The Unique Source Mechanism of an Explosively Induced Mine Collapse

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ABSTRACT

Mining explosions and collapses, in addition to earthquakes, may trigger the future Comprehensive Test Ban Treaty (CTBT) monitoring system. Most naturally occurring mine collapses have source mechanisms similar to a closing void which might provide a physical basis to discriminate them from explosions.

In this study, an explosively induced mine collapse is investigated. The collapse occurred immediately after the support pillars of an underground mine opening were destroyed by explosives. We estimated the time-dependent source moment tensor of the collapse by inverting the surface ground motion data (<1200 m). The results indicate that the source mechanism of the collapse can be represented by a horizontal crack. A unique source characteristic of the induced collapse is that, unlike natural collapses, the induced collapse initiated as a tensile crack. Because of the initial expansion source mechanism, induced mine collapses may pose some difficulties to the seismic discrimination problem. On the other hand, the collapse has a more band limited source spectrum than a typical underground explosion.

Key Words: explosively induced, mine collapse, tensile crack, expansive

OBJECTIVE

The objective of this study is to understand the source mechanism of an explosively induced mine collapse which generated regional seismic signals (Pearson *et al.*, 1996). These kinds of events are of interest to the monitoring of a Comprehensive Test Ban Treaty (CTBT) because of their similar source characteristics to underground explosions and their ability to trigger the CTBT monitoring system.

RESEARCH ACCOMPLISHED

Experiment and Data

Data used in this study were collected in a controlled field experiment conducted at the White Pine Copper Mine near Lake Superior on the Upper Peninsula of Michigan. Figure 1 is the map showing the location of the mine. The plan view of the test area and the layout of a

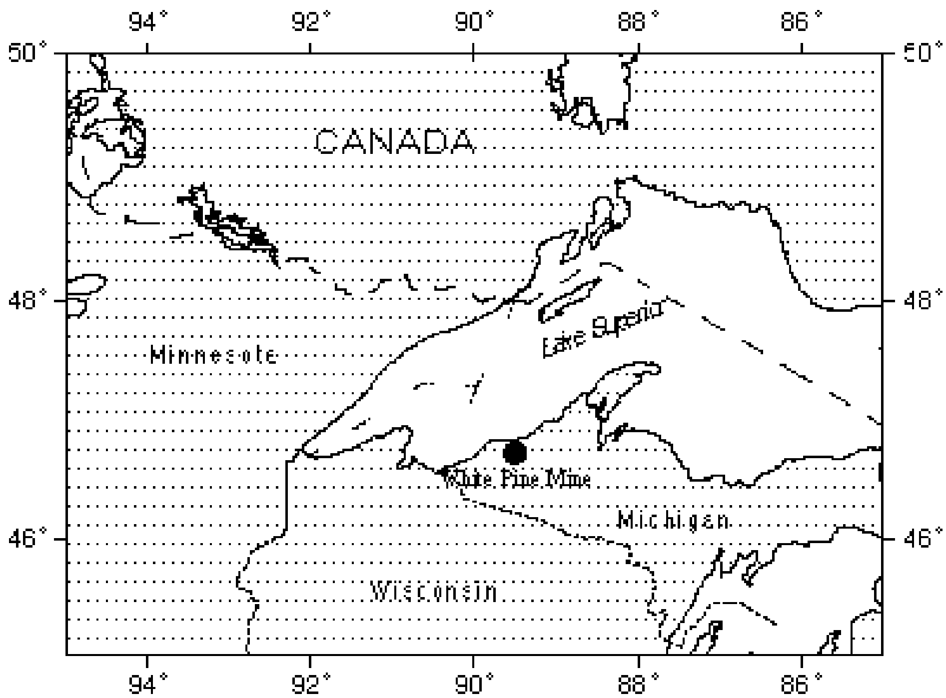

Figure 1 Location of the mine where the explosively induced collapse experiment was conducted.

near-source, surface, three-component seismometer array are presented in Figure 2. The horizontal and slant source-receiver distances and receiver azimuths are listed in Table 1. Detailed documentation of the mine, the experiment and the data acquisition can be found in Pearson *et al.* (1996).

