

**Seismological Report on the 6 Aug 2007
Crandall Canyon Mine Collapse in Utah**

by

James C. Pechmann, Walter J. Arabasz, Kris L. Pankow, and Relu Burlacu
University of Utah Seismograph Stations, Dept. of Geology and Geophysics, University of Utah

Michael K. McCarter
Dept. of Mining Engineering, University of Utah

Submitted to Seismological Research Letters
May 2, 2008

Seismological Report on the 6 Aug 2007 Crandall Canyon Mine Collapse in Utah

James C. Pechmann, Walter J. Arabasz, Kris L. Pankow, Relu Burlacu, and Michael K. McCarter

ABSTRACT

A large and tragic underground collapse occurred in the Crandall Canyon coal mine in east-central Utah on 6 Aug 2007, causing the loss of six miners and attracting national attention. This collapse was accompanied by a local magnitude (M_L) 3.9 seismic event having a location and origin time coincident with the collapse, within current uncertainty limits. Two lines of evidence indicate that most of the seismic wave energy of this event was generated by the mine collapse rather than a naturally-occurring earthquake: (1) the observation that all of the observed P-wave first motion directions are down and (2) the results of a moment tensor inversion by Ford et al. (2008). We propose one possible model for the collapse that has dimensions of 920 m E-W by 220 m N-S and an average roof-floor closure of 0.3 m. This model is consistent with the seismic moment, volumetric constraints on the amount of closure, available underground observations, and our best location for the M_L 3.9 epicenter. This epicenter is near the western end of our proposed collapse area, suggesting that the collapse propagated mostly eastward from its initiation point. Our locations for the M_L 3.9 event and for other seismic events that occurred in the area before and after it were greatly improved by the use of a double difference method and data from a 5-station temporary network that the University of Utah deployed near the mine beginning on 8 Aug.

The Crandall Canyon Mine is in an area of Utah where there is abundant mining-induced seismicity, including events with both collapse and shear-slip sources. Prior to the 6 Aug

collapse, and within a 3 km radius of it, there were 28 seismic events during 2007 that were large enough to be detected and located as part of the routine data processing for the University of Utah regional seismic network: 8 in the 2.5-week period prior to the collapse ($M_L \leq 1.9$) and 15 during an earlier period of activity in late February and early March ($M_L \leq 1.8$). These events occurred primarily in areas where there was concurrent or recent mining activity. By the end of August, the 6 Aug collapse had been followed by 37 locatable seismic events of $M_L \leq 2.2$, which clustered near the eastern and inferred western ends of the collapse area. One of these “aftershocks” (M_L 1.6) occurred in conjunction with the violent burst of coal from the mine walls on 17 Aug (UTC) that killed three rescuers and injured six others. The aftershocks have an exponential frequency-magnitude distribution with a lower ratio between the frequencies of smaller- and larger-magnitude events (lower b-value) than for the prior events in the area. Aftershock rates generally decreased with time through August. However, there was a noteworthy 5.8-day hiatus in activity, above a completeness threshold of coda magnitude (M_C) 1.6, that began 37 hours after the collapse.

INTRODUCTION

At 2:48 am MDT (08:48 UTC) on 6 Aug 2007, a major collapse occurred in the Crandall Canyon coal mine in east-central Utah. This collapse resulted in the loss of six miners who were working underground in the area of the collapse when it occurred. Ten days later, a much smaller collapse in this mine killed three rescue workers and injured six others (Stricklin, 2007).

A local magnitude (M_L) 3.9 seismic event occurred at approximately the same time and place as the Crandall Canyon Mine collapse. Seismological evidence summarized in this paper and in a companion paper by Ford et al. (2008) indicates that most of the seismic wave energy in

this event was generated by the mine collapse and not by a naturally-occurring earthquake. The M_L 3.9 event was preceded and followed by numerous smaller ($M_L \leq 2.5$) seismic events in the same area, most of which are probably mining related as well. These events include an M_L 1.6 shock associated with the coal burst that killed three rescuers. For convenience, we will refer to the M_L 3.9 event as the Crandall Canyon Mine “main shock” and to the events that followed it as “aftershocks,” even though these terms are normally used for naturally occurring earthquakes.

There is a high-quality data set for the Crandall Canyon Mine seismic events from surrounding stations of the University of Utah regional seismic network, a 5-station temporary network that we deployed in the mine area after the 6 Aug collapse, the National Science Foundation EarthScope Transportable Array, and other networks. In this paper, we analyze the seismological data for the Crandall Canyon Mine main shock and for preceding events and aftershocks in order to gain a better understanding of these events and the 6 Aug. collapse.

MINING-INDUCED SEISMICITY IN UTAH

Seismicity caused by underground mining in the arcuate crescent of the Wasatch Plateau and Book Cliffs coalfields in east-central Utah (figure 1) is a well-recognized phenomenon that has been studied since the 1960s (see reviews and case studies by Arabasz *et al.*, 1997, 2005, 2007; Arabasz and Pechmann, 2001; Ellenberger *et al.*, 2001). The majority of the coal production in this region comes from longwall mining, but room-and-pillar methods are also used (see Arabasz *et al.*, 2005, and references therein, for a description of these mining methods). Nearly all of the abundant seismicity located by the University of Utah within the Wasatch Plateau and Book Cliffs coalfields ($> 17,000$ events from 1978 through August 2007) is attributed to underground mining because of its strong correlation with locations of active mining and very shallow focal

depths. Most of this mining-induced seismicity (MIS) is smaller than M_L 3, and probably all of the MIS is at or very close to mine level (e.g., Ellenberger *et al.*, 2001; Arabasz *et al.*, 2005). Coal miners refer to these mining-induced earthquakes as “bumps” or “bounces.” About 2600 seismic events ($M_L \leq 2.7$) were located by the University of Utah in the Wasatch Plateau-Book Cliffs coal-mining region from Aug 2006 through July 2007.

The MIS in east-central Utah is predominantly the result of: (1) implosions caused by partial or complete collapse of underground mine workings and (2) shear-slip motion on rock fractures (Wong *et al.*, 1989; Taylor, 1994; Arabasz and Pechmann, 2001; Fletcher and McGarr, 2005). Waveform modeling suggests that some events have sources that are combinations of these two mechanisms (Fletcher and McGarr, 2005; Ford *et al.*, 2008). Arabasz and Pechmann (2001) summarized information for 17 mining-related tremors of $3.0 \leq M_L \leq 4.2$ in the Wasatch Plateau-Book Cliffs region between 1978 and June 2000. Two of the largest were shocks of M_L 3.8 in February 1998 and M_L 4.2 in March 2000; both had shear-slip focal mechanisms and occurred adjacent to workings in the Willow Creek mine, located 45 km northeast of the Crandall Canyon mine. The remaining events were shown or inferred to be caused by sudden roof-floor convergence associated with pillar failures in room-and-pillar mine workings or with the planned roof caving that follows the nearly complete removal of coal seams during longwall mining. The event with the best evidence for this type of implosional mechanism is an M_L 3.8 shock that occurred on May 14, 1981, in association with a major (possibly 150 m by 150 m) collapse which occurred during pillar recovery operations at the U.S. Fuel Company King Mine. Taylor (1994) argued that the collapse generated the seismic event based on waveform modeling and energy considerations, a conclusion supported by the observation that all of the P-wave vertical component first motions observed for this event are down (Arabsz and Pechmann,

2001). Mine collapses have produced even larger seismic events elsewhere. Notable examples include an M_L 5.2 shock from the 1995 collapse of a 1 x 2 km section of a trona mine in southwestern Wyoming (Pechmann et al., 1995) and an M_L 5.6 event produced by the 1989 collapse of a 6-km² section of a potash mine in Germany (Knoll, 1990).

Arabasz and Pechmann (2001) found only one clearly tectonic earthquake in their study of $M_L \geq 3.0$ seismic events in the Wasatch Plateau-Book Cliffs mining region—an M_L 3.0 shock with a well-constrained depth of 11 ± 1.5 km and a normal-faulting focal mechanism. In systematic attempts to discriminate tectonic earthquakes within the regions of the coalfields, we have typically found only a small number of events ($< 2\%$ of the catalog sample) that arguably might represent tectonic earthquakes, based on focal depth, source-mechanism and/or P-wave first motion information (e.g., Arabasz and Pechmann, 2001, p. 3-5; Arabasz *et al.*, 2005).

THE CRANDALL CANYON MINE DISASTER

The 6 Aug Crandall Canyon Mine collapse occurred in the “west mains” section of the mine, which was developed in the nearly horizontal Hiawatha coal seam (dip rarely $> 3^\circ$) at depths of 300 to 670 m below the surface (Hucka, 1991; Crandall Canyon Mine Roof Control Plan, 2007). This section of the mine has five east-west entry tunnels—the west main entries—that are connected by mostly north-south crosscuts and are bounded on the north and south by 140-m-wide blocks of coal called the north and south barrier pillars, respectively (figure 2). The coal seam to the north and south of the barrier pillars, out to the mine boundaries, was largely removed by longwall mining during 1997-2003 (figures 2 and 3; public records, Utah Division of Oil, Gas, and Mining; Jahanbani, 2000; Allred and Vanden Berg, 2004).

The 6 Aug collapse occurred during mining operations to recover coal in the south barrier

pillar. The basic mining plan for this area is summarized in two amendments to the Crandall Canyon Mine Roof Control Plan (2007) that were approved by the Mine Safety and Health Administration (MSHA) on 8 March and 15 June 2007. Initially, coal was removed along east-west entries and north-south crosscuts that were ~6 m wide, leaving behind pillars of about 33 by 18 m (figure 2). The next phase of the plan was to mine the coal in some of these pillars, working from west to east and allowing the roof around these pillars to collapse. This process is known as pillar recovery or pillar extraction. A mine map from public records at the Utah Division of Oil, Gas, and Mining shows that 11 pillars had been extracted from the western end of the south barrier pillar in July 2007 (figure 2). A similar mine map posted on the MSHA web site (Mine Safety and Health Administration, 2007a) shows these same 11 pillars, plus three more immediately to the east, as having been removed in July 2007. However, the three additional pillars were actually removed in August 2007 (Richard A. Gates and Thomas Morley, MSHA, personal communication, 2008). The next three rows of pillars to the east, between crosscuts 139 and 142, were to be skipped according to the Crandall Canyon Mine Roof Control Plan (2007). The last known working location of the six missing miners was in or just east of these three rows of pillars (figure 2).

A mining plan similar to the one for the south barrier pillar was proposed, approved, and partially carried out in the north barrier pillar during late 2006 and early 2007 (figure 2; Crandall Canyon Mine Roof Control Plan, 2007). Mining in the north barrier pillar was abandoned after a large “bump” occurred in this area sometime on 10 March (MST), resulting in “heavy damage to the entries located between XCs [crosscuts] 133 and 139” (Gilbride, 2007; date from Gates and Hayashi, 2007). The largest seismic event in the mine area that day was an M_L 1.8 (M_C 2.3) shock at 5:22 pm (00:22 on 11 March UTC). Figure 2 shows the east-west extent of the March

damage and a plausible, but speculative, north-south extent. The pillars shown in the middle of this damage area had been left behind in an effort to mitigate “poor roof conditions.” The resumption of mining east of these pillars (east of crosscut 135) apparently served to trigger the damaging 10 March (MST) event (Gilbride, 2007). Because of this event, mining operations were shifted from the north barrier pillar to other sections of the mine and ultimately to the south barrier pillar (Intermountain Power Agency, 2007; Gehrke, 2007; Stricklin, 2007). The mining plan for the south barrier pillar was modified to increase the size of the pillars (figure 2; Gilbride, 2007; Stricklin, 2007).

The 6 Aug collapse occurred shortly before 2:48:53 am MDT (8:48:53 UTC), the time that the mine’s atmospheric monitoring system (AMS) data logger reported a loss of contact with a carbon monoxide monitor located near the last known working location of the missing miners (figure 2; Thomas Morley and Joseph Zelanko, MSHA, personal communication, 2007). The time lag between the actual failure of a carbon monoxide sensor and the time that the AMS reports a loss of contact with it is unknown, but is being investigated by the MSHA Accident Investigation Team. We will return to the topic of the collapse time in a subsequent section.

MSHA’s preliminary estimate of the collapse’s east-west extent was from crosscut 120 to 137 (Mike Gauna, personal communication, 12 Sept 2007). The eastern end of the collapse is known from direct observation. The western end is fairly well constrained by borehole data, but could be several crosscuts farther to the west (see figure 2 and Table 1). The north-south extent of the collapse is not well known, but a likely minimum is across the four east-west entries in the south barrier pillar. Based on this information, we constructed a minimum estimate of the collapse area that is shown as the heavy solid box in the south barrier pillar on figure 2. We are not aware of any publicly available geodetic data that would help to constrain the boundaries of

the collapse area or the amount of subsidence over it.

