ACTA MONTANA 1992
Series A, No. 3(89), 73-88

SOURCE MODELLING OF SOUTH AFRICAN MINE TREMORS

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ABSTRACT

McGarr *et al.* (1989) [1] have shown mine tremors from the Klerksdorp and Carletonville mining districts of South Africa have distinctly different spectral characteristics above the corner frequency, probably the result of pre-existing deformations in the Klerksdorp region as compared to relatively simple Carletonville district structure. Spectral analysis and moment tensor inversions from the joint US Geological Survey-Phillips Laboratory 1989 field experiment suggest the Carletonville f^{-3} S-wave roll-off is source related. The Carletonville events exhibit double-couple sources, with stress drops from 80 to 220 bars. Preliminary results on the Klerksdorp events confirms the lower S-wave roll-off above the corner frequencies as compared to the Carletonville events at close-in stations. Preliminary attempts at moment tensor inversions suggest a much stronger role for geology in shaping the signals from the Klerksdorp region as compared to Carletonville events.

Key Words: rockbursts, mining seismicity, induced seismicity, source mechanisms, moment tensors

INTRODUCTION

Mining induced seismicity presents a hazard in nearly all countries engaged in extensive mining operations. Only recently have there been efforts to understand these complex phenomena in terms of generic characteristics. An understanding of source properties of mining induced seismic events is imperative for this global view. Lack of information on concurrent mining operations and configurations has been a deterrent in the analysis of rockburst databases from around the Earth. Recently, international symposia and conferences have directed attention to the problem and have provided scientific forums for discussion and comparison of mining seismicity from differing tectonic and geologic regimes. Many areas of study still need to be addressed, such as the spatial/temporal patterns - pre/post large events, prediction methods, events in inactive mine areas, relationship to tectonic stress regime, as well as the basic physics of the phenomena that leads to nonshear components in some instances.

This paper presents some results of a study of mining seismicity in the gold mining districts of the Republic of South Africa, specifically, the Carletonville and Klerksdorp gold mining districts.

Between March 1986 and January 1989, the US Geological Survey (USGS) maintained a regional seismic network in the Witwatersrand Basin of South Africa. In January, 1989, the Solid Earth Geophysics Branch of Phillips Laboratory (PL) supplemented the USGS network with 6 additional stations forming a linear profile, approximately 90 km long, between two of the main mine tremor source regions in the basin, Klerksdorp and Carletonville. This effort was designed to improve our understanding of rockburst source mechanisms and of near-regional seismic wave propagation in the Witwatersrand Basin.

Figure 1 shows the location of the Witwatersrand Basin, site of the seismic network in southern Africa, and the location of the USGS-PL long seismic profile. For reference, the closed triangles are stations of the World-Wide Standard Seismograph Network, the open triangles are stations in the Geological Survey of South Africa Network and the closed boxes are the locations of sites used in the 1986-1989 USGS network, including the sites operated during January of 1989 with additional equipment provided by Phillips Laboratory. During the joint field program two smaller experiments were carried out. First, a long profile was established extending from the Carletonville mining district to Klerksdorp district in the south. Western Deep Levels Mine, located in the Carletonville mining district, is the deepest mine in the world with active mining at approximately 4 km depth. Second, a small seismic array was established near Klerksdorp district. This paper will be limited to discussion of results from the long profile experiment.

INSTRUMENTATION

This figure (Figure 2) also provides an enlarged view of the long profile station layout. The open triangles in the blow-up are USGS General Earthquake Observation System (GEOS) stations operating at 200 samples per second with digitally recorded acceleration and velocity output [2]. The closed triangles show the locations of the PL supplied Terra-Technology DCS-302 recorders which operated at 100 samples per second with Sprengnether S-6000 triaxial 2 Hz velocity transducers. At the PL sites, only velocity output from the sensors was digitally recorded. The PL sites were designated A101 through A106 going from the most northern to the most southern station. Both the GOES and Terra-Technology systems are capable of triggered operation and were operated in that mode.

Time synchronization between stations was a significant problem in this deployment. The PL recorders were primarily intended for use in North America and did not have an adequate method for clock synchronization for use in South Africa. As a result, timing from the PL sites is not sufficiently accurate for applications such as velocity modeling. In addition, potential clock errors could also lead to mis-association of some signals.

