

Appendix N - Seismic Analysis

University of Utah Seismograph Stations

Continuous earthquake monitoring has been conducted at the University of Utah since 1907. The University of Utah Seismograph Stations (UUSS) is an entity within the Department of Geology and Geophysics. The mission of the UUSS is primarily academic research while also providing earthquake information to the general public and public officials. The UUSS is also a participant in the Advanced National Seismograph System (ANSS). The mission of the ANSS is to provide accurate and timely data for seismic events.

The UUSS maintains a regional/urban seismic network of over two hundred stations. An average of one thousand seismic events is detected in Utah each year. The number of events depends on the magnitude threshold of reporting. The number of recorded events includes those from natural sources (tectonic earthquakes) as well as those related to mining activity. In the Wasatch Plateau and Book Cliffs mining areas, at least 97% of the events have been identified as being related to mining activity. These events are termed mining-induced seismicity. Both tectonic and mining-induced seismic events can be referred to as earthquakes.

The majority of coal mining in Utah occurs in the Wasatch Plateau and Book Cliffs area. The coal fields form the shape of an inverted “U” in Carbon and Emery counties. In the coal mining region, nearly all the seismic events are mining-induced. Again, the number of events depends on the magnitude threshold. Special studies have recorded several thousand such events in a single year. Figure 104 is a plot of mining-induced seismicity from 1978 to 2007. Over 19,000 events are included. Mining-induced seismicity occurs regularly from normal mining activity in the Utah coal fields.

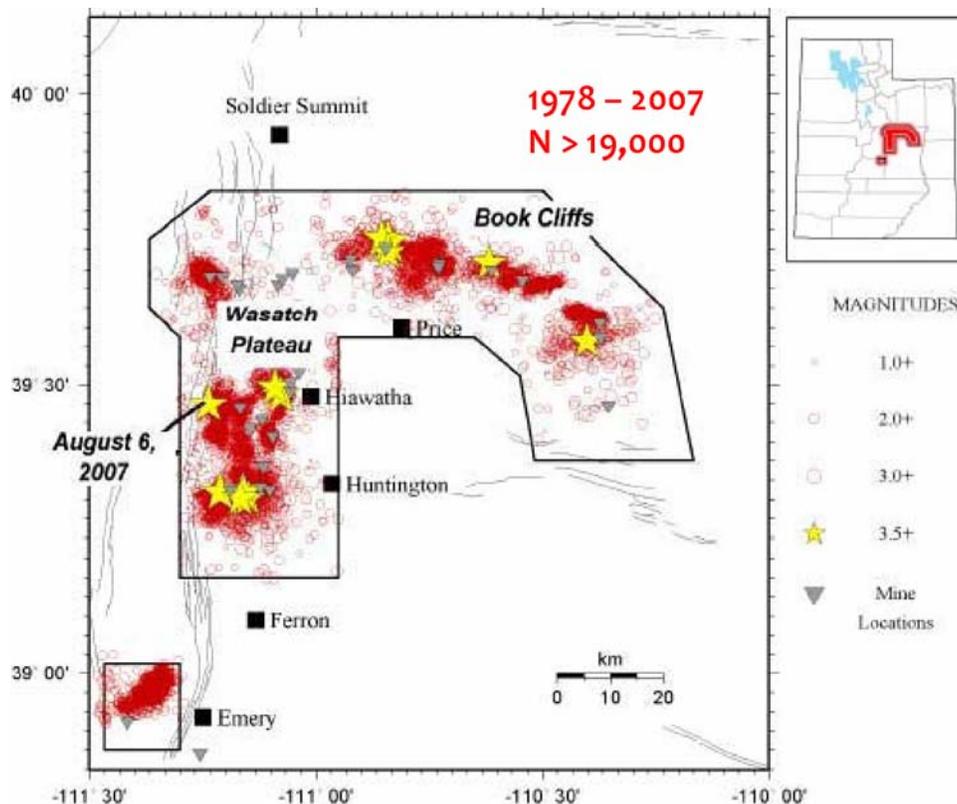


Figure 104 - Mining-Induced Seismicity in Utah
(from W. Arabasz presentation to Utah Mining Commission, November 2007)

The regional seismograph network includes several stations situated in the mining region. The location of these stations is shown in Figure 105. The stations are connected by telemetry to the UUSS central recording laboratory.