Following the 6 Aug collapse, rescue workers began drilling holes into the area of the mine where the six missing miners were believed to have been working. Other rescuers began digging westward through the collapse debris in the Number 1 (southernmost) entry of the south barrier pillar (figure 2; Stricklin, 2007). This tunneling was possible because the roof was still largely intact in this part of the collapse area (Carlisle, 2007). After the debris had been cleared in entry 1 from crosscuts 120 to 127, there was a violent outburst of coal from the walls of the freshly-cleared entry between crosscuts 126 and 127 that killed three rescue workers and injured six others (Gates and Hayashi, 2007; Stricklin, 2007; Frosch and Lee, 2007; Mine Safety and Health Administration, 2007b). This collapse registered as an M_L 1.6 (M_C 2.0) event with an origin time of 00:38 UTC on 17 Aug (6:38 pm on 16 Aug MDT). The underground rescue effort was abandoned after this tragic event. Because the location of this event is known, its arrival time data have been extremely useful for improving the locations of other seismic events in the Crandall Canyon Mine area.

DATA SET

For this study, we decided to analyze seismic events that occurred between 1 July 2005 and 31 Aug 2007 and had initial epicenters located within 3.0 km of a point ($39^\circ 28.16' N$, $111^\circ 13.21' W$) near the center of the inferred location of the 6 Aug 2007 mine collapse (dotted 3-km-radius circle, figure 3). This circular area encompasses virtually all MIS associated with the Crandall Canyon mine since January 2004 and avoids the inclusion of MIS from neighboring mines.

The data for this study came primarily from stations of the University of Utah regional seismic network (see Arabasz et al., 2006). These data were supplemented by data from five

temporary stations that we installed in the Crandall Canyon Mine area after the 6 Aug collapse and data from other networks such as the U.S. National Seismic Network (USNSN) and the EarthScope Transportable Array (TA; Busby, 2007). The TA stations in the Crandall Canyon Mine area began operating between late May and July 2007. We used the data from the three closest TA stations, located at epicentral distances of 40 to 62 km, for our analyses of the 6 Aug M_L 3.9 event and subsequent events.

The first of the University of Utah temporary stations became operational at 00:50 UTC on 8 Aug 2007. The first two temporary stations installed, CM1 and CM2, were the two closest to the collapse and were equipped with 3-component Applied MEMS accelerometers and REF TEK 130 digitizers that initially recorded continuous data on site (Table 2; figure 3). Digital telemetry of CM1 data began on 24 Aug but the telemetry of the CM2 data failed to work properly after it was installed on 22 Aug. The other three temporary stations were equipped with short-period, vertical-component, Mark Products L-4 seismometers and were recorded via analog telemetry beginning at ~04:00 UTC on 11 Aug. At 18:40 UTC on 13 Aug, we began using the data streams from these three stations in the University of Utah Seismograph Stations (UUSS) automatic event detection system.

Magnitude of Completeness

Unless otherwise noted, we restricted our study to seismic events that were large enough to be automatically detected and manually located as part of the routine data processing for the University of Utah regional seismic network (see University of Utah Seismograph Stations, 2007). We determined the minimum magnitude of completeness, M_{comp} , for this data set using the methodology of Wiemer and Wyss (2000, 2003) and utilizing the software package ZMAP,

v.6, (Wiemer, 2001, and references therein). For the data described in this paper, M_{comp} is 1.6 (coda magnitude). With the incorporation of data from the portable telemetered seismographs near the Crandall Canyon mine into the event detection system on 13 Aug, M_{comp} was reduced to 1.2; however, the time samples used for our statistical analyses invariably required using the higher threshold for uniformity.

MAGNITUDE DETERMINATIONS

The seismic event magnitudes reported herein are of two types routinely determined by UUSS: local magnitude (M_L), which is calculated from maximum peak-to-peak amplitudes on synthetic Wood-Anderson (W-A) records (Pechmann et al., 2007), and coda magnitude (M_C), which is calculated from seismic signal durations on records from short-period, vertical-component, velocity sensors (Pechmann et al., 2006). For Utah earthquakes, there is no significant systematic difference between M_L and M_C and both are consistent with available moment magnitude (M_W) determinations (Pechmann et al., 2006, 2007). M_L is the preferred size measurement, but could only be determined for 74 of the 189 events in our Crandall Canyon data set due to inadequate signal-to-noise ratios on the synthetic W-A records of the other events.

For the 6 Aug Crandall Canyon Mine main shock, the UUSS M_L is 3.9 and the M_C is 4.5. The moment magnitude (M_W) determined by Ford et al. (2008) is 4.1, which is between the M_L and M_C . The difference between the M_C and M_L is typical of our Crandall Canyon data set, for which the M_C s are systematically higher than the M_L s by an average of 0.44 magnitude units. One possible explanation for this M_C - M_L difference is that the signal durations of the Crandall Canyon events are longer than normal because their sources have unusually shallow depths. Mayeda and Walter (1996) and Myers et al. (1999) show that very shallow (< 2 km depth)

sources produce enhanced coda wave amplitudes over frequency bands of ~2-3 octaves, with observed peaks at frequencies ranging from 0.2 to 2 Hz. Meyers et al. (1999) present evidence that these enhanced coda wave amplitudes are due to the excitation of short-period Rayleigh waves (Rg), followed by Rg-to-S-wave scattering from shallow velocity heterogeneities within tens of kilometers of the source. On the other hand, it is worth noting that M_{WS} estimated by Fletcher and McGarr (2005) for six small mining-related events in an area ~20 km south of the Crandall Canyon Mine are in good agreement with revised UUSS M_{CS} (and with the older M_{CS} in their paper), with a mean difference of 0.06.

EVENT DURATIONS

It is well known among seismologists that the durations of seismic waves recorded on high-gain instruments are orders of magnitude greater than the duration of the source that generates the waves. The longer duration of the former is caused by the superposition of multiple seismic wave arrivals that have traveled many different paths through the earth, especially backscattered waves from small-scale velocity heterogeneities (e.g. Lay and Wallace, 1995, 107-108). Nevertheless, some people have interpreted a four-minute seismic signal duration reported for the Crandall Canyon main shock, presumably measured on a high-gain record, as indicative of an extraordinarily long collapse duration (e.g., Ferriter, 2007; U. S. Senate Health, Education, Labor and Pensions Committee, 2008, p. 4). In reality, the duration of the collapse was probably only a few seconds, at most, as evidenced by reports that the surface building at the Crandall Canyon Mine portal vibrated for a few seconds at the time that the collapse occurred (Richard A. Gates, MSHA, written communication, 2008). We have attempted to determine the duration of the Crandall Canyon Mine main shock using empirical

Green's function methods but our efforts to date have not been successful.

As further evidence of the difference between seismic signal durations and source durations, we note that the mean of the signal durations used to compute the M_C for the fatal M_L 1.6 event on 17 Aug (UTC), measured from the first arrival to the time that the signal drops below a typical noise level threshold, was 63 sec. In contrast, underground observers reported that this event was instantaneous in character with no noticeable duration (Richard A. Gates, written communication, 2008).

HYPOCENTER RELOCATION METHODS

In order to improve the hypocentral locations of the seismic events in our data set, we relocated them using two different methods: (1) the calibrated master event (station delay) method (e.g., Corbett, 1984) and (2) the double difference method of Waldhauser (2001; see also Waldhauser and Ellsworth, 2000). Although the latter method is more accurate, it has the disadvantage of being typically unable to locate all of the events in a given set due to its more extensive data requirements and its rejection of events that move above the datum during the location iterations. Only P-wave arrival times were used in computing the master event locations, due in part to concerns about whether or not the S-wave arrival times were picked on direct S-wave arrivals. Although S-wave arrival times were used in computing the double difference locations, they were assigned a maximum weight equal to one-tenth the maximum weight of the P-wave data.

For both the master event and double difference methods, the velocity model used was modified from a horizontally-layered model constructed for the Trail Mountain Mine area ~20 km to the south (Arabasz et al., 2005). The main modification was to increase the datum from 2600 m to 3100 m to account for the higher surface and stratigraphic elevations in the Crandall

Canyon Mine area. Another modification, needed only for the double difference locations with Waldhauser's (2001) program HypoDD, was to replace the S-wave velocities by values calculated from the P-wave velocities and a constant P-to-S velocity ratio. We set this ratio to 1.96—the value in the original velocity model between 0.10 and 2.04 km depth where the mine, and presumably most of the events, are located.

Master Event Method

In the master event method, empirical station delays are subtracted from observed arrival times before using them in locations in order to compensate for inaccuracies in the velocity model, especially unmodeled lateral velocity variations. We calibrated empirical P-wave station delays for 23 stations, all at epicentral distances of less than 100 km, using arrival time data from the three largest events in our data set that occurred while all five temporary stations were installed ($1.4 \leq M_L \leq 1.7$). The primary master event was the fatal M_L 1.6 event at 00:38 UTC on 17 Aug. We began by fixing this event to its known location ($39^\circ 28.02' \text{ N}$, $111^\circ 13.02' \text{ W}$, 0.6 km below datum) and computing its origin time and predicted arrival times at the stations using the location program Hypoinverse (Klein, 1978), incorporating elevation corrections calculated for a velocity of 4.0 km/sec. Next, we obtained a preliminary set of station delays by setting them equal to the differences between the observed and predicted arrival times (the travel time residuals). We then located the other two, secondary, master events using Hypoinverse, the preliminary station delays, elevation corrections, no distance weighting, a starting location at the hypocenter of the primary master event, and data only from stations for which we had determined delays. The final delay for each station was set equal to the median of the travel time residuals for all three master event locations, after accounting for any preliminary station delays applied. Finally, we

relocated all of the events with the same procedure as for the secondary master events but using the final station delays and a starting location at the median hypocenter of the three master events.

The station delays reduce the median weighted root-mean-square travel-time residual (rms) of the locations from 0.14 sec to 0.04 sec. The 189 hypocenters determined with the master event method all have depths between zero and 0.67 km, with 93% within 100 m of the mine depth of ~0.6 km. However, the focal depths for all of the events before 8 Aug 2007 are very poorly constrained because the closest station is 17 to 20 km away.

Double Difference Method

The double difference method uses a set of travel time differences for seismic event pairs recorded at the same station to invert for the relative hypocentral locations of the events (Waldhauser and Ellsworth, 2000). Using the double difference code HypoDD (Waldhauser, 2001) with its conjugate gradient (CG) inversion option, we successfully relocated 150 (79%) of the 189 events in our data set. This total included 55 (83%) of the 66 events in 2007. Sensitivity tests on the 2007 events using both CG and singular value decomposition (SVD) inversions showed that the overall pattern of the relocated hypocenters was not greatly affected by the inversion method or use of an alternative velocity model, but that good starting locations were important. For our final HypoDD locations, we used the master event locations as the starting locations.

Because SVD produces more reliable uncertainty estimates than CG, we ran SVD inversions on subsets of ~50 events (limited by computer capabilities) in order to evaluate the uncertainties in the locations. The means of the resulting 95% confidence limits reported by

HypoDD were 23, 18, and 50 m in the east, north, and vertical directions, respectively. We converted the relative locations calculated by HypoDD into absolute locations by subtracting the known mislocation vector for the event on 17 Aug 00:38 UTC. Taking into account the uncertainty limits on HypoDD's relative location of this event, the estimated mean 95% confidence limits for the absolute locations are ~30 m horizontal and ~75 m vertical. The latter, at least, may be an underestimate for the events that occurred before 8 Aug due to the large distance to the nearest station. The focal depths for the 150 events located by HypoDD range from the surface to 1.29 km, with 90% between 0.14 and 0.85 km. For the 22 events with data from the temporary stations, the depth range is 0.19 to 0.85 km.

PRIOR SEISMICITY

Figure 4a displays a 2.1-year record of seismicity recorded by the University of Utah's regional seismic network in the vicinity of the western Crandall Canyon mine (3-km-radius circle, figure 3). For uniformity, all plotted magnitudes are M_C , for which reporting is complete for shocks of $M_C \geq 1.6$. General features of figure 4a include (1) quasi-continuous seismicity from mid-2005 to mid-2006, (2) episodic seismicity from mid-2006 to mid-2007 with distinct temporal clustering in October 2006 and late February to early March 2007, and (3) seismic activity beginning on July 20, 2007, that includes the M_C 4.5 event at the approximate time of the mine collapse (star) and its subsequent aftershocks. The rates of MIS depicted in figure 4a are significantly lower than prior to early 2003, when longwall equipment was operating in the Crandall Canyon mine (Vanden Berg, 2007). Figures 3 and 5 show that most of the events from July 2005 through 2006 (open squares) were located 1-2 km southeast of the August 2007 collapse in an area where coal was being mined during this time period (public records, Utah

Division of Oil, Gas, and Mining).