SEISMICITY

The mines of the Witwatersrand Basin are among the world's most prolific generators of mine related seismic events. During the four days of network operation over 150 distinct mine-related events were detected in the Carletonville district at station A101, the northern-most PL station. Even this number is only a limited sampling of the total mine tremor activity during this period, however, as the Terra-Technology data tapes typically were filled before the data loggers could be serviced.

The crosses in Figure 2 represent epicentral locations for a limited subset of the seismic activity recorded during the long profile. The 24 plotted events have well constrained hypocentral locations as determined by the mine networks and were recorded by at least two USGS instruments and one PL recorder. As is readily apparent, the seismic activity in this region is concentrated at Klerksdorp and Carletonville and associated with the mining activity. The mine network locations for these events are considered to be accurate within 300 meters for both the horizontal and vertical coordinates.

In Figure 3, the network stations and the epicenters displayed in Figure 2 are projected along a vertical plane extending from Klerksdorp on the left to the northeast. Although spatially close, the two mine tremor source regions of Klerksdorp and Carletonville demonstrate several unique source characteristics.

The activity near Klerksdorp is less frequent than in the Carletonville area, as shown by the significantly fewer number of events recorded in this area during the long profile experiment. Historically, however, the Klerksdorp area has generated higher magnitude events than the Carletonville mining district. Events as large as Richter magnitude 5 have been recorded from the Klerksdorp district. The four events recorded from Klerksdorp during this deployment had magnitudes between 0.7 and 2.5. It should also be noted that most of the active mining in the Klerksdorp area is confined to depths at about 2.5 km and this is seen in the concentration of activity at that depth in the vertical plane. Previous works by McGarr *et al.* [3] and Gay *et al.* [4] have indicated that mine tremors in the Klerksdorp region are controlled by stresses associated with pre-existing fault and dike systems. In the Carletonville district the rockburst activity is obviously more frequent and more diffuse in terms of depth and magnitude but generally of lower magnitude than at Klerksdorp. The reefs in this area are not offset by major geologic faults or dikes and it appears that mine tremors in the Carletonville district are not as strongly influenced by pre-existing conditions and may represent stress release in competent rock.

VELOCITY AND Q MODELS

Before attempting moment tensor inversion for several of the mine tremors it was desired to estimate a shallow crustal model for the Witwatersrand Basin. Modelling of the structure is severely constrained by the poor timing across the network. The lack of clock synchronization required the use of differential S-P times, with an assumed P velocity to examine the shallow crustal structure of the region. The derived structural model is not significantly different from previous models proposed for the district [5,6,7].

Figure 4 shows a plot of S-P intervals as a function of epicentral distance obtained for the 24 well located events using all stations that triggered. In addition, the dotted lines are the predicted S-P time curves for a 2 km deep event using four previously proposed velocity models for the Witwatersrand Basin. For the distance ranges being considered each of these models, with the exception of the Shapira model [7], reduces to a simple half-space with a linear S-P relation. At least out to distances between 60 and 70 km the observed data does not indicate any structure more complex than a half-space.

The solid line in Figure 4 is the least squared error best fit half-space model for the S-P times. Assuming a P-wave velocity of 5.5 km/sec, this model implies a shear velocity of 3.5 km/sec. As can be seen in the figure, the assumed P-wave velocity model nearly overlays the Gane, *et al.* model of 1956 [5], and the Lawrence model of 1984 [6]. In any case, it is apparent that the S-P interval data supports a half-space model with V_p and V_s velocities of 5.5 km/sec and 3.5 km/sec for the near-regional structure. It should be noted, however, that this model is highly weighted towards the Carletonville region due to the volume of data from that region.

Estimates of coda Q, Q_c, for the Witwatersrand Basin were also obtained by analysis of the same set of shallow events [8] and are shown in Figure 5. The Q_c estimates are found to be much lower than might be predicted from the tectonic setting of the Kapvaal Craton which has been largely undisturbed for the past 3 billion years. Using a combined set of data from all stations, Q_c is found to be approximately 30 at 1.5 Hz and 1350 at 24 Hz. The frequency dependence of Q_c estimated from this data is extremely high. These values are more typical of tectonically active regions of Europe and the United States rather than relatively stable settings comparable to the Witwatersrand Basin [9,10]. These results do not, however, appear to agree with previous studies specifically for this area, such as those of Frankel *et al.* [11,12] and Shapira [13].

