Mining-Induced Seismicity near Joes Valley Dam: Summary of Ground-Motion Studies and Assessment of Probable Maximum Magnitude

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ABSTRACT

This report summarizes key findings, interpretations, and conclusions from a study of ground-shaking hazard at Joes Valley Dam potentially posed by mining-induced seismicity (MIS) in the Cottonwood Coal Tract. Two earlier reports provide more detailed information. The project was undertaken by members of a Joint Working Group from the University of Utah, the U.S. Geological Survey, and the U.S. Bureau of Reclamation at the request of the State of Utah School and Trust Lands Administration.

This report is written in the style of an extended executive summary, with major sections outlining (1) the project objectives, (2) results of seismic monitoring and ground-motion studies reported earlier in two separate reports by the University of Utah and the U.S. Geological Survey, (3) an assessment of the probable maximum magnitude for future MIS in the Cottonwood Coal Tract, and (4) conclusions.

The project objectives were successfully met. The strategic recording and analysis of MIS associated with longwall mining in the Trail Mountain (TM) Mine provided an effective way to characterize future MIS in the Cottonwood Coal Tract—most critically, ground motion as a function of distance and size. The TM data were limited in magnitude (≤ 2.2) but well suited to developing ground-motion attenuation relationships for the environs of the Joes Valley Dam, especially when augmented with data from the magnitude 4.2 Willow Creek Mine earthquake of March 2000.

The attenuation relationships developed in this study can be used to estimate the predicted ground motion for a given magnitude and hypocentral distance to the Joes Valley Dam in terms of peak acceleration **a** (cm/s/s), peak velocity **v** (cm/s), or pseudovelocity response ps(T) (also in units of cm/s) at 5-percent damping at a set of periods T ranging from 0.1 s to 2 s.

We have assessed the "probable maximum magnitude" (PMM) for future MIS in the Cottonwood Coal Tract. It is the consensus of the Joint Working Group that the maximum magnitude m_{max} is best represented using a probability distribution. We define the PMM to be a specified value in a probability distribution of m_{max}. Recognizing that a single value is often required for use in conventional engineering assessments, we propose using the 84^{th}-percentile value of the cumulative distribution function of m_{max} as the PMM.

Our consensus probability distribution for m_{max} has a lower-bound value of 2.7, a mode of 3.1, and an upper-bound value of 4.6. The mean of the distribution is 3.47, the median is 3.41, and the 84^{th}-percentile value of the cumulative distribution function is 3.92.

To illustrate the potential hazard at the site of Joes Valley Dam due to seismic ground motion for the PMM, the peak expected ground velocity for canyon site conditions for an event of magnitude 3.9 is about 8 cm/s at a distance of 1 km; this, and other, ground motion predictions must be adjusted according to the actual response of the dam itself.

Besides serving to address the objectives for ground-motion estimation, the data acquired in this project have provided a rich source of information useful for studying MIS in the Trail Mountain Mine as a valuable case study.

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1.0 INTRODUCTION

- *Multi-institutional project*
- *Two reports already submitted*
- *This report summarizes the whole project*

The subject of this report is the outcome of a multi-institutional investigation of ground-shaking hazard at Joes Valley Dam posed by nearby mining-induced seismicity (MIS). Important results for basic parts of the project have already been presented in two reports delivered to the State of Utah School and Trust Lands Administration (SITLA):

1. Arabasz, W. J., S. J. Nava, M. K. McCarter, and K. L. Pankow—with contributions from J. C. Pechmann, M. E. Jensen, and J. D. McKenzie (March 29, 2002). *Ground-Motion Recording and Analysis of Mining-Induced Seismicity in the Trail Mountain Area, Emery County, Utah*: Technical Report (prepared for State of Utah School and Trust Lands Administration), University of Utah Seismograph Stations, Salt Lake City, Utah, 28 pp. plus 5 tables, 22 figures and 6 appendices.

2. McGarr, A. and J. B. Fletcher—with contributions from R. Sell, L. Baker, and P. Spudich (March 28, 2002). *Development of Ground-Motion Attenuation Relationships Relevant to Mining-Induced Seismicity in the Trail Mountain Area, Emery County, Utah*: Technical Report (prepared for State of Utah School and Trust Lands Administration), U.S. Geological Survey, Menlo Park, California, 11 pp. plus 7 figures.

The first report, by investigators at the University of Utah Seismograph Stations (UUSS) and the University of Utah Department of Mining Engineering, is hereafter referred to as the "UUSS Report"; the second, by investigators at the U.S. Geological Survey, as the "USGS Report."

This *summary report*—authored by the principal members of a Joint Working Group from the University of Utah, the U.S. Geological Survey, and the U.S. Bureau of Reclamation (fulfilling the promise of a joint final report)—presents a distillation of key findings, interpretations, and conclusions for the whole project. It articulates the collective judgment of the principal investigators and brings to closure the investigative tasks that were defined.

1.1 The Problem

- *Vulnerability of Joes Valley Dam to adverse impact by future mining-induced seismicity (MIS) in the Cottonwood Coal Tract?*
- *Upper size limit of future MIS in the Cottonwood Coal Tract?*
- *Strategic recording of MIS at the Trail Mountain Mine to help solve the problem*

The core issue here is whether Joes Valley Dam, a zoned earthfill dam 58 m (190 ft) high that impounds Joes Valley Reservoir, may be vulnerable to adverse impact by future underground coal mining in the nearby Cottonwood Coal Tract, a planned lease tract in the Trail Mountain area of northwestern Emery County, Utah (see Figure 1). We refer the reader to the *UUSS Report* for extensive additional background information, including technical context, geological setting, and the characteristics of MIS in the general study area.

The problem posed at the outset of this study was: *How close to the Joes Valley Dam should future underground mining be allowed in the Cottonwood Coal Tract in order to avoid adverse impact on the dam by mining-induced seismic events?*

In order to help solve the problem, the objectives for this project were defined by SITLA to be (1) the collection of relevant seismological data and an assessment of the maximum credible earthquake (MCE) that might be induced by future underground mining in the Cottonwood Coal Tract and (2) determination of the expected attenuation of ground motion as a function of distance and magnitude. A strategic part of the plan was the recording and use of MIS at the (then) active Trail Mountain Mine (Figure 1), owned and operated by PacifiCorp and its subsidiaries, as an opportune active source for investigating ground motion as a function of event size and distance. These results now serve as a basis for describing the expected characteristics of future MIS in the Cottonwood Coal Tract—notably the likely size of upper-bound seismic events and the attenuation of ground motion.

Evaluating the response of Joes Valley Dam to potential ground shaking resulting from MIS in the Cottonwood Coal Tract is the separate responsibility of the U.S. Bureau of Reclamation. Decision-making regarding any exclusionary distance of mining from the dam appropriately rests with those state and/or federal agencies with regulatory control.

1.2 Joint Working Group

- *University of Utah–U.S. Geological Survey–U.S. Bureau of Reclamation*
- *Co-authors of this report include three seismologists and one mining engineer*

To address the objectives posed by SITLA, an instrumentation and work plan was formulated jointly in May to July 2000 (and was subsequently carried out from August 2000 through February 2002) by Dr. Walter Arabasz of the University of Utah Seismograph Stations (UUSS), Dr. Art McGarr of the U.S. Geological Survey (USGS), and Dr. Jon Ake of the U.S. Bureau of Reclamation (USBR)—together with the involvement of colleagues from their respective institutions (see *UUSS* and *USGS Reports*). We refer to these collaborating participants as the "Joint Working Group." The authors of this report include the three principal seismologists named above together with Dr. Michael K. McCarter of the University of Utah Department of Mining Engineering, a co-author of the *UUSS Report* who as a mining engineer adds critical expertise to the Joint Working Group.

1.3 Scope of <u>This</u> Report

- *Distillation of key findings, interpretations, and conclusions for whole project*
- *Formal assessment of "probable maximum magnitude"*

The *UUSS* and *USGS Reports* summarized parts of the project for which those two institutions were separately responsible (elaborated below in section 2.0). Here, as noted earlier, we aim to present a distillation of key findings, interpretations, and conclusions for the whole project. First, in section 2, we summarize important results respectively from the *UUSS Report* and the *USGS Report*. In section 3 we then deal with the issue of the "maximum credible earthquake" (MCE)—replacing the term with the better-suited concept of a "probable maximum magnitude," for which we make a formal probabilistic assessment for the case at hand. Finally, we present major conclusions for the project.

2.0 SUMMARY OF GROUND-MOTION STUDIES

- *Data acquisition, among other things, summarized in UUSS Report*
- *Ground-motion analysis summarized in USGS Report*
- *No separate USBR report—collaborative results folded into UUSS Report and this report*

Key elements of the UUSS-USGS-USBR coordination planned for the joint ground-motion studies are described in section 1.2.2 of the *UUSS Report*. Under the work plan, the division of labor was basically as follows:

UUSS: Primary responsibility for data acquisition—involving the installation and operation of a multi-element seismic array designed both for detailed monitoring of the Trail Mountain Mine source region and for precise digital recording of ground motions; lead responsibility for assessing the maximum credible earthquake (MCE) associated with MIS in the Cottonwood Coal Tract.

USGS: Primary responsibility for ground-motion analysis—involving the special processing and analysis of digital ground-motion data acquired by UUSS for (1) selected events in the Trail Mountain study area and (2) a magnitude 4.2 seismic event near the Willow Creek Mine in the nearby Book Cliffs coal field in March 2000; responsibility for developing attenuation relationships to quantify ground motion as a function of distance and magnitude.

USBR: Responsibility for upgrading seismic instrumentation on Joes Valley Dam to digitally record ground motions from the Trail Mountain Mine source region as part of the project; lead responsibility for formulating a probabilistic approach to quantifying the ground-shaking hazard, including corresponding uncertainties, at the Joes Valley dam site due to future MIS in the Cottonwood Coal Tract.

The *UUSS* and *USGS Reports* addressed the respective tasks assigned to these two groups, and we proceed to summarize their important results. Because the USBR role was mainly collaborative, there is not a separate USBR report for the tasks undertaken by the Joint Working Group. Details of the USBR instrumentation on Joes Valley Dam are included in the *UUSS Report*; USBR efforts relating to a probabilistic assessment of ground-shaking hazard at Joes Valley Dam due to nearby MIS are incorporated into <u>this</u> report.

2.1 UUSS Report

- *[Key points summarized below]*

The *UUSS Report* focused on (1) the design of the seismic array that was installed in the Trail Mountain (TM) study area in late 2000 to acquire necessary data, (2) a description of details relating to the recording, processing, and routine analysis of the seismic data acquired by the special-study array, and (3) a description of the MIS that was observed as a result of continuous seismic monitoring during the period October 3, 2000–April 30, 2001. The report also includes an important contribution by M. K. McCarter (Appendix F in the *UUSS Report*) entitled, "Trail Mountain Project—Mining Engineering Considerations for Assessing Maximum Magnitude for Seismic Events."

The following are some of the key results described in the *UUSS Report:*

- A 12-station local seismic array (combining 8 triaxial accelerometers and varied velocity sensors) was installed in the TM area in late 2000 and successfully met dual requirements for (1) high-quality digital ground-motion recording and (2) continuous monitoring of MIS accompanying the mining of the last two longwall panels in the TM Mine in order to accurately locate (< 1 km) the seismic sources giving rise to the recorded ground motions.
- A change in mine plan and schedule at the TM Mine in October 2000, due to unmanageable bumps and unsafe conditions, reduced the total duration of expected mining by 4–5 months; the creation of a barrier pillar for mining the last longwall panel in the TM Mine (1st Right) from November 7, 2000, to March 7, 2001, significantly reduced the rate and size of MIS.
- Despite the change in mine plan and schedule, sufficient data were successfully captured to meet the project objectives—thanks to the use of highly sensitive digital accelerographs.
- Digital accelerographic data for 50 selected earthquakes were transmitted by UUSS to the USGS for further analysis; these included multi-station recordings of 49 shocks (magnitude ≤ 2.2) in the TM area (see Figure 2) plus data captured by two triaxial digital accelerographs installed by the University of Utah that were about 2 km and 7.5 km from the magnitude 4.2 shock near Willow Creek Mine on March 7, 2000 (UTC date).
- A data set of 1,913 earthquakes (magnitude ≤ 2.2) located in the TM study area between October 3, 2000, and April 30, 2001, was used to describe (1) temporal variations in rate and magnitude of MIS, (2) space-time variations in earthquake locations, and (3) source-mechanism information.