A total of 28 seismic events of $M_C \leq 2.6$ ($M_L \leq 1.9$) occurred in the study area during 2007 prior to the 6 Aug collapse. Fifteen of these events were in the late February to early March cluster. Nine of the 15 occurred before the 11 March (00:22 UTC) event that we suspect caused the March damage, and four occurred later that same day. The double difference epicenters of the February-March events are located mostly in the vicinity of the mining activity during this time period, which was in and west of the March damage area (figures 2 and 5b). Eight of the pre-collapse events in 2007 occurred during the 2.5-week period from July 20 to 6 Aug. Three shocks occurred during the three days prior to the mine collapse, the last of which was an M_C 2.2 (M_L 1.8) event seven hours before the collapse (figure 4b). The double difference epicenters of these three events, plus one on July 30, all cluster around the western end of the crosshatched box showing the minimum extent of the 6 Aug collapse. All four epicenters are within 350 m of the double difference epicenter of the 6 Aug M_L 3.9 event, which is near the eastern end of the area mined in July (figures 2 and 5b).

To search for other seismic events before the Crandall Canyon Mine main shock, we examined the preceding seven hours of continuous digital short-period records from the nearest seismic station, located 19 km to the south. As is typical of stations near active coal mines in Utah, the records show very small local events every few minutes. Most of these events are too small to locate with the available data, but epicenters that we determined for five of the larger ones were all in the Crandall Canyon Mine area. The arrival time of the last event visible on these records is 35.6 sec before that of the main shock. This event was too small to be located, but based on waveform comparisons it could have been in the Crandall Canyon Mine area. If we assume that it occurred near the Crandall Canyon Mine main shock, then from the signal

duration at the closest station we estimate an M_C of ~ 0.2 for this event. The seven-hour record shows no indication of accelerating seismic activity preceding the main shock.

MAIN SHOCK

Location and Origin Time

Table 3 compares three different hypocentral locations for the M_L 3.9 Crandall Canyon Mine main shock. The “standard UUSS” location was posted on the UUSS and U. S. Geological Survey (USGS) web sites on the day of the event. It was determined from P-wave arrival time data at stations out to 160 km distance using standard UUSS velocity models and location procedures. The master event and double difference locations were determined using a revised set of arrival time picks and the procedures described previously. The double difference location should be the most accurate of the three, followed by the master event location.

The standard UUSS location serves to illustrate the limitations of using routine catalog locations for MIS studies. The epicenter for this location is outside the boundaries of the Crandall Canyon Mine and one kilometer WSW of the double difference epicenter (figure 3). The 95% confidence limits for the standard epicenter, as calculated by Hypoinverse (Klein, 1978), do not encompass the double difference or master event epicenters (figures 3 and 5). These confidence limits represent the random error in the solution, but do not fully account for possible systematic errors caused by inadequacies of the one-dimensional velocity models used.

The master event epicenter is 240 m NW of the boundaries of the minimum mine area estimated to have collapsed on 6 Aug, but its 95% confidence limits cover most of this area (figure 3). The double difference epicenter is 270 m west of the western edge of the minimum collapse area (figure 5). Its 95% confidence limits, based on HypoDD output, are 34 m E-W and

30 m N-S—smaller than the star marking the epicenter on figure 5. The focal depths for the master event and double difference hypocenters are 0.6 and 0.5 km, respectively, which are at or near the mine depth of 0.6 km. These depths are not well constrained because the nearest station is 19 km away. However, waveform modeling by Ford et al. (2008) indicates a source depth of 1 km or less. Fixing the master event hypocenter to the double difference hypocenter and solving for the origin time produces a fit to the data that is equally as good as the fit for the master event hypocenter.

The three origin times that we computed for the M_L 3.9 event are all, after rounding to the nearest sec, at 08:48:40 UTC (Table 3). As discussed previously, the time estimated for the mine collapse based on the loss of contact with a carbon monoxide monitor is shortly before 2:48:53. The difference of less than 13 sec between the seismic event origin time and the estimated mine collapse time is not considered to be significant given the current level of uncertainty in the latter (Thomas Morley, MSHA, personal communication, 2007; see the section on the Crandall Canyon Mine Disaster).

Given the locations and times of the M_L 3.9 seismic event and the Crandall Canyon Mine collapse, along with their uncertainties, it is reasonable to assume that these two events are coincident in space and time. The location of the double difference epicenter ~270 m west of the western edge of the minimum collapse area suggests that the collapse extends to the west of this area and that the collapse started near its western edge.

Waveform Comparisons

Figure 6 compares broadband velocity waveforms from the M_L 3.9 Crandall Canyon Mine main shock with those of an M_L 3.9 earthquake that occurred 40 km to the WSW in the

Sanpete Valley on 5 Nov 2007. The waveforms in figure 6 are from the TA station Q16A, located ~60 km from both events. The focal depth for the Sanpete Valley earthquake in the UUSS catalog is not well constrained, but waveform modeling by Herrmann (2007) indicates a depth of 15 km.

In comparison to the Sanpete Valley earthquake, the Crandall Canyon Mine event has more emergent P-wave first arrivals, a lower dominant frequency, and larger surface waves. Similar waveform differences are seen at other stations. The prominent surface waves observed for the Crandall Canyon Mine main shock are also typical of aftershock waveforms that we examined, and are consistent with the very shallow source depths that are known or inferred for these events. The other waveform differences are suggestive of a longer source duration for the Crandall Canyon Mine event than for the Sanpete Valley earthquake, but the difference in focal depth might also be a factor. The distinct waveform differences between the Sanpete Valley and Crandall Canyon Mine events suggest that the latter is not an ordinary earthquake.

Source Mechanism

The P-wave first motions for the M_L 3.9 Crandall Canyon Mine event are all down, which suggests an implosional focal mechanism consistent with a mine collapse (figure 7a). However, the first motion data alone do not provide definitive results because normal-faulting mechanisms can also be fit to the data—at least if the focal depth is 0.6 km (e.g., figure 7b). Ford et al. (2008) have performed a full moment tensor inversion of 3-component broadband waveform data from TA, UUSS, and USNSN stations in Utah and neighboring states. Their results show that the source mechanism is dominantly implosional. Their best-fitting shear-slip mechanism, obtained by constraining the source to have zero volume change, gives a much poorer fit to the

waveform data. Their best shear-slip solution is also completely incompatible with the first motion data (figure 7c). Ford et al.'s (2008) moment tensor results, in combination with the first motion data, shows that the primary source of the seismic waves for the M_L 3.9 Crandall Canyon Mine event was the mine collapse itself rather than tectonic or mining-induced shear slip.

The fatal M_L 1.6 event on 17 Aug is a likely small-scale analog to the M_L 3.9 event on 6 Aug. All of the P-wave first motions for the 17 Aug event are also down. In this case, because of the expanded focal sphere coverage enabled by the nearby temporary stations, it is not possible to fit a shear-slip mechanism to the data. Therefore, the first motion data are best interpreted as the result of an implosional source (figure 7d). This interpretation is consistent with underground observations. We know that an outburst of coal from the north wall of entry Number 1 in the south barrier pillar occurred at the time of this event (Gates and Hayashi, 2007; Frosch and Lee, 2007). The resulting sudden loss of structural support would be expected to cause the roof to sag and/or the floor to buckle upwards, creating the implosional source of the seismic waves for the M_L 1.6 event. In the case of the 6 Aug M_L 3.9 event, clear evidence for roof-floor convergence was observed along the eastern edge of the associated collapse. This evidence consists of compressional damage to roof support timbers (Gates and Hayashi, 2007).

In order to facilitate the physical interpretation of their moment tensor solution for the M_L 3.9 Crandall Canyon Mine event, Ford et al. (2008) decompose it into the sum of two components representing the following: (1) a collapse model, consisting of a flat-lying tension crack which closes by means of purely vertical particle motion along the crack walls (Aki and Richards, 1980, pp. 52-53), and (2) a remainder, which they further decompose into other types of sources, including shear-slip. For their first and most straightforward version of this decomposition, the collapsing crack model has a scalar moment of 1.71×10^{15} N-m (as defined

by Bowers and Hudson, 1999), which is 80% of the sum of the scalar moments for the two moment tensor components. The collapsing crack model alone cannot explain the data, because it produces no Love waves but Love waves were observed at some of the stations (Ford et al., 2008).

Ford et al.'s (2008) decompositions of the remaining part of the moment tensor all include a contribution from a source with a shear-slip (double couple) focal mechanism similar to that shown in figure 7c. It is important to note that these double-couple mechanisms, and a different double-couple mechanism in one of Ford et al.'s (2008) moment tensor decompositions, are all incompatible with the first motion data shown in figure 7. Consequently, the shear-slip contribution to the moment release for the M_L 3.9 Crandall Canyon Mine event could not have occurred at the beginning of this seismic event and cannot be interpreted as an earthquake that triggered the mine collapse.

Ford et al. (2008) discuss various possible explanations for the shear-slip component of the moment tensor. In our opinion, the most likely of these explanations is slip on a crack or crack zone that developed in the mine roof during the course of the collapse. In this model, the fault plane would be the steeply dipping, SSE-striking, nodal plane along which the sense of motion is east side down (figure 7c). The crack could have developed along the western edge of the collapse or in between areas of greater and lesser roof subsidence. N-S-trending joints observed above the Crandall Canyon Mine (Hucka, 1991, figure 14c) and underground in the west mains rescue area (Richard A. Gates and Thomas Morley, MSHA, written communication, 2008) could have facilitated the development of roof cracks. However, the strike of the nodal plane that we are interpreting as a possible roof crack differs by $\sim 30^\circ$ from that of the joints.

Collapse Model

For the collapsing crack model ,

$$M_{xx} = \lambda S \bar{u} \quad (1)$$

where M_{xx} is the xx element of the moment tensor, λ is Lamé's modulus, S is the area of the crack, \bar{u} is the average amount of vertical closure between the two crack surfaces, and the x coordinate is horizontal (Aki and Richards, 1980, pp. 52-53). Ford et al.'s (2008) moment tensor decomposition yields an M_{xx} of 6.03×10^{14} N-m. At the 1 km source depth of their moment tensor solution, the λ in their velocity model is 1.0×10^{10} N/m². Using these values for M_{xx} and λ , and our minimum 6 Aug collapse area (figure 2) of 680 m by 80 m, equation (1) predicts $\bar{u} = 1.1$ m.

As a check on this predicted roof-floor closure, we estimate the maximum allowable closure, \bar{u}_a based on volumetric considerations. Assuming that the pillars are completely converted to rubble during the collapse, and that the roof and floor remain approximately planar and parallel, we derived the following equation for \bar{u}_a :

$$\bar{u}_a = h[1 - (1 - e)(1 + s)] \quad (2)$$

where h = the original pillar height, e = the extraction fraction, and s = the swell fraction. The swell fraction is the fractional increase in the coal volume when it is converted to rubble. We estimate the swell to be in the range of 0.4 to 0.5, based on values in the literature of 0.34 for mined coal (Caterpillar Inc., 2003, pp. 22-2 to 22-3) and 0.54 for surface-blasted coal (Kennedy, 1990, pp. 569-570), and our judgment that the swell resulting from underground pillar failures would be intermediate between these two values. Within our minimum collapse area box, $h = 2.4$ m and $e = 0.42$. Substituting these values into (2) gives us allowable closure values of 0.3 to 0.5 m. These values are a factor of two to four smaller than the roof-floor closure of 1.1 m

predicted from the M_{xx} moment, suggesting that the actual collapse area is at least twice as large as the minimum area indicated on figure 2.

We now construct a collapse model that satisfies the constraints of equations (1) and (2) and other information on the collapse that is available to us (dashed box, figure 2). As noted previously, the eastern end of the collapse is reasonably well known from direct observation. Drill hole information constrains the western boundary to be between drill holes #3 and #4, if it is assumed that all of the observed debris was from the large 6 Aug collapse (Table 1) rather than later collapses. We place the western boundary near the double difference epicenter, which is within two crosscuts of the eastern edge of the area mined out in July and August 2007. A southern boundary along the Number 1 entry in the south barrier pillar seems reasonable, as the pillar to the south is 37 m wide and was found to be reasonably intact by rescuers removing coal debris adjacent to it (Gates and Hayashi, 2007). Finally, it seems plausible that the collapse extended northward through the west main entries to the southern end of the areas mined in February and March 2007 because poor roof conditions and deteriorating pillars were reported in the west main entries before they were sealed off in 2005 (Utah Mine Safety Commission, 2008, pp. 37, 40; United States Senate Health, Education, Labor and Pensions Committee, 2008, pp. 24-25).

The collapse dimensions in our model are 920 m E-W by 220 m N-S, which gives an area of $2.0 \times 10^5 \text{ m}^2$ (figure 2). Within this area, the original height of the pillars is 2.4 m and the extraction fraction is 0.37. Substituting these numbers into equation (2) gives an allowable roof-floor closure of 0.1 to 0.3 m for a swell of 0.4 to 0.5. From (1), the roof-floor closure needed to explain M_{xx} for our model collapse area is 0.3 m. Therefore, the collapse model that we have presented here is feasible, provided that the swell fraction is 0.4 or less. Although this model is

by no means unique, it serves to illustrate one possibility that is consistent with both the seismological data and the underground observations. It also shows that a plausible model for the mine collapse can quantitatively account for the 80% of the seismic moment release that comes from a collapse-type source.

