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Seismic Signals from Underground Cavity Collapses and Other Mining-Related Failures

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ABSTRACT

The sudden collapse of man-made underground cavities have generated seismic signals as large as magnitude 5.4. Collapses are just one of the many types of mining associated seismicity including coalbumps and rockbursts which need to be identified and distinguished from potential clandestine nuclear explosions under the recently signed Comprehensive Test Ban Treaty (CTBT). Collapses, coalbumps and rockbursts are of concern for seismically monitoring a CTBT for a number of reasons. First, they can look like explosions when using some seismic discriminant measures, such M_s:m_b, M_o:m_b regional P/S ratios and depth. Second, underground nuclear explosions themselves produce cavities that might collapse, possibly aiding in the detection of a clandestine event. Finally, because all mine-related events occur in the vicinity of underground cavities, they may come under special scrutiny because of the concern that very large, specially constructed cavities could be used to evasively decouple a clandestine test. For these reasons mine-related seismicity in both active and former mining regions have the potential to be false alarms under a CTBT.

We are investigating techniques to identify collapses, either directly via waveform modeling, or indirectly by combining several seismic discriminants. We are also investigating the source mechanisms of coalbumps and collapses to better understand the performance of seismic discriminants for these events. In particular we have found similarities in point source models of some longwall coalbumps, room-and-pillar mine collapses and NTS nuclear explosion cavity collapses. In order to understand coalbumps we are analyzing events from central Utah recorded at regional distances in Utah and Nevada including at the auxiliary station ELK. Some of these have anomalous, explosion-like high frequency P/S ratios. We are combining this new study with results from previous field work done in 1995 at a Colorado long-wall coal mining operation. Similarly to longwall coal mines in Utah and elsewhere, this Colorado mine completely excavates a 3m high coal seam in 250 m wide panels leaving the material above unsupported. The roof material above the excavated seam eventually collapses resulting in seismic events.

Key Words: seismic, source, collapse, mining, discrimination, coalbump, rockburst

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OBJECTIVES

To reduce potential seismic false alarms under the Comprehensive Test Ban Treaty (CTBT) by improving our understanding and ability to uniquely identify mine-related seismicity from coalbumps, room-and-pillar collapses and rockbursts. To better understand and discriminate post-nuclear-test cavity collapses from industrial mine-related seismicity.

RESEARCH ACCOMPLISHED

As part of the overall Department of Energy CTBT Research and Development program, LLNL is pursuing a comprehensive identification research effort to improve our physical understanding and ability to seismically characterize and discriminate potential underground nuclear tests from other natural and man-made sources of seismicity. Here we focus of understanding and discriminating mine-related seismicity and underground cavity collapses. We present preliminary results in three parts: 1) Mechanisms for underground cavity collapses from both large accidental mine failures and post-nuclear shot collapses via waveform modeling; 2) Investigation of longwall coal mine seismicity in Colorado and Kentucky; 3) Investigation of discriminant performance of central Utah coalbumps.

Point Source Mechanism from the Collapse of Underground Cavities

Ground failures in underground mines are examined and categorized in quite different ways by mining engineers and seismologists. Mining engineers distinguish events based on rock type (hardrock rockbursts vs. coal bumps); by whether the event was planned (first caves, block caves, controlled pillar failure) or not (rockbursts, coal bumps, cascading pillar failure); and by whether any damage occurred in the mine. Seismologists distinguish subsurface mine events by their point source mechanism (e.g. Gibowicz, 1990; Knoll and Kuhnt, 1990; Wong and McGarr, 1990). Type 1 events, occur in the direct vicinity of mine openings and the source of energy is the rock mass at or surrounding the rock opening. These events tend to have a large implosional component leading to all dilatational first motions. Type 2 events are associated with shear slip along fault planes hundreds of meters to kilometers way from mining. They have normal earthquake focal mechanisms. Discrimination of type 1 and 2 is non-trivial and depends critically on being able to resolve the precise location of the event and the focal mechanism of primary energy release. From the point of view of monitoring a CTBT, type 2 events are shallow earthquakes while type 1 events with their unusual mechanisms may pose more of a challenge to identify. This abstract focuses on Type 1 collapses.