- Coda magnitude (M_C), an empirical estimate of Richter local magnitude (M_L) typically made for events smaller than about magnitude 3, was carefully calibrated for the TM study area to provide size estimates judged to be well-founded for earthquakes of magnitude ≥ 1.
- Observed seismicity was highly correlated with mining activity in both space and time, and the preponderance of seismicity coincides with known areas of contemporaneous or past mining (see Figure 3); densely clustered epicenters coincident with mining of the 1st Right longwall panel (Figure 3) tracked with the eastward advance of the panel on a time scale of days and weeks.
- The vast majority (96 percent) of computed focal depths are very shallow (< 1 km); only three very small shocks (magnitude < 1.0) were reliably located with a depth ≥ 2.5 km.
- The purpose and design of the TM seismic array differed from an in-mine microseismic array, which allows fine-scale spatial resolution of mine tremors on a scale of tens of meters. For the TM array, better-located events (using a site-specific seismic velocity model) had a mean standard horizontal error of about 0.3 ± 0.2 km (95-percent confidence interval of about 0.7 ± 0.4 km); focal-depth resolution was generally not as good as map resolution, but most of the better-located events were conservatively constrained within ± 0.6 km of mine level, which was at a depth of 0.5–0.6 km.
- Only 2 percent of the 1,913 located earthquakes were recorded with at least one compressional P-wave first motion—implying either (a) non-observation of compressional P-wave first motions was due to consistent under-sampling, (b) dominance of an implosional or collapse-type source mechanism (rather than shear-slip-type), or (c) some combination of the above.
- An evaluation of geologic and mining factors which may influence the frequency and severity of future MIS in the Cottonwood Coal Tract was made by M. K. McCarter (*UUSS Report*, Appendix F), including comparison to four relevant case studies:
    1) the magnitude (M_L) 4.2 seismic event near the Willow Creek Mine in March 2002;
    2) an M_L 3.5 seismic event in the nearby Cottonwood Mine in July 1992;
    3) an M_L 3.3 seismic event that occurred in an old room-and-pillar section of the TM Mine in pre-Energy West workings in December 1987; and
    4) MIS (≤ M_C 2.5) associated with longwall mining in the TM Mine.
- Two basic scenarios for the development and mining of longwall panels in the Cottonwood Coal Tract were considered by M. K. McCarter (*ibid.*; see Figure 10 here):
    1) a mine plan that has longwall mining starting to the north of the last panel mined in the TM mine (~4 km from Joes Valley Dam) and later progressing southward toward the dam—with the benefit of accumulated operating experience and the possibility of making safety adjustments, if needed, as the dam is approached; and
    2) initial mining in the southwestern corner of the Cottonwood Coal Tract close to the dam.

  Based on these two scenarios, M. K. McCarter subjectively assessed the relative risk of future MIS in the Cottonwood Coal Tract compared to the four case studies noted above. His assessments are presented here in Table 1(a) and 1(b) for Scenarios 1A and 2, respectively, and are discussed further in section 3.2.4.

2.2 USGS Report

- *[Key points summarized below]*

The primary focus of the *USGS Report* is (1) the development of ground-motion attenuation relationships for the Joes Valley Dam–TM area using data collected as part of this project. The report also describes (2) independent checks on magnitude estimates made by UUSS, (3) moment tensors (explained below) for four selected TM earthquakes, and (4) a comparison of the derived attenuation relationships to several relationships developed for natural earthquakes.

The following are some of the key results described in the *USGS Report*:

- New ground-motion relationships, appropriate for quantifying ground shaking caused by MIS in the vicinity of Joes Valley Dam, were developed for each of the following ground-motion parameters: peak acceleration **a** (cm/s/s), peak velocity **v** (cm/s), and pseudovelocity response ps(T) (also in units of cm/s) at 5-percent damping at a set of periods T ranging from 0.1 s to 2 s.

- The attenuation relationships are assumed to have the form

  $$\log(y) = a + b\boldsymbol{M} + d\log(R) + kR + s$$

  where y is the maximum horizontal component of the ground-motion parameter under consideration, $\boldsymbol{M}$ is intended to be moment magnitude, R is hypocentral distance in km, and logs are base 10; s is the site factor (0 to 1), one of five constants—together with a, b, d, and k—inverted from the ground-motion data. The relationships basically account for the effects of:

  1) magnitude,
  2) geometrical spreading of radiated seismic energy ($d\log R$),
  3) anelastic attenuation and scattering (kR), and
  4) ground-motion amplification due to site-specific near-surface structure, s.

  Specific constants for the new ground-motion attenuation relationships are reproduced in Table 2 here. Graphs for attenuation of peak velocity and peak attenuation as a function of distance and magnitude are shown in Figure 4; as an example, the distribution of data used to invert for the peak-velocity attenuation relationship is shown in Figure 5.

- High-quality ground-motion data from a set of 12 shallow, mining-related earthquakes were ultimately used to derive the new attenuation relationships. The data set included triaxial recordings of 11 seismic events ($0.98 \le M_C \le 2.17$) in the TM study area, each recorded by at least six stations, and two triaxial recordings of the M_L 4.2 earthquake near the Willow Creek Mine in March 2000. The latter data were important for extending the limited magnitude range of the TM earthquakes, as apparent in Figure 5.

- When the new attenuation relationships developed for shallow MIS in the TM area are compared with those developed for natural earthquakes by Joyner and Boore (1993) and Spudich et al. (1999), there is good agreement for values of peak acceleration and peak velocity predicted for an $\boldsymbol{M}$ 4.0 earthquake at distances less than 1 km. Beyond this distance, the new attenuation relationships diminish more rapidly with distance than the counterpart relationships for earthquakes, presumably because of the higher-frequency data in the MIS data set and perhaps also because of the shallow source depths of the MIS.

- Moment tensors (i.e., mathematical descriptions of the orientation and relative values of force-couple components describing a seismic source) were determined for four TM seismic events using a waveform modeling approach. The selected events included two events closely associated with active mining of the 1st Right longwall panel in the TM Mine and two events in other parts of the mine associated with prior longwall mining. All four moment tensors are consistent with a source mechanism involving a normal-faulting component plus an implosive component of comparable magnitude. The normal faulting is consistent with the extensional tectonic setting here but the strikes of these faults probably are controlled by the mine geometry. These mechanisms indicate strong interactions with the mine openings.

- Coda magnitudes (M_C) determined by UUSS for the TM earthquake catalog were found to be reasonably good approximations to moment magnitude $\boldsymbol{M}$ based on two independent checks: (1) a comparison of M_C with values of $\boldsymbol{M}$ from the moment-tensor results and (2) a linear correlation with magnitude of the peak velocity parameter $R\mathbf{v}$ measured at close-in stations and calibrated with data from MIS in South Africa, which argues that M_C is essentially equivalent to $\boldsymbol{M}$.

- The results of this study can be used to estimate the predicted ground motion for a given magnitude and hypocentral distance to the Joes Valley Dam. However, the actual response of the dam site must be determined to estimate the ground motion at the dam itself. This part of the analysis, which can be done using ground-motion data recorded at the dam site as part of the TM field project, is left to the USBR.

3.0 ASSESSMENT OF PROBABLE MAXIMUM MAGNITUDE

3.1 Terminology

- *Moment magnitude is preferred standard*
- *Probable maximum magnitude versus Maximum Credible Earthquake*

It will be useful at the outset in this section to clarify terminology. First, in our consideration of "magnitude," we will ultimately use moment magnitude $\boldsymbol{M}$ (Hanks and Kanamori, 1979), which is preferentially used as the uniform size measure of earthquakes in seismic hazard analysis and associated ground-motion characterization. Second, we discard the term "Maximum Credible Earthquake" in favor of "probable maximum magnitude."

Magnitudes routinely determined by UUSS are either Richter local magnitude M_L or coda magnitude M_C, an empirical estimate of M_L commonly relied on for measuring the size of shocks smaller than magnitude 3. Conveniently, M_L is equivalent to $\boldsymbol{M}$ for M_L less than about 5.5–6.0 (Hanks and Boore, 1984). Further, M_C has been carefully calibrated to M_L by the University of Utah (see *UUSS Report*, p. 3-7), and independent testing by the USGS confirmed that M_C values in the TM earthquake catalog are reasonably good approximations to $\boldsymbol{M}$ (as described above). Thus, for all practical purposes in this report, UUSS magnitude values reported as either M_L or M_C are equivalent to $\boldsymbol{M}$ and will ultimately be considered as such.

Although the term Maximum Credible Earthquake (MCE) was used in describing a key project objective, the term is ill-defined and often contentious. One expert has humorously asked, "When does the Maximum Credible Earthquake become the Minimum Incredible Earthquake?" The lack of a clear definition for the MCE makes it difficult to apply in practice. A concept better suited to meet the needs of this project, particularly in light of agreement to approach the issue of an upper-bound magnitude in a probabilistic way, is that of a probable maximum magnitude. In seismic hazard analysis, the maximum magnitude m_{max} is conventionally understood to be the largest magnitude that a seismic source is capable of generating, where a seismic source is a geometrically defined plane, area, or volume with relatively uniform seismicity characteristics (e.g., Senior Seismic Hazard Analysis Committee, 1997).

It is the consensus of the Joint Working Group that the maximum magnitude is best represented using a distribution (discussed specifically in Section 3.3). However, we acknowledge that for use in conventional engineering assessments, a single value is often required. Thus, we define the probable maximum magnitude (PMM) to be a specified value in a probability distribution of m_{max} for a given seismic source. We propose using the 84^{th}-percentile value of the cumulative distribution function of m_{max} as the PMM.

For the problem at hand, the seismic source region is the Cottonwood Coal Tract, within the areal boundaries of which only shallow MIS will be considered. To make this point clear: we give no consideration to the possible size of naturally occurring tectonic earthquakes beneath the Cottonwood Coal Tract. We assume that such earthquakes are appropriately evaluated as part of existing seismic hazard assessments for Joes Valley Dam.

3.2 Considerations

3.2.1 MIS Worldwide

- *International reviews provide useful perspective*
- *Largest mine tremors ever observed in magnitude 5 range*
- *Largest MIS in coal mines in magnitude 4 range*

Gibowicz and Kijko (1994) and the Department of Energy Working Group (1999) reviewed MIS associated with underground mines on a worldwide basis, including useful documentation of the largest events. The latter report was compiled for the purpose of assessing MIS as a potentially confounding factor in monitoring the Comprehensive Nuclear-Test-Ban Treaty.

The largest mine tremor observed to date had a magnitude (M_L) of 5.6 (m_b = 5.5) and was associated with cascading pillar failures in a room-and-pillar potash mine in the former German Democratic Republic in March 1989 (Knoll, 1990); a smaller prior event in this same mining district also reached magnitude 5 (see Gibowicz and Kijko, 1994, p. 2). A notable mine failure in February 1995 in the Solvay Trona Mine, a room-and-pillar mine near Green River Wyoming, produced a seismic event of magnitude (M_L) 5.2 (m_b = 5.3, M_S = 4.6) (Pechmann et al., 1995; Swanson and Boler, 1995). Mine tremors in the mid-to-upper magnitude (M_L) 3 range are included among other instances of cascading pillar failures in room-and-pillar mines documented by the Department of Energy Working Group (1999)—including two cases in Utah coal mines (Taylor, 1994; Boler et al., 1997).

Mine tremors in hard rock mines have been reported as large as magnitude (M_L) 5.2 in the South African gold mining district, magnitude (M_L) 4.5 in a copper mining district in Poland, and magnitude (M_L) 4.1 in the Couer d'Alene mining district in northern Idaho (Gibowicz and Kijko, 1994; Department of Energy Working Group, 1999).

In terms of larger mine tremors in coal mines, it is apparent from the international review of Gibowicz and Kijko (1994, p. 1-10) that MIS in the mid-to-upper magnitude (M_L) 3 range has been observed in many coal districts around the world, but large MIS in the magnitude (M_L) 4 range has been relatively rare.