The best fit relationship between Q_c and frequency is given by $Q_c = 25.5*f^{1.117}$ and is shown by the solid line in Figure 5. The power associated with the frequency term is considered indicative of the mechanism of attenuation. In general it is assumed that higher powers indicate a stronger scattering mechanism. The value found in this study, 1.117, is one of the highest, if not the highest, value I have seen. This suggests a very strong scattering mechanism for the raypaths being studied. The shallow depths of the events and the short epicentral ranges covered indicate that the available ray provide only shallow penetration into the crust. Strong heterogeneity of the shallow crust would not be a surprising conclusion.

Finally, the dashed line in Figure 5 represents the expected curve for a frequency independent Q, Q_i, of 1500 with a mean free path between scatterers of 15 km. This is the intrinsic Q hypothesized by Frankel *et al.* [11,12]. With the possible exception of the coda Q estimate at 24 Hz, this curve could equally well represent the data presented in Figure 5.

Again, the implication of this data is of a strongly heterogeneous shallow crust. Given the previous extensive analysis by Frankel *et al.* of attenuation in South Africa this is the preferred interpretation of the Q_c data. Accepting a high, frequency independent Q with strong scattering in the crust suggested that moment tensor inversions based on P and S-wave first pulse amplitudes, should not be strongly influenced by attenuation factors.

SOURCE CHARACTERISTICS

The remainder of this paper will discussion the analysis of two small subsets of events recorded during the long profile experiment. The first of these is a set of three events located near the Western Deep Levels mine (WDL) in the Carletonville mining district and the second is a set of two events that occurred in the Klerksdorp mining district. The locations of these events are shown in Figure 6. As was noted earlier, these two districts show distinctly different patterns of seismicity with events in the Klerksdorp region much more strongly influenced by pre-existing stresses than those in the Carletonville district. It is of great interest to determine if this condition is somehow reflected in the source mechanics of the two regions.

The seismograms depicted in Figures 7 and 8 demonstrate one variable observed between mine tremor source mechanisms in these two districts. Note that the amplitudes of these displacement seismograms are instrument response corrected and are given in units of meters. In the Figure 7 two events are shown that have been bandpass filtered to the band 1 to 10 Hz. These events were recorded at distances of 2.4 and 3.4 km for the upper and lower traces respectively. The event in the upper trace is from the Klerksdorp district while the event in the lower trace is from the Carletonville region. Figure 8 shows the same events bandpassed between 10 and 30 Hz. It is quite clear that the upper trace in each case is a less complex event than the lower trace which has indications of multiple subevents. It is clear that mine tremors can occur as either simple, single slip events as in the upper trace or as complex processes with multiple subevents. It is noted that the multiple subevents at WDL could also represent the effects of site dependent response, however, as simple and complex events can be seen at both sites, this interpretation does not appear to be acceptable. In attempting to examine the distinctions between the Carletonville and Klerksdorp district source mechanisms, it will be necessary to remain cognizant of the fact that even within each source region distinctions exist between earthquake mechanisms.

One of the more interesting results of previous studies of mine tremors in the Witwatersrand Basin is the fact that events from the Klerksdorp region have spectral roll-offs of f^2 above the corner frequency while events in the Carletonville region show f^{-3} decay[1,3,15].

Figure 9 shows the normalized S-wave spectra for four stations from event E115, a mine tremor in the Klerksdorp region. The stations range from an epicentral distance of 1.9 km to 71.1 km. At short ranges, out at least to 13 km, the S-wave spectra show the commonly accepted high-frequency asymptotic decay of f^2, similar to that of natural earthquakes. At stations beyond that range the high-frequency asymptote appears to roll-off at f^3. The higher decay at these greater ranges could be associated with either a radiation pattern effect as might result from particular orientations of the rupture front and observing station, or simply attenuation.

Figure 10 shows the normalized S-wave spectra of the seismic signals recorded from event E112, an event that was located in the Carletonville region. A spectral decay of f^{-3} or more above the corner frequency for each of the plotted curves is obvious. It is noted that the corner frequency appears to be consistent between stations indicating that the high-frequency signal is not being corrupted by attenuation. As it has previously been shown that this characteristic is found at very short ranges, of the order of 1 km or less [1,3,14], and here demonstrated at a range of take-off angles and azimuths, it is difficult to develop an explain except as a characteristic of the event source, itself.