For the decomposition of the non-collapse component of the moment tensor shown in figure 9b of Ford et al. (2008), the seismic moment (M_0) of the major double couple is 4.16×10^{14} N-m. For this shear-slip source,

$$M_0 = \mu S \bar{d} \quad (3)$$

where μ = rigidity = 9.25×10^9 N/m² at the source depth in Ford et al.'s (2008) velocity model, S = the slip area, and \bar{d} is the average slip. In the interpretation of the shear-slip component discussed previously, the slip is on a steeply dipping plane with a strike of $\sim 150^\circ$. The slip surface could extend from the mine level to the surface, a distance of ~ 600 m, and across the 220 m width of the model collapse area, giving it an area of $\sim 1.5 \times 10^5$ m². Assuming this area, solving for \bar{d} in (3) gives an average slip of 0.3 m. This average slip estimate is the same as the roof-floor convergence estimate for our collapse model and is a reasonable possibility, given our interpretation of this slip as an accommodation to the collapse along a crack in the mine roof. If a 0.3 m displacement propagated to the surface along a single crack or a narrow zone of cracks, then it should be observable at the surface. We are not aware of any reports of such displacements above the mine, but we also do not know if the rugged terrain above the mine collapse has been searched for surface offsets.

AFTERSHOCKS

Figure 4b is a plot of magnitude vs. time for seismicity in the vicinity of the Crandall Canyon Mine (3-km-radius circle, figure 3) during August 2007. The events shown include the 6 Aug mine collapse, plotted with its coda magnitude of 4.5 (star), and 37 subsequent aftershocks of $M_C \leq 2.8$ ($M_L \leq 2.2$). Twelve aftershocks ($M_C \leq 2.8$) occurred during the first 38 hours after the mine collapse. After an apparent hiatus of 5.8 days, aftershock activity resumed on 13 Aug and diminished by the end of August. The 5.8-day aftershock hiatus did not extend to shocks smaller than the routine detection and location threshold, as shown by a separate study under way of continuous recordings from temporary and permanent stations near the mine.

Aftershock epicenters located with both the master event and double difference methods cluster near the eastern and western ends of the estimated 6 Aug collapse area (figure 5). The double difference aftershock epicenters have less scatter and form N-S lineations along the eastern and western boundaries of our collapse area model (figures 2 and 5b). Aftershock activity began the day of the main shock on both the eastern and western ends of the aftershock zone, and continued to occur on both ends through August. The spatial distribution of the aftershock activity suggests that the aftershocks were triggered by stress concentrations around the edges of the collapse. But if so, why aren't there clusters of aftershocks along the northern and southern edges of the collapse? Assuming that the aftershocks represent additional pillar failures, two possible explanations are that: (1) the remnants of the barrier pillars along these edges were strong enough to withstand the additional stress without failure and/or (2) the collapse broke through the barrier pillars along these edges into parts of the mine that had previously collapsed (figure 2).

Temporal Decay

The plot of magnitude vs. time for located events following the mine collapse (figure 4b) has the general appearance of a decaying aftershock sequence, except for the unusual 5.8-day gap relatively early in the sequence. We modeled the rate of occurrence of the aftershocks using the modified Omori law:

$$N(t) = k / (t + c)^p \quad (4)$$

where $N(t)$ is the number of events per day as a function of time t after the main shock and k , c , and p are constants. The parameter p measures the exponential decay rate and k , a measure of aftershock productivity, is the number of events per day at $t = 1.0 - c$ days. Because the magnitude of completeness (M_{comp}) was $M_C 1.6$ until several days after the mine collapse, we carried out the rate modeling using the 15 aftershocks of $M_C \geq 1.6$ that occurred from 6 through 31 Aug. Using ZMAP we determined the following values for the 15-event aftershock sample: $p = 0.8 \pm 0.3$, $c = 0 \pm 0.2$, $k = 2.5 \pm 1.4$ (std. errors). Because of the small size of the aftershock sample, we were concerned that these results might be sensitive to the time intervals used by ZMAP to calculate the observed aftershock rates. Therefore, we also determined the Omori parameters using observed rates calculated for overlapping uniform intervals of logarithmic time (figure 8). A least squares fit of the modified Omori's law to these rates, assuming $c = 0$, yielded results in good agreement with the ZMAP results: $p = 0.75 \pm 0.11$ and $k = 1.9 \pm 0.4$ (std. errors). The fit to the data is reasonably good (figure 8). For comparison, Arabasz and Hill (1994) determined a mean p -value of 0.80 ± 0.13 (std. dev.; median = 0.75) for 11 aftershock sequences in Utah following main shocks of $M_L 4.5$ to 6.0, 1975–1992. Using their parameters for a “generic” Utah aftershock sequence, in which $c = 0.02$ days, the predicted value of k for $M_C \geq 1.6$ aftershocks following an $M_C 4.5$ main shock is 1.6. Thus, the rate of aftershock activity

following the Crandall Canyon Mine collapse, and its decrease with time, are both remarkably similar to the behavior of naturally occurring aftershock sequences in Utah.

Frequency-Magnitude Relations

We examined the frequency-magnitude (F-M) relations for the aftershocks of the Crandall Canyon Mine collapse and for the prior seismicity in the area in order to see if the magnitude distributions might be different for these two groups of events. The F-M relations for both time periods are approximately linear on a log-linear plot, as is typical of naturally occurring seismicity (figure 9; Gutenberg and Richter, 1949). Note that the slopes or b -values of these relations cannot be directly compared with those computed from *declustered* earthquake catalogs from which dependent events such as foreshocks and aftershocks have been removed. As shown in figure 9, the b -value for the aftershocks (0.90 ± 0.24) is almost 50 percent lower than that for the prior seismicity (1.74 ± 0.15), indicating that the aftershocks have a higher proportion of larger-magnitude events. For the prior seismicity, we sampled the catalog from March 1, 2005, up to the time of the mine collapse on 6 Aug. The start date marked the beginning of quasi-continuous seismicity at the Crandall Canyon mine during 2005, after a period of sparse earlier activity. To check whether the b -value for prior seismicity might have actually decreased earlier than 6 Aug, we checked subsets of the data including a sample starting on February 27, 2007 (see figure 4a), approximately coinciding with the start of pillar mining in the north barrier pillar. The subsets of prior seismicity consistently exhibited high b -values comparable to that shown in figure 9.

We used Utsu's (1992) test, described by Wiemer and Wyss (1997), to quantitatively test the probability that the two F-M distributions shown in figure 9 come from the same population.

The calculated probability is 0.011, verifying that the two b -values are different with a high level of statistical confidence. Based on evidence that b -values correlate inversely with differential stress (Wiemer and Schorlemmer, 2007, and references therein), the lower b -value for the Crandall Canyon aftershocks suggests the influence of higher differential stress compared to stress conditions before the mine collapse. This interpretation does not necessarily imply that the mine collapse resulted in widespread higher stresses. The higher b -value for the aftershocks could simply reflect their clustering at the eastern and western ends of the inferred mine collapse area (figure 5), where local stress concentrations would be expected.

CONCLUSIONS

1. The source mechanism of the M_L 3.9 seismic event (“main shock”) on 6 Aug 2007 was dominantly implosional and consistent with the collapse of an underground cavity—but not consistent with a naturally occurring tectonic earthquake.
2. The seismologically determined origin time of the main shock is less than 13 sec before the time that communications were lost from a carbon-monoxide monitoring device in the mine.
3. A possible, but non-unique, collapse model that is consistent with the seismological data and other information available to us has an area of 920 m E-W by 220 m N-S and an average roof-floor closure of 0.3 m.
4. Our best epicenter for the main shock is near the western end of our model collapse area, suggesting that the collapse propagated mostly eastward from where it started.

5. Broadband waveforms for the main shock, in comparison to those of a nearby earthquake with nearly the same M_L , have more emergent P-wave first arrivals, a lower dominant frequency, and larger surface waves.

6. The record of prior seismic events within 3 km of the 6 Aug mine collapse includes 28 events during 2007 of up to M_C 2.6 (M_L 1.9)—with distinct clustering in late February and early March close to mining activity and to the location of a damaging collapse on March 10 (MST).

7. Three seismic events above our routine detection and location threshold of M_C 1.6 occurred near the main shock epicenter during the three days preceding the main shock; the last one was seven hours before the main shock and had an M_C of 2.2 and an M_L of 1.8.

8. Well-located aftershocks have focal depths at or near mine level and cluster near the western and eastern ends of the inferred collapse area.

9. The rate of seismic events following the main shock gradually decreased over the following month—with a 5.8-day gap between 7 and 13 Aug for events above the threshold for complete detection of M_C 1.6.

10. The b -value of the aftershocks is about a factor of two lower than that of the prior seismic events in the same area.

ACKNOWLEDGMENTS

We thank M. Hale and P. Roberson for assistance with compiling and processing data; D. Drobeck, K. Whipp, J. Rusho, and G. Johansen for installing and maintaining the temporary stations; H. Benz for providing equipment for some of these stations; and P. Roberson for assistance with graphics. We also thank W. Walter, D. Dreger, S. Ford, the MSHA Accident Investigation Team, and others for sharing information with us. Figure 6 was partially generated

using the Seismic Analysis Code (Goldstein et al., 2003). This project was supported by the USGS, Department of the Interior, under USGS award number 07HQAG0022, and by the State of Utah under a line-item appropriation to the University of Utah Seismograph Stations.

REFERENCES

- Aki, K., and P. G. Richards (1980). *Quantitative Seismology: Theory and Methods*, W. H. Freeman, San Francisco, California, 932 pp.
- Allred, J., and M. D. Vanden Berg (2004). Annual review and forecast of Utah coal production and distribution – 2003, Utah Energy Office, State of Utah Department of Natural Resources, <http://geology.utah.gov/utahgeo/energy/coal/index.htm#coalrpt> , 33 pp.
- Arabasz, W. J., and S. J. Hill (1994). Aftershock temporal behavior and earthquake clustering in the Utah region, in Smith, R. B., W. J. Arabasz, J. C. Pechmann, and C. M. Meertens, Seismicity, ground motion, and crustal deformation—Wasatch Front, Utah, and adjacent Intermountain Seismic Belt, *Technical Report*, U.S. Geological Survey Grant no. 1434-93-G-2348, University of Utah, Salt Lake City, Utah, Attachment no. 2, 31 pp.
- Arabasz, W. J., and J. C. Pechmann (2001). Seismic characterization of coal-mining seismicity in Utah for CTBT monitoring, *Technical Report UCRL-CR-143772*, Lawrence Livermore National Laboratory, Livermore, California, LLNL Research Agreement No. B344836, <http://www.quake.utah.edu/Reports/llnl2001/index.shtml> , 120 pp.
- Arabasz, W. J., S. J. Nava, and W. T. Phelps (1997). Mining seismicity in the Wasatch Plateau and Book Cliffs coal mining districts, Utah, USA, in *Rockbursts and Seismicity in Mines*, S. J. Gibowicz and S. Lasocki (editors), A. A. Balkema, Rotterdam, The Netherlands, 111-116.
- Arabasz, W.J., S. J. Nava, M. K. McCarter, K. L. Pankow, J. C. Pechmann, J. Ake, and A. M. McGarr (2005). Coal-mining seismicity and ground-shaking hazard—A case study in the

- Trail Mountain area, Emery County, Utah, *Bulletin of the Seismological Society of America* **95**, 18–30.
- Arabasz, W. J., R. B. Smith, J. C. Pechmann, K. L. Pankow, and R. Burlacu (2006). Integrated regional and urban seismic monitoring—Wasatch Front area, Utah, and adjacent Intermountain Seismic Belt, *Final Technical Report*, U.S. Geological Survey Cooperative Agreement No. 04HQAG0014, <http://www.quake.utah.edu/MONRESEARCH/research.htm> , 134 pp.
- Arabasz, W. J., R. Burlacu, and K. L. Pankow (2007). An overview of historical and contemporary seismicity in central Utah, in *Central Utah—Diverse Geology of a Dynamic Landscape*, G. C. Willis, M. D. Hylland, D. L. Clark, and T. C. Chidsey, Jr. (editors), Utah Geological Association Publication 36, 540 pp.
- Black, B. D., S. Hecker, M. D. Hylland, G. E. Christenson, and G. N. McDonald (2003). Quaternary fault and fold database and map of Utah, *Utah Geological Survey Map 193DM*, scale 1:500,000, CD-ROM, ISBN 1-55791-593-8 .
- Bowers, D., and J. A. Hudson (1999). Defining the scalar moment of a seismic source with a general moment tensor, *Bulletin of the Seismological Society of America* **89**, 1390-1394.
- Busby, B. (2007) TA, in *2006 Annual Report*, Incorporated Research Institutions for Seismology, Washington, D. C., 22-23.
- Carlisle, N. (2007). Regulator, miners rule out ceiling collapse, *Salt Lake Tribune*, 12 Aug 2007, A8.
- Caterpillar Inc. (2003). *Caterpillar Performance Handbook*, Caterpillar Tractor Company, Peoria, Illinois,