Over the last couple years we have found that some of the largest known accidental mine collapses, reaching up to mb=5.4, can be well fit with a closing tensile crack point source mechanism. Examples include the February 3, 1995 Wyoming mine collapse (Pechmann et al. 1995); the January 5, 1995 event near the Urals in Russia (Walter, 1995) and the March 13, 1989 Volkershausen event in Germany (Bowers and Walter, manuscript in preparation). We have also found this model fits some of the larger coalbump events as will be discussed in the next section. We will show several examples at the meeting.

The closing tensile crack source is basically the same as the tabular collapse under gravity model used by Taylor (1994) for a Central Utah mine collapse near Gentry Mountain in 1984. The Taylor (1994) study reduced the collapse to vertically oriented point forces which can be shown to be mathematically similar to a shallow closing tensile crack (Day and McLaughlin, 1991). To examine the differences between pure implosional models and the closing crack models we examined a post NTS shot collapse (Walter, 1995). The 1982 NTS shot ATRISCO was followed twenty minutes later by a cavity collapse large enough to generate surface waves at near regional distances. Figure 1A shows the synthetic fits of a pure spherically symmetric explosion source to the explosions and a similarly good fit of the closing crack model to the collapse at the planned primary station MNV. Note that this closing crack mechanism differs from a pure implosion (the opposite of the explosion source) since the Mzz couple is larger in magnitude than the Mxx and Myy. Figure 1B shows a comparison of the data (left) and synthetics (right) for the explosion and collapse at the planned auxiliary station ELK. We have multiplied the by a negative quantity to match the Rayleigh waves. Note that the Pnl waves do not match up, as would be expected if the collapse were a pure implosion or negative explosion. The change in the Pnl comes from Mzz>Mxx=Myy in the closing crack or tabular collapse source. With a very well calibrated structure (or an explosion for comparison) this phase shift can be used to discriminate between pure implosional and closing crack models. In all the mine-related collapses examined so far the closing crack appear to fit better than a pure implosion.

Coalbumps from Longwall Mines

To learn more about the seismic characteristics of long-wall collapse events, LLNL designed and conducted an experiment in cooperation with the Cyprus Amax Company at their Twentymile Coal Mine (Walter et al., 1996). This longwall mine held the world record for monthly underground coal production (534,557 tons in September 1994), and set a new world record during our experiment in September 1995. The experiment consisted of an 11-station seismic deployment, covering the immediate vicinity of the mine and extending to a distance of roughly 100 km. We recorded all the seismicity associated with the mining of a new panel, beginning with the "first cave" of an estimated 25,000 m^2 roof panel, and continuing with the monitoring of aftershocks and subsequent collapses for an approximate 3 month period.

The Twentymile operation completely excavates the 3 meter (10 foot) high Wadge coal seam at a depth of approximately 350 m (1100 feet) underground in 244 m (800 foot) wide panels. The roof rock above the coal seam is supported hydraulically in the immediate vicinity of the area of active mining. The entire mining machinery moves forward as the coal is removed and the region behind the active mining is allowed to collapse as shown in Figure 2A. It is believed that the softer shale rocks collapse until reaching the more competent sandstone layers, which can support more weight. It is the failure of these sandstone layers that LLNL believes leads to the $M \approx 2\text{-}3.5$ seismic events which have been detected by the U. S. Geological Survey station 160 km away in Golden Colorado. These seismic events do not cause significant air waves underground and do not generally impede the operation of the mine. After failure of the sandstone layers, the collapsed zone spreads up to the surface, where the ground above the region that has been mined eventually subsides about 1.4 m (4.5 feet). This surface settling tapers near the edges and is not easily detectable by the naked eye (see Figure 2B), it would require a leveling survey or similar measurement to quantify. On the other hand, the thick outcropping Twentymile sandstone bed can exhibit distress due to the subsidence from the underground mining. This has taken the form of substantial cliff collapses.

During the experiment (August to November, 1995) LLNL recorded hundreds of seismic events.. The largest event was an ML(Coda) 2.9 (K. Mayeda pers. comm.) and there were five events between magnitude 2 and 3. The seismic records indicate they were shallow and occurred in or above the active mining panel. Seismometers on top of the mine indicated downward first motion consistent with either a shallow normal earthquake or a collapse mechanism (block collapses vertically under gravity). A comparison of the seismic waveforms with calculated indicates the gravity driven collapse model fits these large events better than normal earthquake model as shown in Figure 3. Thus the larger seismic events coming from the long-wall mine have a similar point-source seismic mechanism as the larger accidental collapses described above. Although these events have not been tested using seismic identification algorithms, we expect their behavior to be similar to the large unplanned collapses based on their shallow depth and collapse mechanism. We examine the discrimination performance of what we believe to be similar events in Utah in the next section.