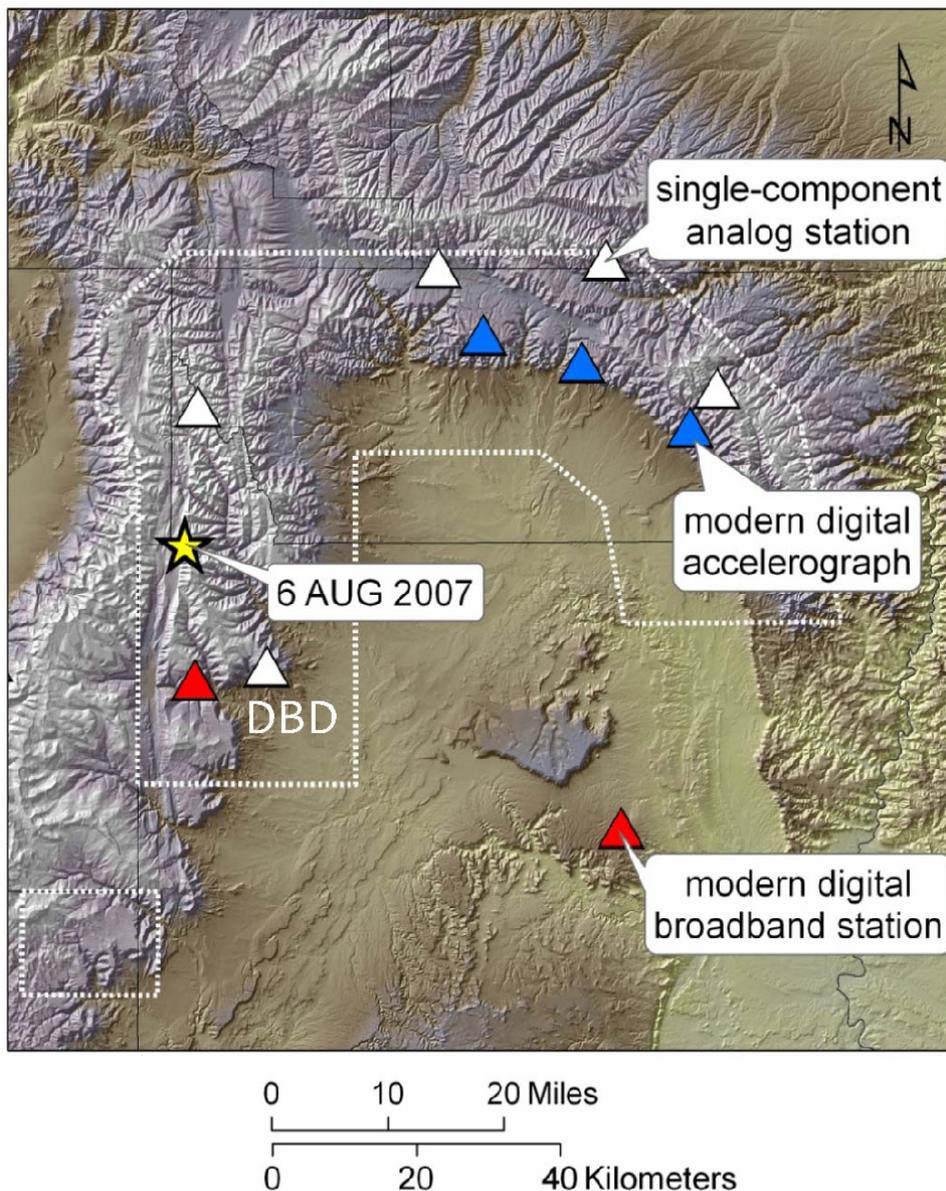


Figure 105 - Locations of UUSS Seismographs in the Wasatch Plateau
In the Book Cliffs Mining Area²⁴

Seismic Event Locations and Magnitudes

The magnitude of earthquakes is often reported in terms of the local magnitude (M_L). The local magnitude scale is a logarithmic scale developed by Charles Richter to measure the relative sizes of earthquakes in California. The scale was based on the amplitude recorded on a Wood-Anderson seismograph. The scale has been adapted for use around the world and is also known as the Richter scale.

Many additional scales have been used to measure earthquakes. Most scales are designed to report magnitudes similar to the local magnitude. The coda magnitude (M_C) is based on the length of the seismic signal. The coda magnitude scale used by the UUSS was calibrated to

provide similar results on average with the local magnitude scale for naturally occurring earthquakes. The UUSS has observed that mining related seismic events are shallow compared to most naturally occurring earthquakes and the duration or coda tends to be longer. This results in a slightly higher coda magnitude than local magnitude for mining-induced events.

It was not possible for the UUSS to calculate the local magnitude for all events. The coda magnitude was available for all reported events. While the local magnitude or M_L was the preferred scale, to maintain consistency, the coda magnitude or M_C was used in this report except where noted. The coda magnitude for the 3.9 M_L event on August 6, 2007, was 4.5.

Following the August 6, 2007, event, a location was automatically calculated and posted on the UUSS and USGS websites. The plotted location was not over the Crandall Canyon Mine and contributed to speculation that the event was not mining-related.

The location of a seismic event is determined by the travel times to each seismograph station and the velocity of the seismic wave through the earth. The velocity varies with depth. To calculate locations, a model of the velocity at different depths needs to be created. Any difference between the velocity model and actual velocities or lateral non-homogeneity in actual velocities can result in errors in the location.

Depths of the events were difficult to determine due to the distance to the nearest recording station and the shallow depths involved. According to UUSS seismologists, in order to accurately determine the depth of a seismic event, a seismograph station is generally needed at a distance less than or equal to the depth of the event. Because the depth of the August 6, 2007, accident was approximately 2000 feet, and the nearest station was approximately 11 miles away, the initial calculated depths were uncertain.

The UUSS deployed five additional portable units to the site to improve their ability to locate seismic events. Installation of the portable units began on August 7 and was completed on August 9, 2007.

A review of the seismic data revealed that several seismic events could be correlated to coal bursts that were observed underground. Known locations could be used to reduce the effect of errors in the velocity model, thus improving the accuracy for locating other events. Therefore, MSHA provided Dr. Pechmann of the UUSS with the known location of the August 16, 2007, accident to use as a fixed point to improve the locations for the other events. Two different methods were used by UUSS to improve the locations.

The first method was the calibrated master event method. In this method, corrections were made to the arrival times to fit the August 16 event to the known location. For each other event, the corrections were applied and new locations calculated. These corrections were applied to 189 recorded events going back approximately two years to August 2, 2005. This method relocated the August 6, 2007, event to the North barrier section at approximately crosscut 149.