SOURCE MODELLING

Source parameter modelling was performed using spectral analysis and moment tensor inversion of the mine tremors. Spectral estimates of source parameters were made on the basis of the Brune model [15] and moment tensor inversions were based on first-arrival amplitudes for the direct P- and S-waves [16,17,18]. The moment tensor inversion assumed a traceless moment tensor implying that the sources have no isotropic component. Software for the moment tensor inversion was kindly provide by Dr John Ebel of Boston College [19].

Independent source parameter estimates were made based on P- and S-wave spectra for each station at which an event was recorded. Seismic moments, M_0, were calculated using the relationships

$$M_o = \frac{4\pi\varrho c^3 R|\Omega_o|}{F(c)} \tag{1}$$

where ρ is density, c is either the P- or S-wave velocity, α or β, respectively, R is hypocentral distance, Ω_0 is the low-frequency level of the P- or S-wave displacement spectra and F(c) is a factor depending on the radiation pattern and equal to 0.39 for the P-wave and 0.57 for the S-wave [14]. The rupture radius, r_0, is estimated from the S-wave corner frequency, f_c and is given by

$$r_o = \frac{2.34\beta}{2\pi f_c} \tag{2}$$

and the stress drop, $\Delta\sigma$, is related to the moment and rupture radius by

$$\Delta\sigma = \frac{7M_o}{16r_o^3} \tag{3}$$

The results of the spectral modelling are shown in Figures 11 and 12. It should be noted that a high level of agreement was found among the independent solutions for each event. As can be seen in Figure 11, the results for the Carletonville events appear to be reasonable solutions both in terms of the estimated moment and stress drop. This is concluded from the fact that the moment magnitudes for each event are comparable to the observed magnitudes and that the estimated stress drops are not unrealistic although they do tend to be high as compared to natural earthquakes, particularly in the cases of E134 and E136. For one of the Klerksdorp events, E115, the results, shown in Figure 12, do not appear to be as reliable. The moment magnitude and the observed magnitude for this event are in good agreement but the stress drop is extremely high. This suggests that either the estimated stress drop is too large or the rupture radius is too small. At this point, there is insufficient evidence to infer that the error lies with one or the other parameter.

Finally, moment tensor inversions were carried out for these same five events and the results are also shown on Figures 11 and 12. The inversions were made on the basis of the best fit to the direct upgoing P- and S-wave first arrivals. A source time function for each event was determined using the mean half-pulse width of the first P-wave arrival as suggested by Liu *et al.* (1991). For all of the events the source duration determined in this manner ranged from 0.03 to 0.07 s. All inversions were carried out using the mean time function of 0.05 s.

The moment tensor inversions for the events from the Carletonville mining district were all well fit by a double couple source with less than 1.60% of the moment assigned to a compensated linear vector dipole (CLVD). The estimated moments are in good agreement with the spectrally estimated moments and the orientations of the focal planes are not inconsistent with the trends of mapped faults in the Carletonville region, such as the Arrarat or Wesselia fault. It would appear then that seismic sources in the Carletonville mining district are well modelled by simple, natural earthquake source models.

In the Klerksdorp region, however, there is less agreement between the spectral and moment tensor estimates of seismic moment (Figure 12). The stress drop derived from the Brune source model is extremely high for event E115 while the estimate for event E150 does not appear to be unreasonable. On the other hand, the moment tensor solution for event E115 has a low CLVD component while event E150 has a very high non-double couple component. The fault planes determined in the inversion process are, again, consistent with those identified by Gay et al. (1984). Improvements in the inversion results obtained by varying the hypocentral locations and velocity models used in inverting the Klerksdorp events imply that a significantly more complex crustal structure is required for this district than the half-space model presented above.

CONCLUSIONS

During January of 1989 the USGS and Phillips Laboratory operated a 90 km long linear seismic network between the mining districts of Klerksdorp and Carletonville in the Witwatersrand Basin of South Africa. Analysis of the data taken during this field effort indicates that the structure in this array is adequately modelled by a half-space with an assumed P-wave velocity of 5.5 km/s and a S-wave velocity of 3.5 km/s. Attenuation in the region appears to be characterized by very low Q but there is reason to believe that this is largely the result of intense scattering along the very shallow crustal raypaths available in this study. It should be noted that the data sample from which these conclusions are drawn is dominated by events from the Carletonville mining district and might not be applicable to the Klerksdorp region which is known to have a more complex geology.

