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FALSE ALARMS AND MINE SEISMICITY: AN EXAMPLE FROM THE GENTRY MOUNTAIN MINING REGION, UTAH

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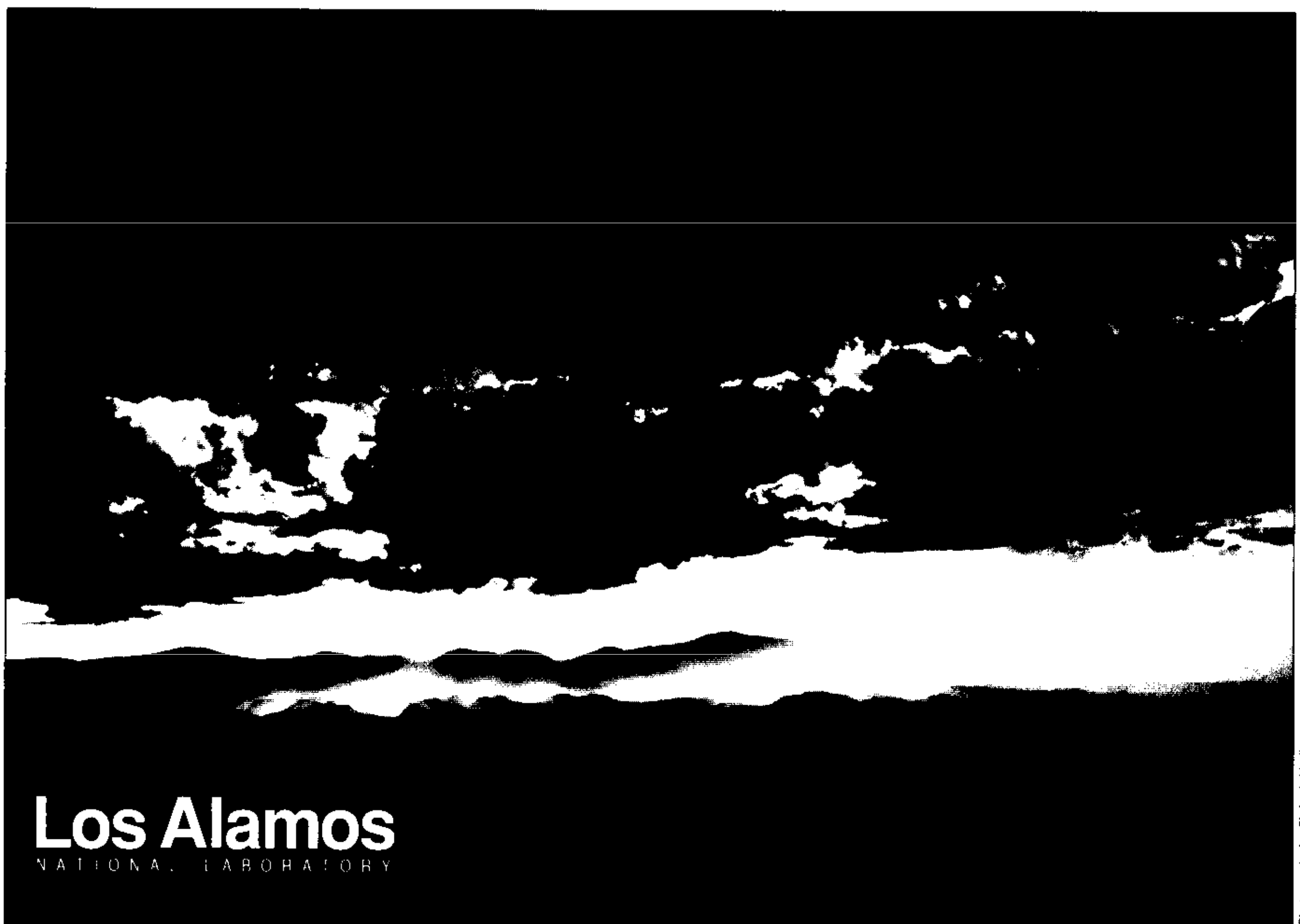
September 1992

LOS ALAMOS SOURCE REGION PROJECT



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ABSTRACT

Mining regions are a cause of concern for monitoring of nuclear test ban treaties because they present the opportunity for clandestine nuclear tests (i.e. decoupled explosions). Mining operations are often characterized by high seismicity rates and can provide the cover for excavating voids for decoupling. Chemical explosions (seemingly as part of normal mining activities) can be used to complicate the signals from a simultaneous decoupled nuclear explosion. Thus, most concern about mines has dealt with the issue of missed violations to a test ban treaty. In this study, we raise the diplomatic concern of false alarms associated with mining activities. Numerous reports and papers have been published about anomalous seismicity associated with mining activities. As part of a large discrimination study in the western U.S. (Taylor *et al.*, 1989), we had one earthquake that was consistently classified as an explosion. The magnitude 3.5 disturbance occurred on May 14, 1981 and was conspicuous in its lack of Love waves, relative lack of high-frequency energy, low Lg/Pg ratio, and high m_b - M_s. Additionally, a moment-tensor solution by Patton and Zandt (1991) indicated the event had a large *implosional* component. The event occurred in the Gentry Mountain coal mining region in the eastern Wasatch Plateau, Utah. Previous microearthquake studies in the region have demonstrated the existence of numerous small implosional events associated with the mining activities. The event is more comparable in appearance (at the broad band station KNB) to the ATRISCO collapse at NTS than from another double-couple event near the mining region. Using a simple source representation, we modeled the event as a tabular excavation collapse that occurred as a result of normal mining activities. This study raises the importance of having a good catalogue of seismic data and information about mining activities from potential proliferant nations.

INTRODUCTION

With the demise of the Soviet Union, technical issues associated with nuclear test ban verification have been rapidly changing. Previously, focus was on verification of the 150 Kt Threshold Test Ban Treaty (TTBT) and yield estimation problems were of primary importance. A large research effort was still geared towards monitoring at reduced yield thresholds or a Comprehensive Test Ban Treaty (CTBT). For CTBT monitoring in the Soviet Union, detection and discrimination studies were of interest. The problem was of great magnitude because of the shear size of the Soviet Union. Little information was available about regional geology and geophysics, and wave-propagation characteristics. Now, much of the nuclear-test monitoring research is directed towards nonproliferation, which is basically CTB monitoring on a world-wide basis. The technical problems associated with nonproliferation monitoring are daunting.

For CTBT research, much attention was paid to the study of chemical mining explosions. The large number of mining explosions would cause problems for any monitoring system. Much of the concern over mining regions is that they can provide the cover for hiding a decoupled nuclear explosion. Mining operations are often characterized by high seismicity rates and can provide the cover for excavating voids for decoupling. Chemical explosions (seemingly as part of normal mining activities) can be used to complicate the signals from a simultaneous decoupled nuclear explosion. Additionally, it has been suggested that a nuclear explosion could be detonated simultaneously with a large rockburst (a characteristic of many mining regions). Statistical studies of the number and size of chemical explosions in the United States illustrate the large number of events that can be detonated in a single work day in a large industrialized nation (about 30 greater than 50 tons, and one greater than 200 tons; Richards *et al.*, 1992). However, many of these are ripple fired and much research has been conducted to identify ripple-fired explosions (cf. Hedlin *et al.*, 1989; Smith, 1989).