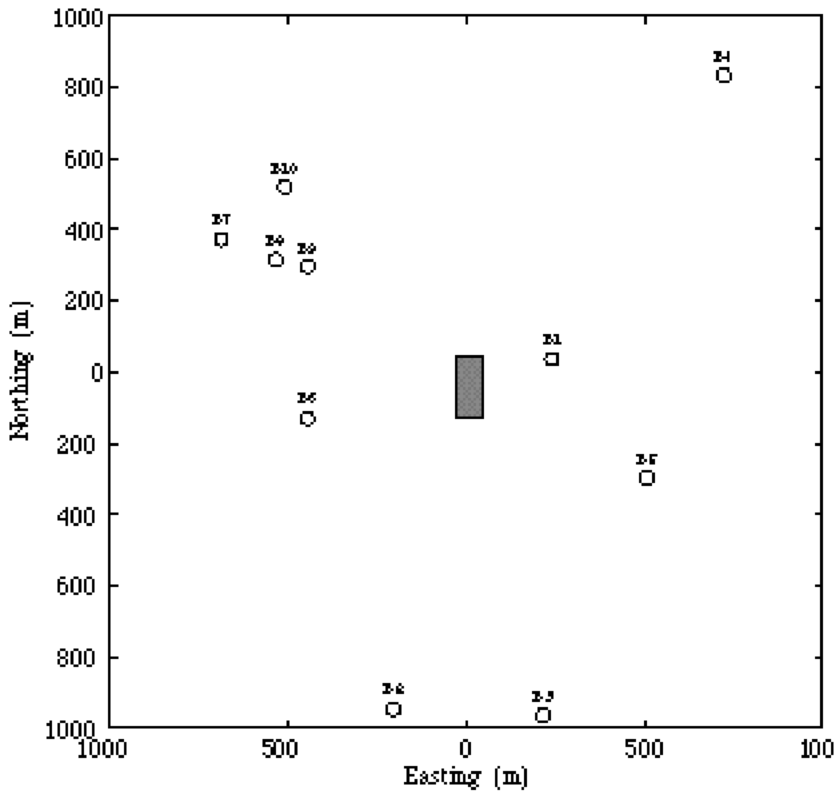

Figure 2 Plan view of the test area. The rectangle marks the collapsed panel. Instrument array is indicated by the open circles.

The section of the underground working designated for the experiment was a rectangular panel at 320 m depth. The area was roughly 20000 m^2 with a room height of 3 m. During the experiment, explosives were emplaced in the supporting pillars in the section and detonated. The pillars were destroyed by the explosion and the roof collapsed a fraction of a second after the explosion. A millisecond-delay firing pattern, 325 ms in length, was used to minimize ground vibration.

Ground motion from the collapse was recorded by the seismometer array and transformed into vertical, radial and transverse components. Instrument response was removed from the data. Figure 3 shows an example of the data set and its spectra.

Table 1 Source to receiver distances and receiver azimuths from north

Receivers	Slant distance (m)	Horizontal range (m)	Azimuth* (°)

B1	402	244	81.3
B2	1018	967	192.1
B3	1039	988	167.4
B4	1149	1104	41.0
B5	669	588	120.3
B6	563	463	253.7
B7	843	780	298.4
B8	698	620	300.6
B9	623	534	303.7
B10	793	726	315.6