Spectral analysis of events from the Klerksdorp region suggest that the source processes are probably similar to commonly accepted models for natural earthquakes with high-frequency asymptotes falling off as f^2 for stations at short epicentral before attenuation significantly effects the roll-off. In contrast, events from the Carletonville region show unusual f^3 high-frequency roll-off at all observed ranges and azimuths.

At the same time, moment tensor solutions and spectral estimates for seismic moment are in good agreement from the Carletonville events while the moment tensor inversions are considered much less reliable for events from the Klerksdorp mines. It is felt that this could result, at least in part, from the more complex geologic structure in the Klerksdorp region and the inadequacy of a simple half-space model for modelling of events from that district.

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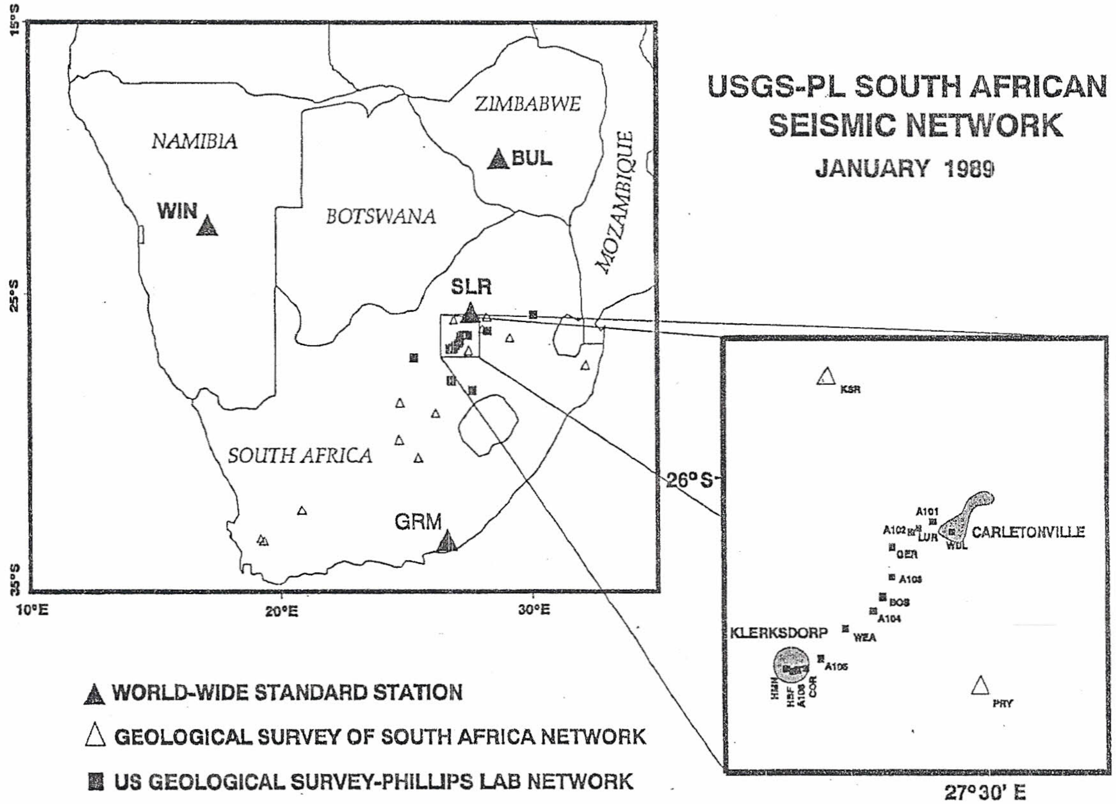
USGS-PL SOUTH AFRICAN
SEISMIC NETWORK
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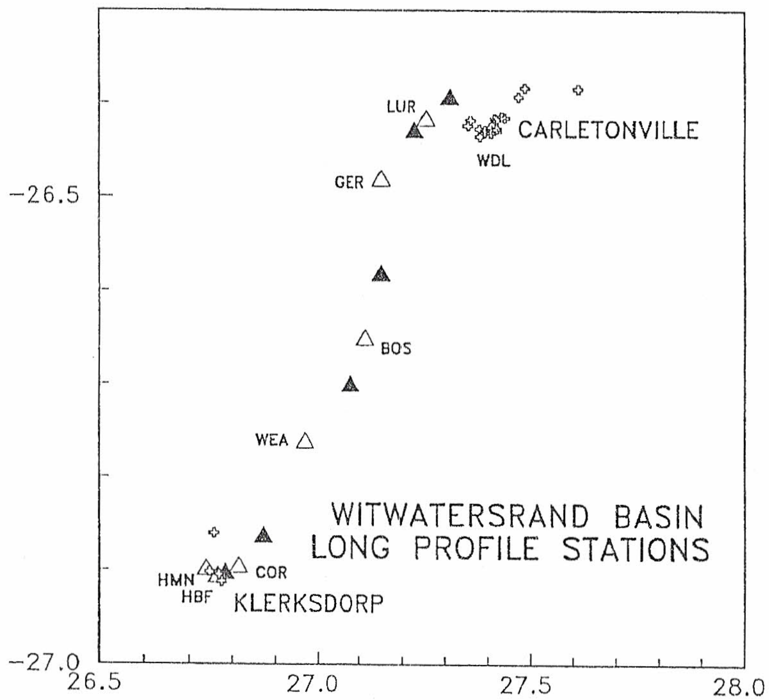
FIGURE 1.