The above-mentioned evasion scenerio is still valid in a nonproliferation context. However, the issue of unidentified, naturally occurring events (false alarms) is also of primary concern for nonproliferation monitoring. False alarms are an important issue because they can result in a raising of regional tensions between neighboring proliferant nations. In this study, through an example of an anomalous event from the Gentry Mountain mining region in central Utah, we highlight the technical problem of false alarms associated with mining activities.

Numerous reports and papers have been published about anomalous seismicity associated with mining activities many of which have been summarized by Johnston (1988). In general, there are two types of seismicity associated with mining operations: those directly associated with mining activities (Type 1), and triggered (or induced) events that can occur at distances up to a few kilometers from a mine (Type 2). The temporal and spectral characteristics of mine seismicity is a function of the local geology and type of mining operation and will not be reviewed here. However, a literature search illustrates that signal characteristics can be very complicated and in many regions, signals can be significantly different than what would be expected for "typical" tectonic events.

As part of a large discrimination study in the western U.S. (Taylor *et al.*, 1989), we had one earthquake that was consistently classified as an explosion. The event occurred on May 14, 1981 (MAY1481) in the Gentry Mountain coal mining region in the eastern Wasatch Plateau, Utah (Figure 1). The region is characterized by high seismicity rates and anomalous seismicity associated with the mining activities (cf. Wong *et al.*, 1989; Williams and Arabasz, 1989).

In this paper, we present a detailed study of the MAY1481 event through a comparison with a nearby "normal" tectonic event that occurred on May 24, 1980 (MAY2480) and Nevada Test Site (NTS) events recorded at the Lawrence Livermore National Laboratory (LLNL) broad band station at Kanab, UT (KNB). We first review the micro-seismicity studies in the eastern Wasatch Plateau and then discuss the anomalous character of the MAY1481 from a discrimination study. We then discuss modeling results of the MAY1481 in terms of a room collapse associated with longwall mining activities.

SEISMICITY ASSOCIATED WITH MINING IN THE EASTERN WASATCH PLATEAU

Seismicity maps of the Colorado Plateau indicate that high seismicity rates are associated with the eastern Wasatch Plateau and Book Cliffs region of north-central Utah (Wong *et al.*, 1989; Williams and Arabasz, 1989). The seismicity appears to be related to the large underground coal-mining operations in the area. Other coal mines in Utah are not characterized by such high seismicity rates, and two-dimensional finite-element models suggest that the interaction of the ridge and canyon topography with the regional tectonic stress field and pre-existing faults results in stress concentrations in the vicinity of the mined-out regions (Wong, 1985). This further results in triggered earthquakes within a few kilometers of the actual mine workings that occur on favorably-oriented zones of weakness.

Microearthquake studies in the region have indicated the presence of two types of seismic events: 1) small, high-frequency events directly associated with mining activities (such as caving of the roof from longwall mining) and 2) events located at some distance (up to a few kilometers laterally and/or vertically) from the mine workings (Wong *et al.*, 1989; Williams and Arabasz, 1989). The first type of events are generally smaller than the second type. Many of the second type are characterized by dilatational focal mechanisms and apparent low stress drops (0.01 to 1 MPa; as evidenced by their lack of high frequencies). The fact that many of these apparently non-double-couple submine events were characterized by the presence of shear waves, lead Wong *et al.* (1989) to propose that they were shear-induced implosions. However, Williams and Arabasz (1989) pointed out that the dilational events could be fit with double-couple normal-faulting mechanisms if the events were located *above* the mine workings (consistent with subsidence above the mine).

A number of different studies have discussed the possible mechanisms associated with anomalous mine seismicity (cf. MacBeth and Redmayne, 1989; Wong and McGarr, 1990; Hasegawa *et al.*, 1989). Most of these studies involve comparison of different force representations arising from various possible physical mechanisms of mine seismicity. These models include various combinations of shear failure and crack mechanisms (such as a shear-induced implosion), pillar burst, and tabular or spherical excavation collapse. Based on observations from a number of different mining regions, Wong and McGarr (1989) preferred the tabular excavation collapse. The tabular collapse produces dilational first motions and shear waves often observed with the Type 2 mine seismicity.

MacBeth and Redmayne (1989), modeled observed low-frequency events having abundant surface waves from a coalfield in Scotland with a vertical point force. This was interpreted to represent a subsurface slump or collapse. However, an alternative mechanism could be obtained from a vertical dipole with a low stress drop. Kuhnt *et al.*, (1989) discuss the effects of different stress-drop models on spectral characteristics of mine seismicity.

DISCRIMINATION ANALYSIS OF MAY1481 EVENT

As part of a large discrimination study of western U.S. earthquakes and NTS explosions, we found that one earthquake was consistently misclassified (Taylor *et al.*, 1989). The M_L 3.5 event occurred on May 14, 1981 in central Utah (Figure 1). Close examination of the event shows that it was located in the Gentry Mountain mining region. Figure 2 shows plots of four discriminants with the MAY1481 event highlighted. The MAY1481 event was characterized by relatively small Rayleigh and Love waves, a low Lg/Pg ratio, and was deficient in low-frequency energy (as evidenced by its low spectral ratio). In every case, the event plots within the explosion population. Additionally, a moment-tensor solution using regional surface waves by Patton and Zandt (1991) indicated the event had a large *implosional* component. Results from two surface-wave inversions (with and without the trace of the moment tensor constrained to zero) are shown in Figure 1 and had depths of 4 and 5 km, respectively. The mechanism with the trace constrained to zero is similar to that presented in Wong *et al.*, (1989).

For comparison, we have selected a nearby "normal" tectonic earthquake of M_L 4.2 that occurred on May 24, 1980 (MAY2480) 93 km to the northwest of MAY1481. The location and focal mechanism from a regional surface-wave moment tensor solution [with a depth > 10 km; Patton and Zandt (1991)] for the MAY2480 event is shown in Figure 1. The mechanism is similar to that obtained from first motions by Bjarnason and Pechmann (1989). The MAY2480 event was also processed as part of the discrimination study and is highlighted in the discrimination plots in Figure 2.

Figure 3 compares KNB seismograms from the MAY2480 and MAY1481 events with the ATRISCO collapse and the NTS nuclear explosion PERA. All of the events are of similar magnitude and distance range from KNB and show some interesting similarities and differences. First, the MAY2480 event shows a much higher frequency content, better developed Lg and Rayleigh waves, and shorter coda than MAY1481. The MAY1481 event is characterized by a narrow band, long reverberating wave train with few well-defined phases except Pn and Pg. The reasons for the differences will be further discussed below, but they may be due to source differences and/or due to the fact that the MAY1481 event occurred at a much shallower depth than the MAY2480 event (resulting in more energy being trapped in low Q near-surface, sedimentary layers). Interestingly, the MAY1481 event is more comparable in appearance to the ATRISCO collapse than the earthquake or the nuclear explosion.

ANALYSIS OF THE MAY1481 EVENT

In order to model the MAY1481 event, it was necessary to obtain a velocity model from the source region to the station KNB. Synthetics calculated using Block 13 (the Colorado Plateau block) of Taylor and Patton (1986) failed to match the arrival times of the various regional phases. This is probably due to the fact that much of the path from the two events is confined to the Basin and Range/Colorado Plateau transition zone. Thus, we decided to measure and invert group velocities from the MAY2480 event at KNB. The group velocities were measured using the multiple-filter technique (Landisman *et al.*, 1969) and inverted using weighted least squares (Taylor and Toksoz, 1982). The observed and calculated group velocities are shown in Figure 4a and the corresponding shear-velocity model is shown in Figure 4b. For comparison, we show the derived shear-velocity model with those from Block 12 (Basin and Range) and Block 13 (Colorado Plateau) from Taylor and Patton (1986). The model appears to generally fall between those from the two blocks which is not surprising since the path runs down the Basin and Range/Colorado Plateau transition zone.