The report of the Department of Energy Working Group (1999, p. 28) includes a tabulation of larger mining seismic events in the U.S. for the period 1981–1999 that contains five coal bumps in eastern U.S. coal mines in the magnitude 4 range: M_L 4.0 (1988, Buchanan, VA), M_L 4.0 (1995, Lynch, KY), M_L 4.2 (1995, Lynch, KY), M_L 4.0 (1997, Shoal Creek , AL), and M_L 4.0 (1999, Shoal Creek , AL). Given the relative rarity of MIS in the magnitude (M_L) 4 range in coal mines worldwide, the size of these events may be overestimated, but it is difficult to verify accuracy without scrutiny of the original seismological data.

3.2.2 History of MIS in the WP-BC Coal-Mining Region

- *Uniform catalog of largest MIS in Utah since 1962 available*
- *M_L 4.2 (Willow Creek Mine) largest historical mining-related seismic event since 1962*
- *Larger historical events (except for Willow Creek Mine events) predominantly implosional?*
- *Bimodal distribution of MIS suggests larger shocks form a separate set*

Arabasz et al. (1997) developed a catalog of the larger mining-related seismic events in the Wasatch Plateau (WP)–Book Cliffs (BC) coal mining districts from July 1962 (when systematic instrumental monitoring began) through March 1996. Importantly, careful efforts were made to achieve homogeneous size estimates. The largest event in the catalog had a weighted-average estimate of M_L (termed M_L') of 3.8, associated with inferred cascading pillar failures in a remote part of a room-and-pillar mine in the Gentry Mountain area (about 23 km [14 mi] NNE of the TM area) in May 1981 (Taylor, 1994). The magnitude assigned to an earthquake is intended to be the mean of measurements made at multiple, azimuthally diverse, recording stations, with a typical standard deviation of ±0.3. Accordingly, Arabasz et al. (1997) identified the (then) largest historical MIS in the WP-BC region as M_L 3.8 ± 0.3.

The catalog of the larger MIS in the WP-BC region was slightly refined and updated by Arabasz and Pechmann (2001), who systematically examined all earthquakes of $M_L \geq 3.0$ in the WP-BC region from January 1978 through June 2000. Their listing is reproduced here in Table 3. Since June 2000, no other earthquakes of $M_L \geq 3.0$ have occurred in the WP-BC region through the date of this report. Two important additions to this list of larger MIS in the WP-BC region were two sizable earthquakes near the Willow Creek Mine—one of M_L 3.8 on February 5, 1998, and another of M_L 4.2 on March 7, 2000 (Arabasz and Pechmann, 2001; Ellenberger et al., 2001). The latter earthquake now represents the largest historical MIS in Utah instrumentally recorded since 1962.

Table 3 identifies 18 earthquakes of $M_L \geq 3.0$ in the WP-BC region since 1978. Three of these had unambiguous shear-slip-type source mechanisms (Arabasz and Pechmann, 2001): the M_L 3.8 and M_L 4.2 earthquakes near the Willow Creek Mine in 1998 and 2000, respectively, and an earthquake of M_L 3.0 in June 1996 south of the Skyline Mine, for which there is convincing evidence that the shock was a non-mining-related tectonic earthquake more than several kilometers deep. 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 *P*-wave first motions were recorded by the UUSS regional seismic network, and multiple pillar failures are documented for four of these events. According to Arabasz and Pechmann (2001, p. iv; see also Arabasz et al. 2001), "Available evidence favors the working hypothesis that the predominant mechanism of larger (magnitude ≥ 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."

Using data compiled by Arabasz and Pechmann (2001), we constructed plots of frequency of occurrence versus magnitude, shown in Figure 6, for MIS in the WP-BC region for January 1978 through June 2000. The inset shows a standard plot of cumulative number of shocks greater than or equal to a specified magnitude. On the low-magnitude end, the plot flattens as usual due to incomplete sampling below some threshold, here identified as magnitude 1.85. The maximum-likelihood recurrence relation illustrated in Figure 6 was determined using the procedure of Weichert (1980) for a doubly-truncated exponential, assuming $m_{min} = 1.85$ and $m_{max} = 4.6$. To calculate $N(M)$, the cumulative number of earthquakes per year of magnitude M and greater in the sample region, one uses the equation (e.g., Pechmann and Arabasz, 1995):

$$N(M) = A \frac{10^{-b(M-m_{min})} - 10^{-b(m_{max}-m_{min})}}{1 - 10^{-b(m_{max}-m_{min})}}$$

where $A = 0.12\mathrm{E}{+}03$ and $b = 1.91 \pm 0.04$. The error bars in Figure 6 show the 90-percent confidence intervals for the plotted frequencies. An observation of particular significance for us is the systematic departure from linearity in log–magnitude space shown by the plots in Figure 6 to the right of the upper magnitude 2 range. This feature suggests that the earthquake sample is bimodal (e.g., Gibowicz and Kijko, 1994, p. 22f) with the larger shocks belonging to a set of events separate from the lower-energy events routinely accompanying extraction—and not simply an extrapolation of the lower-energy events following a power-law scaling. From the data of Figure 6 we infer that the boundary between what might be called normal background MIS and infrequent large seismic events in the WP-BC mining region is roughly in the upper magnitude 2 range, perhaps close to magnitude 3.

To guide our evaluation of how the largest MIS in the WP-BC region is distributed in size, we constructed a probability mass distribution for the 17 mining-related events listed in Table 3, excluding the one event (#17) identified as a deeper tectonic earthquake. The results are shown in Figure 7. The distribution has a mode at magnitude 3.1 and an upper bound at magnitude 4.2, the size of the March 2000 Willow Creek Mine earthquake.

3.2.3 History of MIS at the TM Mine

- *Continuous record of MIS available from UUSS regional network for entire period of longwall mining (1995–2001) in the TM Mine*
- *Largest mine tremor in TM Mine during* this *period had magnitude (M_C) 2.5*
- *5.4-year record of MIS during longwall operations did not include any extreme events*

Thanks to continuous monitoring by the University of Utah's regional seismic network, we have a temporal record of MIS associated with the TM Mine spanning the entire period of longwall mining from October 1995 through March 2001. A magnitude-versus-time plot for the TM local study area, including the time period of special study as part of this project, is shown in Figure 8. For the data sample in Figure 8, M_C values from the regional network catalog were recomputed using the same procedures as for the TM catalog (see sections 3.3.3 and 4.2 of the *UUSS Report*) to ensure uniformity of magnitudes.

An important observation from Figure 8 is that the largest earthquake recorded during 5.4 years of longwall operations in the TM Mine had a magnitude (M_C) of 2.5. As emphasized in the figure caption, the gaps in the seismicity time series are not due to gaps in monitoring. Rather, they are inferred to be associated variously with interruptions in mining, such as during longwall moves, and variations in mine characteristics such as cover depth.

The *UUSS Report* discusses the reduction in size of MIS that was recorded during the period November 2000–March 2001, which is apparent in Figure 8. In order to get a representative sample of energetic MIS associated with the TM Mine, we used Figure 8 as a guide and selected the time period November 1, 1998–September 30, 2000. Using the same procedures described earlier for Figure 6, we constructed frequency-of-occurrence versus magnitude plots for this 23-month sample of MIS, with the results shown in Figure 9. In this case, the cumulative-number plot (inset) indicates a threshold of completeness at magnitude 1.75, above which there is simple linearity. The position of the data point for the largest magnitude class ($\geq$ 2.45) below the extrapolated trend suggests inadequate temporal sampling for this size event. What is apparent from Figure 8 is that the MIS recorded during longwall operations at the TM Mine did not include any extreme events but rather consisted exclusively of lower-energy seismicity accompanying the regular release of mine-induced stresses.

3.2.4 Characteristics of the Cottonwood Coal Tract

- *Subjective comparison of Cottonwood Tract to four other areas of MIS in the region*
- *Inferred geologic conditions of the Hiawatha coal seam in the Cottonwood Tract*
- *In the absence of a proposed mining plan, different scenarios are considered*
- *Both ameliorating and exacerbating factors for MIS are present in the Cottonwood Tract*

A quantitative means for assessing m_{max} for MIS based on site factors is not available at this time. A useful approach is to compare conditions in the Cottonwood Tract with those in mining areas elsewhere in the Wasatch Plateau-Book Cliffs region. In this way, a subjective measure can be made as to whether m_{max} is likely to be larger or smaller than past events in areas where conditions and mining practices can be compared. For this purpose, four relevant case studies were selected and examined by M. K. McCarter in Appendix F of the *UUSS Report*. These include: the Willow Creek event (M_L 4.2 on March 7, 2000); the Cottonwood event (M_L 3.5 on July 5, 1992); the Trail Mountain event (M_L 3.3 on December 16, 1987); and the largest MIS associated with longwall mining in the Trail Mountain Mine (M_C 2.5 on April 7, 2000).

Geologic conditions in the Cottonwood Tract were inferred utilizing publicly available logs for ten drill holes together with information from the Trail Mountain Mine provided by Energy West. These logs along with available topography allowed estimation of the structural contour of the Hiawatha coal seam and interpretation of depth of cover. The orientation of the coal seam and depth of cover are critical factors in assessing m_{max} relative to other mines in the Wasatch Plateau and Book Cliffs. These factors are based on limited data which are not optimally distributed spatially. The actual structure, depth of cover, and geological conditions will undoubtedly be refined in the detailed planning required prior to mining. Some changes in interpretation are expected, but the analyses presented in the *UUSS Report*, Appendix F, provide reasonable estimates and the best information publicly available at this time.

The topography of the Tract is similar to conditions at the Trail Mountain Mine and the Cottonwood Mine. It is dominated by canyons and steep slopes on the north and on the south, highlands with more gradual slopes truncated at the margins by cliffs formed by stream erosion and the Joes Valley escarpment. It is not as steep or varied as that present at the Willow Creek Mine. Sharp transitions in topography seem to induce stress gradients which may exacerbate MIS. On the basis of topographic transitions, conditions for most of the Tract are less likely to produce MIS compared to Willow Creek and would be about the same for the Trail Mountain and Cottonwood areas.

In the central region of the Tract, the cover depth is likely to be 730 m (2,400 ft) or greater (see Figure 10). Consequently, m_{max} is potentially higher than in the TM study area (cover depth up to 670 m or 2,200 ft), the pre-Energy West Trail Mountain workings (cover depth up to 580 m or 1,900 ft), or the Cottonwood Mine (cover depth of 550–610 m or 1,800–2,000 ft). The depth of cover is comparable to the Willow Creek Mine or slightly higher. On the basis of cover depth, m_{max} in the central part of the Tract could be higher than in the Trail Mountain and Cottonwood areas. It could be equal to or even higher than the Willow Creek area. The cover depth for about one-half (~48 percent) of the Tract is in excess of 550 m (1,800 ft) and is expected to be bounce-prone.

The Hiawatha seam ranges in thickness from about 4.4 meters (14 ft) near the center of the Tract to about 1.5 m (5 ft) on the south and 2.6 m (8.5 ft) on the north; therefore, thickness is comparable to the other four areas. The coal strength is similar to the Trail Mountain and Cottonwood areas. Coal in the Willow Creek area (Castlegate D seam) is typically stronger and perhaps more brittle. Consequently, the effect of coal strength on producing MIS in the Tract should be about the same as at the Trail Mountain and Cottonwood mines while the stronger coal at the Willow Creek Mine would likely produce higher magnitudes.

As in the Cottonwood and Trail Mountain areas, the Hiawatha seam occurs near the bottom of the Blackhawk Formation. This formation contains sand channels which have been associated with MIS in the past. It also contains shales, mudstones and siltstones which promote caving. The sand channels exacerbate MIS while the ease of caving ameliorates MIS. The nature of the main roof in the Tract is lithologically similar to Cottonwood and Trail Mountain areas. The thickness of the overlying Castlegate Sandstone for the Tract is about the same as for Cottonwood and Trail Mountain areas, perhaps even less. The thickness over the Willow Creek mine is about twice that for the Wasatch Plateau and may have contributed to the larger events recorded in the Book Cliffs area.

The major structures in the Tract include the Straight Canyon syncline and Joes Valley fault. Several other structures are projected into the area. These include the Mill Fork graben and the Roan's Canyon graben with associated faults. Similar fault structures have been known to increase vertical stresses at the margins of grabens. These structures may complicate mining and exacerbate MIS relative to the Cottonwood and Trail Mountain areas. Unusual stress fields may exist in the Willow Creek area as evidenced by a substantial bounce early in the development stages of the mine. Based on the possible presence of tectonic structures, m_{max} may be greater in the Tract than in the Cottonwood and Trail Mountain areas but probably less than Willow Creek.