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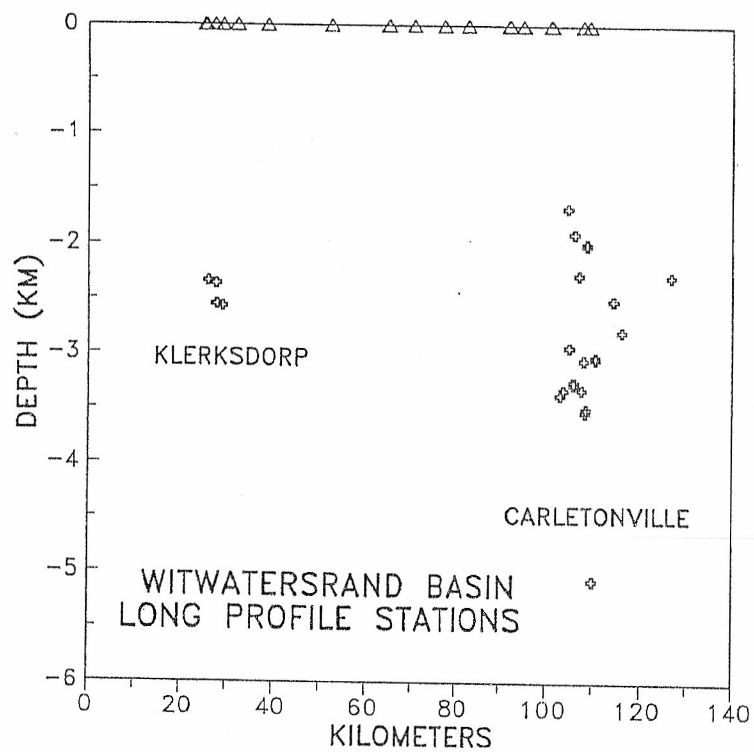