In order to make more realistic appearing synthetic seismograms, we used a 10% random perturbation to the inverted velocity model (Figure 5). The overall characteristics of the synthetic seismograms using the randomized velocity model remain unchanged, but the coda waves are enhanced giving them a more realistic appearance. The Basin and Range attenuation model of Patton and Taylor (1984) was used in the synthetic calculation (with the Q_α and Q_β of the upper 1 km changed to 67 and 30, respectively).

We used the velocity model shown in Figure 5 and the double-couple focal mechanism of Patton and Zandt (1991) to generate a synthetic seismogram [using the technique of Kennett (1983)] for the MAY2480 event at the range and azimuth corresponding to station KNB (for a stress drop of 10 MPa and depth of 10 Km). This enables us to check the adequacy of the velocity model so that we can model the MAY1481 event. The observed and calculated seismogram are shown in Figure 6 and it can be seen that the comparison is reasonable. The phase arrival times are matched well. However, the data appears to show more coda and the observed surface waves are of greater amplitude than calculated. However, low-pass filtering the data at 0.1 Hz indicates that the phasing of the surface waves is quite good (Figure 6).

Our ability to obtain good comparisons at KNB for the MAY2480 event indicates that the velocity model shown in Figure 5 is reasonable and allows us to model the

MAY1481 event. We found that using a source consisting of a vertical dipole (Mzz; representing a tabular excavation collapse) acting at a depth of 0.2 km could be used to match the seismogram at KNB quite well (Figure 7). A schematic illustrating the collapse and the model used is shown in Figure 8. A low stress drop of 0.1 MPa was used in an attempt to match the frequency content of the observed seismograms. The frequency content of the synthetic seismogram is slightly higher than that observed at KNB, but the overall characteristics are matched quite well. The long reverberating wave train is presumably due to the shallow depth of the source and the resultant energy being trapped in the low-velocity near-surface layers. The shape of the calculated fundamental-mode Rayleigh wave also matches the data well.

The modeling performed above is very simple and non unique. A number of other source models could probably be fit to the data at KNB. For example, use of just the M_{zz} with a Brune time function may not be a physically correct model of the tabular excavation collapse because it does not explicitly account for the detachment, earth rebound during free flight, and subsequent impact. However, numerical experiments using the spall model of Day and McLaughlin (1991) [which is probably a good representation of the excavation collapse] yield seismograms similar to those shown in Figure 7. Regardless of the details of the model used to simulate the collapse, the major point of this section is that the complicated signals from the MAY1481 event can be reasonably matched with a model simulating a room collapse as part of a longwall mining operation.

It is interesting to note that the MAY1481 event most closely resembled the cavity collapse from the NTS explosion ATRISCO (Figure 3). The cavity collapse model of Hannon and Nakanishi (1982) shows many similarities to the spall model of Day and McLaughlin (1991) with the exception of the failure of the hoop stresses established around the explosion cavity. Hannon and Nakanishi hypothesized that the failure of the hoop stresses (which can have magnitudes greater than 30 MPa) was potentially a more effective seismic wave source than the actual detachment and impact of the falling material. As pointed out by Wong (1985), the residual stresses in the actual vicinity of the mine workings can be as high as 70 MPa. Thus, the source models necessary to accurately simulate excavation collapses may be very complicated and beyond the scope of this paper.

Contact was made with the mining engineers at U.S. Fuel Company who operate the Gentry Mountain mine. Although they do not keep records, they did vividly remember a major collapse that occurred on May 14, 1981. They had restarted mining in some old workings and were having a very difficult time with collapses and estimated that the room size that collapsed could have been as large as 150 m on a side. Given the fact that the mined coal seam is 4 m thick, how much falling material could cause a M_L 3.5 event? Using the relationship $Log(E) = 4.8 + 1.5 M_L$ (J; Kasahara, 1981), $E = 1.1 \times 10^{10} J$. The mass is given by $m = E/(g \cdot h)$ so $m = 2.8 \times 10^8 Kg$ for a 4 m coal seam. Assuming the density of coal/rock is $2.7 \times 10^8 Kg/m^3$, the volume of collapse is approximately 10^5 m^3. Assuming the room was 150 m^2, a 5 m column collapsed. For a partial room collapse, the column height would be higher. The major point is that the numbers are not unreasonable and that a major room collapse could cause and event of the size observed for MAY1481.

DISCUSSION AND CONCLUSIONS

Analysis of the MAY1481 event illustrates some of the difficulties associated with mine seismicity on monitoring nuclear test ban or nonproliferation treaties. Mining regions are often regarded as a cause of concern because of their potential for hiding a clandestine nuclear explosion (missed violation). The mining operations could cover the construction of a cavity (for decoupling) and simultaneous surface chemical explosions detonated as part of seemingly normal mining operations could complicate signals from a small, partially decoupled nuclear explosion. The issue raised in this paper is the false alarm problem caused by the complicated seismicity often associated with mines. Unidentified events located within proliferant nations have the potential to raise regional tensions and it is important to have the capabilities to resolve them.

As part of a large discrimination study by Taylor *et al.*, (1989), the MAY1481 event was misclassified as a nuclear explosion. The fact that a large database of NTS nuclear explosions, NTS cavity collapses, and naturally-occurring earthquakes were available at the broad-band seismic station KNB, allowed us to demonstrate that the MAY1481 event was the result of normal mining activities. It was also useful that the mining region in question was well-studied (cf. Wong *et al.*, 1989) and contact could be made with the mining operators to verify our results. In many regions of proliferation concern, this information will be difficult to obtain and these types of events may remain unidentified. Thus, it is important that all available seismic data from areas of concern be collected, analyzed, and categorized along with information on mining activities.

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FIGURE CAPTIONS

Figure 1. Map of western U.S. showing locations of MAY1481 and MAY2480 events and focal mechanisms from moment-tensor inversion of regional surface waves (Patton and Zandt, 1991). Also shown is the location of NTS and the LLNL seismic station KNB (Kanab, UT). For the MAY1481 event, the mechanism from the complete moment-tensor inversion is shown on the left, and that with the trace constrained to be zero is shown on the right.

Figure 2. Discrimination plots and decision line for western U.S. earthquakes (open squares) and NTS nuclear explosions (asterisks). MAY1481 and MAY2480 points are shown with the filled and open arrows, respectively. m_b - M_s is shown in upper left, Love wave energy in lower left, Lg/Pg amplitude ratio (upper right), and the 1 to 2 Hz and 6 to 8 Hz Lg spectral ratio in the lower right [see Taylor *et al.*, (1989) for details].

Figure 3. Comparison of broadband seismograms at station KNB for four different events. From the top; MAY2480, MAY1481, ATRISCO collapse (from NTS), and NTS nuclear explosion PERA. The epicentral distance for each event to KNB is labeled in parentheses.