* measured with reference to the center of the array of pillars

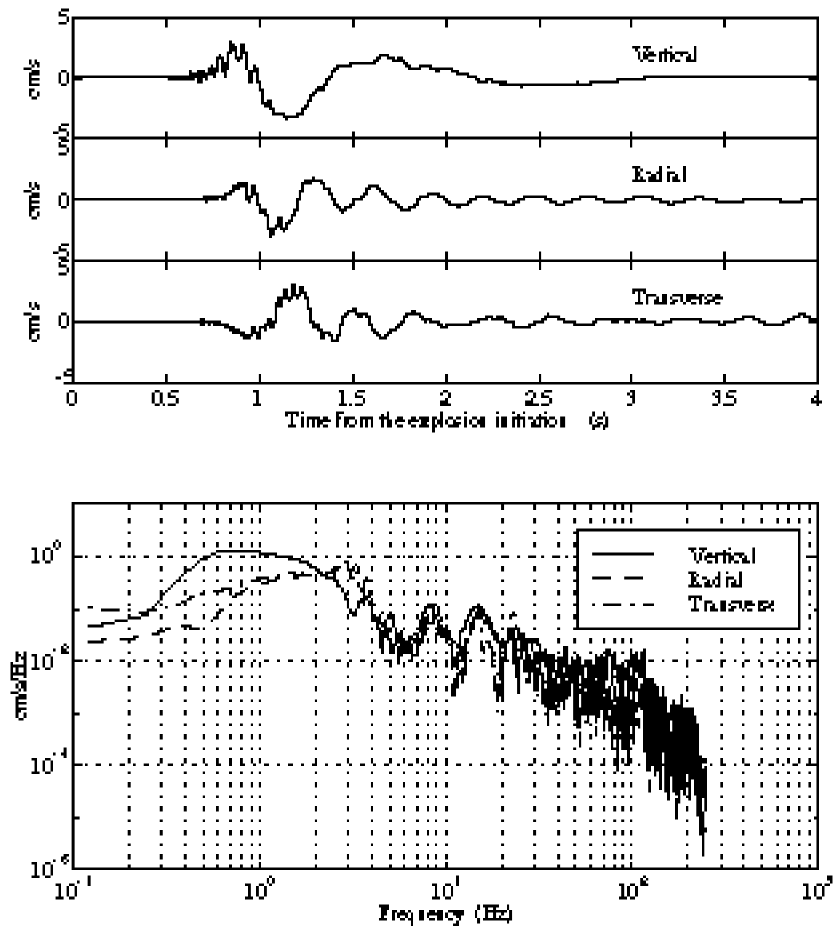

Figure 3 Ground velocities recorded at station B1 and their spectra.

Source Moment Tensor Inversion

To investigate the source characteristics of the induced mine collapse, we estimated second order source moment tensor of the collapse with the linear inversion method described by Stump and Johnson (1977). The basic assumption behind the moment tensor representation is that the wavelength of interest is much longer than the dimension of the source so that the source can be treated as a point source. In our case, the dominant wavelengths of the source signal are between 1600 and 2900 m, 8 to 14 times longer than the dimension of the source, thus satisfying the point source assumption.

The inversion was performed in the frequency domain to take advantage of the linear relationship between the source and observations, thus recovering source phase and modulus. Green's functions were calculated with the velocity model listed in Table 2. The velocity model was derived from the results of a reflection survey (Geosphere, 1995) and aftershock P and S arrival times. The singular value decomposition method (Lanczos, 1961) was employed to solve the set of equations relating the source moment tensor to the ground motion. The time dependent source moment tensor of the induced collapse was recovered by the inverse Fourier transform of the frequency domain results and is presented in Figure 4.

Table 2 Velocity model used in the inversion

Thickness (m)	V_p (m/s)	V_s (m/s)	ρ (g/cm^3)
140	3660	2000	2.2
180	4270	1800	2.5
∞	5460	3070	3.2

The moment tensor is dominated by its diagonal components. On average, the amplitudes of the off-diagonal components are only about 13% of the amplitudes of the diagonal components. Among the diagonal components, the vertical dipole M_{33} is the largest. These moment tensor components are consistent with a horizontal crack model. The diagonal components of the moment tensor estimates have similar time histories. They have sinusoidal behavior with a period of about 0.8 s. The first motions of the time histories are all positive which imply an initially expanding source.