The second method used by UUSS was the double difference method. This method determines the relative location between multiple events by minimizing differences between observed and theoretical travel times for pairs of events at each station.²⁵ Only 150 of the 189 events could be located using this method. Figure 106 shows the progressively refined locations for four selected events together with their known locations and the calculated locations for the August 6, 2007, accident. Shown on the figure are the initial standard locations, the locations as revised by the

master event method, and the locations as revised by the double difference method. As shown on the figure, the double difference locations match the known locations most closely. The location for the August 6 accident is given at the No. 3 entry of the South Barrier section between crosscuts 143 and 144. The August 6 accident was known to extend over a wide area. Because locations of seismic events are determined by the first arrival of the seismic waves, only the location of the initiation of the August 6 accident can be calculated. Therefore, the location shown indicates where the event began, not the center of the event.

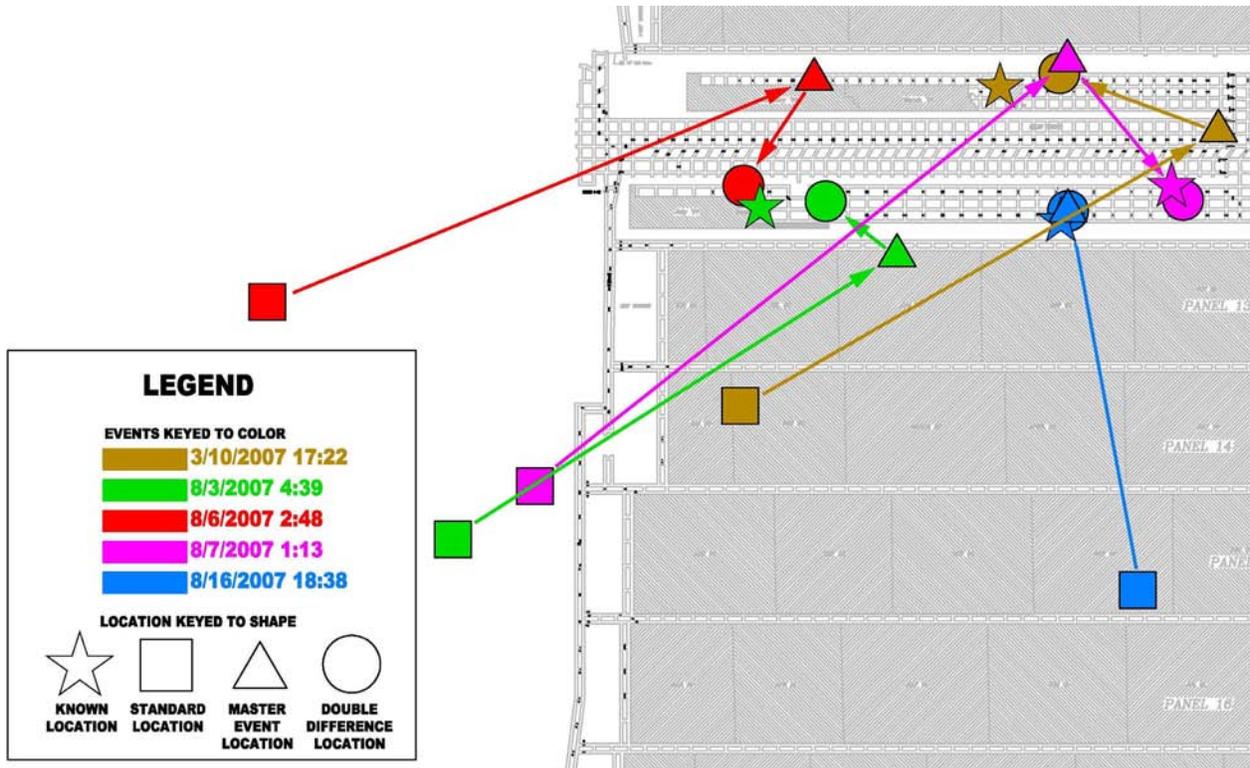


Figure 106 – Locations of Selected Events showing Progressive Refinements Using Three Methods

A review of mine records and records from the rescue and recovery operations revealed that ten events were both noted underground and recorded by the USS. Figure 107 shows the high degree of correlation with the underground locations and the double difference locations calculated by the USS. This provides some measure of the accuracy of the locations. Only the location of the August 16, 2007, accident had been provided to the USS. Excluding the August 16 accident event that was used for calibration, the mean distance between the reported locations and calculated locations was 450 feet. The median distance was 421 feet.