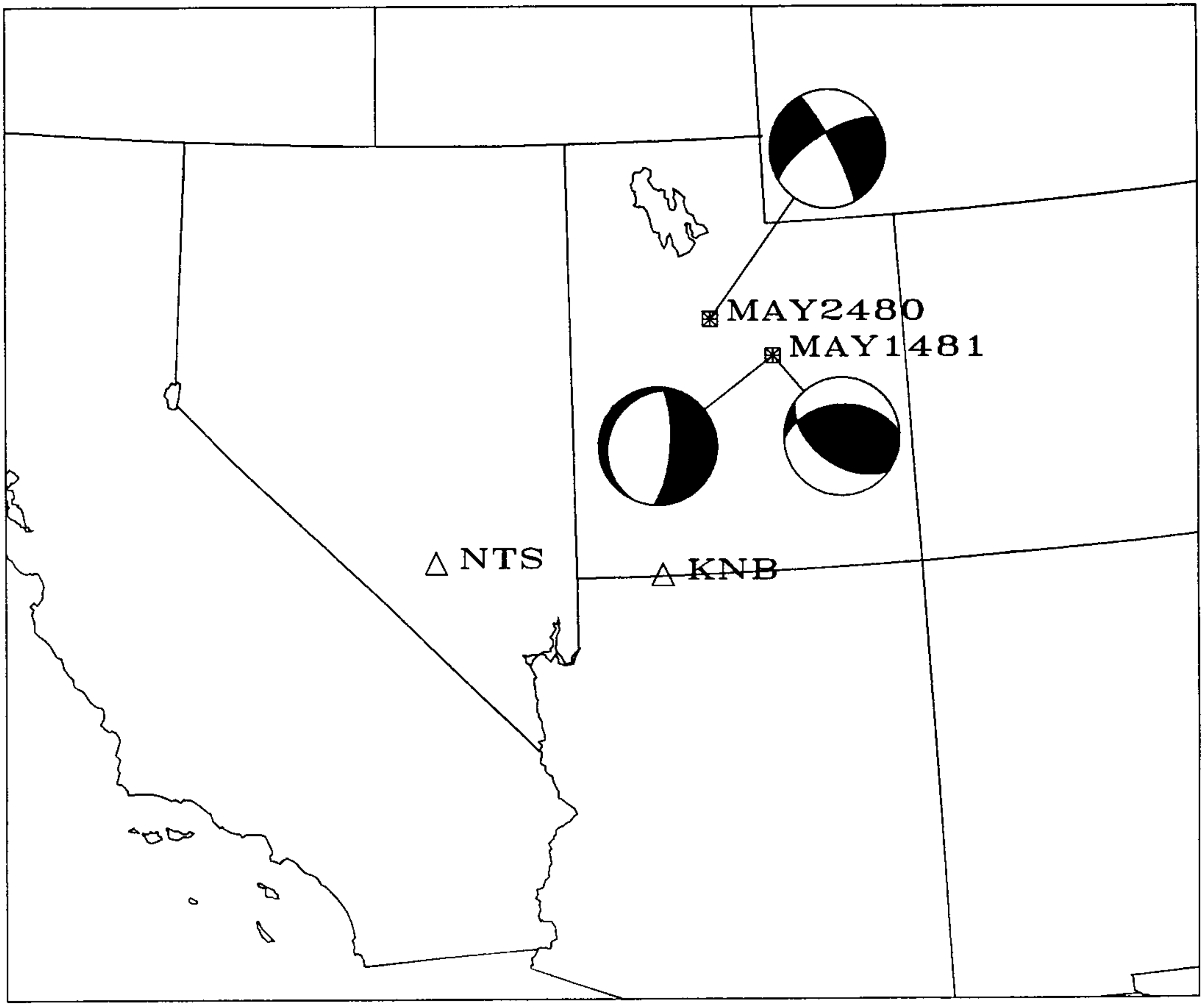
Figure 4. (a) Measured (triangles) and calculated (solid line) group velocity from the path between MAY2480 and KNB. (b) Shear velocity versus depth from inversion of group velocity between MAY2480 and KNB, compared to that from Block 12 (Basin and Range) and Block 13 (Colorado Plateau) of Taylor and Patton (1986).

Figure 5. Shear velocity model from inversion of group velocity between MAY2480 and KNB (solid line) and 10% randomized model used in synthetic seismogram calculations (dashed line).

Figure 6. Comparison of calculated and observed seismograms at station KNB for the MAY2480 event. Synthetic seismogram calculated using randomized velocity model shown in Figure 5 and a Brune stress drop of 10 MPa. Top two traces and bottom two traces are low-pass filtered at 5 Hz and 0.1 Hz, respectively. Source mechanism from Patton and Zandt (1991; see text for details).

Figure 7. Same as Figure 6, but for MAY1481 event using a Mzz source and a Brune stress drop of 0.1 MPa.

Figure 8. Schematic showing the model used to simulate the tabular excavation collapse. The figure on the left shows the room prior to collapse. The upper right figure shows the collapse and the various dipoles and shear couples. It is assumed that the shear couples cancel. We also illustrate the configuration for a shear-induced collapse. The bottom right figure shows the final configuration of the collapsed room.



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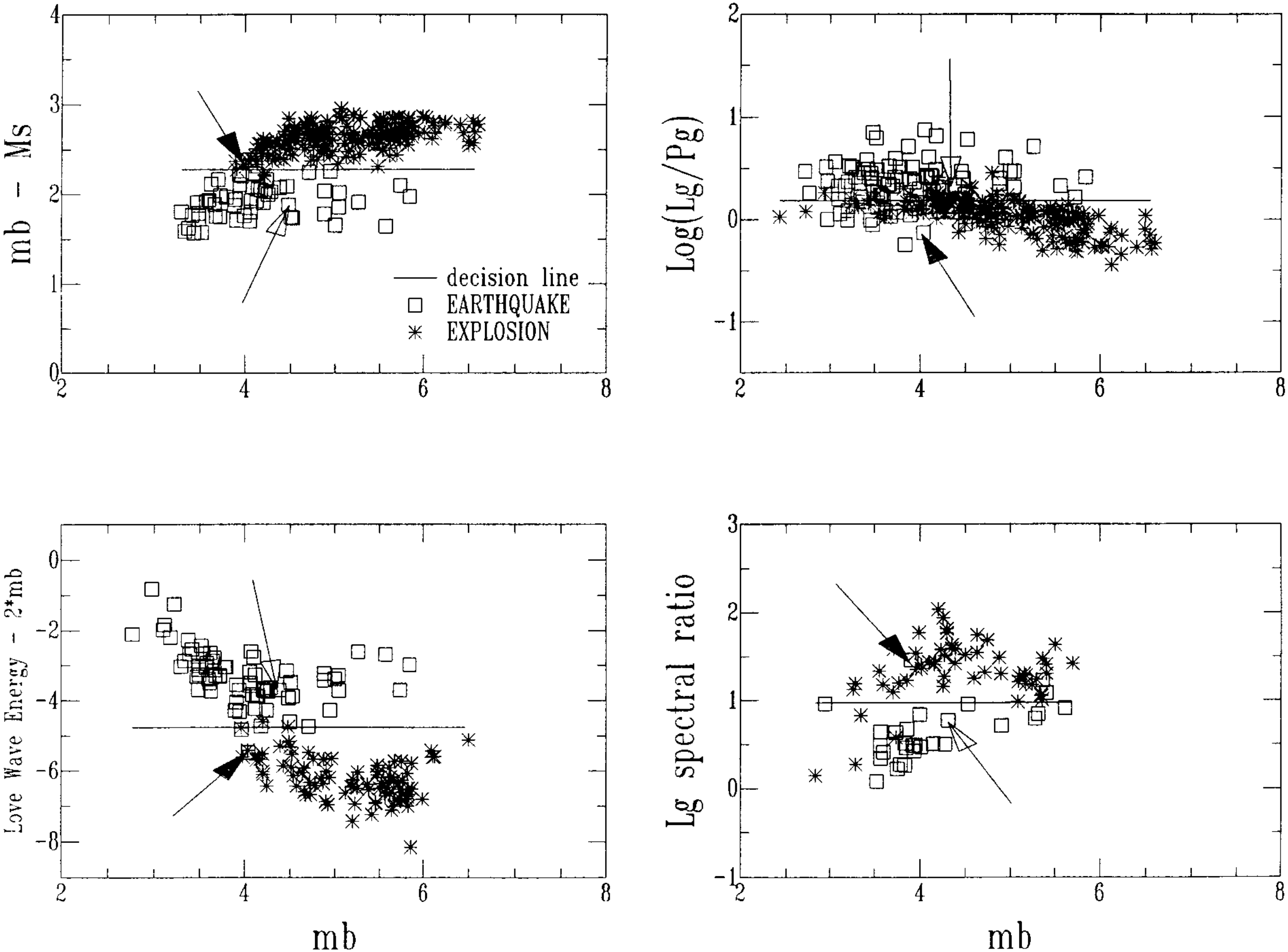