In addition to the geological and topographical factors, the details of the mining plan to be used in the Tract will also influence the magnitude of MIS. A mining plan has yet to be proposed and may require access to proprietary information as well as additional drillholes. In the absence of a mining plan, two scenarios can be considered for a preliminary assessment. Scenario 1A would involve developing panels beginning just north and west of the last panel mined in the Trail Mountain Mine. This is identified as Scenario 1A with a possible variant identified as Scenario 1B (see *UUSS Report*, Appendix F for additional details). The other option, identified as Scenario 2, initiates panel development in the southwest corner of the tract.

The most advantageous place to begin longwall mining is at 1A. This is near the thickest portion of the coal seam in the Tract and can be reached with a minimum of development work. Unfortunately, it is also where the depth of cover is greatest and will likely have the highest potential for MIS. Initiation of mining at 1A has the additional advantage that the distance from Joes Valley Dam would begin at approximately 4.0 km (13,000 ft) and would increase as mining progresses northward. Beginning mining operations at this point and working towards the Dam would allow an opportunity to limit how close mining would be allowed based on accumulated operating experience.

The advantage of Scenario 2 would be to maximize recovery of the coal resource. This location must be far enough to the north of the boundary so as not to cause stability problems with the Straight Canyon escarpment. The main advantage of this location is lower cover relative to Scenario 1A (430–610 m or 1,400–2,000 ft). The disadvantages include high development costs, substantial delay and close proximity to the Dam (0.9 km or 3,000 ft).

A comparison of conditions for the two scenarios relative to the case histories is summarized on Table 1(a) and 1(b). As indicated, some factors are ameliorating, some are exacerbating and others have little influence or the influence is unknown. For the low-cover areas in the Tract, m_{max} would probably be less than that historically observed for the Cottonwood or Trail Mountain mines (M_L 3.3 to 3.5). In the high-cover areas (in excess of 550 m or 1,800 ft), m_{max} might exceed 3.3 to 3.5 observed in the case studies. Because the exact cause of the Willow Creek event is not well understood, an event of 4.2 cannot be ruled out entirely, but the probability of an event of this magnitude is considered low for the Tract as a whole.

3.3 Probability Distribution of m_{max}

- *Informed consensus as opposed to independent assessments*
- *Consensus probability distribution has a lower bound of 2.7, a mode of 3.1, and an upper bound of 4.6 (mean = 3.43, median = 3.41)*
- *"Seismically large" events do not necessarily equate with hazardous rockbursts*
- *Probable maximum magnitude (proposed as 84th-percentile value) is 3.9*

Based on all the considerations discussed in the preceding sections, we proceed to assess a probability distribution for m_{max}. Because the problem is not simply amenable to an analytical solution, we use a subjective probability approach for quantifying our expert opinion. In terms of methodology, we made the decision to use a simple triangular distribution to capture our best judgment of the central tendencies and bounding values of m_{max}. Further, we agreed to pursue by iterative interaction an "informed consensus," as opposed to a mathematical aggregation of independent assessments.

Our consensus probability distribution for m_{max} is presented in Figure 11 both as a probability density function (PDF) and a cumulative distribution function (CDF). Values of m_{max} and cumulative probability for the CDF are given in Table 4. The PDF has a lower-bound value of 2.7, a mode of 3.1, and an upper-bound value of 4.6. The mean of the distribution is 3.47 and the median is 3.41.

Our upper-bound value of 4.6 rules out the likelihood of energy release comparable to the magnitude 5 earthquakes produced by cascading pillar failures in room-and-pillar mines or by failures in deep South African gold mines. We do not consider those situations relevant to the Cottonwood Coal Tract. At the same time, we do not believe that we can completely rule out (i.e., assign zero probability) to an event like the magnitude 4.2 Willow Creek Mine earthquake. Simply put, without a clear understanding of what caused that earthquake, we are forced to be reasonably conservative—including some allowance for a typical standard deviation of ± 0.3 in magnitude determinations—in considering what may happen in mining the Cottonwood Coal Tract. We do not know, for example, what the detailed mine plan will be.

From Table 4, our implied probability for a magnitude 4.2 or larger earthquake in the Cottonwood Coal Tract is approximately 0.06.

For the mode of our PDF, we are influenced by the historical experience of MIS in the WP-BC mining region, notably by the probability mass function shown in Figure 7, and we adopt the observed mode of 3.1. While this size event may have the greatest relative frequency, our CDF (Table 4) indicates that there is a substantial probability (approximately 0.8) that m_{max} will exceed 3.1.

To explain our choice of 2.7 for a lower bound for m_{max}, recall that what we are assessing is the largest MIS that the Cottonwood Coal Tract is capable of generating. From considerations discussed above in section 3.2.2, we recognize two sets of MIS and place the lower bound of large-class events at 2.7. This makes some allowance, once again, for $\pm$ 0.3 uncertainty in magnitude determinations. Because no large-class events occurred during the 5.4 years of longwall mining in the TM Mine (section 3.2.3), the observation of magnitude 2.5 as the largest MIS during that period is not inconsistent with the lower bound of our PDF for m_{max}.

Finally, we emphasize that our considerations of m_{max} relate to earthquake size in terms of radiated seismic energy and its manifestation as surface ground shaking. It is well recognized that "seismically large" events do not necessarily equate with hazardous rockbursts, and vice-versa (e.g., Arabasz et al., 1997; Ellenberger et al., 2001). Thus, the relevant consideration here is not the likelihood of a damaging rockburst, but rather the triggering of seismic energy release large enough to have an adverse vibratory impact on Joes Valley Dam.

Based upon our definition of the probable maximum magnitude (PMM) defined in Section 3.1 and the probability distribution developed for m_{max} (Figure 11 and Table 4), our estimate of the PMM for the Cottonwood Coal Tract is 3.9.

4.0 CONCLUSIONS

- The project objectives were successfully met.
- The strategic recording and analysis of abundant mining-induced seismicity (MIS) associated with active longwall mining at the Trail Mountain (TM) Mine provided an effective way to characterize future MIS in the Cottonwood Coal Tract—most critically, ground-motion as a function of distance and size.
- The 12-station seismic array installed above, within, and surrounding the TM Mine captured high-quality data that were limited in magnitude ($\leq$ 2.2) but well suited to developing ground-motion attenuation relationships for the environs of the Joes Valley Dam, especially when augmented with data from the magnitude 4.2 Willow Creek Mine earthquake.
- The attenuation relationships developed in this study can be used to estimate the predicted ground motion for a given magnitude and hypocentral distance to the Joes Valley Dam in terms of peak acceleration **a** (cm/s/s), peak velocity **v** (cm/s), or pseudovelocity response ps(T) (also in units of cm/s) at 5-percent damping at a set of periods T ranging from 0.1 s to 2 s.

- Coda magnitudes (M_C) and local Richter magnitudes (M_L) assigned by the University of Utah to the MIS that was considered in this study appear to be essentially the same as moment magnitudes (***M***), a more universal measure of earthquake size, and thus provide a sound basis for seismic hazard analysis and associated ground-motion characterization.
- Based on considerations of the characteristics of the Cottonwood Coal Tract, together with seismological observations of MIS worldwide, in the Wasatch Plateau-Book Cliffs mining region, and in the TM Mine, we have assessed the "probable maximum magnitude" (PMM) for future MIS in the Cottonwood Coal Tract. It is the consensus of the Joint Working Group that the maximum magnitude m_{max} is best represented using a probability distribution. We define the PMM to be a specified value in a probability distribution of m_{max}. Recognizing that a single value is often required for use in conventional engineering assessments, we propose using the 84^{th}-percentile value of the cumulative distribution function of m_{max} as the PMM.
- Our consensus probability distribution for m_{max} has a lower-bound value of 2.7, a mode of 3.1, and an upper-bound value of 4.6. The mean of the distribution is 3.47, the median is 3.41, and the 84^{th}-percentile value of the cumulative distribution function is 3.92.
- To illustrate the potential hazard at the site of Joes Valley Dam due to seismic ground motion for the PMM, the peak expected ground velocity for canyon site conditions for an event of ***M*** 3.9 is about 8 cm/s at a distance of 1 km; this, and other, ground motion predictions must be adjusted according to the actual response of the dam itself.
- From a mining-engineering perspective, the consensus probability distribution for m_{max} is consistent with possible geologic conditions and mitigating factors present in the Cottonwood Coal Tract. Seismicity associated with underground longwall mining of coal is strongly influenced by depth of cover, lithology of strata above and below the coal seam, and coal strength. Based on limited drill hole information, conditions present in parts of the Cottonwood Tract are likely to be similar to those associated with seismic events ranging from M_L 3.3 to 4.2 at other mines in the Wasatch Plateau-Book Cliffs region. The assessed probability of a seismic event of magnitude ≥ 4.2 is small but finite (~0.06); the distribution rules out events larger than 4.6 which have occurred in non-coal mines utilizing methods far different than those applicable in the Cottonwood Tract. In considering the distance from the Dam to the hypocenter of an event with the PMM of 3.9, it is likely that events of this magnitude would be limited to areas with cover depths in excess of 550 m (1,800 ft).
- Finally, the data acquired in this project have provided a rich source of information useful for studying MIS in the Trail Mountain Mine as a valuable case study. The observed seismicity (including more than 1,900 earthquake locations) was highly correlated with mining activity in both space and time. Source mechanisms are consistent with implosive failure with a normal-faulting component of comparable size; the moment tensors determined for four of the Trail Mountain events indicate strong interactions with the mining.

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Tables and Figures

Table 1 (a)

Risk of Scenario-1A Conditions Producing Greater MIS Magnitude in the Cottonwood Coal Tract Relative to the Comparison Area (reproduced from McCarter, 2002: *UUSS Report*, Appendix F)

Category	**Willow Creek**	**Cottonwood Mine**	**Old Trail Workings**	**Trail Mountain Study Area**
Depth of Cover	Equal	Higher	Higher	Higher
Topography	Lower	Lower	Lower	Equal
Strength of Coal	Lower	Equal	Equal	Equal
Presence of Sand Channels	Equal	Equal	Equal	Equal
Distance to Castlegate SS	Lower	Lower	Lower	Lower
Thickness of Castlegate SS	Lower	Equal	Equal	Equal
Regional/Local Stress	Lower	?	?	?
Tectonic Features	Higher	Higher	Higher	Higher
Panel Width	?	Equal	Equal	Equal
Design of Panel Entries	Equal	Lower	?	Equal
Floor Conditions	Equal	Equal	Equal	Equal
Extraction Rate	?	?	?	?

Table 1 (b)

Risk of Scenario-2 Conditions Producing Greater MIS Magnitude in the Cottonwood Coal Tract Relative to the Comparison Area (reproduced from McCarter, 2002: *UUSS Report*, Appendix F)

Category	**Willow Creek**	**Cottonwood Mine**	**Old Trail Workings**	**Trail Mountain Study Area**
Depth of Cover	Equal	Higher	Higher	Equal
Topography	Equal	Equal	Equal	Higher
Strength of Coal	Lower	Equal	Equal	Equal
Presence of Sand Channels	Equal	Equal	Equal	Equal
Distance to Castlegate SS	Lower	Equal	Equal	Equal
Thickness of Castlegate SS	Lower	Equal	Equal	Equal
Regional/Local Stress	Lower	?	?	?
Tectonic Features	Higher	Higher	Higher	Higher
Panel Width	?	Equal	Equal	Equal
Design of Panel Entries	Equal	Lower	?	Equal
Floor Conditions	Equal	Equal	Equal	Equal
Extraction Rate	?	?	?	?