- Corbett, E. J. (1984). Seismicity and crustal structure studies of southern California: Tectonic implications from improved earthquake locations, *Ph.D. Thesis*, California Institute of Technology, Pasadena, California, 231 pp.
- Crandall Canyon Mine Roof Control Plan (2007). <http://www.msha.gov/Genwal/CrandallCanyon.asp>
- Ellenberger, J. L., K. A. Heasley, P. L. Swanson, and J. Mercier (2001). Three dimensional microseismic monitoring of a Utah longwall, in *Rock Mechanics in the National Interest*, D. Elsworth, J. P. Tinucci, and K. A. Heasley (editors), A. A. Balkema, Rotterdam, The Netherlands, 1321-1326.
- Ferriter, R. L. (2007). Statement of R. L. Ferriter, Director of Mine Safety and Health Program, Colorado School of Mines, Golden, Colorado, before the United States Senate Committee on Health, Education, Labor, and Pensions, October 2, 2007.
- Fletcher, J.B., and A. McGarr (2005). Moment tensor inversion of ground motion from mining-induced earthquakes, Trail Mountain, Utah, *Bulletin of the Seismological Society of America* **95**, 48–57.
- Ford, S. R., D. S. Dreger, and W. R. Walter (2008). Source characterization of the August 6, 2007 Crandall Canyon Mine seismic event in central Utah, submitted to *Seismological Research Letters*.
- Frosch, D., and J. Lee (2007). Rescue halted at mine after 3 deaths and 6 injuries, *New York Times*, 17 Aug 2007, <http://www.nytimes.com/2007/08/17/us/17cnd-mine.html> .
- Gates, R. A., and S. Hayashi (2007). Status report of MSHA investigation into Crandall Canyon Mine accident, presentation at Utah Mine Safety Commission Public Meeting, 20 Nov 2007, University of Utah S. J. Quinney College of Law, Salt Lake City, Utah.

- Gehrke, R. (2008). Crandall Canyon bombshell: Months before deadly cave-ins, owners knew of structural woes, Salt Lake Tribune, 17 Jan 2008.
- Gilbride, L. (2007). GENWAL Crandall Canyon Mine main west south barrier mining evaluation, letter to L. Adair, 18 April 2007, in *Crandall Canyon Mine Roof Control Plan*, <http://www.msha.gov/Genwal/CrandallCanyon.asp>, 175-184 .
- Goldstein, P., D. Dodge, and M. Firpo (2003). SAC2000: Signal processing and analysis tools for seismologists and engineers, in *International Handbook of Earthquake and Engineering Seismology, Part B*, W. H. K. Lee, H. Kanamori, P. C. Jennings, and C. Kisslinger (Editors), 1613-1614.
- Gutenberg, B., and C.F. Richter (1949). *Seismicity of the Earth and Associated Phenomena*, Princeton University Press, 1st ed., Princeton, New Jersey, 310 pp.
- Herrmann, R. B. (2007). Focal mechanism for the 2007/11/05 21:48:00 Utah event, in St. Louis University Focal Mechanism Catalog, http://www.eas.slu.edu/Earthquake_Center.
- Hucka, B. (1991). Analysis and regional implication of cleat and joint systems in selected coal seams, Carbon, Emery, Sanpete, Sevier, and Summit Counties, Utah, *Utah Geological Survey Special Study 74*, 2 pl., 47 pp.
- Intermountain Power Agency (2007). Minutes of the regular monthly IPA Co-Owners meeting, March 21, 2007, in IPA offices in South Jordan, UT, http://extras.mnginteractive.com/live/media/site297/2008/0115/20080115_032830_Crandall_minutes.pdf (Link provided by www.sltrib.com in Gehrke, 2008), 6 pp.
- Jahanbani, F. R. (2000). 1999 Annual review and forecast of Utah coal production and distribution, Office of Energy and Resource Planning, State of Utah Department of Natural Resources, <http://geology.utah.gov/utahgeo/energy/coal/index.htm#coalrpt> , 40 pp.

- Kennedy, B. A. (1990). *Surface Mining (2nd edition)*, Society for Mining, Metallurgy, and Exploration, Inc., Littleton, Colorado, 1194 pp.
- Klein, F.W. (1978). Hypocenter location program HYPOINVERSE, *U.S. Geological Survey Open-File Report 78-694*, 113 pp.
- Knoll, P. (1990). The fluid-induced tectonic rockburst of March 13, 1989, in the “Werra” potash mining district of the GDR (first results), *Gerlands Beitrage zur Geophysik* **99**, 239-245.
- Lay, T., and T. C. Wallace (1995). *Modern Global Seismology*, Academic Press, San Diego, California, 521 pp.
- Mayeda, K., and W. R. Walter (1996). Moment, energy, stress drop, and source spectra of western United States earthquakes from regional coda envelopes, *Journal of Geophysical Research* **101**, 11,195-11,208
- Mine Safety and Health Administration (2007a). Drill hole map, <http://www.msha.gov/Genwal/CrandallCanyon.asp> .
- Mine Safety and Health Administration (2007b). Fatalgram added...(for the accident occurring 16 August 2007), <http://www.msha.gov/Genwal/CrandallCanyon.asp> .
- Myers, S. C., W. R. Walter, K. Mayeda, and L. Glenn (1999). Observations in support of Rg scattering as a source for explosion S waves: Regional and local recordings of the 1997 Kazakhstan depth of burial experiment, *Bulletin of the Seismological Society of America* **89**, 544-549.
- Pechmann, J. C., W. R. Walter, S. J. Nava, and W. J. Arabasz (1995). The February 3, 1995, M_L 5.1 seismic event in the trona mining district of southwestern Wyoming, *Seismological Research Letters* **66**, no. 3, 25-34 [minor correction, including revision of the magnitude to M_L 5.2, added in **66**, no. 4, 28].

- Pechmann, J. C., J. C. Bernier, S. J. Nava, and F. M. Terra (2006). Correction of systematic time-dependent coda magnitude errors in the Utah and Yellowstone National Park region earthquake catalogs, 1981-2001, in Arabasz, W. J., R. B. Smith, J. C. Pechmann, K. L. Pankow, and R. Burlacu, Integrated regional and urban seismic monitoring—Wasatch Front area, Utah, and adjacent Intermountain Seismic Belt, *Final Technical Report*, U.S. Geological Survey Cooperative Agreement no. 04HQAG0014, University of Utah, Salt Lake City, Utah, Appendix C, 45 pp.
- Pechmann, J. C., S. J. Nava, F. M. Terra, and J. C. Bernier (2007). Local magnitude determinations for Intermountain Seismic Belt earthquakes from broadband digital data, *Bulletin of the Seismological Society of America* **97**, 557-574.
- Stricklin, K. G. (2007). Statement of K. G. Stricklin, Administrator for Coal Mine Safety and Health, Mine Safety and Health Administration, U. S. Department of Labor, before the Committee on Health, Education, Labor, and Pensions, United States Senate, October 2, 2007, <http://www.msha.gov/Genwal/CrandallCanyon.asp> .
- Taylor, S. R., (1994). False alarms and mine seismicity: An example from the Gentry Mountain mining region, Utah, *Bulletin of the Seismological Society of America* **84**, 350–358.
- University of Utah Seismograph Stations (2007). Utah region earthquake catalog, <http://www.quake.utah.edu/EQCENTER/LISTINGS/utCatalog.htm> .
- United States Senate Health, Education, Labor and Pensions Committee (2008). Report on the August 6, 2007 Disaster At Crandall Canyon Mine, 75 pp.
- Utah Mine Safety Commission (2008). Utah Mine Safety Commission Report and Recommendations to Governor Jon M. Huntsman, Jr., Utah Division of Oil, Gas, and Mining, Salt Lake City, Utah, 97 pp.

- Utsu, T. (1992). On seismicity, in *Report of the Joint Research Institute for Statistical Mathematics* **34**, Institute for Statistical Mathematics, Tokyo, p. 139–157.
- Vanden Berg, M.D., 2007, Annual review and forecast of Utah coal—Production and distribution, 2006, *Utah Geological Survey Circular 103*, 37 pp, <http://geology.utah.gov/utahgeo/energy/coal/index.htm#coalrpt>.
- Waldhauser, F. (2001). HypoDD – A program to compute double-difference hypocenter locations (hypoDD version 1.0 – 03.2001), *U. S. Geological Survey Open-File Report 01-133*, 25 pp.
- Waldhauser, F., and W. L. Ellsworth (2000). A double-difference earthquake location algorithm: Method and application to the northern Hayward fault, *Bulletin of the Seismological Society of America* **90**, 1353–1368.
- Weichert, D.H. (1980). Estimation of the earthquake recurrence parameters for unequal observation periods for different magnitudes, *Bulletin of the Seismological Society of America* **70**, 1337–1346.
- Wiemer, S. (2001). A software package to analyze seismicity—ZMAP, *Seismological Research Letters* **72**, no. 3, 373–382.
- Wiemer, S., and M. Wyss (1997). Mapping the frequency-magnitude distribution in asperities: An improved technique to calculate recurrence times, *Journal of Geophysical Research* **102**, 15,115–15,128.
- Wiemer, S., and M. Wyss (2000). Minimum magnitude of completeness in earthquake catalogs: examples from Alaska, the western United States, and Japan, *Bulletin of the Seismological Society of America* **90**, 859–869.
- Wiemer, S., and M. Wyss (2003). Reply to “Comment on ‘Minimum magnitude of completeness in earthquake catalogs: examples from Alaska, the western United States,

and Japan,' by S. Wiemer and M. Wyss," by Rydelek, P. A., and I. S. Sacks, *Bulletin of the Seismological Society of America* **93**, 1868–1871.

Wiemer, S., and D. Schorlemmer (2007). ALM—An asperity-based likelihood model for California, *Seismological Research Letters* **78**, 134–140.

Wong, I. G., J. R. Humphrey, J. A. Adams, and W. J. Silva (1989). Observations of mine seismicity in the eastern Wasatch Plateau, Utah, U.S.A.: A possible case of implosional failure, *PAGEOPH* **129**, 369-405.

University of Utah Seismograph Stations

University of Utah

Department of Geology and Geophysics

135 South 1460 East, Room 705 WBB

Salt Lake City, UT 84112-0111

(J. C. P., W. J. A., K. L. P, and R. B.)

University of Utah

Department of Mining Engineering

135 South 1460 East Room 705 WBB

Salt Lake City, UT 84112-0111

(M. K. M.)

TABLE 1 Drill Hole Observations of the Crandall Canyon Mine Collapse (West to East)			
Hole Number	UTC Date¹ (2007)	Void Space (m)²	Depth of Debris (percent of tunnel height)³
3	15 Aug	2.44	0
4	18 Aug	1.22	50
6	25 Aug	0	100
1	10 Aug	1.68	31
7	30 Aug	0.82	66
2	11 Aug	1.74	29
5	22 Aug	0.15	94
¹ Mine breach dates from Mine Safety and Health Administration, 2007a ² Void space from borehole cameras for holes 3 and 4 and from driller's logs for other holes, provided by Richard A. Gates and Thomas Morley, MSHA, written communication, 2008 ³ Depth of debris calculated from void space assuming a tunnel height of 2.44 m (8 ft)			

TABLE 2 Temporary Seismograph Stations Deployed in the Crandall Canyon Mine Area							
Station	Latitude (N)	Longitude (W)	Elev. (m)	Sensor	Telemetry	Start of Recording (UTC)	Last Event Recorded (UTC)
CM1	39° 27.99'	111° 14.08'	2762	Applied MEMS accelerometer	Digital after 24 Aug ~22:39 UTC; none before	8 Aug 00:50	27 Sept. 23:48
CM2	39° 28.13'	111° 13.06'	3217	Applied MEMS accelerometer	None	8 Aug 19:54	21 Aug 14:53
CM3	39° 26.78'	111° 12.86'	3193	Mark Products L-4 seismometer	Analog	11 Aug ~04:00	03 Oct 08:22
CM4	39° 30.53'	111° 15.68'	2765	Mark Products L-4 seismometer	Analog	11 Aug ~04:00	24 Sept 21:54
CM5	39° 28.04'	111° 8.90'	2359	Mark Products L-4 seismometer	Analog	11 Aug ~04:00	02 Oct 07:40

TABLE 3 Hypocentral Locations for the 6 Aug 2007, M_L 3.9 Crandall Canyon Mine Seismic Event								
	Origin Time, UTC (hr: min: sec)	Latitude (N)	Longitude (W)	Depth (km)	No	Gap (deg)	Dmin (km)	Rms (sec)
Standard UOSS	08: 48: 40.39	39° 27.92'	111° 14.19'	1.6	33	46	18.9	0.19
Master Event	08: 48: 39.88	39° 28.17'	111° 13.39'	0.6	18	51	19.1	0.10
Double Difference	08: 48: 39.87	39° 28.05'	111° 13.49'	0.5	--	--	--	--
No = number of P-wave arrival times used in the location Gap = largest azimuthal separation between stations used in the location Dmin = epicentral distance to the closest station used in the location Rms = weighted root-mean-square of the travel-time residuals								

FIGURE CAPTIONS

Figure 1. Epicenter map of seismicity within polygons outlining the Wasatch Plateau–Book Cliffs coal-mining region of Utah (black polygons) from January 1978 through August 2007. Almost all of this seismicity is inferred to be caused by underground mining. The stars mark locations of $M \geq 3.5$ events, including the M_L 3.9 Crandall Canyon Mine event on 6 Aug 2007. The grey lines are Quaternary fault traces from Black et al. (2003). The inverted triangles mark entrances to active and recently active mines.