mb - Ms
decision line
EARTHQUAKE
EXPLOSION
Log(Lg/Pg)
Love Wave Energy - 2*mb
Lg spectral ratio
mb
mb

Figure 2

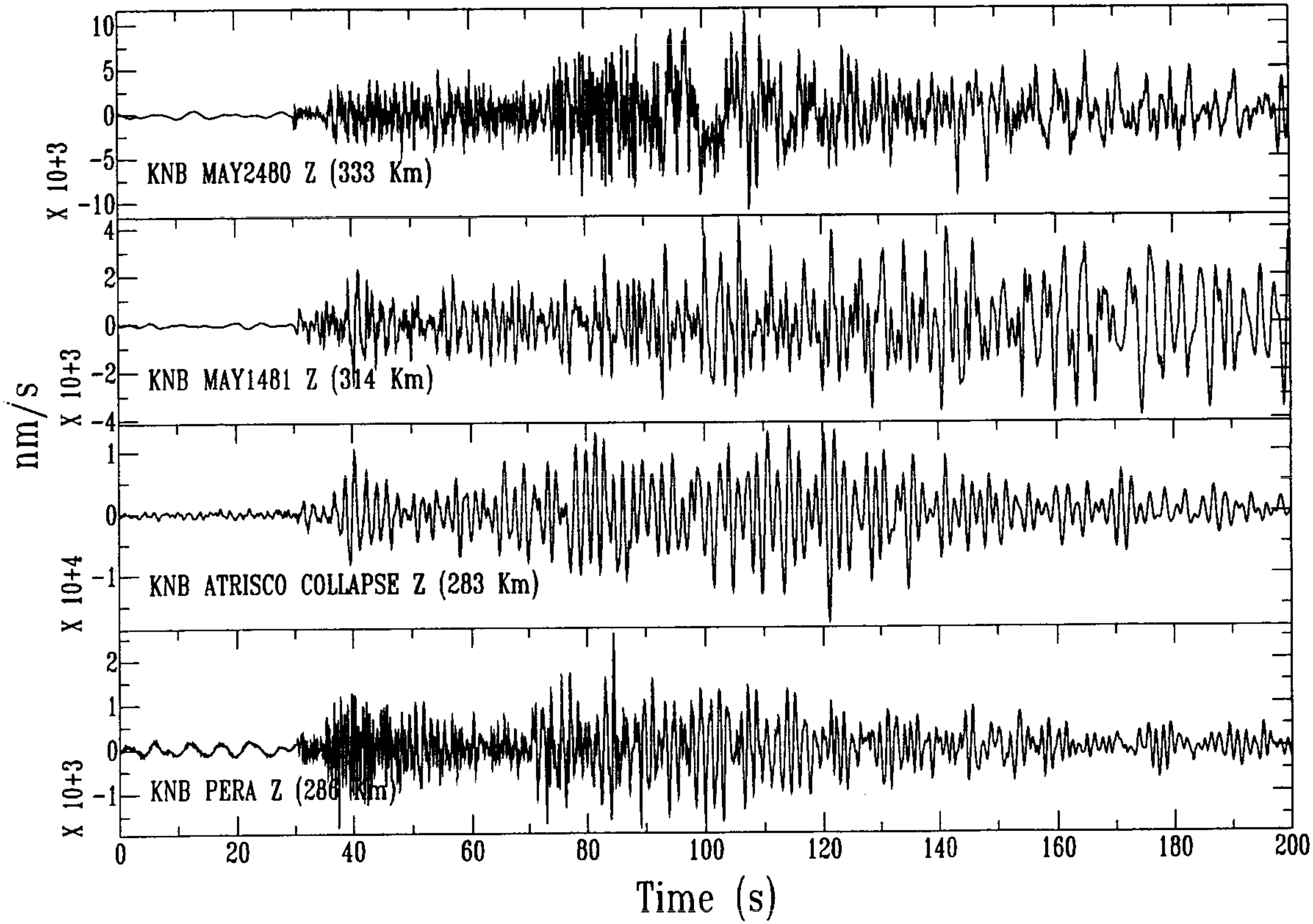

KNB MAY2480 Z (333 Km)
KNB MAY1481 Z (314 Km)
KNB ATRISCO COLLAPSE Z (283 Km)
KNB PERA Z (286 Km)
X 10+3
X 10+3
X 10+4
X 10+3
nm/s
Time (s)
0
20
40
60
80
100
120
140
160
180
200

