that these four events were collapse-type events with implosional mechanisms. We also consider it plausible that the other events with only dilatational first motions had similar source mechanisms, with variable likelihood depending on available data.

Available evidence favors the working hypothesis that the predominant mechanism of larger (magnitude $\geq$ 3.0) mining-induced seismic events in the WP-BC region is implosional and caused by sudden roof-floor closure, either partial or total, due to loss of pillar support. The shallow shear-slip earthquakes of magnitude 4.2 and 3.8 near the Willow Creek Mine in March 2000 and January 1998, respectively, are notable exceptions.

Finally, we investigated the source mechanisms of three seismic events that occurred in the trona-mining district of southwestern Wyoming between January and August 2000. A seismic event of magnitude 4.3 on January 30, which coincided with a major roof fall at the Solvay Minerals trona mine, had an implosional collapse-type mechanism. We were unable to find any ground-truth information for shocks of magnitude 3.0 on July 16 and magnitude 3.1 on August 17. P-wave first-motion data and regional broadband waveforms indicate that the July 16 event was a shear-slip earthquake and suggest that the August 17 event was a collapse-type event.