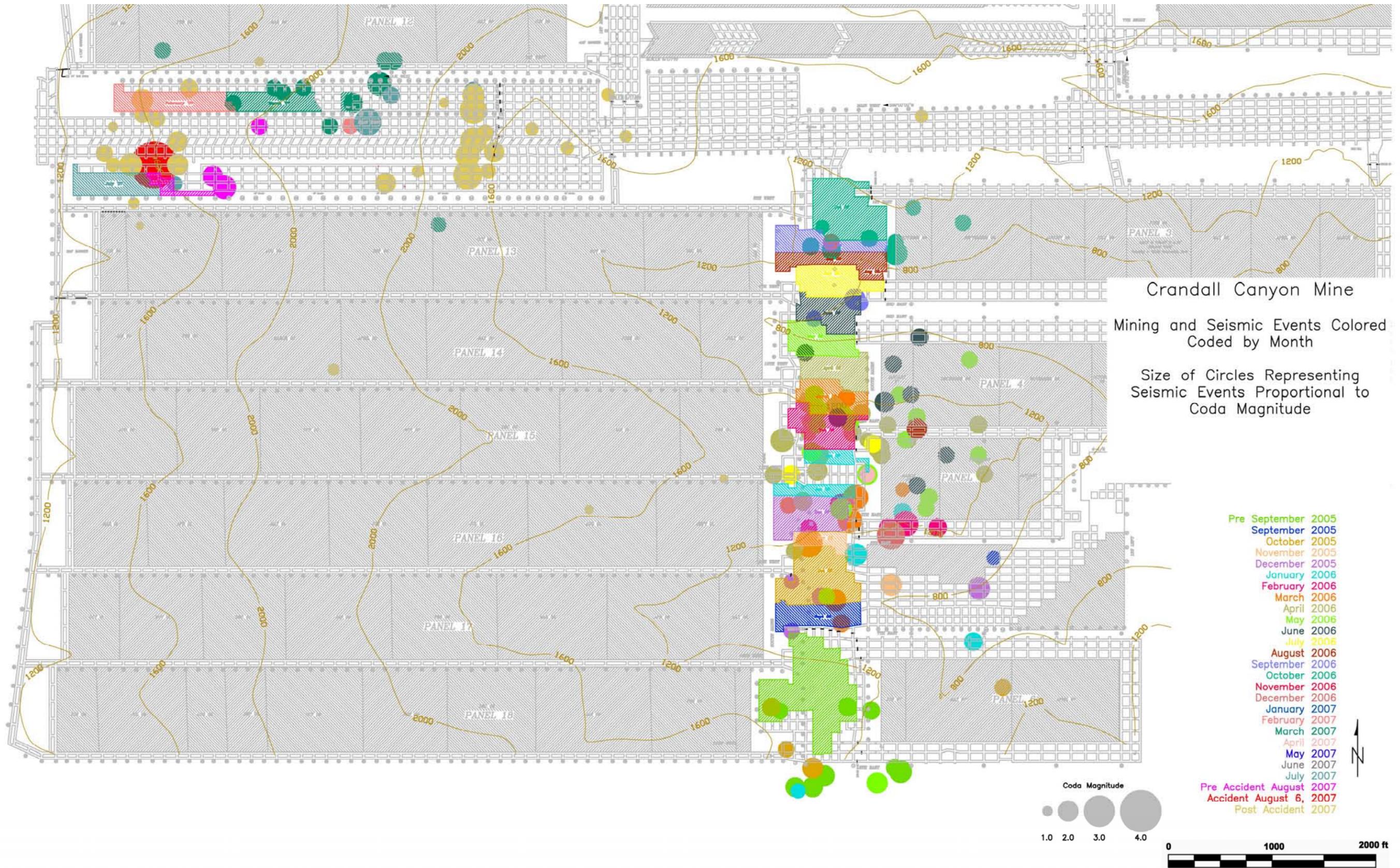


Figure 108 - Calculated Double Difference Locations and the Location of Mining Color Coded by Month

Figure 108 shows all of the calculated double difference locations and the location of mining activity color coded by month. The symbols are sized according to the coda magnitude of the events. The double difference locations show a high degree of correlation with pillar recovery mining in South Mains and the Main West barriers.

Figure 109 shows the seismic location of the August 6, 2007, accident in red. The events occurring after the accident on August 6 and 7 are shown in tan. Events occurring on August 8 to 27 inclusive are shown in blue. The locations of seismic events occurring on August 6 and 7 are notably clustered along a north to south line near crosscut 120 of the South Barrier section. The location corresponds with the outby extent of the collapse in the South Barrier section as determined by underground observation in the South Barrier section entries and Main West inby the breached seal. The seismic events extend from the South Barrier to the North Barrier. The initiation point for the collapse is located at the western boundary of the area. The collapse would have progressed to the east. The continuing events may have been the result of residual stress at the edge of the collapsed area. The events colored in blue occurred later and may represent settling at the west end of the collapse area.