Coalbumps from longwall mines can get much larger than observed at the Twentymile mine in Colorado. For example three events in 1995-1996 with mb>3.5 are shown in Figure 4A. All were large enough to be detected teleseismically, for example the March 11, 1995 event was given an mb of 4.2 (NEIC) The three events show a high degree of correlation indicating similar locations and mechanisms. All three are associated with a particular longwall mine in Kentucky. Discussions with mine personnel indicated that these events produced relatively little damage inside the mine for the size of the events. We believe that like the Twentymile mine the larger events are associated with collapses occurred above the previously mined out regions. To examine the mechanisms of these events we have been comparing the surface wave data with synthetics at available broadband stations such as the National Seismic Network. An example of the fit of the collapsing crack model is shown in Figure 4B. The fit is quite good except at MCWV which is dominated by noise. In particular the absence of Love waves on the Transverse components is indicative of these collapse type mechanisms.

Discrimination Performance of Central Utah Coalbumps

One of the most active regions in the U.S. for coalbumps is central Utah. More than 30 coalbumps with ML>3 have occurred since 1962 (W. Arabasz and S. Nava, written comm.). The largest event was the 1984 Gentry Mountain collapse studied by Taylor (1994) who noted that it failed many regional discriminants. Patton and Walter (1993,1994) also found this event failed the Mo:mb discriminant measure. Given the shallow depth, possibility for non-double couple mechanism and concerns for evasion (e.g. Heuze, 1995), mine-related seismicity has the potential to be a significant source of false alarms under a CTBT. For these reasons we have begun a study to examine the regional discriminant performance of these Utah events at the LLNL run stations in the Western U.S. (see top of Figure 5). These stations were previously used for a major discrimination study of earthquakes and explosions at NTS (Walter et al. 1995). By using the same stations we can compare the coalbumps with our large databases of Western U.S. earthquakes and explosions. In addition these studies help calibrate the proposed IMS stations at MNV and ELK.

The initial study of the Utah coalbumps reveals they have larger high-frequency P/Lg ratios than nearby earthquakes as the examples at the bottom of Figure 5 show. Large P/Lg ratios are a characteristic of nuclear explosions and can be used to discriminate them (e.g. Walter, et al. 1995). The Utah events occur in very similar geology to the Twentymile mine in Colorado and it seems plausible to think they may have similar mechanisms. The closing crack type mechanisms as we observed for coalbumps in Colorado and Kentucky should have higher P/S ratios than double couple events (e.g. Walter and Brune, 1993). Bennett et al. (1996) have noted that rockbursts and coalbumps in general have P/Lg ratios in between that of earthquakes and explosions but it is not clear whether this is due to mechanism depth, time function or other phenomena. By determining mechanism, depth, time functions and path corrections to these data so that we may compare them to our large Western U.S. dataset of earthquakes and explosions we hope to sort out the relative contributions of each to the observed P/S ratios. We will report initial results of this study at the meeting.

CONCLUSIONS AND RECOMMENDATIONS

Mine-related seismicity including collapses, coalbumps and rockbursts can look like explosions based on some regional and teleseismic discriminants and therefore have the potential to be false alarms under the CTBT. In addition because they involve underground cavities they raise evasion concerns and need more careful study. In order to better understand the empirical discrimination performance of these type of events as well as model their physical source processes we are investigating regional records of coalbumps in Utah. When combined with previous coalbump field work and western U.S. discrimination studies we hope to greatly improve our understanding of these events. We are continuing to collect and analyze the best data available from collapses, rockbursts and coalbumps worldwide to continue to improve our physical models for these types of events.