Table 2

Constants for Ground-Motion Attenuation Relationships
(reproduced from *USGS Report*)

$$\log(y) = a + b\boldsymbol{M} + d\log(R) + kR + s$$

$y^{\dagger}$	No.	a	b	d	k	s_1*	s_2*	s_3*	$\sigma^{\S}$
a	72	-1.421	0.8553	-1.601	-0.1245	1.0	0.645	0.844	0.255
v	72	-3.758	0.9539	-1.524	-0.0484	1.0	0.887	0.578	0.242
ps(0.1)	72	-3.044	0.8473	-1.228	-0.1204	0.7619	0.6082	0.0	0.228
ps(0.2)	72	-3.762	1.006	-1.152	-0.0651	0.738	0.884	0.0	0.234
ps(0.5)	54	-4.355	1.115	-1.241	-0.0278	0.687	0.7613	0.0	0.206
ps(1.0)	39	-4.492	1.127	-1.128	0.0	0.494	0.4781	0.0	0.207
ps(2.0)	31	-3.923	0.8486	-1.362	0.0	0.7819	0.0	0.1108	0.205

† y = maximum horizontal component of the ground-motion parameter under consideration

* s = site factor (constrained to be in the range 0 to 1); three categories include: s_1 for sites near the bottoms of the canyons (TB1, TB2, TB3, WCS, EMU); s_2 for sites on the plateau top of Trail Mountain (TS2, TS3, TMU); and s_3 for underground site (TU1)

§ standard deviation of the residuals res_i for all observations obs_i such that $res_I = \log(obs_I) - \log(y_I)$; a residual of 0.2, for example, would correspond to a ratio obs_i/y_i of 1.58

Table 3

Focal-Mechanism and Summary Information for Seismic Events of Magnitude 3.0 or Larger in the WP-BC Coal-Mining Area, January 1978-June 2000, Ranked by Size (from Arabasz and Pechmann, 2001)

ID	Yr	MoDa (UTC)	HrMin (UTC)	Lat N	Long W	Depth* (km)	Mag.**	Closest Active Mine	Focal Mechanism	Ground-Truth Info. Available?
1	2000	03/07	02:16	39-44.95	110-50.19	1.8	ML 4.2	Willow Creek	**Shear Slip**	YES
2	1981	05/14	05:11	39-28.86	111-04.72	0.7	ML’ 3.8	King #4	Collapse-type?	YES
3	1998	02/05	05:19	39-45.05	110-50.73	1.3	ML 3.8	Willow Creek	**Shear Slip**	YES
4	1992	07/05	12:22	39-18.81	111-09.60	5.6	ML’ 3.5	Cottonwood	Collapse-type?	YES
5	1981	09/21	08:01	39-35.48	110-25.47	1.6	ML’ 3.4	Sunnyside #3	Collapse-type?	
6	1981	09/22	05:03	39-35.35	110.23.61	7.5	ML’ 3.3	Sunnyside #3	Collapse-type?	
7	1987	12/16	17:43	39-18.70	111-12.92	0.5	ML’ 3.3	Trail Mountain	Collapse-type?	YES
8	1992	06/03	05:08	39-19.04	111-09.80	0.6	ML’ 3.2	Cottonwood	Collapse-type?	YES
9	1991	02/06	13:46	39-29.99	111-04.61	4.3	ML’ 3.1	Star Point #2	Collapse-type?	
10	1996	10/25	18:32	39-42.12	110.39.24	3.3	ML 3.1	Soldier Canyon	Collapse-type?	
11	1986	02/14	00:56	39-41.18	110.31.50	0.2	ML’ 3.1	Soldier Canyon	(data problem)***	
12	1991	05/23	07:38	39-17.89	111-08.92	12.4	ML’ 3.1	Cottonwood	Collapse-type?	
13	1992	07/11	13:23	39-18.52	111-08.94	9.3	ML’ 3.1	Cottonwood	(data problem)***	
14	1993	01/21	09:01	39-42.73	110-37.26	1.3	ML’ 3.1	Soldier Canyon	Collapse-type?	YES
15	1983	03/22	11:12	39-32.78	110-25.32	1.6	ML’ 3.0	Sunnyside #3	Collapse-type?	
16	1984	03/21	11:19	39-20.64	111-06.53	0.1	ML’ 3.0	Deer Creek	Collapse-type?	
17	1996	06/02	08:09	39-37.55	111-14.45	5.5	ML 3.0	(Skyline #3)****	**Shear Slip**	
18	1986	10/30	00:05	39-44.11	110-57.93	5.6	ML’ 3.0	Castle Gate #3	Collapse-type?	

* Unreliable
** ML’ is a weighted-average estimate of local magnitude, ML (see Arabasz et al., 1997)
*** P-wave first motions obscured by small preceding event
**** Tectonic earthquake located 7 km south of Skyline Mine

Table 4

Values of m_{max} and Cumulative Probability for the CDF Shown in Figure 11

mmax	CDF	mmax	CDF	mmax	CDF
2.700	0.0000	3.346	0.4482	3.992	0.8703
2.719	0.0005	3.365	0.4648	4.011	0.8783
2.738	0.0019	3.384	0.4812	4.030	0.8860
2.757	0.0043	3.403	0.4973	4.049	0.8935
2.776	0.0076	3.422	0.5131	4.068	0.9007
2.795	0.0119	3.441	0.5287	4.087	0.9077
2.814	0.0171	3.460	0.5440	4.106	0.9144
2.833	0.0233	3.479	0.5591	4.125	0.9208
2.852	0.0304	3.498	0.5739	4.144	0.9270
2.871	0.0385	3.517	0.5885	4.163	0.9330
2.890	0.0475	3.536	0.6028	4.182	0.9387
2.909	0.0575	3.555	0.6168	4.201	0.9441
2.928	0.0684	3.574	0.6306	4.220	0.9493
2.947	0.0803	3.593	0.6442	4.239	0.9543
2.966	0.0931	3.612	0.6575	4.258	0.9590
2.985	0.1069	3.631	0.6705	4.277	0.9634
3.004	0.1216	3.650	0.6833	4.296	0.9676
3.023	0.1373	3.669	0.6959	4.315	0.9715
3.042	0.1539	3.688	0.7082	4.334	0.9752
3.061	0.1715	3.707	0.7202	4.353	0.9786
3.080	0.1900	3.726	0.7320	4.372	0.9818
3.099	0.2095	3.745	0.7435	4.391	0.9847
3.118	0.2294	3.764	0.7548	4.410	0.9873
3.137	0.2490	3.783	0.7658	4.429	0.9897
3.156	0.2684	3.802	0.7766	4.448	0.9919
3.175	0.2875	3.821	0.7871	4.467	0.9938
3.194	0.3064	3.840	0.7973	4.486	0.9954
3.213	0.3250	3.859	0.8073	4.505	0.9968
3.232	0.3434	3.878	0.8171	4.524	0.9980
3.251	0.3615	3.897	0.8266	4.543	0.9989
3.270	0.3793	3.916	0.8358	4.562	0.9995
3.289	0.3969	3.935	0.8448	4.581	0.9999
3.308	0.4143	3.954	0.8536	4.600	1.0000
3.327	0.4314	3.973	0.8621		

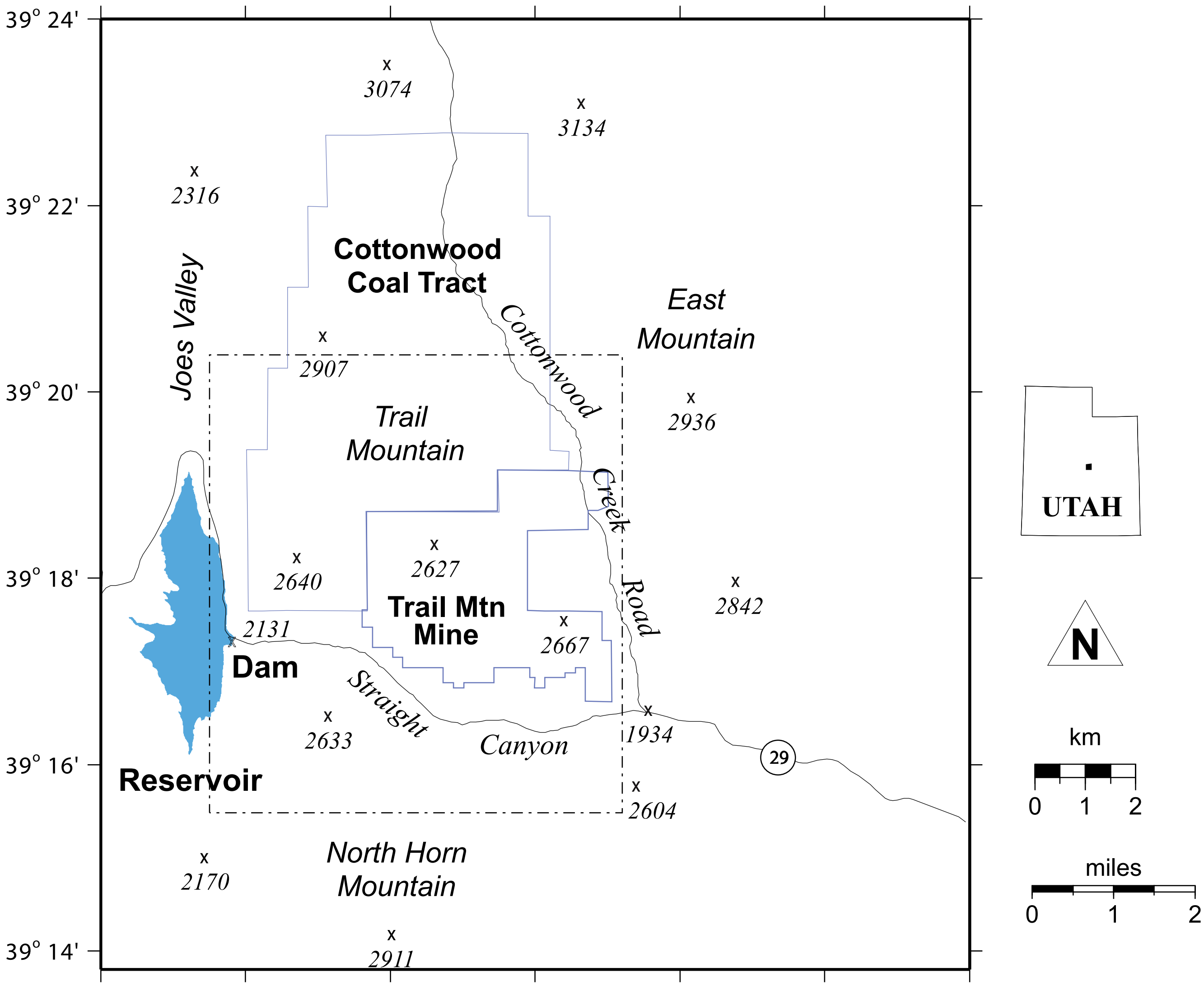

Figure 1. Location map of the Trail Mountain study area. For reference, the bounds of the map define the "extended study area"; dashed rectangular inset, the "local study area"; x's, selected elevations (in meters).