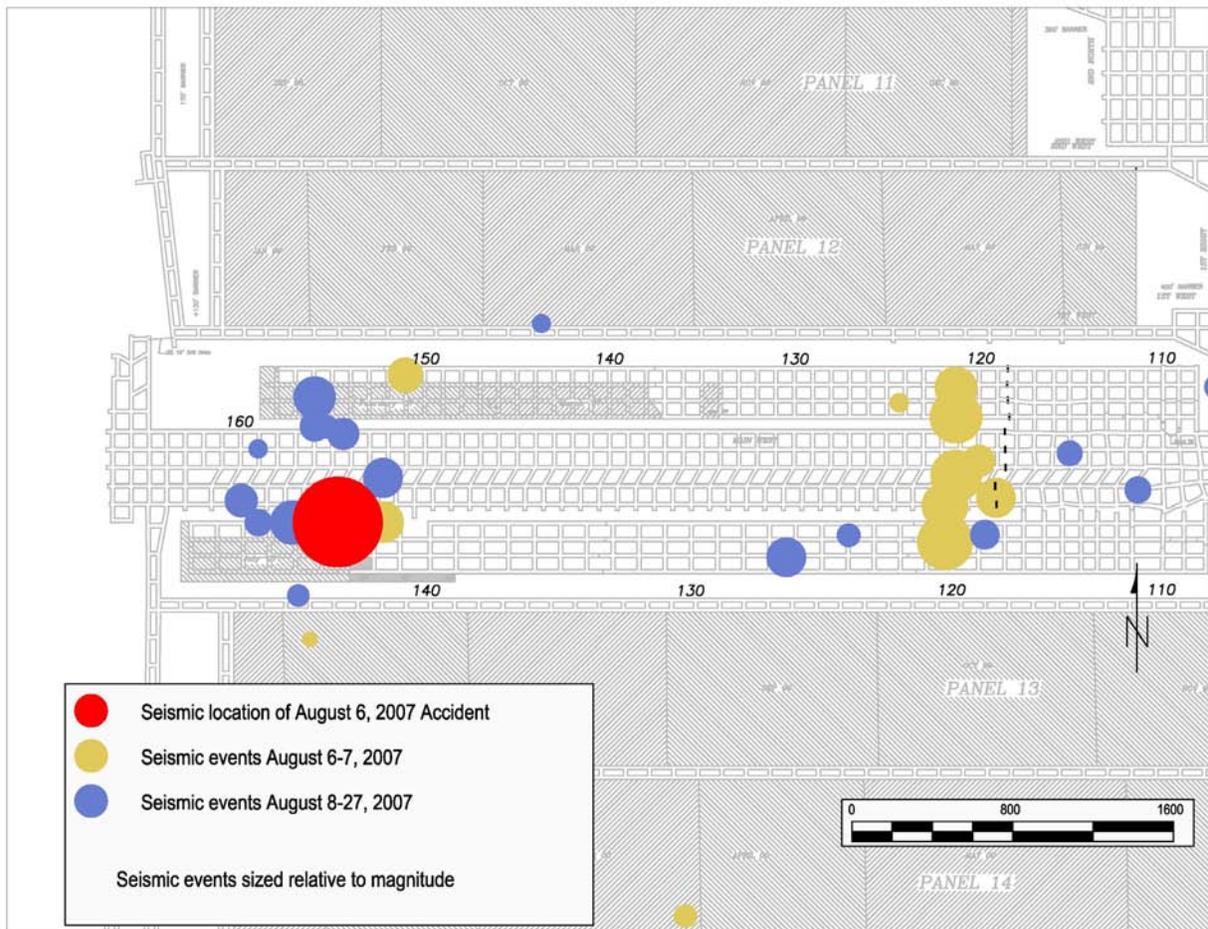


Figure 109 – Seismic Location of the August 6 Accident and Following Events

Analysis of the Seismic Event

The ground motions produced by the August 6, 2007, event were recorded on the UUSS seismographs. Earthquakes produce body and surface waves. Body waves travel through the interior of the earth. P-waves or primary waves and S-waves or secondary waves are types of body waves. P-waves are also known as compressional waves and consist of particle motion in

the direction of travel. P-waves travel faster than any other type of seismic wave and are the first to arrive at a seismograph station after an event.

A typical tectonic earthquake produced by a slip on a fault will result in part of the earth being placed in compression and part in dilation. This type of movement will typically generate P-waves with the initial or first motion on a vertical component seismograph in an upward direction or in compression at some locations and P-waves with a downward first motion or dilatation at other locations.

An analysis of the seismograph recordings from the August 6, 2007, event indicated that the initial or first motion recorded on a vertical component seismograph was downward in all cases (Pechmann 2008)². This is characteristic of a collapse or implosion. Coal mining-related events are commonly collapse type events where caving or a coal burst has sudden roof-to-floor convergence. The lack of compressional or upward first motions is highly suggestive of a collapse but not conclusive. It may be possible that some upward first motions may have been missed. Figure 110 is a simplified diagram illustrating the types of motions expected for mine collapse and normal-faulting earthquakes.