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The NTS explosion ATRISCO (mb=5.7, Ms=4.2) was followed 20 minutes later by a collapse (mb=4.0, Ms=3.5)

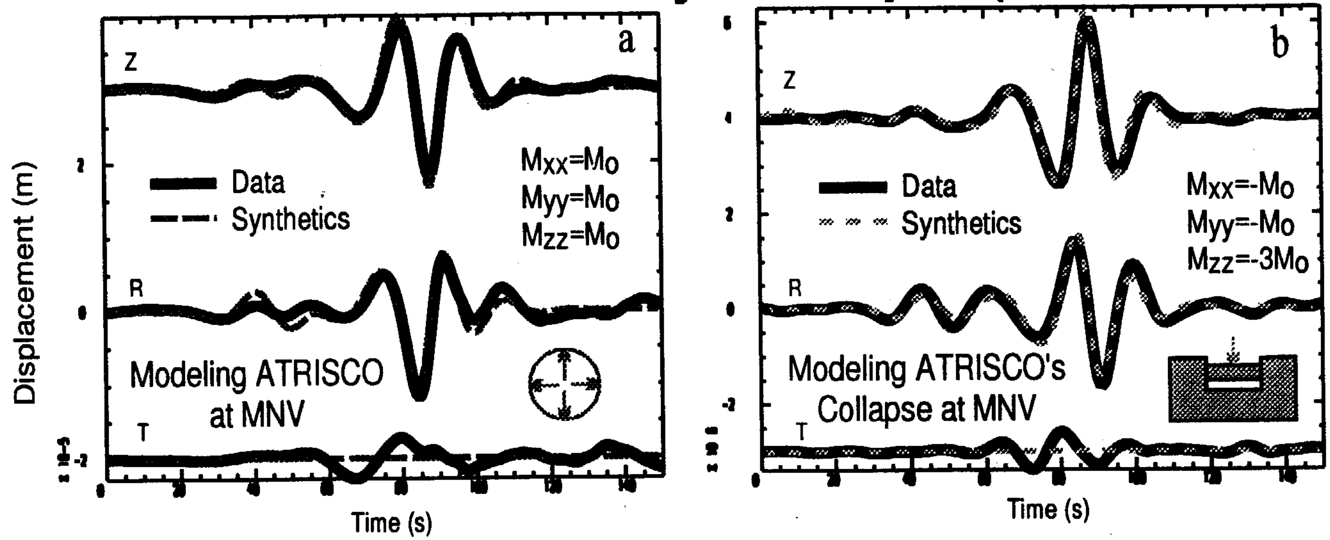

Fig. 1A. Waveform modeling indicates ATRISCO is consistent with explosion point source while it's collapse has a similar mechanism to that found for large room and pillar mine collapses: a tabular gravity driven failure.

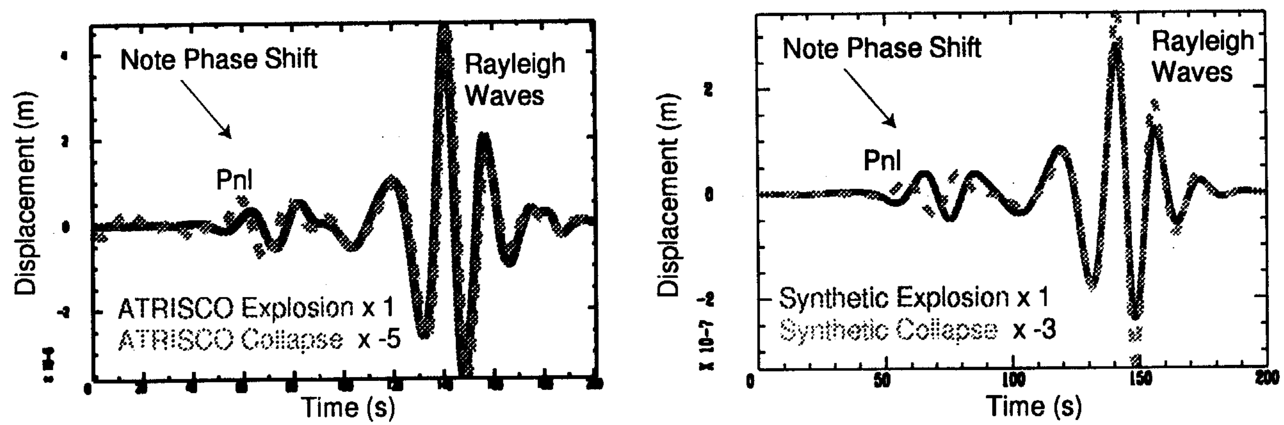

Fig. 1B. A comparison of the ELK radial component long period (15-40 s) data (left) and synthetic (right) seismograms from the NTS explosion ATRISCO and its associated cavity collapse (dashed lines) about twenty minutes later. The Rayleigh waves are out of phase for these two events. We can match the Rayleigh waves of the two events if we multiply the data collapse trace by -5 as shown on the left or for the same M_0 by -3 in the synthetic trace on the right. However the long period body wave phase P_{nl} does not match, indicating the collapse is not an implosion (opposite of an explosion) but more consistent with a tabular gravitational collapse mechanism. (Figure after Walter 1995).