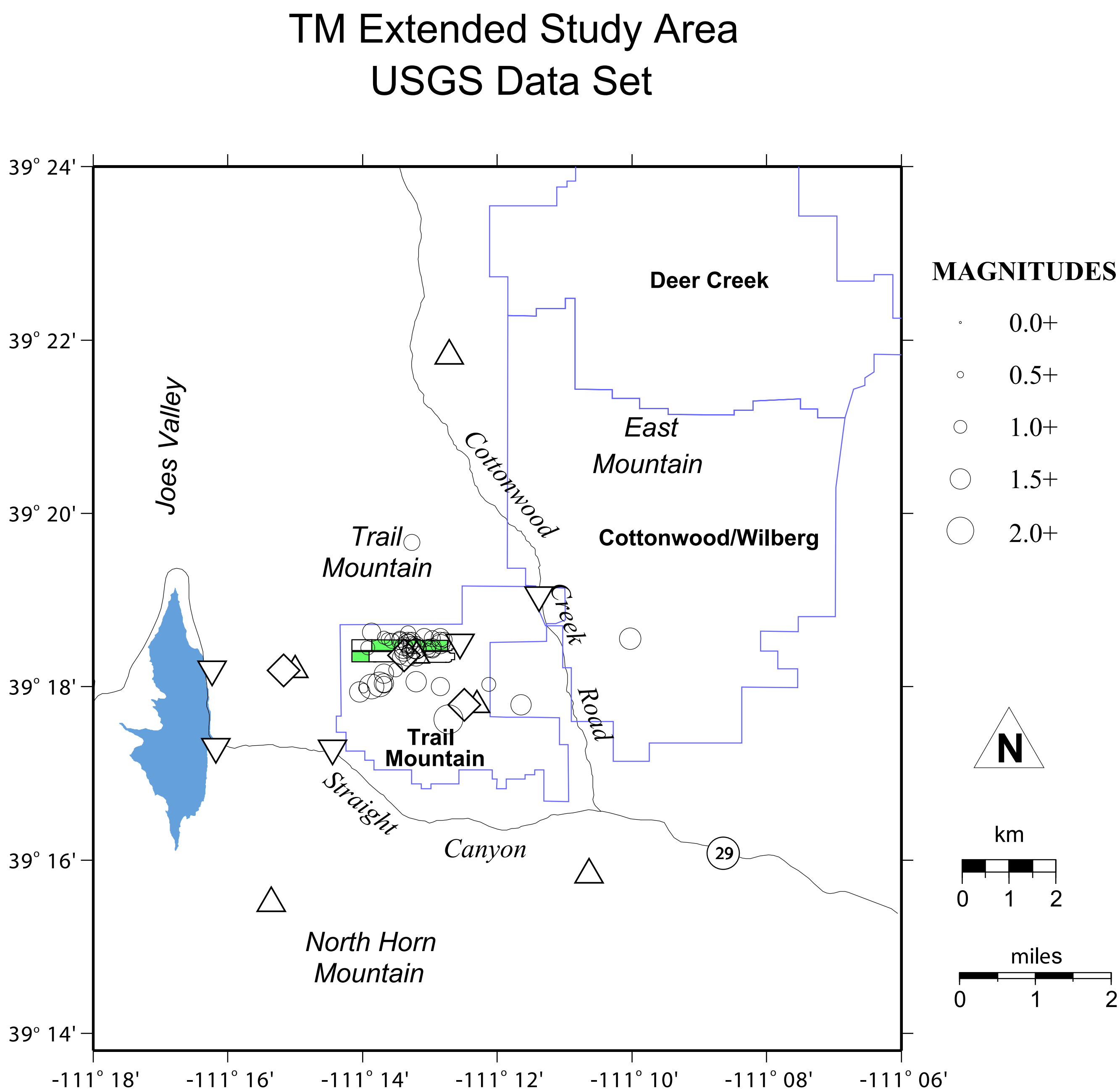

Figure 2. Epicenter map of 49 seismic events (circles, scaled by magnitude) selected as candidates for the USGS to consider for special analysis. Also shown are seismographic stations (trangles and diamonds, explained in *UUSS Report*) and longwall panels (green) mined during the monitoring period of this study. The outline of the Trail Mountain Mine and lease boundaries of the Deer Creek and Cottonwood/Wilberg mines are shown for reference.

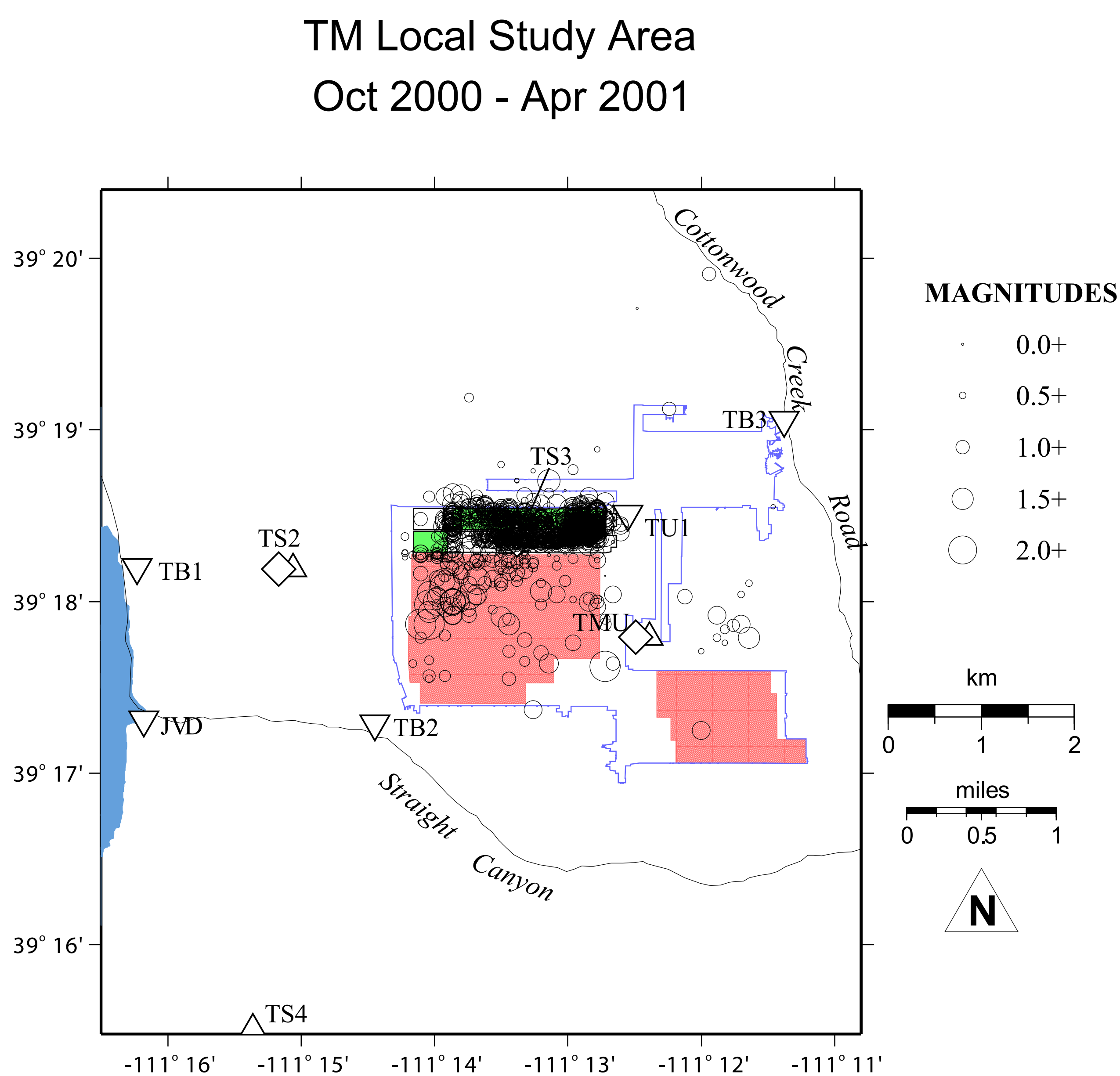

Figure 3. Epicenter map of 1,801 better-located seismic events (circles, scaled by magnitude) within the local study area. Base map includes: seismic stations, as in Figure 2; outline of the Trail Mountain Mine (blue); longwall panels (green) mined during the monitoring period of this study; and areas mined out by longwall operations prior to this study; (shown in pink). The latter include an area in the southeastern part of the mine, mined during October 1995–March 1997, and an area in the western part of the mine where east-west panels were mined, with one exception, from south to north during March 1997–August 2000. Clustered epicenters on the right-hand side of the figure outside the mine boundary coincide with an area of old room-and-pillar mining in pre-Energy West workings.

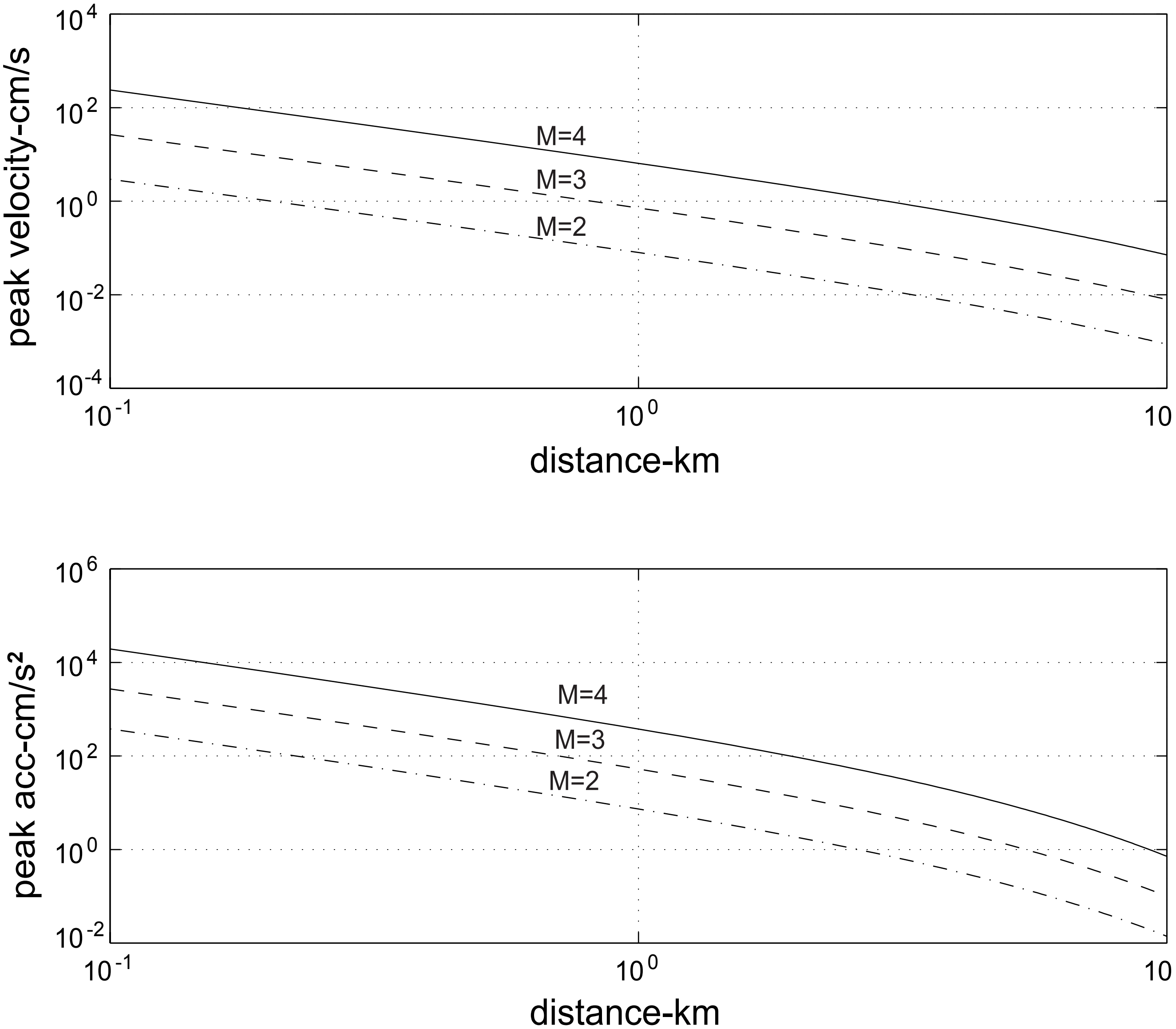

Figure 4. Predicted ground motion as a function of distance for various magnitudes of interest, based on parameters in Table 2, for (a) peak horizontal velocity **v** (assuming 0.8 for the site factor *s*) and (b) peak horizontal acceleration **a** (assuming 0.7 for *s*). (Reproduced from *USGS Report*.)