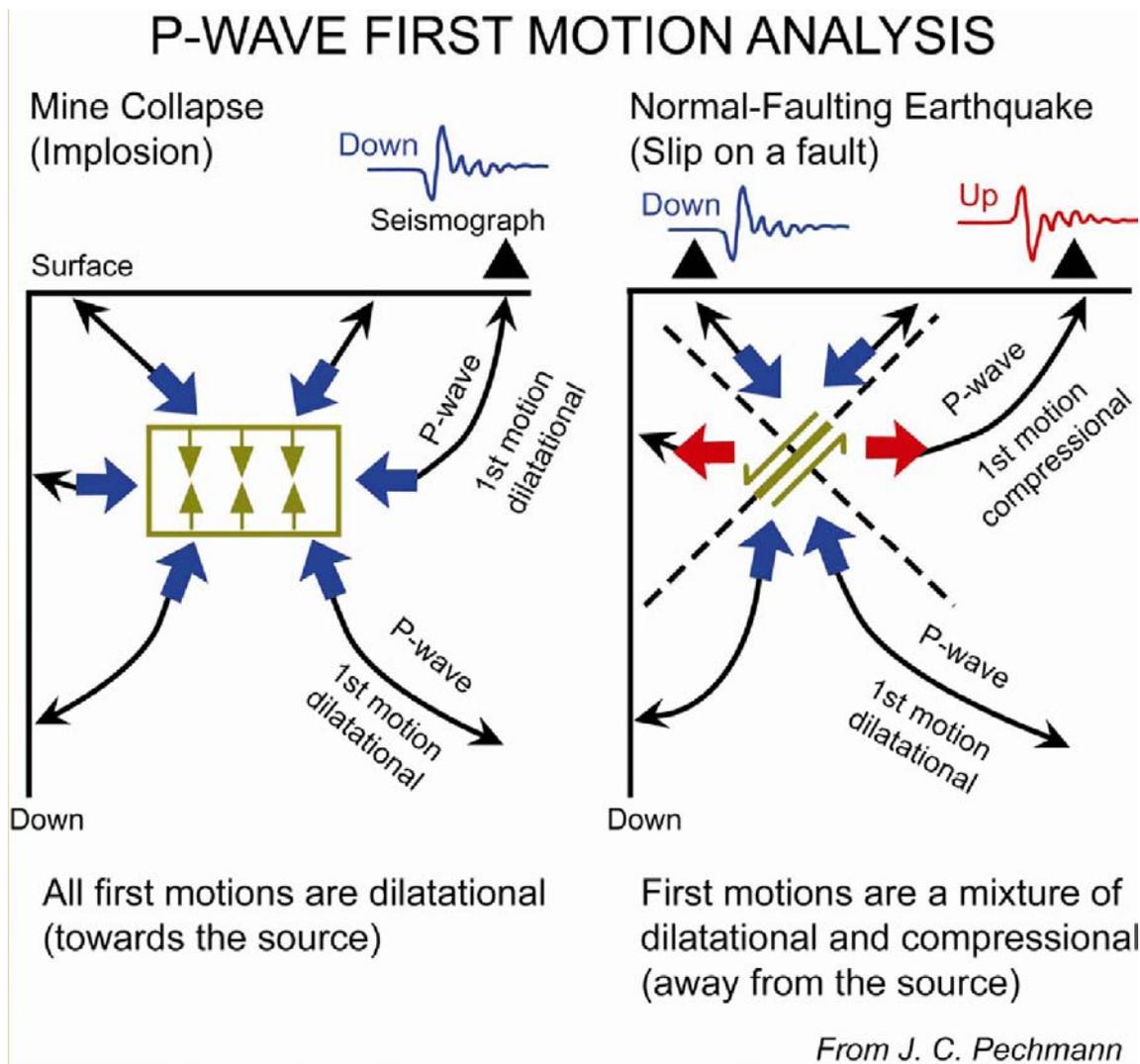


Figure 110 - P-Wave First Motion Analysis Examples
(from W. Arabasz presentation to Utah Mining Commission, November 2007)

Figure 111 shows the seismograph stations in place around the mining district as well as seismic waveforms of the vertical component from selected stations for the August 6, 2007, event. The waveforms are not shown to scale and are intended only to illustrate examples of first motions.

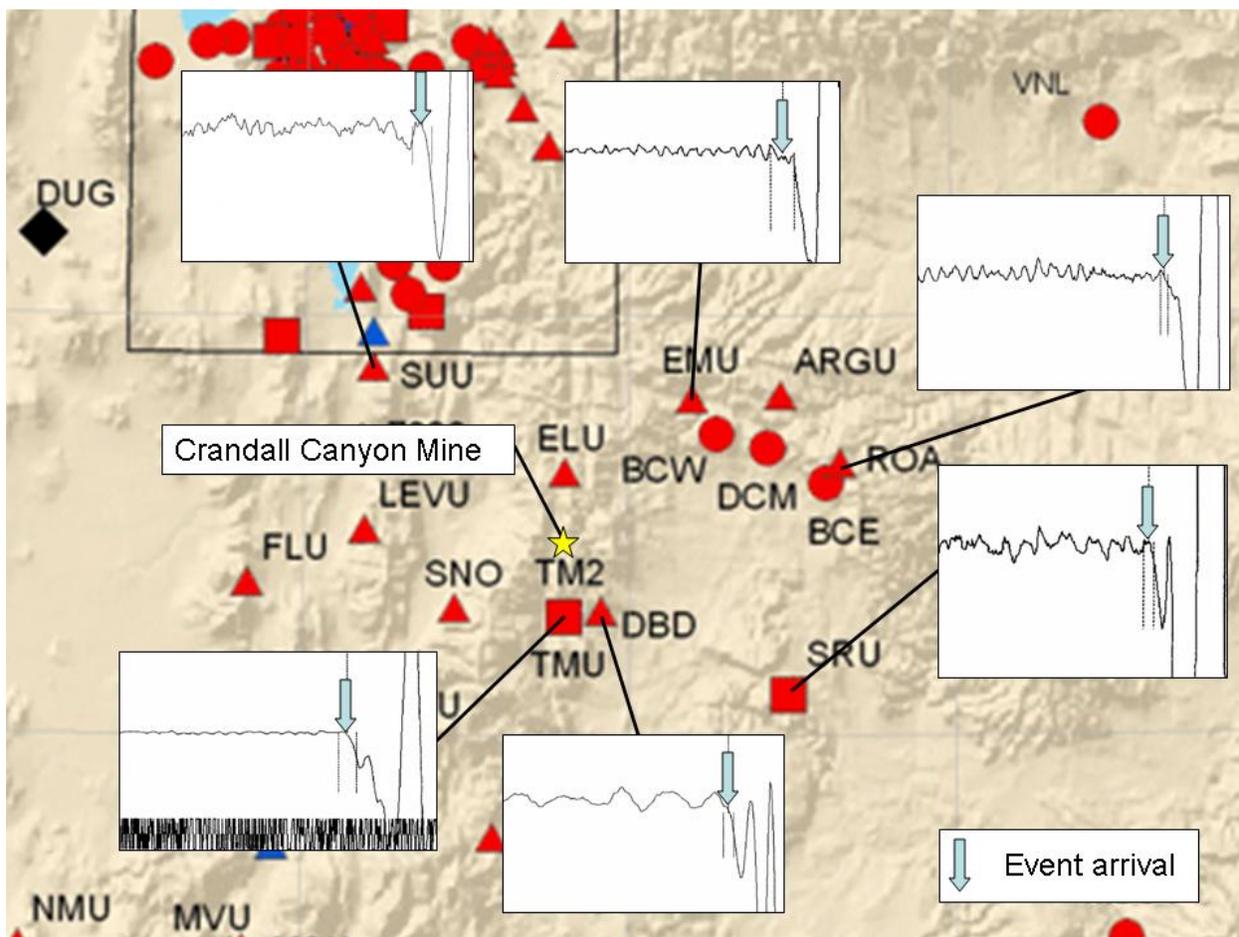


Figure 111 - Vertical Component Waveform Data for August 6, 2007 Event

The source mechanism of a mine collapse involves a change in volume at the source and is unusual compared to fault slip sources where the primary movement is slipping with no change in volume. These unusual mine collapse occurrences are of particular interest to persons engaged in monitoring to ensure compliance with the nuclear Comprehensive Test Ban Treaty. Considerable effort has been expended to distinguish man-made events from naturally occurring tectonic earthquakes.