The isotropic spectrum of the time derivative of the moment tensor, or the moment rate tensor, was calculated as the trace of the moment rate tensor spectra and is shown in Figure 5. Unlike the typical explosion source spectrum, the collapse spectrum is peaked at 1 Hz. The corner frequency is not well defined. This peaked nature corresponds to the sinusoidal behavior of the moment tensor in the time domain.

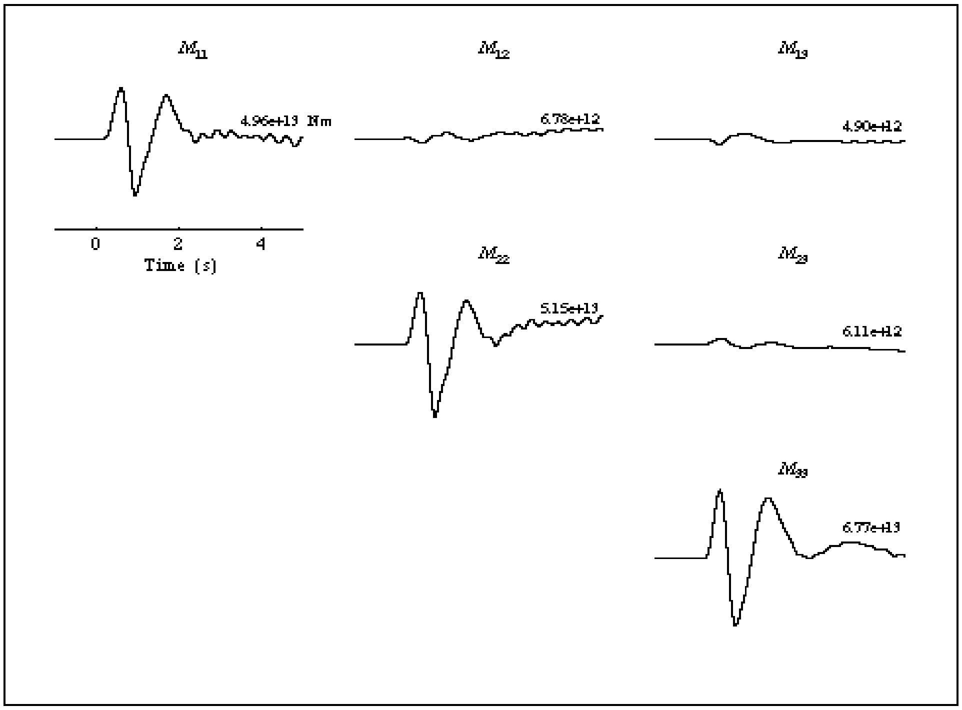

Figure 4 Source moment tensor estimates of the induced mine collapse. The maximum amplitude of the first positive peak in each component is labeled above the component.