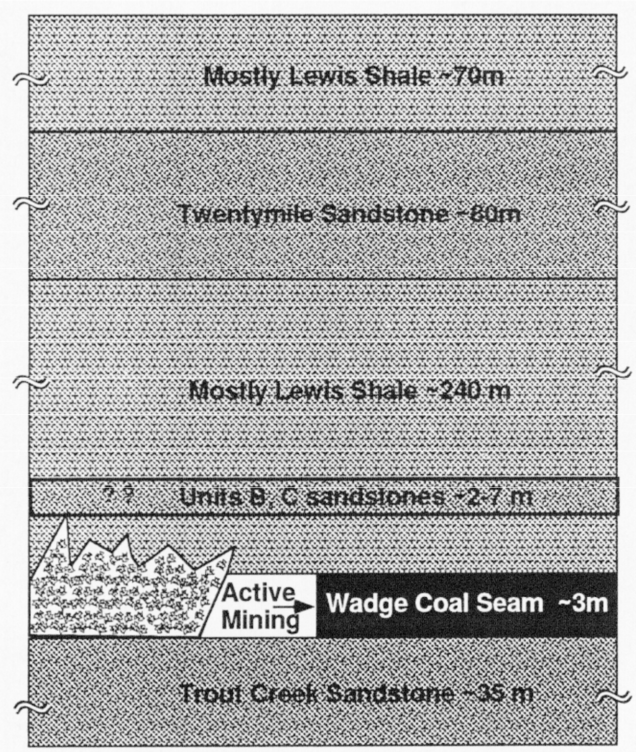

Fig 2A. Simplified schematic cross section of Twentymile coal mine and some of the major rock units. The 3m (10 ft.) high Wadge coal seam is completely excavated within the mining panels and the weak shale rocks are allowed to collapse behind the advancing face of active mining. It is hypothesized that the roof rock collapses until it reaches the stronger sandstone rock layers which can support more weight before failure. It is believed to be the failure of these sandstone layers, either units B, C or the thicker Twentymile sandstone layers that are responsible for the largest seismic events. (Simplified from detailed cross sections provided by Twentymile coal mine).