As early as August 9, 2007, scientists at the University of California at Berkeley Seismological Laboratory and the Lawrence Livermore National Laboratories studied the data and prepared a report titled “*Seismic Moment Tensor Report for the 06 Aug 2007, M3.9 Seismic event in central Utah*” that was made available on the UUSS website. A paper based on this analysis titled “*Source Characterization of the August 6, 2007 Crandall Canyon Mine Seismic Event in Central Utah*” also has been prepared³. The techniques employed in this analysis are beyond the scope of this report. However, the results can be summarized by Figure 112, reproduced from their paper, which shows seismic events plotted according to their source mechanism. The term DC refers to a double couple of forces or opposing forces which create shear or slip type movement resulting in natural earthquakes with no change in volume. The data for the August 6, 2007 event is shown as the red star. Its location characterizes it as an anti-crack or closing crack. This

would be consistent with an underground collapse. Natural or tectonic earthquakes plot near the center of this diagram. The orange star represents a natural tectonic earthquake of similar size that occurred on September 1, 2007 near Tremonton, Utah. The August 6 event is clearly outside this area. The explosion plotted in the figure was a nuclear test explosion. The three other collapses plotted were two trona mine collapses in Wyoming and a collapse of an explosion test cavity.

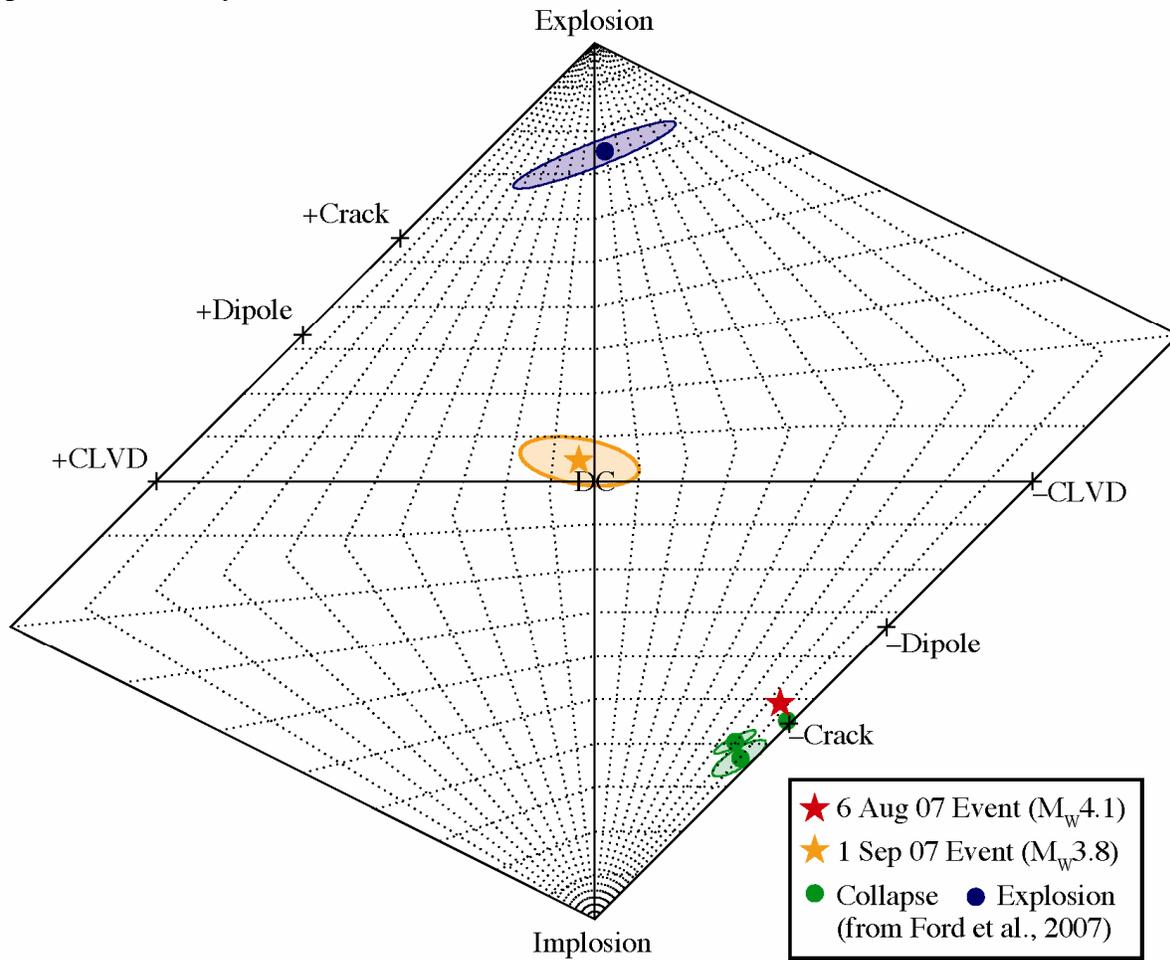


Figure 112 - Source Type Plot from Ford et al. (2008).

An analysis of the source depth for the August 6 event was conducted by Ford et al. (2008). Different depths for the event were assumed and the source type and variance reduction were calculated. Variance reduction is a measure of fit; the greater the reduction, the better the fit. Figure 113 shows the variance reduction results from the analyses in the inset box and the source type for the different assumed depths. As indicated, the shallowest depths (shown in red) result in the best fit. Even at depths up to 5 km, the source type remains as a closing crack and does not indicate the double-couple mechanism typical of natural tectonic earthquakes.