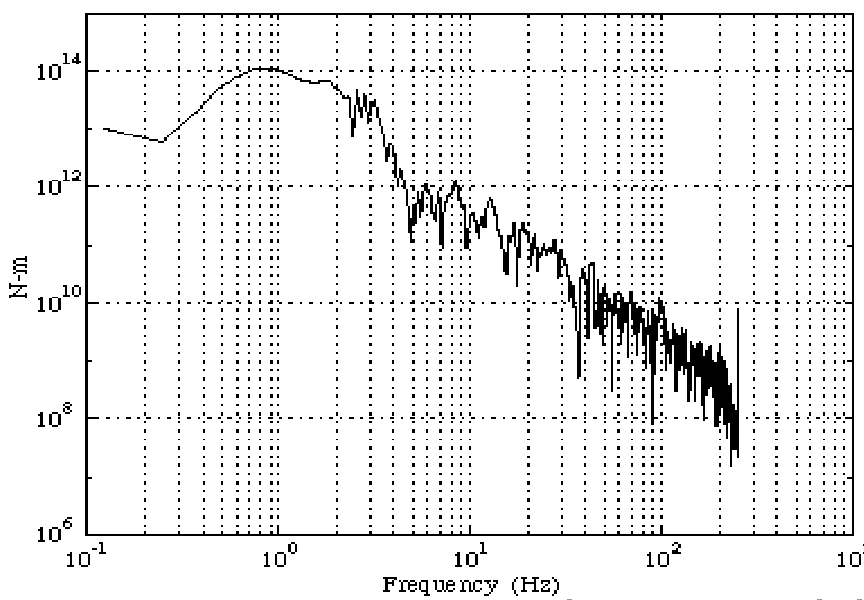

Figure 5 The isotropic source moment rate spectrum. The spectrum is peaked at about 1 Hz. Ground noise analysis indicates that the amplitude increase below 0.2 Hz is probably noise related. High frequency spectrum is estimated to decay as f^{-2}.

Interpretation and Discussion

The moment tensor estimates are dominated by the diagonal components and the time histories of the diagonal components are in phase with one another, suggesting that the induced collapse behaved like a volumetric source. The source is not completely isotropic. The vertical dipole, M_{33}, is the largest among the diagonal components while the amplitudes of the two horizontal diagonal components are about the same, consistent with a horizontal crack model.

One phenomenon particular to this induced collapse is that the source is initially expansive with all diagonal moment tensor components positive. Different results have been obtained in the natural collapse studies (Stump, 1979; Walter *et al*., 1996) . For example, Stump (1979) estimated the source moment tensor of a cavity collapse following an underground nuclear explosion. His results suggested negative first motions for all the diagonal moment tensor components (Stump, 1979; Fig. 7-23).

We reviewed the ground motion data from a natural underground mine collapse. The collapse occurred in a coal mine which employed the long-wall mining method at the depth of about 350 m underground. The collapse was an integral part of the mining activity (Walter *et al.*, 1996). The vertical component seismograms from the collapse recorded by a small aperture array are reproduced in Figure 6. Receivers in the array were distributed along the circumference of a

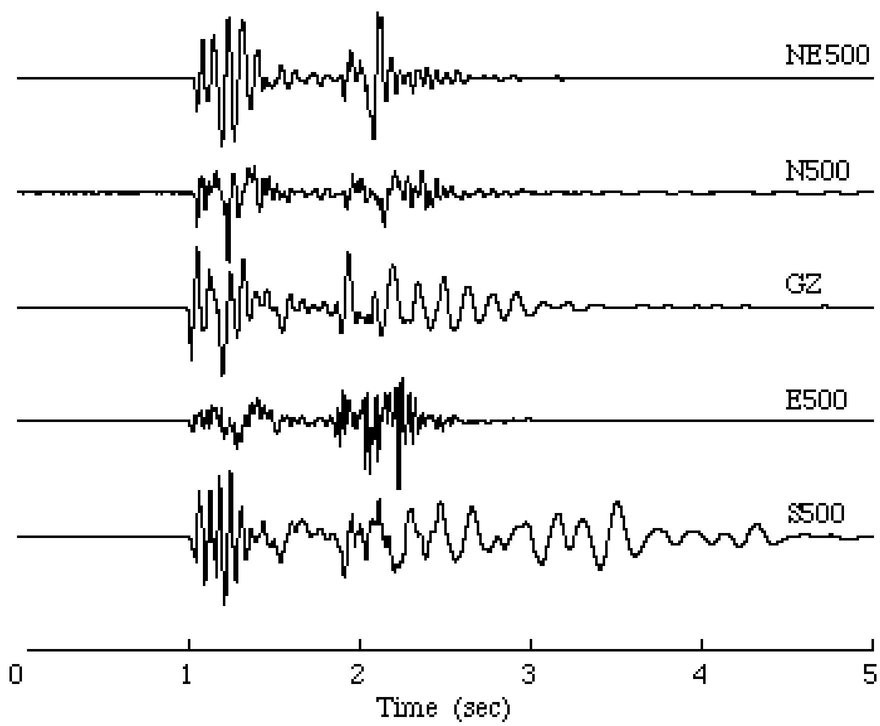

Figure 6 The vertical component near-source seismograms from a natural mine collapse. Station names are written above the corresponding records. Data are from Walter *et al.* (1996).