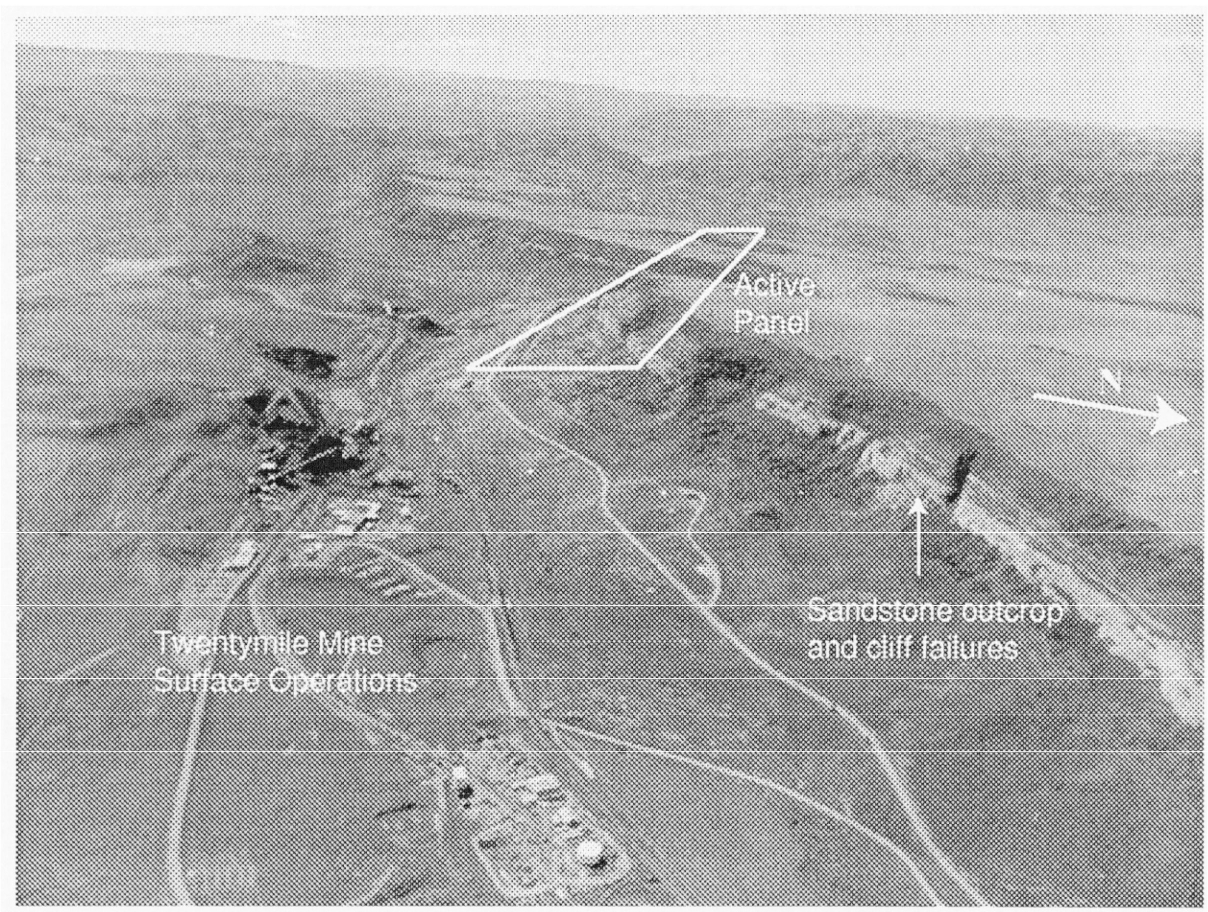

Fig. 2B. Aerial photo of Twentymile Coal Mine area. A surface projection of the mining panel active during the LLNL seismic deployment is superimposed on the picture. The ground above the active panel and previously mined panels to the north has subsided 4.5 m but this is not easily visible to the naked eye. The Twentymile sandstone layer is visible where it outcrops and does show response to the undermining in the form of cliff failures. (Photo by François Heuze).