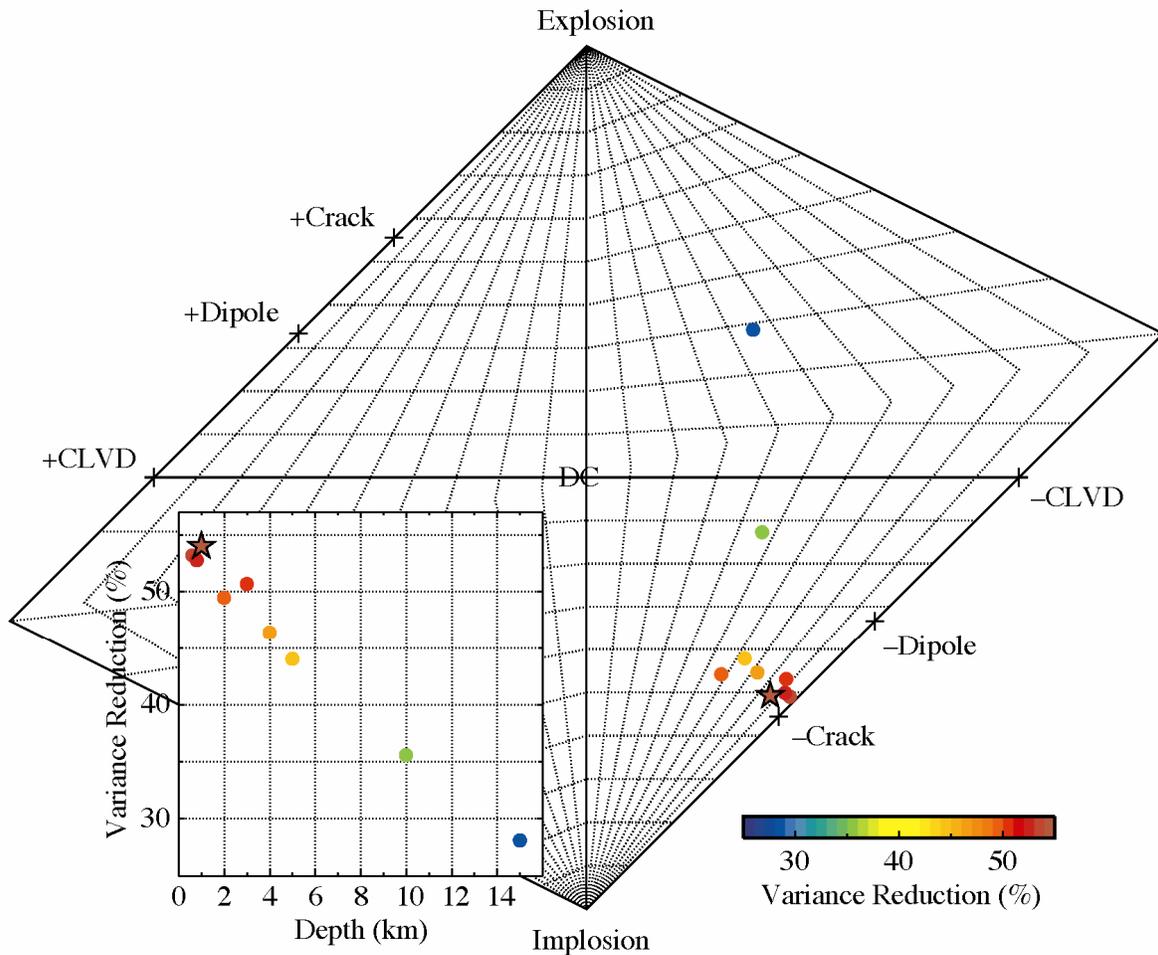


Figure 113 – Depth Analysis of August 6, 2007 event from Ford et al 2008.

Ford et al. (2008)³ noted that while the primary and dominant source mechanism was a closing crack, the seismic record could not be explained by a pure vertical crack closure alone. Love waves that have motion horizontal to the direction of travel were present and can not be produced by the vertical closure. Possible explanations offered included that the collapse was uneven or that there was sympathetic shear on a roof fault adding a shear component to the collapse.

Pechmann et al. (2008)² similarly noted that while the event was dominantly implosional, there was a shear component. The most likely explanation offered was slip on a steeply dipping crack in the mine roof with a strike of approximately 150 degrees and motion downward on the east side.

Given that the event initiated at the west edge of the collapse area and seismic events occurred in the following 37 hours at the east edge of the collapse area (see Figure 109), the most likely explanation is that the event began at the western edge of the area and progressed eastward. The eastern edge, where the collapsed stopped, would have resulted in residual stress at the cantilevered edge and continued seismic activity.

Additionally, careful examination of the seismic waveforms by the USSS did not reveal any indication of an event immediately preceding the main August 6, 2007 event. There was no evidence that the collapse was caused by an immediately preceding natural occurring event.

Duration of Seismic Events

It was initially reported in the media and by others that the August 6, 2007, event lasted four minutes. According to UUSS seismologists, the recorded length of vibratory motion of a seismograph will be orders of magnitude longer than the actual duration of the seismic source event. This is due to the arrival of seismic waves from many different and indirect paths. For example, the August 16 event generated one seismic record 63 seconds long² when the actual event was nearly instantaneous.

It is not straight forward to estimate the duration of a source event from the seismic record. The duration of the August 6 accident can be estimated by eye witness reports. One witness stated that the mine office building shook for several seconds and the shaking subsided quickly. None of the smaller events was reported to have any significant duration by underground witnesses. The building shaking may represent the collapse event and residual vibrations. The best estimate for the duration of the August 6, 2007, event is a few seconds.