Figure 2. Map showing the west mains section of the Crandall Canyon Mine where the 6 Aug 2007 collapse occurred. The southern solid box shows a minimum estimate of the collapse area constructed using the Mine Safety and Health Administration’s preliminary estimate of the collapse’s E-W extent (Mike Gauna, personal communication, 12 Sept 2007) and a likely minimum N-S extent. The dashed box shows a collapse area model that is more consistent with the seismological data, including our best location for the main shock (star). The dashed box is 920 m E-W by 220 m N-S and its SE corner is at $39^\circ 28.018' \text{ N}$, $111^\circ 12.838' \text{ W}$. Base map from public records, Utah Division of Oil, Gas and Mining, dated 14 Aug 2007. March damage area from Gilbride (2007). Last known location of miners from Gates and Hayashi (2007; see also United States Senate Health, Education, Labor and Pensions Committee, 2008, pp. 71-73). Drill hole locations taken from Mine Safety and Health Administration (2007a).

Figure 3. Map of the Crandall Canyon Mine area showing the epicenter of the 6 Aug 2007 M_L 3.9 seismic event determined from standard UUSS data processing (open star), the master event relocation for this epicenter (solid star), and the 95% confidence ellipses for these solutions

(dashed lines). Also shown are master event relocations for the 188 other seismic events in the University of Utah catalog with initial epicenters in the dotted 3-km-radius circle from (i) July 2005 through Dec. 2006 (boxes), (ii) Jan 2007 until the time of the M_L 3.9 event (diamonds), and (iii) subsequent events in Aug 2007 (circles). The crosshatched box shows the minimum estimated area of the 6 Aug Crandall Canyon Mine collapse from figure 3. The solid triangles mark the sites of three of the five temporary seismic stations operated in the area beginning on 8 Aug (UTC).

Figure 4. (a) Plot of magnitude vs. time for 189 seismic events located by the University of Utah during the period July 2005 through August 2007 and within 3 km of a point near the 6 Aug 2007, Crandall Canyon mine collapse (dotted circle, figure 3). Most if not all of the events are mining-related. The horizontal dashed line indicates the magnitude threshold of complete reporting. (b) Expanded plot for August 2007 showing 41 seismic events, including the M_L 3.9 (M_C 4.5; star) Crandall Canyon mine collapse. Note the 5.8-day gap in aftershock activity for $M_C \geq 1.6$ (the applicable magnitude of completeness) between 7 and 13 Aug. Aftershocks smaller than the completeness threshold were detected during this time interval (see text).

Figure 5. Comparison of epicenters relocated using the (a) master event and (b) double difference methods for 150 events (79% of those in figure 3) for which double difference relocations could be successfully computed. The crosshatched boxes show the estimated minimum extent of the 6 Aug collapse (see figure 2) and the damage area from a major pillar failure in March 2007 (Gilbride, 2007), as labeled. The absolute locations for both sets of epicenters were constrained using the known location of the fatal 17 Aug (UTC) M_L 1.6 event

(labeled). The double difference locations are considered the most accurate. They show that most of the 2007 events prior to the 6 Aug collapse (diamonds) clustered near the March damage area and most of the events after the 6 Aug collapse (circles) clustered near the eastern and western ends of the estimated collapse area.

Figure 6. Comparison of broadband velocity waveforms from the Crandall Canyon Mine main shock with those of an M_L 3.9 earthquake that occurred 40 km to the WSW in the Sanpete Valley on 5 Nov 2007. The data were recorded on Transportable Array station Q16A, which is nearly the same distance from both events. The plots show: (a) vertical-components, with epicentral distances and azimuths indicated, (b) vertical-components at a compressed time scale, (c) radial components, and (d) transverse components. Similar waveform differences are seen at other stations.

Figure 7. P-wave first motions for the 6 Aug M_L 3.9 main shock (a-c) and the 17 Aug (UTC) M_L 1.6 event (d). The first motions are all dilatational and are represented by open circles on equal area, lower hemisphere diagrams. Smaller circles indicate readings of lower confidence. Each mechanism is labeled with the origin time and date (yy-mm-dd, UTC), local magnitude (M), and the focal depth of the master event location (H ; fixed for (d)). The triangles show slip vectors and compression and tension axes. The solutions shown for the main shock are (a) an implosion, the preferred model based on waveform inversion results from Ford et al. (2008), (b) one possible normal faulting mechanism that can be fit to the first motion data, and (c) the best-fitting shear-slip mechanism as determined from waveform inversion by Ford et al. (2008; strike = 154° , dip = 80° , rake = 97°). The solution in (c) is clearly incompatible with the first motion

data. The solution shown for the M_L 1.6 event in (d) is an implosion, the only mechanism that fits the data for the assumed focal depth at mine level.

Figure 8. Rate of aftershock occurrence as a function of time following the Crandall Canyon mine collapse. Rates are based on 15 events of $M_C \geq 1.6$ that occurred between 0.08 and 19.4 days after the main event. Beginning with time t after the main event of 0.05 day, the plotted rates are for uniform intervals of logarithmic time in overlapping time bins centered at $t = (.05)2^{n/2}$, $n = 0 \dots 16$, each extending from $0.5t$ to $2.0t$. The least-squares slope of -0.75 ± 0.11 (std. error) defines the average decay constant p for Omori's law with $c = 0$ (equation (4)), and is close to the mean Omori decay constant observed for aftershock sequences of Utah earthquakes.

Figure 9. Frequency-magnitude plots showing significantly different b -values (slopes) for seismicity in the vicinity of the Crandall Canyon Mine (3-km-radius circle, Figure 3) before and after the mine collapse on 6 Aug 2007. Seismicity in each case has a completeness magnitude of M_C 1.6. The sample of prior seismicity (140 events) extends from 1 March 2005; the aftershock sample (15 events) extends through 31 Aug. The b -values and their standard errors were calculated using Weichert's (1980) maximum-likelihood algorithm. The lower b -value of the aftershocks compared to the prior events suggests that the aftershocks occurred in areas of higher deviatoric stress.