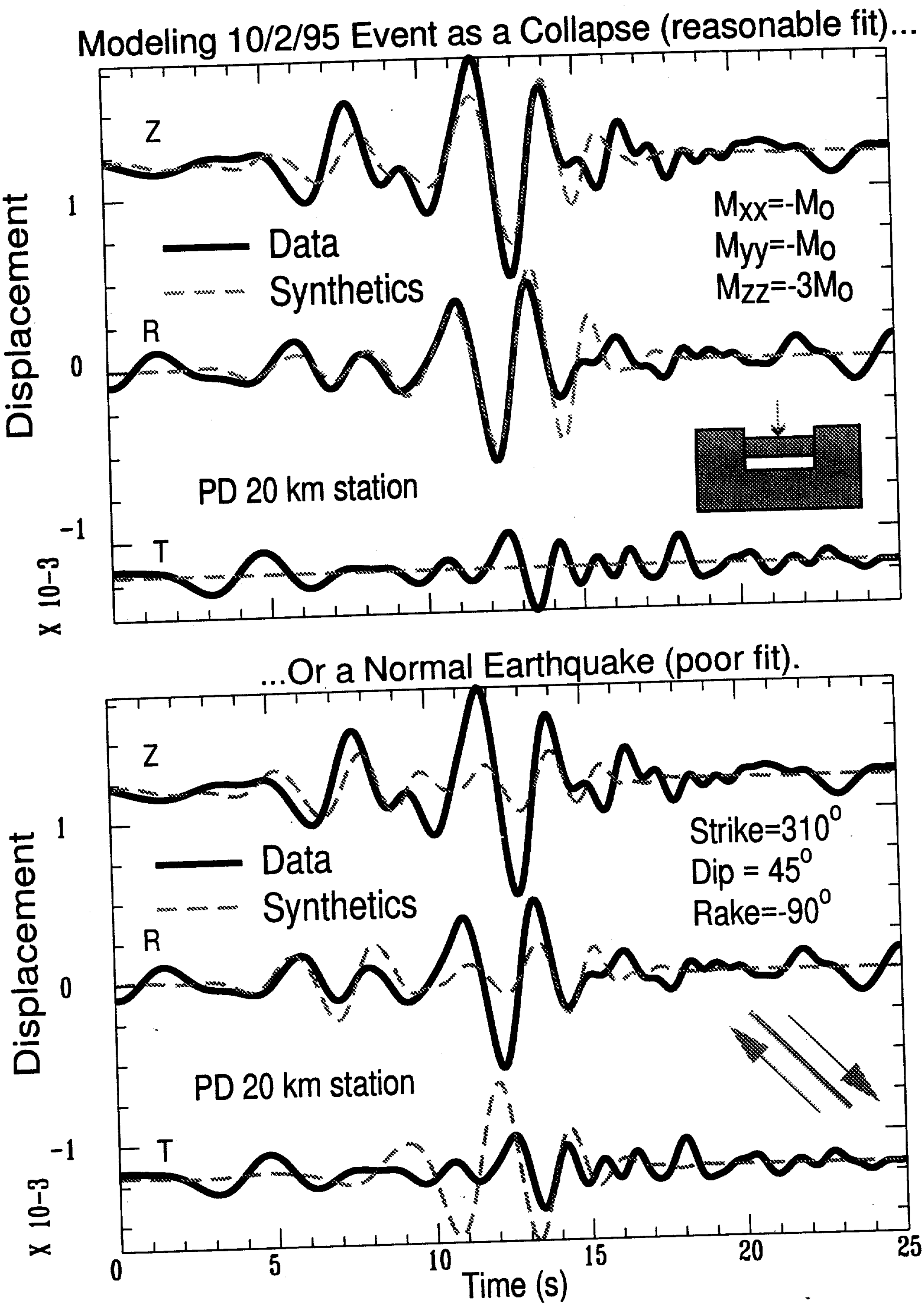

Fig. 3. Preliminary waveform modeling indicates the point-source mechanism for the largest events are more consistent with a gravitational collapse mechanism than a normal earthquake mechanism. This figure compares 3 component, 2-5 s period fits of synthetic seismograms for both mechanism types to the data recorded at a station 20 km away towards Pinedale, Wyoming. (after Walter et al., 1996).

Three Kentucky Coalbumps recorded at NSN station CEH, Chapel Hill, NC

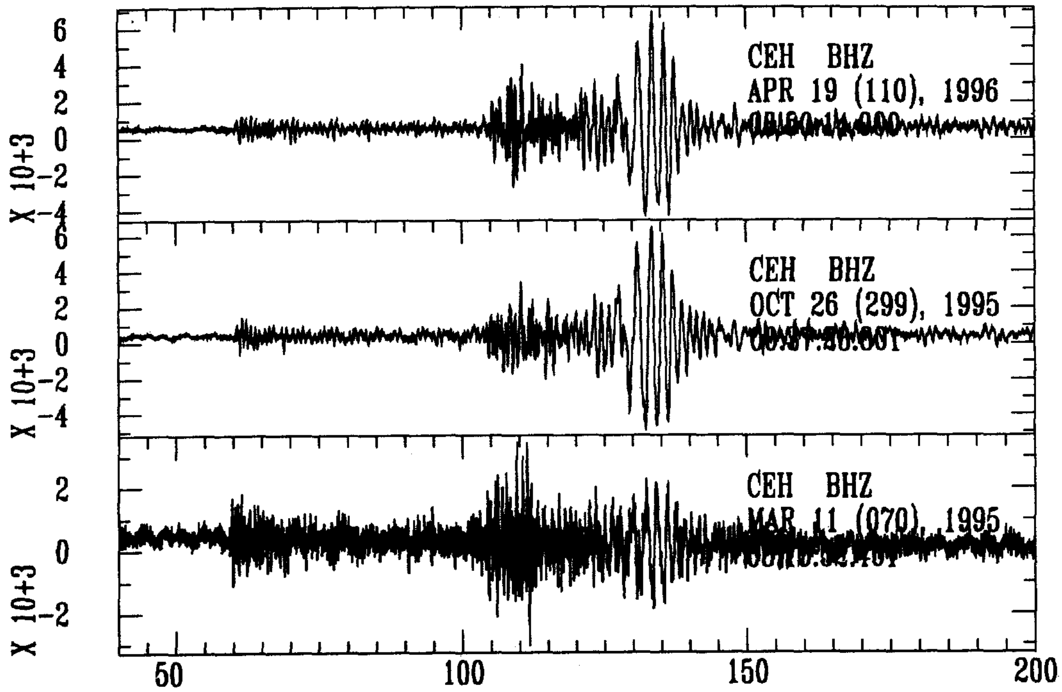

Fig. 4A. Seismic records from three coalbumps associated with the Lynch 37 longwall coal mine in Kentucky show strong correlation indicating similar source mechanisms and locations.