Figure 3

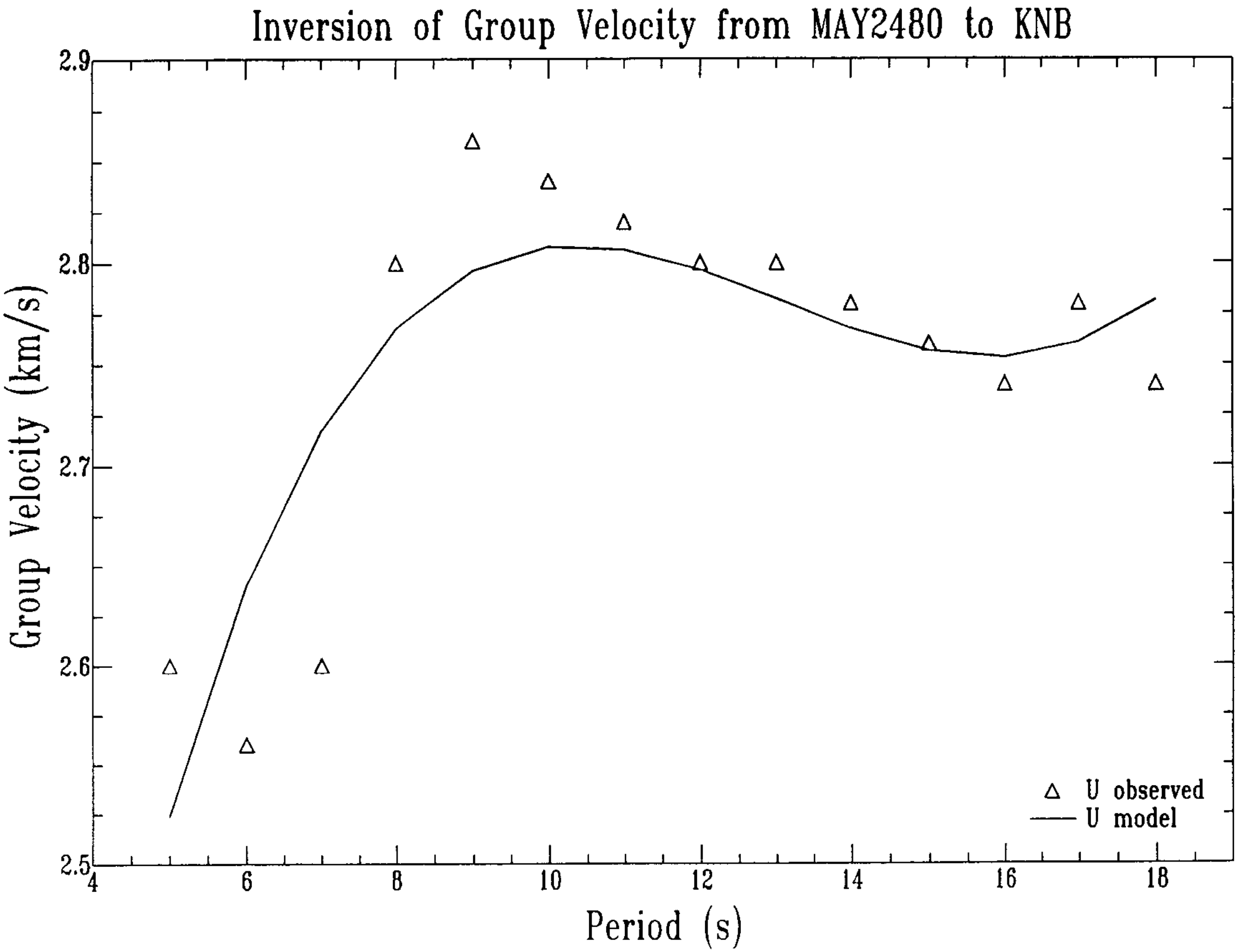
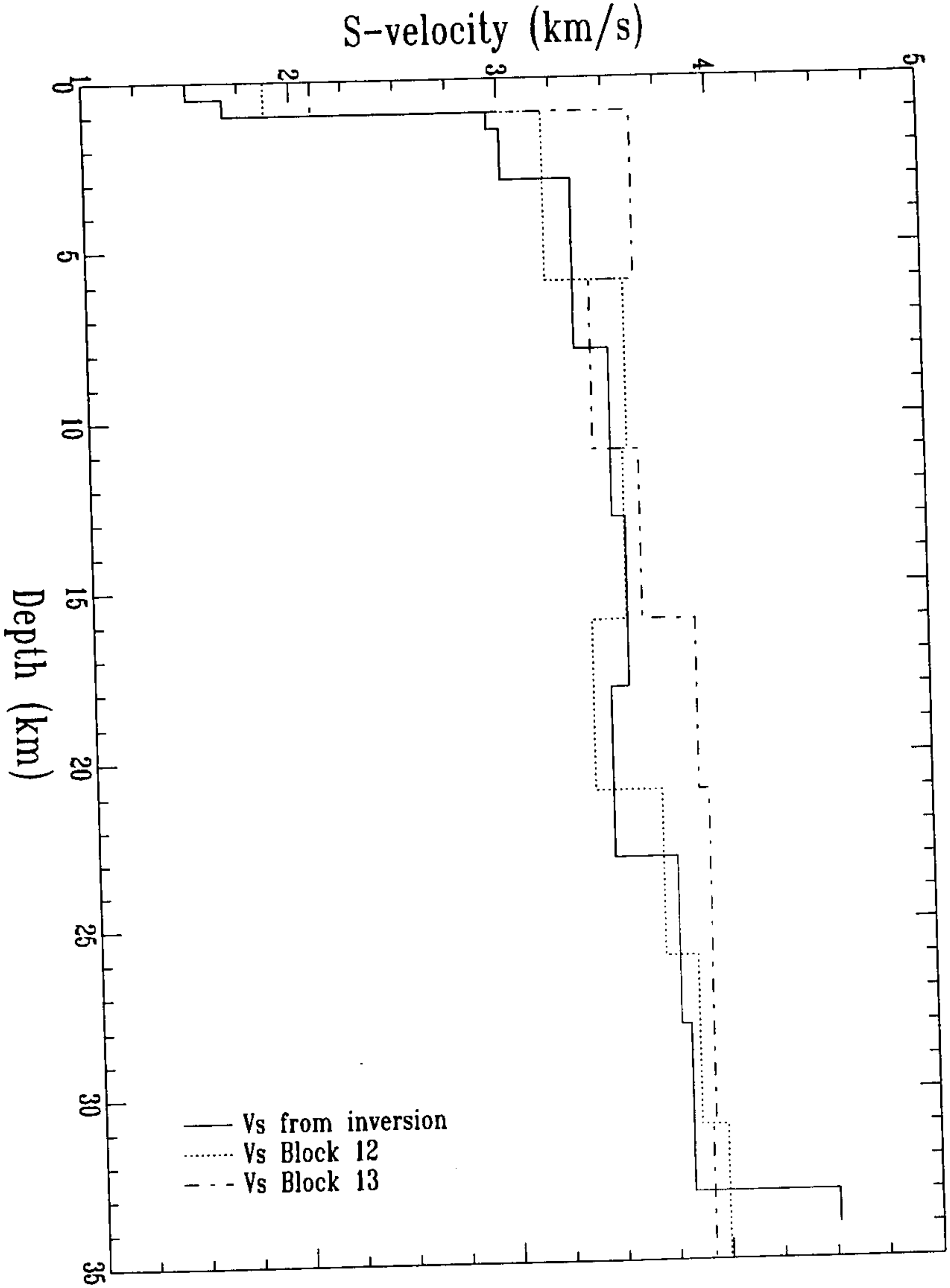
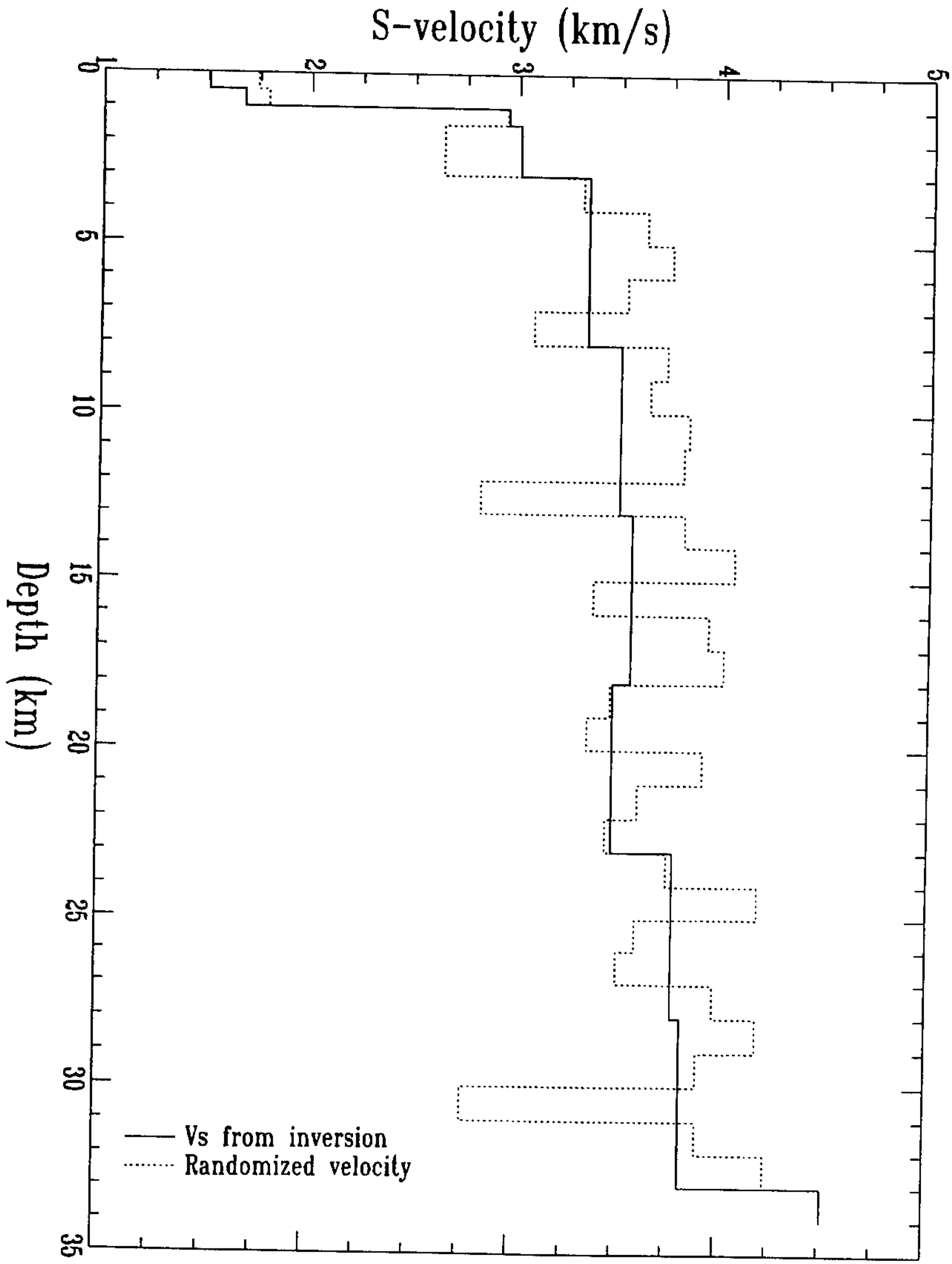