Seismicity in the Utah Coal Mining Region

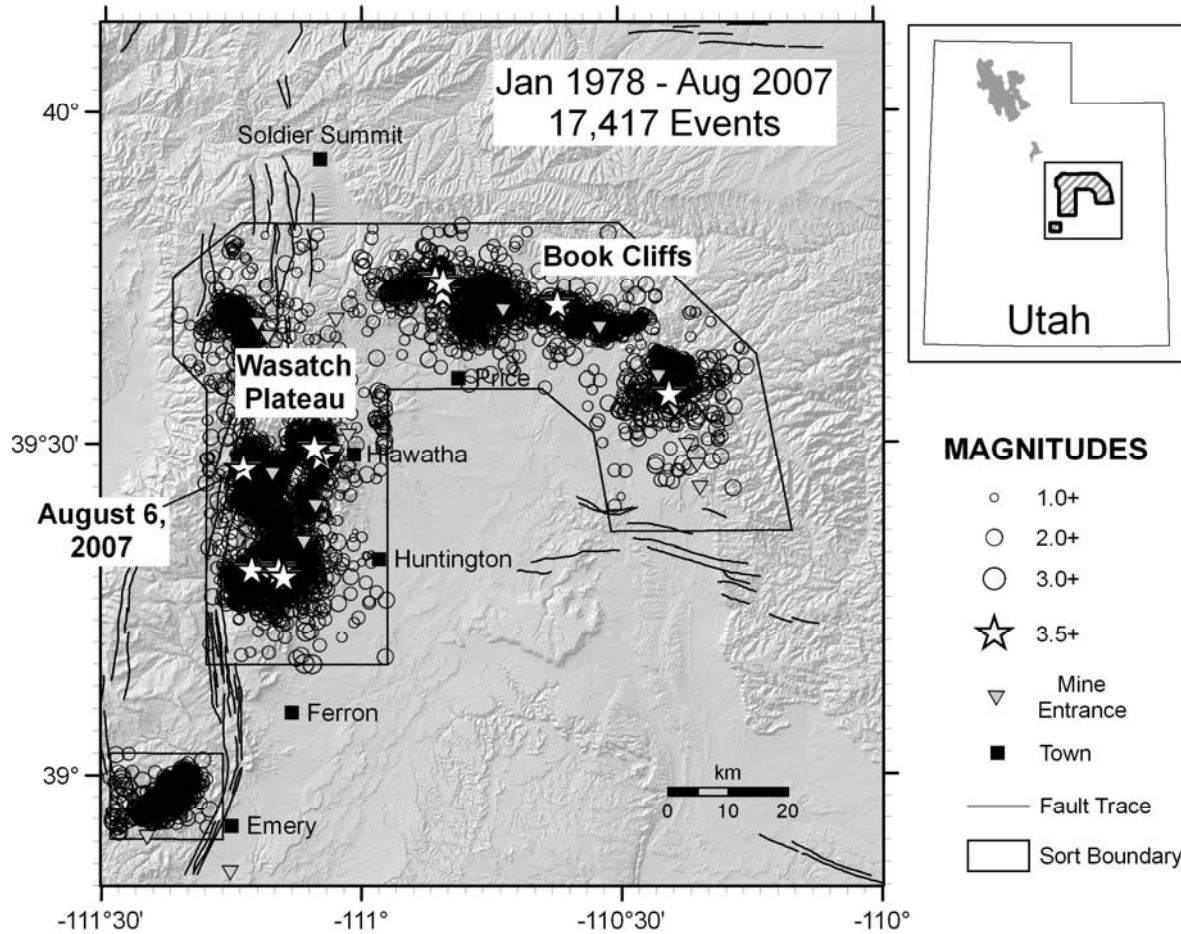


FIGURE 1

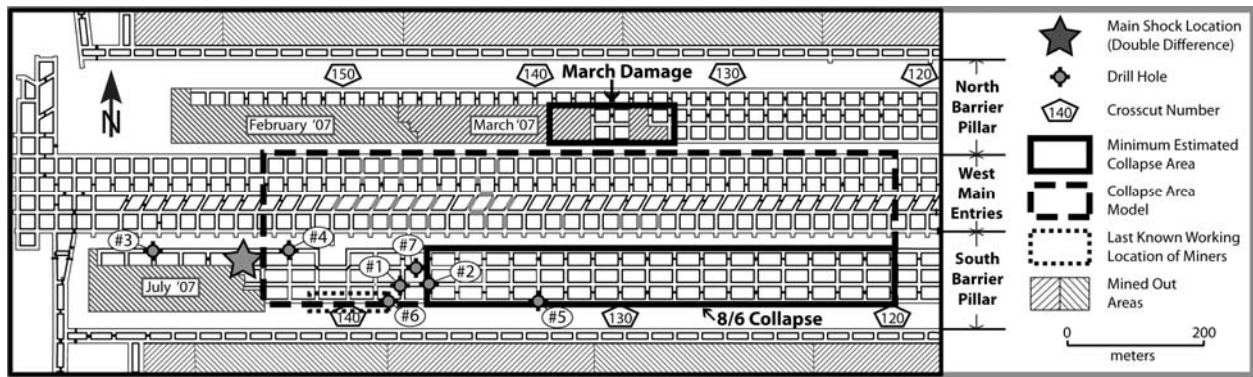


FIGURE 2

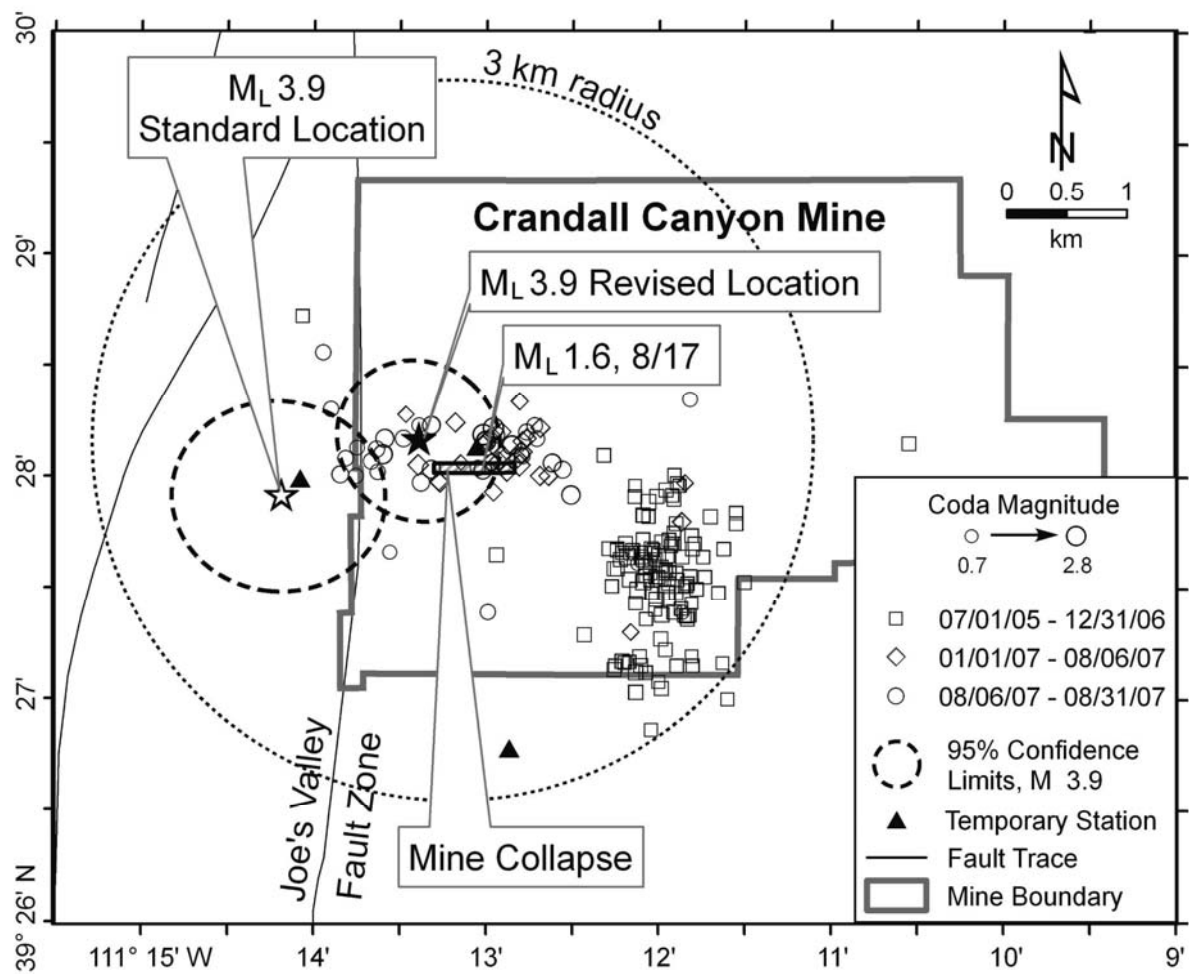


FIGURE 3

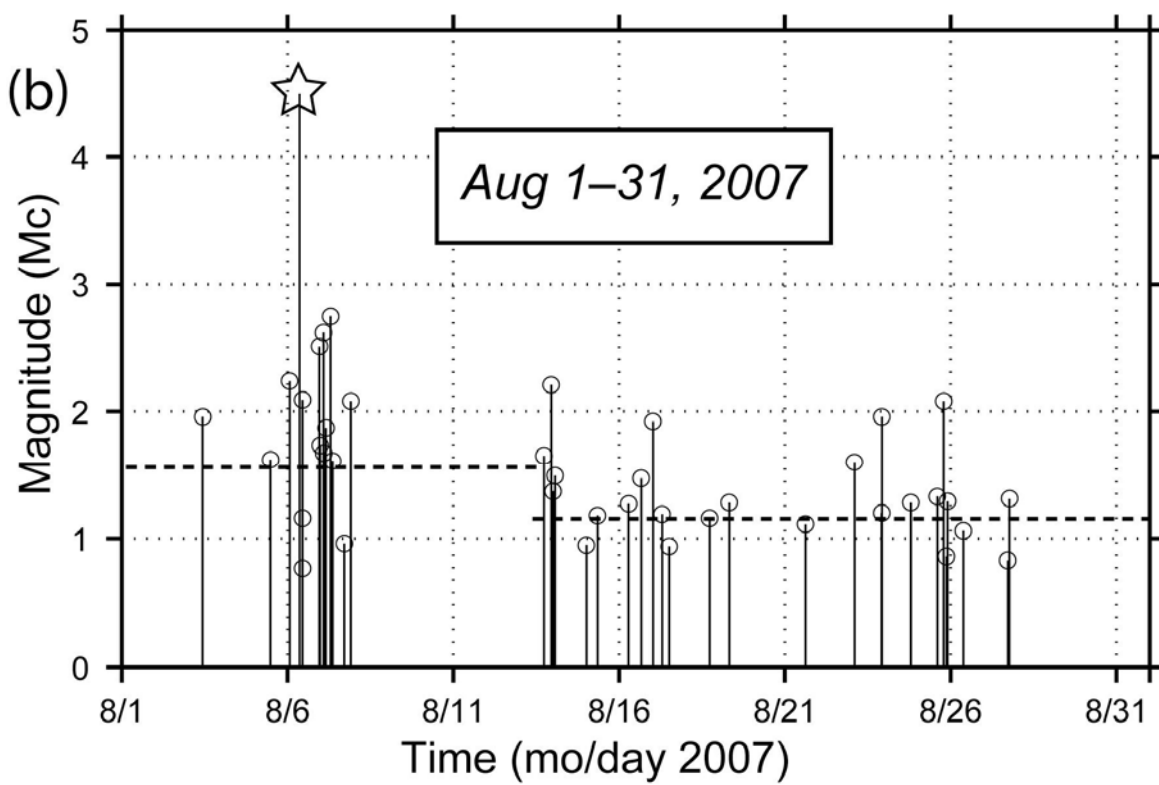
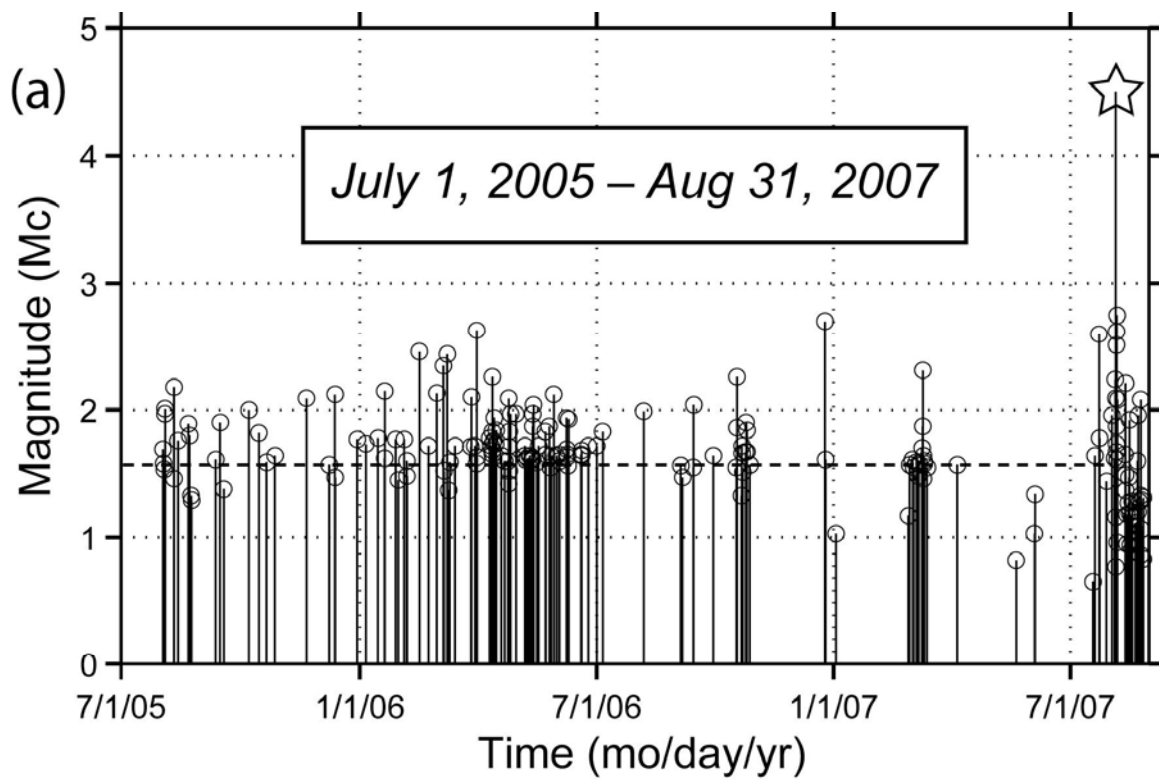