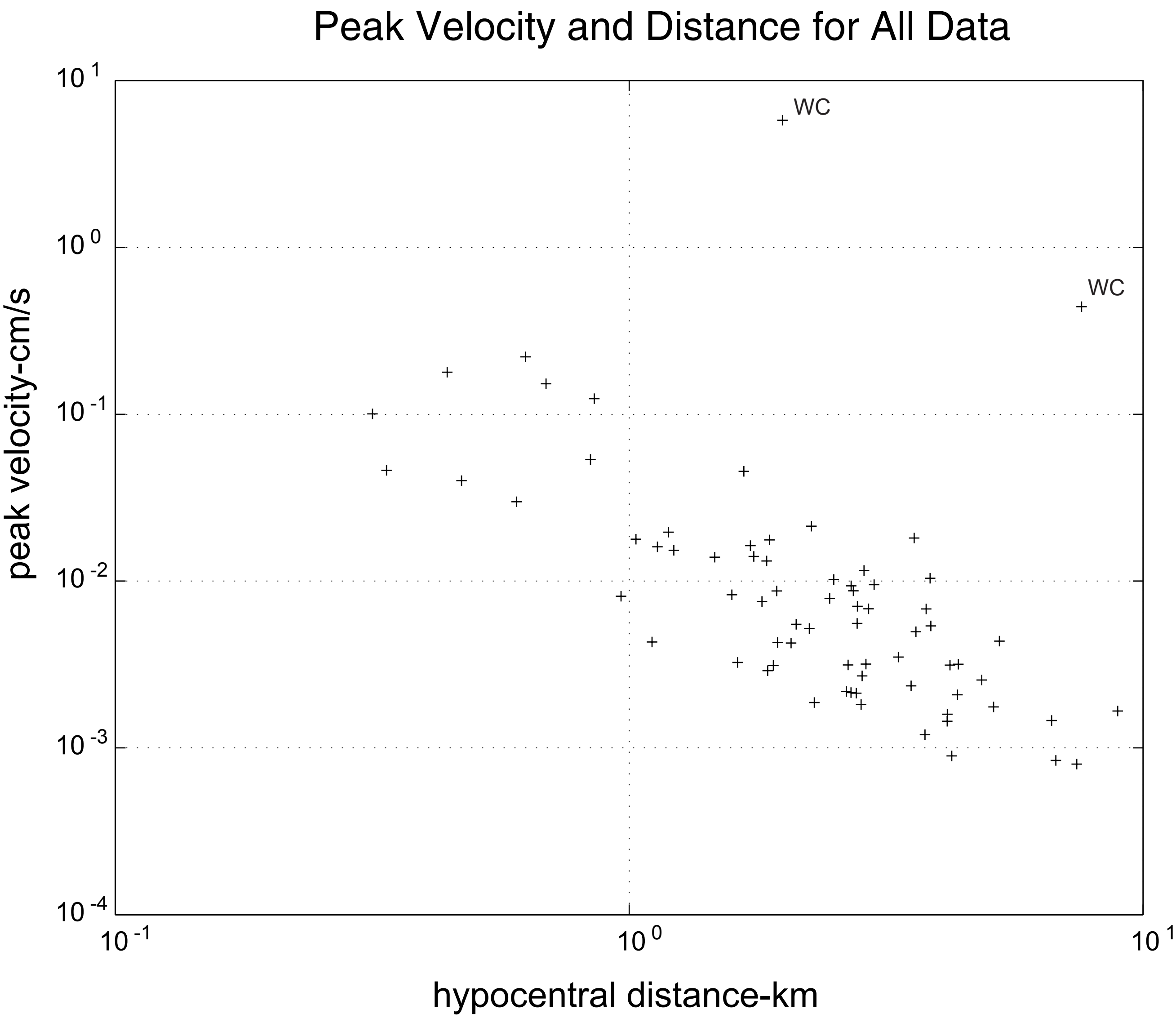

Figure 5. Scatter plot showing the distribution of observations used by the USGS to invert for the attenuation relationship for peak horizontal velocity outlined in Table 2 and illustrated in Figure 4(a) for various magnitudes of interest. Data points are from the TM data set ($0.7 \le M_C \le 2.2$), except for the two points labeled WC from the M_L4.2 Willow Creek Mine earthquake.

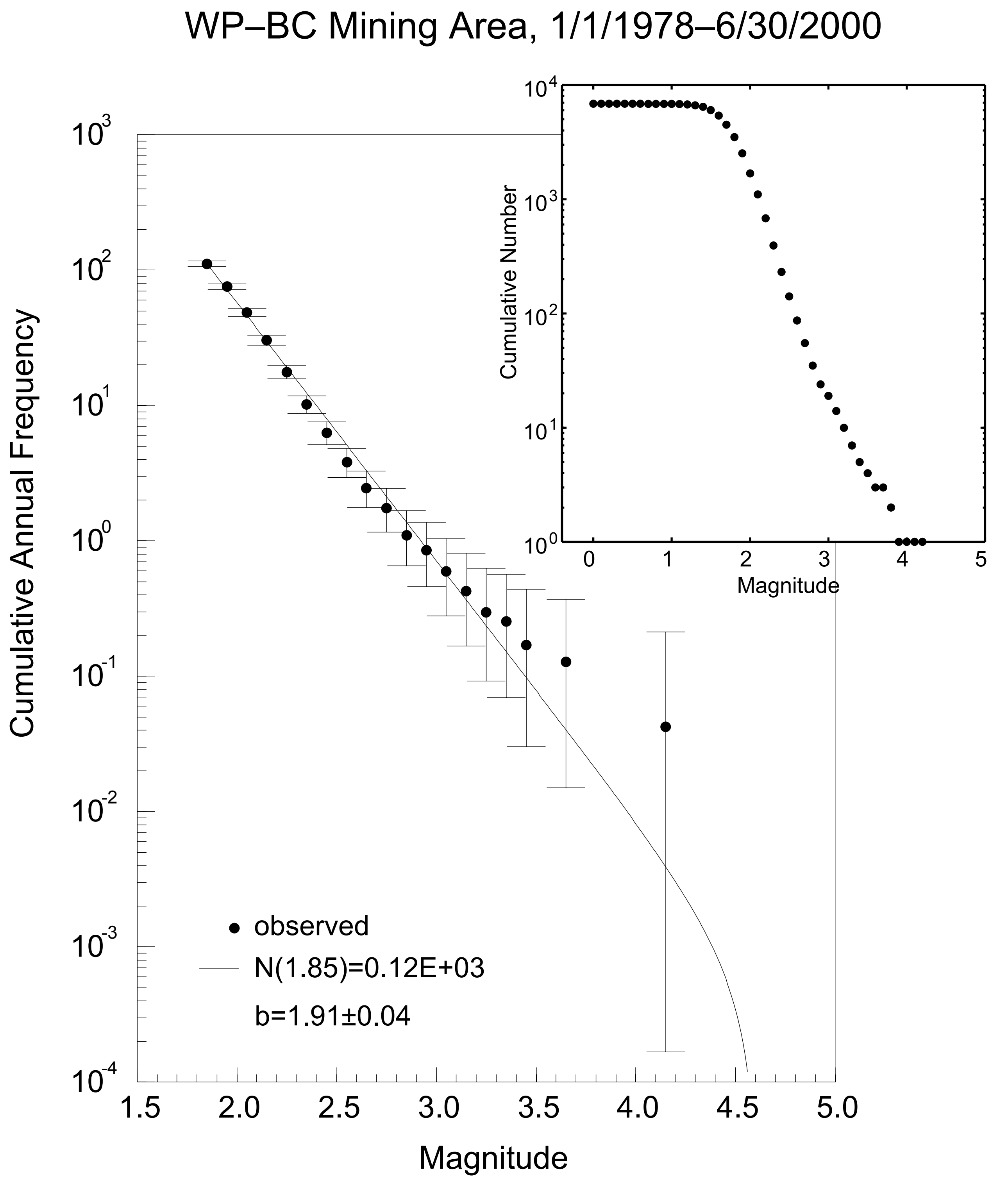

Figure 6. Plots of frequency of occurrence versus magnitude for MIS in the Wasatch Plateau (WP)-Book Cliffs (BC) coal-mining area for the 22.5-yr period January 1, 1978–June 30, 2000 (based on data recorded by UUSS and described by Arabasz and Pechmann, 2001). From the plot of cumulative number (inset, upper right), a threshold of completeness of *M* 1.85 is inferred and used to calculate a maximum-likelihood recurrence relation for a truncated exponential, assuming $m_{max} = 4.6$. Note distinct departure from linearity in both plots to the right of the upper magnitude 2 range.

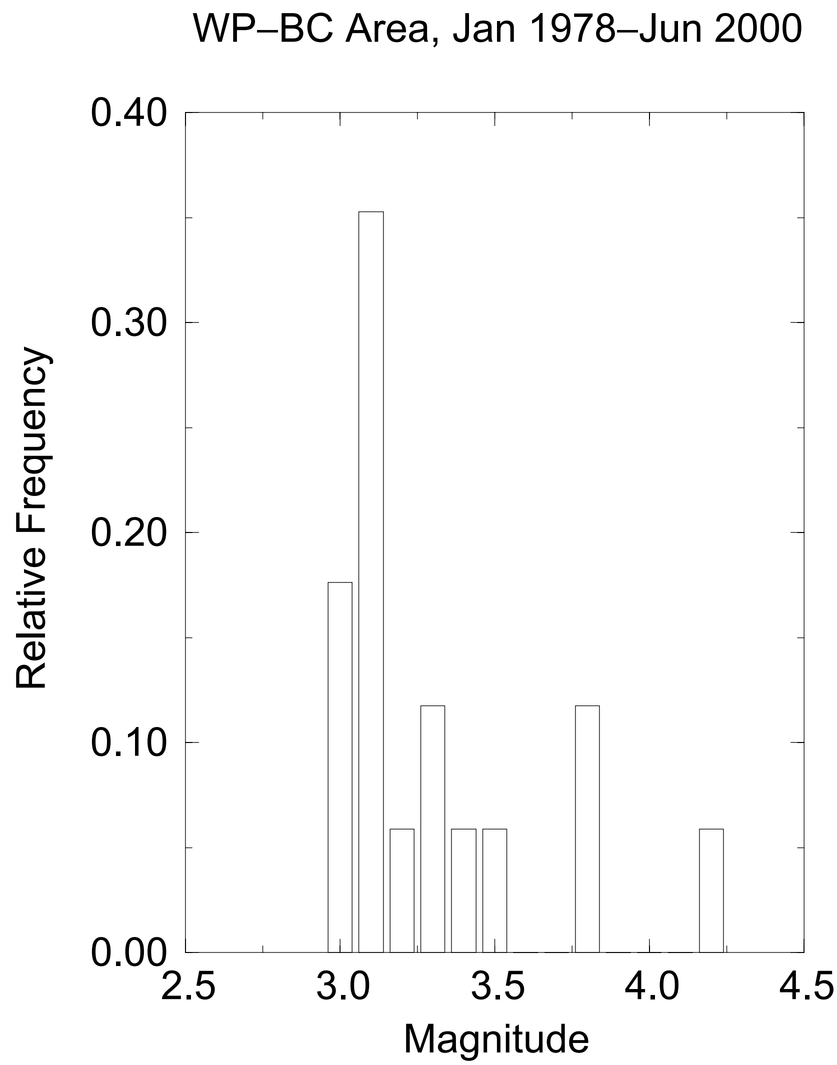

Figure 7. Probability mass distribution for the 17 largest mining-related earthquakes ($M \geq 3.0$) in the Wasatch Plateau−Book Cliffs coal-mining area from January 1978 through June 2000 (Table 3).

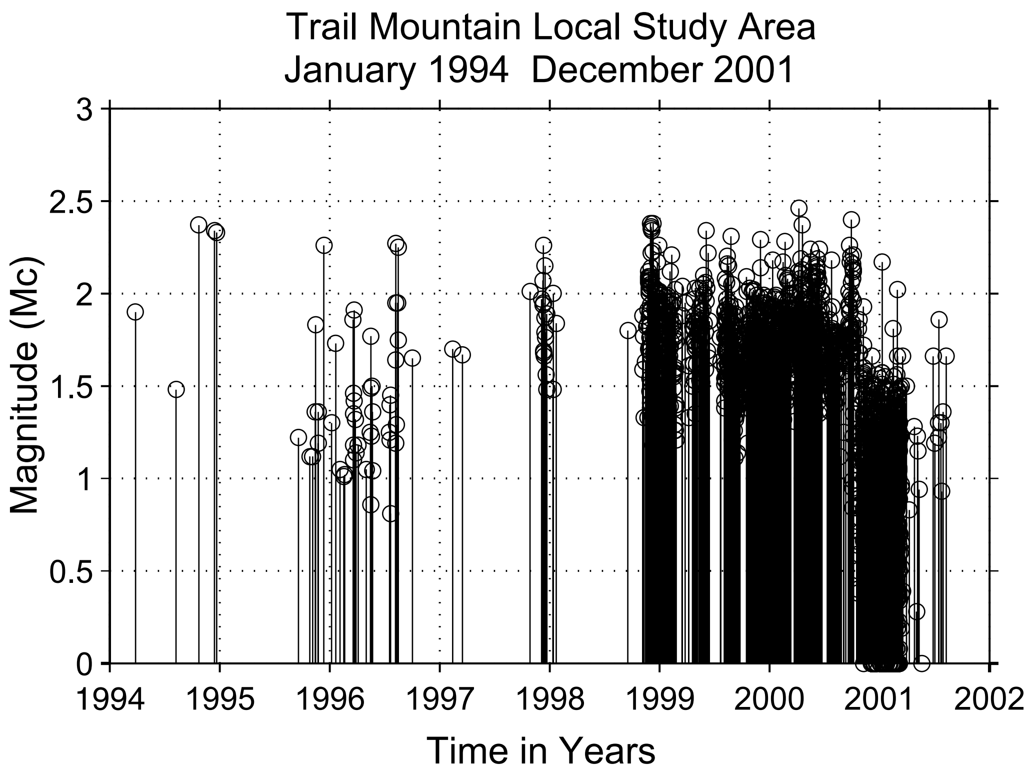

Figure 8. Plot of magnitude versus time for 2,988 seismic events recorded and located in the Trail Mountain local study area by UUSS for the period January 1994 through December 2001. Longwall mining in the Trail Mountain Mine, the only source of MIS within the local study area, began in October 1995 and ended in March 2001. Gaps in seismicity during that time are not due to gaps in monitoring; they are inferred to be associated with interruptions in mining, such as during longwall moves, and/or to variations in mine characteristics such as cover depth. The largest earthquake in the sample is an event of magnitude (M_C) 2.46 on April 7, 2000.