Inversion of Group Velocity from MAY2480 to KNB
Group Velocity (km/s)
2.9
2.8
2.7
2.6
2.5
Period (s)
4
6
8
10
12
14
16
18
U observed
U model

Figure 4a



S-velocity (km/s)
Depth (km)
1
2
3
4
5
0
5
10
15
20
25
30
35
Vs from inversion
Vs Block 12
Vs Block 13

Figure 4b


S-velocity (km/s)
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2
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Depth (km)
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5
10
15
20
25
30
35
Vs from inversion
Randomized velocity

Figure 5

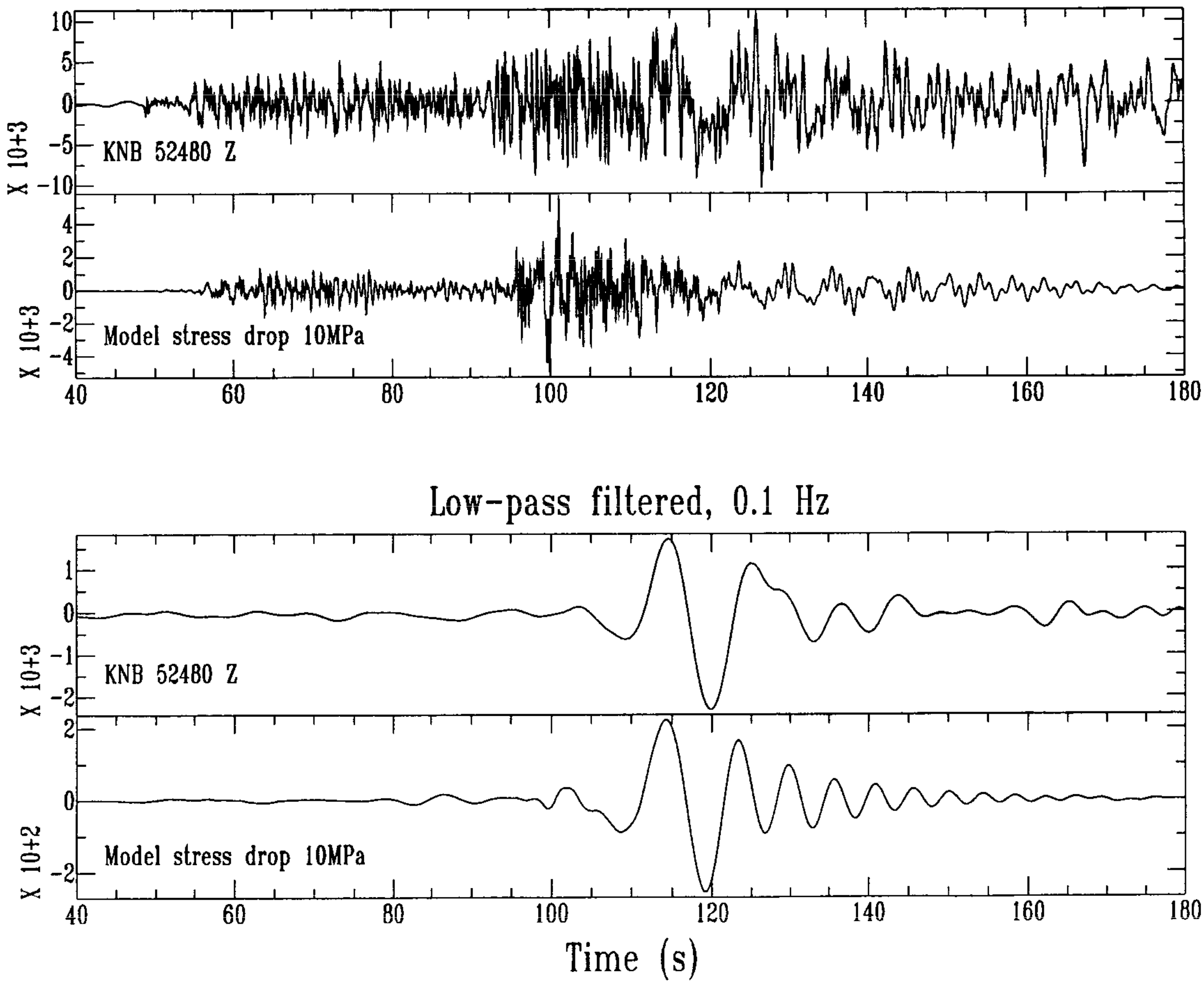
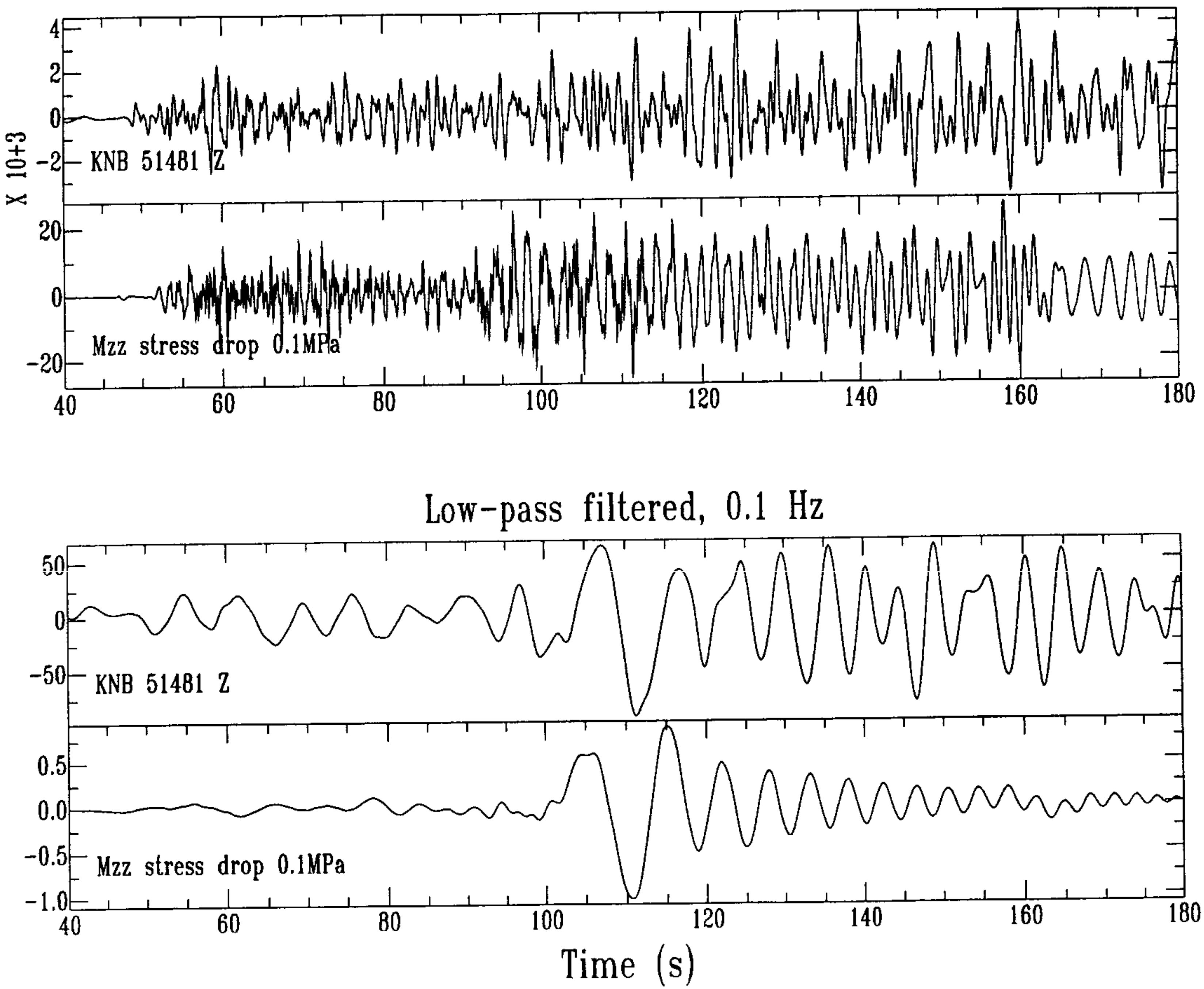