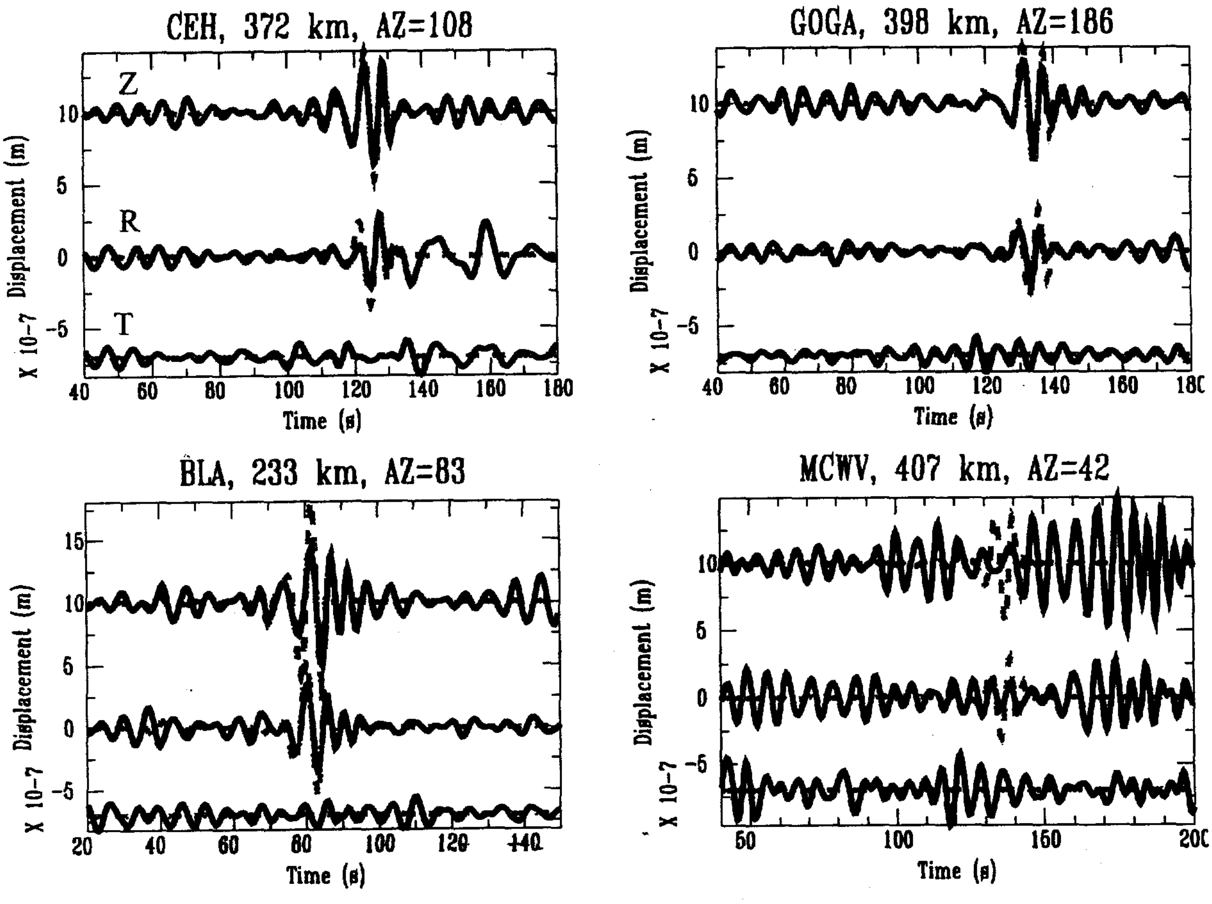

Fig. 4B. Preliminary waveform fits using closing crack mechanism (dashed lines) to regional broadband data from Kentucky coalbump on April 19, 1996 in bandpass from 5-15s period.

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