FIGURE 4

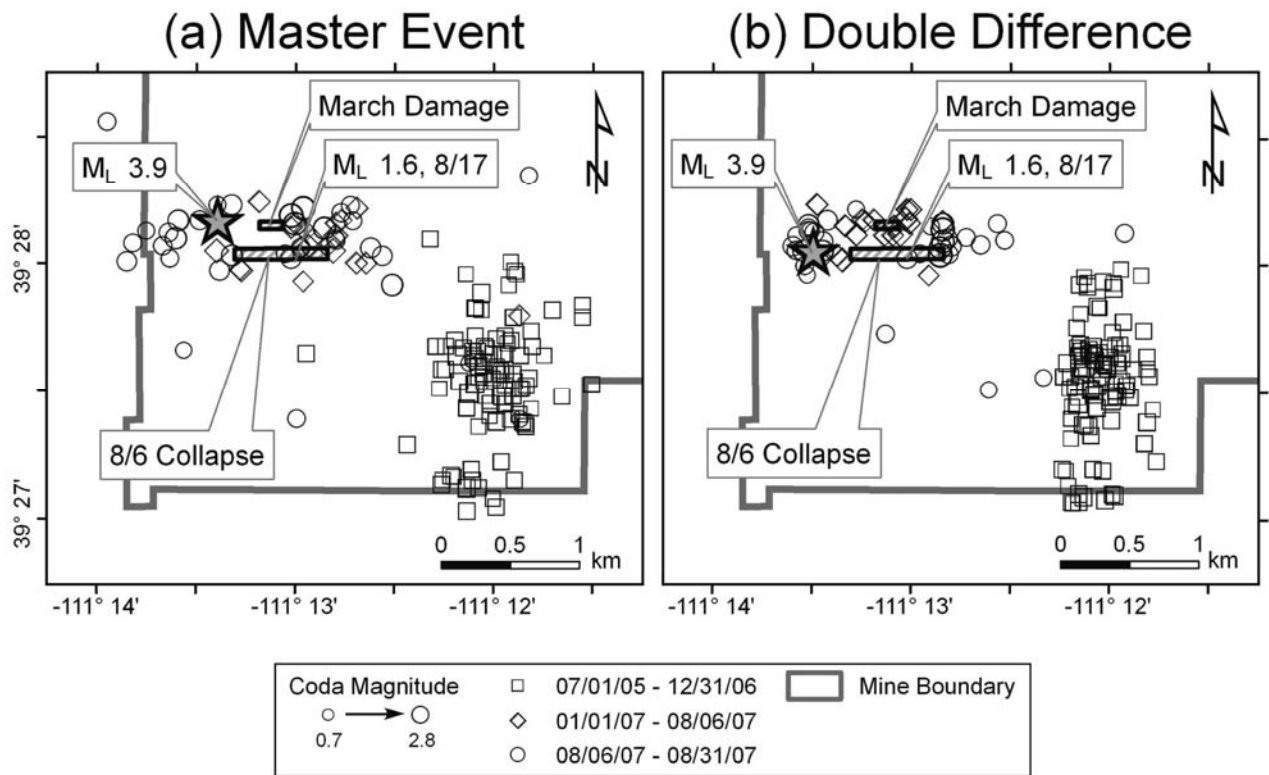


FIGURE 5

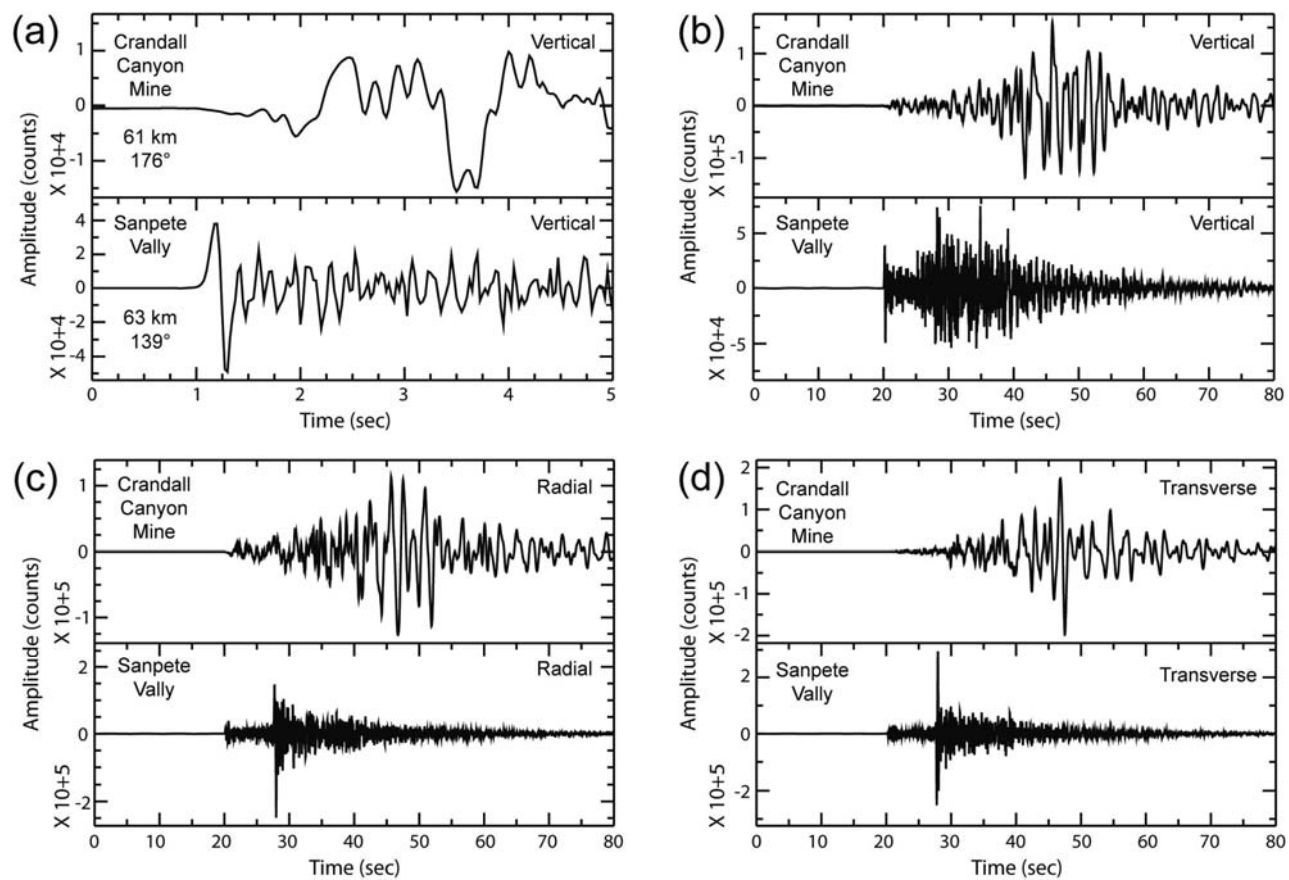
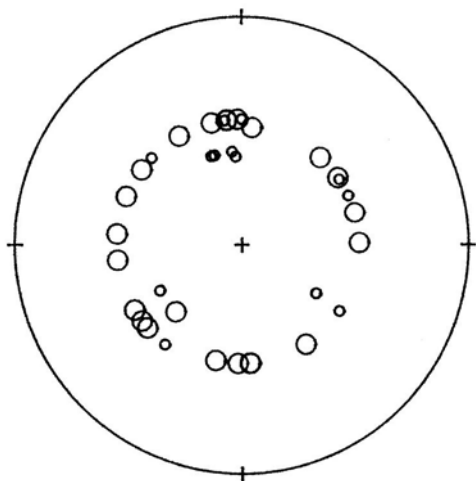
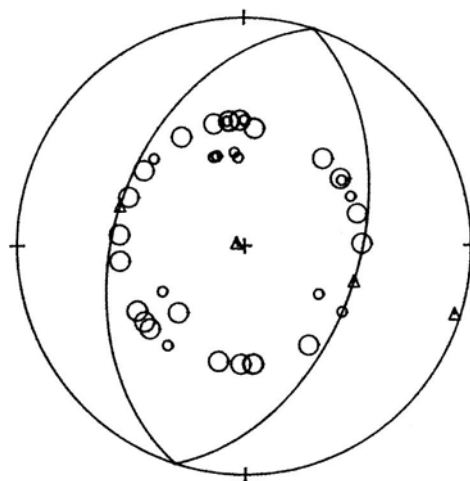


FIGURE 6

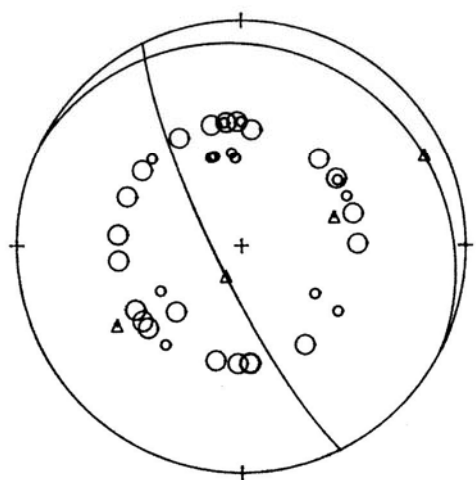
(a) 08:48 07-08-06
M = 3.9, H = 0.62 km



(b) 08:48 07-08-06
M = 3.9, H = 0.62 km



(c) 08:48 07-08-06
M = 3.9, H = 0.62 km



(d) 00:38 07-08-17
M = 1.6, H = 0.60 km

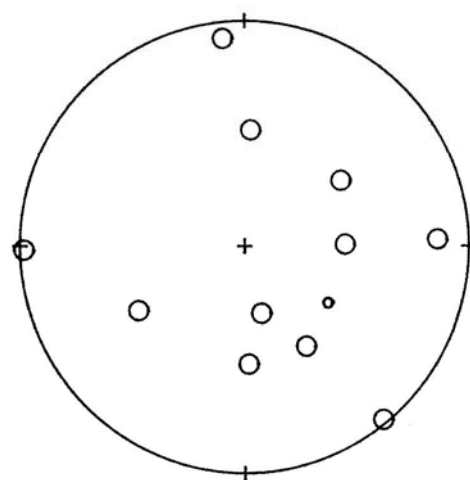


FIGURE 7

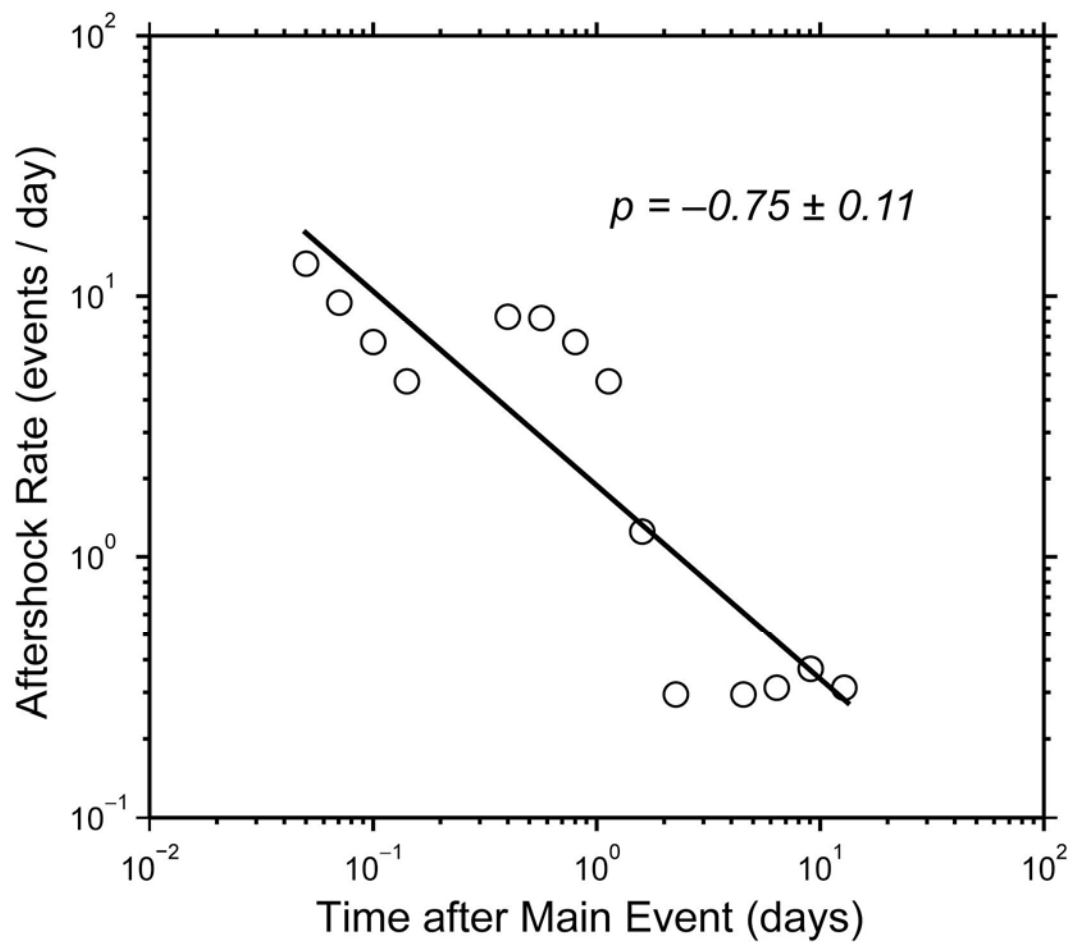


FIGURE 8

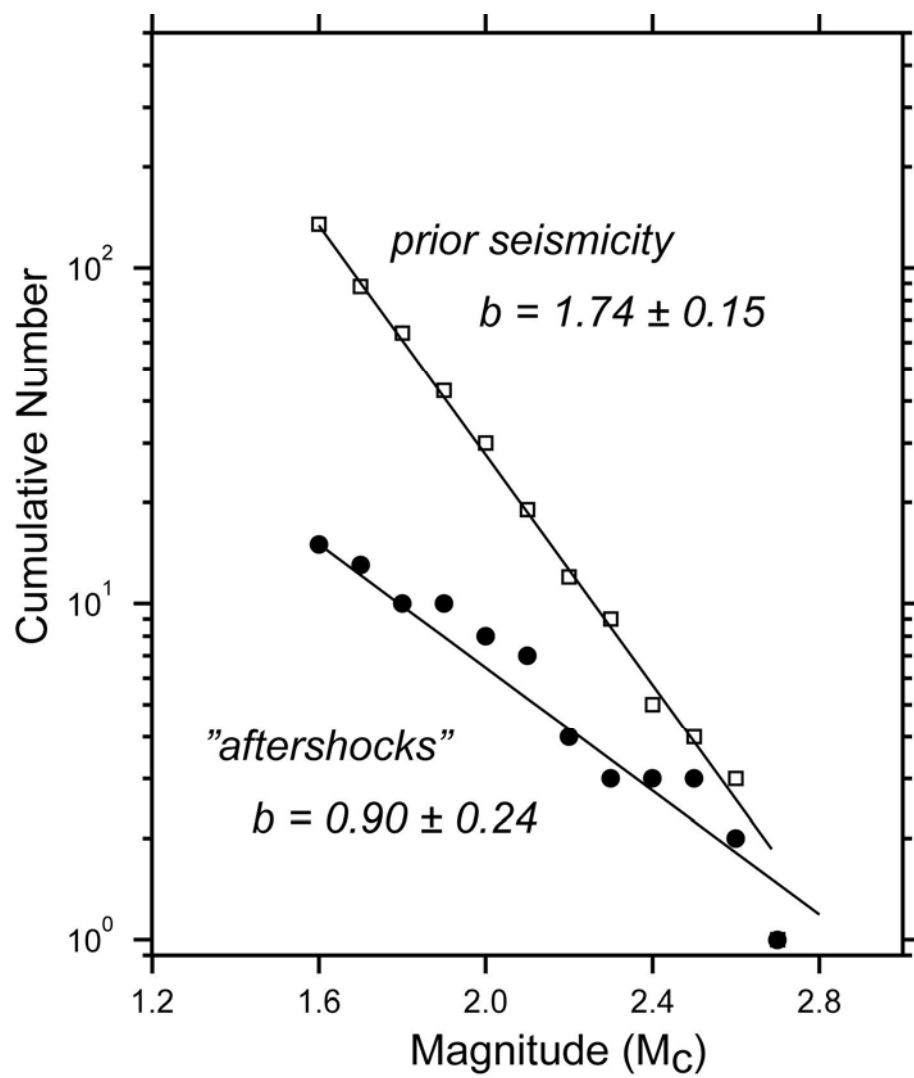


FIGURE 9