KNB 52480 Z
Model stress drop 10MPa
X 10+3
X 10+3
Low-pass filtered, 0.1 Hz
KNB 52480 Z
Model stress drop 10MPa
X 10+3
X 10+2
Time (s)

Figure 6



X 10+3
KNB 51481 Z
Mzz stress drop 0.1MPa
Low-pass filtered, 0.1 Hz
KNB 51481 Z
Mzz stress drop 0.1MPa
Time (s)

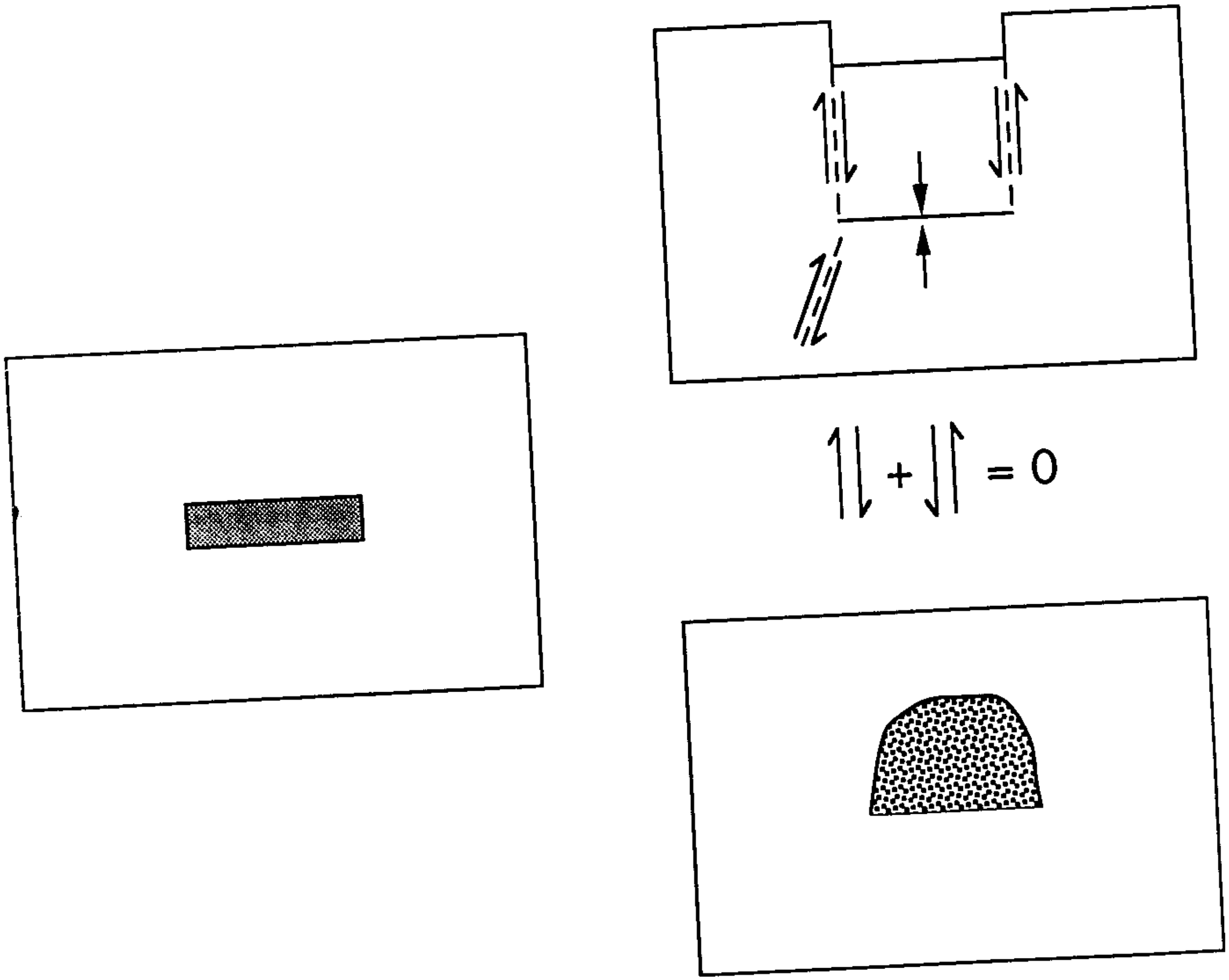


Figure 8