circle, 500 m in radius, with one receiver, GZ, at the center. The collapse was believed to have occurred under receivers NE500, N500 and GZ, and the hypocenter was shallow (< 500 m) (Walter *et al*., 1996). The coda magnitude of the collapse is 2.8. In contrast to the positive vertical first motions recorded from the induced collapse (Figure 3), the vertical first motions from the natural collapse are all sharply negative. Near-regional records from these two types of collapses also show opposite first motion polarities: positive for the induced collapse and negative for the natural collapse (Figure 7).

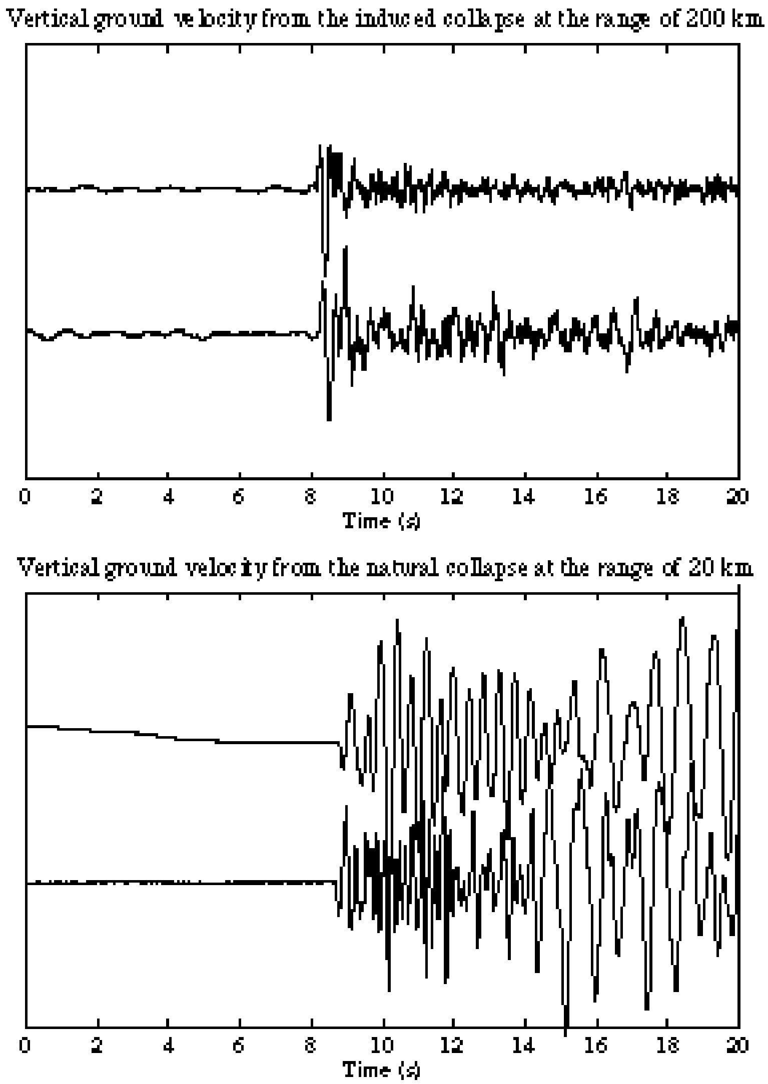

Figure 7 The vertical seismograms from the induced collapse and the natural collapse recorded at near-regional distances. Natural collapse data are from Walter *et al.* (1996).