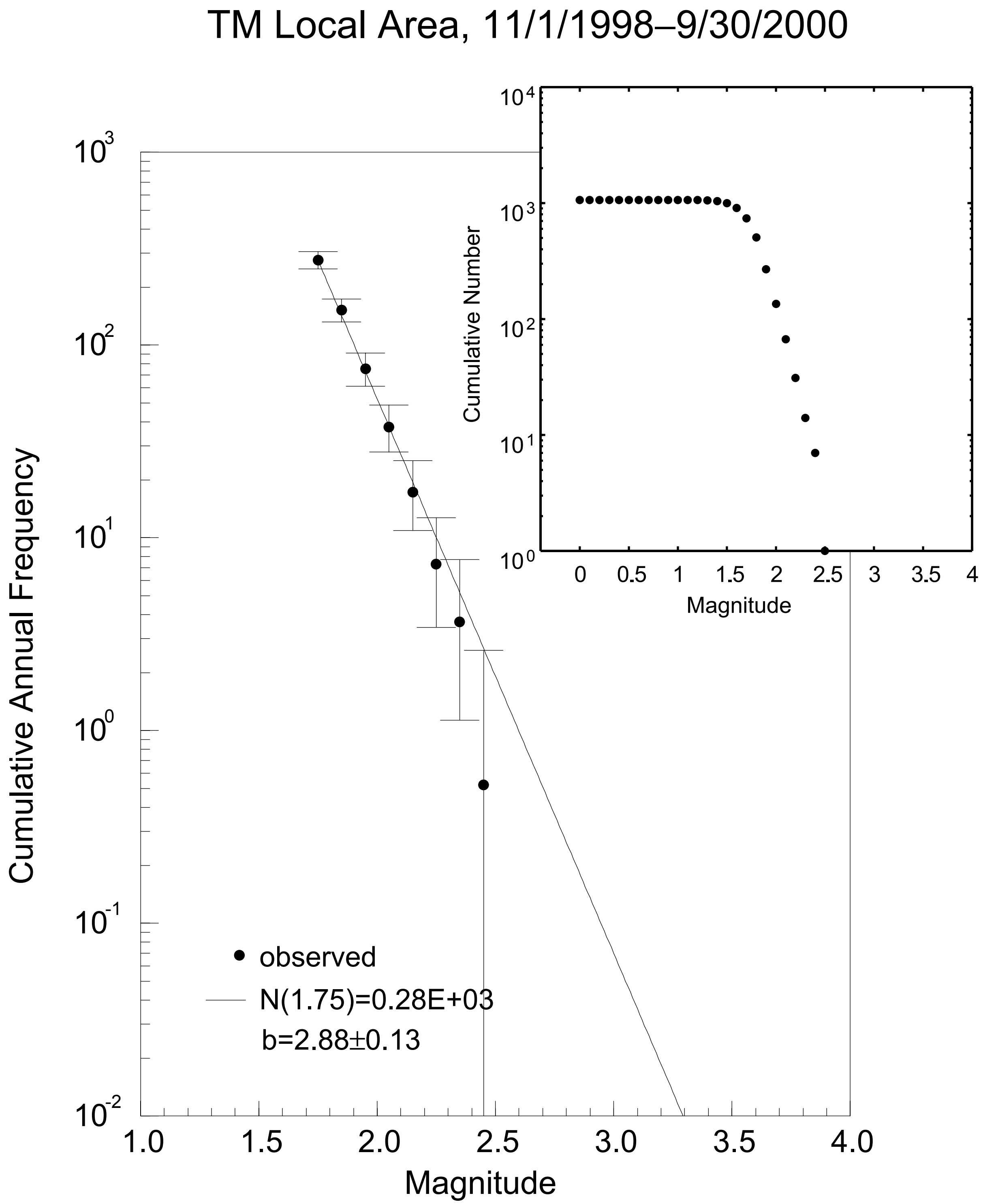

Figure 9. Plots of frequency of occurrence versus magnitude for MIS in the Trail Mountain local study area for the 23-month period November 1, 1998–September 30, 2000 (based on seismic monitoring by UUSS—see Figure 8). From the plot of cumulative number (inset, upper right), a threshold of completeness of *M*1.75 is inferred and used to calculate a maximum-likelihood recurrence relation for a truncated exponential, assuming $m_{max} = 4.6$.

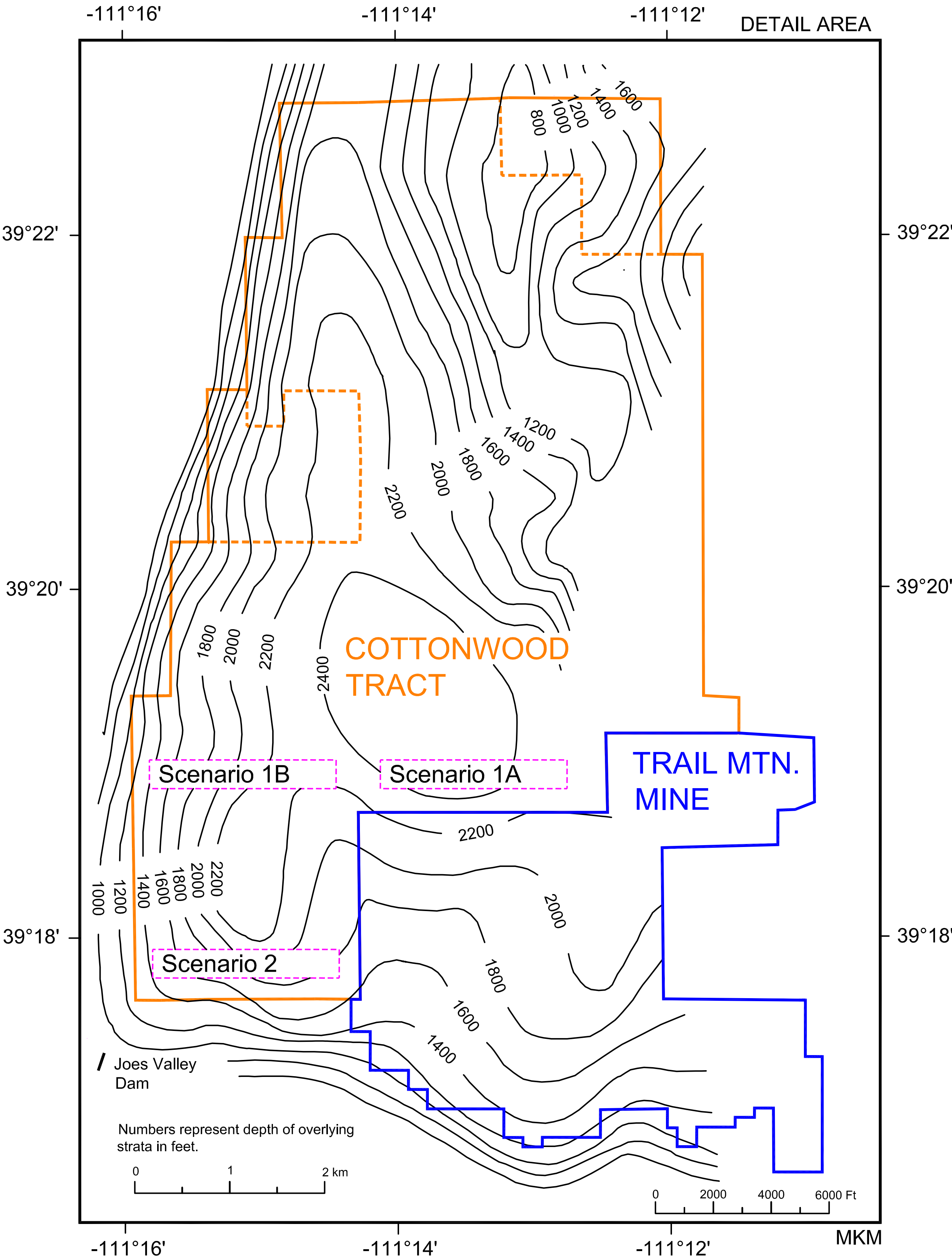

Figure 10. Approximate depth of cover and scenario locations for possible initial longwall panels in the Cottonwood Coal Tract.

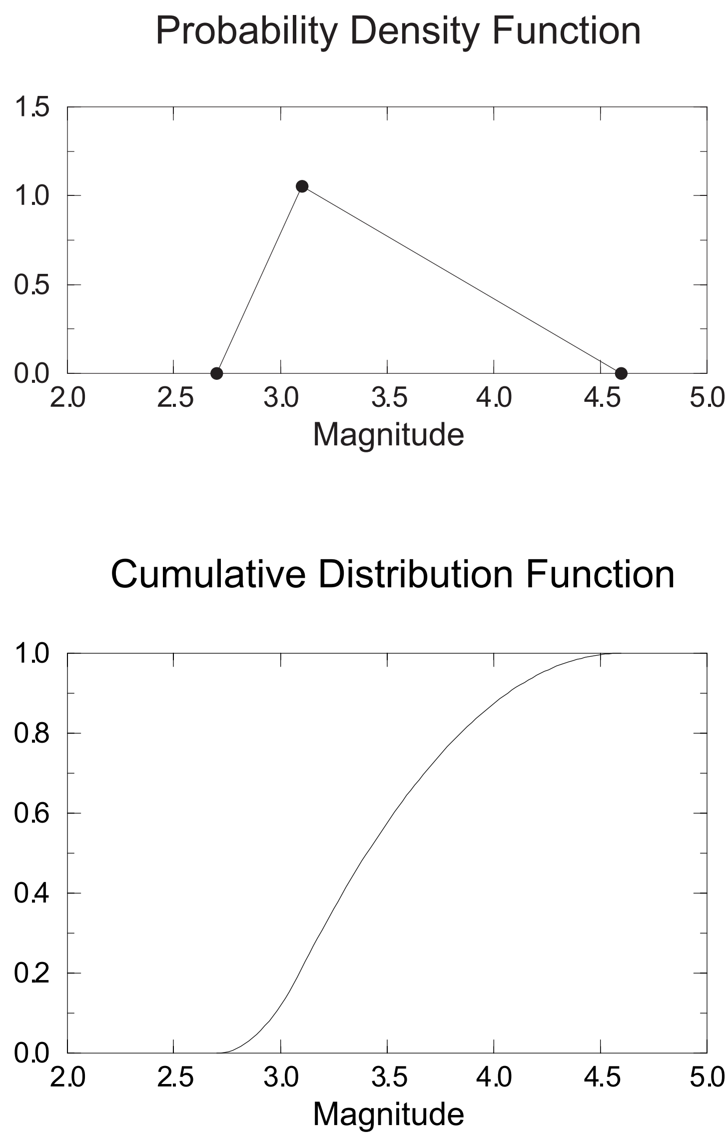

Figure 11. Probability density function (above) and corresponding cumulative distribution function (below) assessed by the authors for the maximum magnitude m_{max} expected for future MIS in the Cottonwood Coal Tract.