The discrepancies observed between the explosively induced collapse and natural collapses may reflect differences in the source processes of these two categories of collapses. One possible difference is that in natural collapses, the failure process of the collapsed material takes a relatively long time because of the static loading of the collapsed material, while the material failure in an induced collapse is almost instantaneous due to the dynamic loading. In a natural collapse, after the cavity is excavated, the weight of the collapsed mass and the traction imposed by the surrounding medium are in equilibrium at first. Then micro-cracks form gradually due to small perturbations to this equilibrium. The time it takes for the material to reach its final failure as the cracks form may be far below the lowest observable frequency with seismic instruments. On the other hand, during an induced collapse, after the instant loading of the collapsed mass due to pillar removal, the equilibrium may never be realized and cracks form rapidly. The material failure threshold is reached in a time period within the observed seismic frequency band. This crack forming process can be modeled as an opening crack with a volumetric expansion, although in a natural collapse, its period is too long for it to be observed.

Based on this argument, we propose a source model for the explosively induced collapse which is shown diagramatically in Figure 8. First the source is modeled as a vertically opening crack representing the failure process of the collapsed mass. Then the collapsed mass enters free fall and finally impacts the rest of the medium. The basic difference between this model and previous natural collapse models used by other investigators (Taylor, 1994; Pechmann *et al.*, 1995) is the inclusion of the opening crack which seems to have significant contribution to seismic wave generation. The moment tensor representation of this source model would be similar to that of the spall model accompanying an underground explosion although the crack opening and closing do not occur at exactly the same depth in a collapse.

By including the opening crack as an effective seismic source process, we can explain the initial expansion of the source estimates obtained in the inversion and the compressional first motions observed in the data.

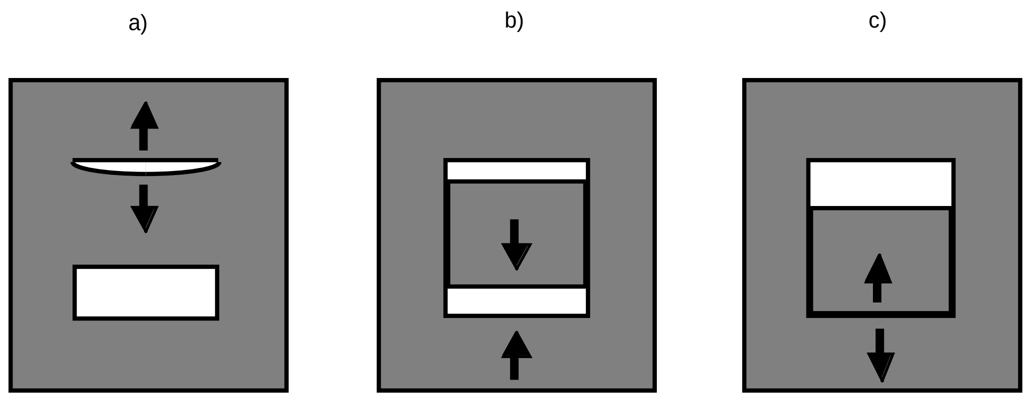

Figure 8 An induced collapse source model. The process undergoes three phases. a) Due to the sudden loading of the collapsed mass after pillar removal, an opening crack forms; b) The collapsed mass is detached from the rest of the medium and goes into free fall; c) The collapsed material rejoins the medium.

CONCLUSIONS AND RECOMMENDATIONS

The source characteristics of an explosively induced mine collapse were investigated with source moment tensor inversion. The results indicate that the source characteristics of the collapse is similar to that of a horizontal crack.

The time histories of the moment tensor estimates illustrate an initial expansion at the beginning of the source. This phenomenon and the observation that the first motions of the observed data are compressional everywhere are in conflict with the implosional nature of traditional collapse models. To explain this, we propose an induced collapse source model which includes an opening crack at the beginning of the source. With this model, the moment tensor time histories recovered by the inversion and the compressional first motions observed in the data can be explained. Because of the initial expansion and volumetric source characteristics of the explosively induced collapse sources, this kind of source may further complicate the discrimination problem. On the other hand, the peaked nature of the isotropic moment rate spectrum could be a diagnostic signature of collapses.

This study is the case study of one explosively induced mine collapse. More analyses on these kind of collapses are needed in order to validate the conclusions reached in this study. The results can be applied to regional distances to investigate the effects of different source models on regional observations.

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