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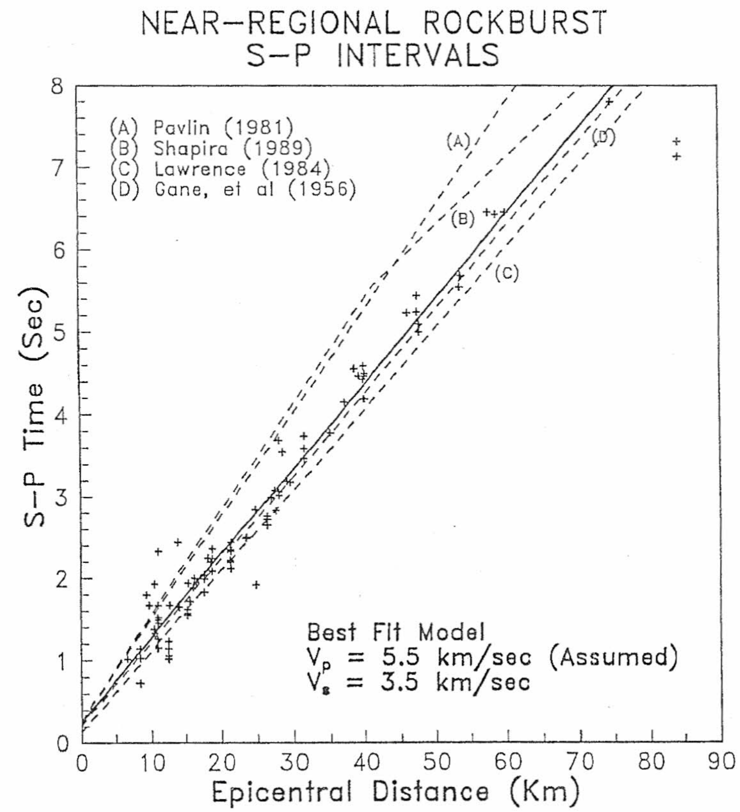
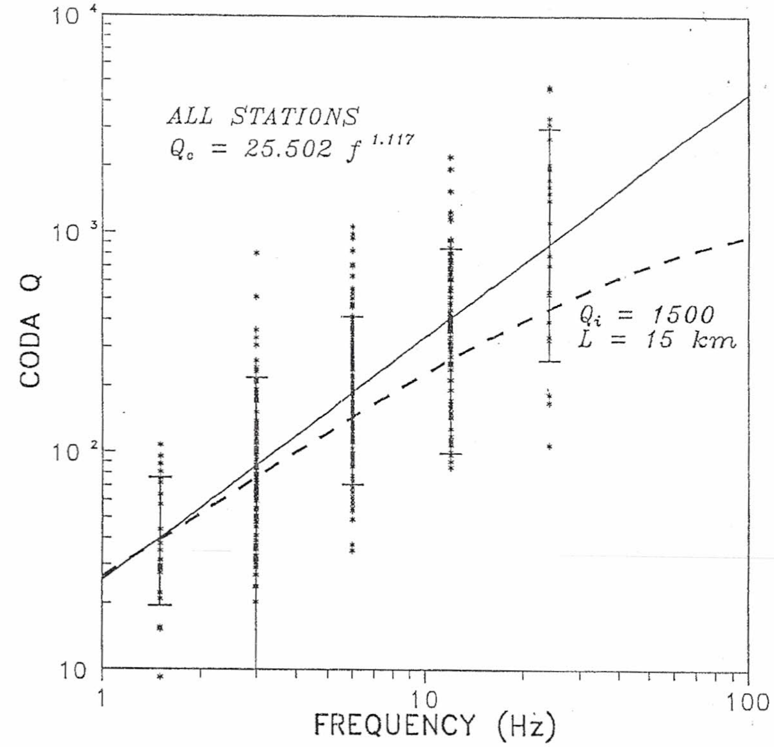


FIGURE 4.



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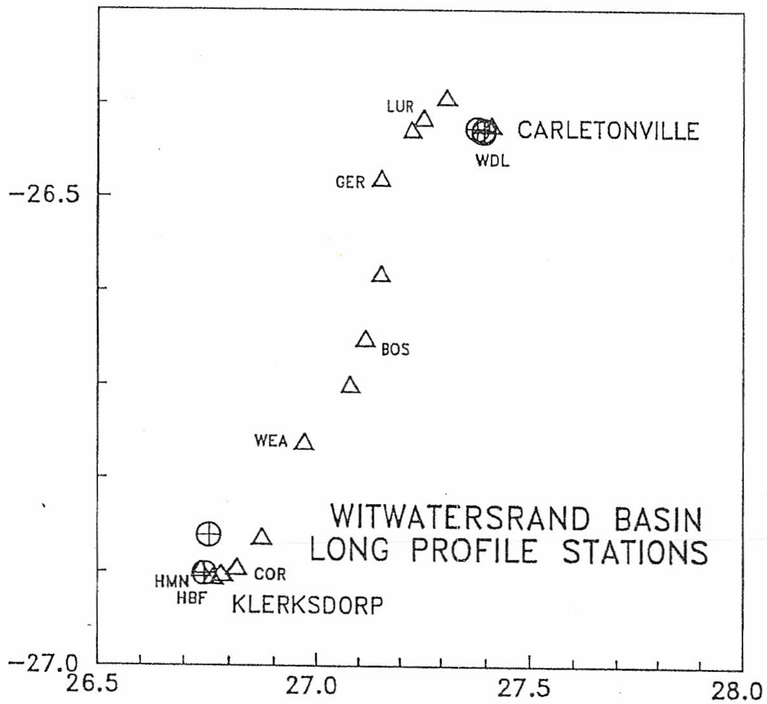

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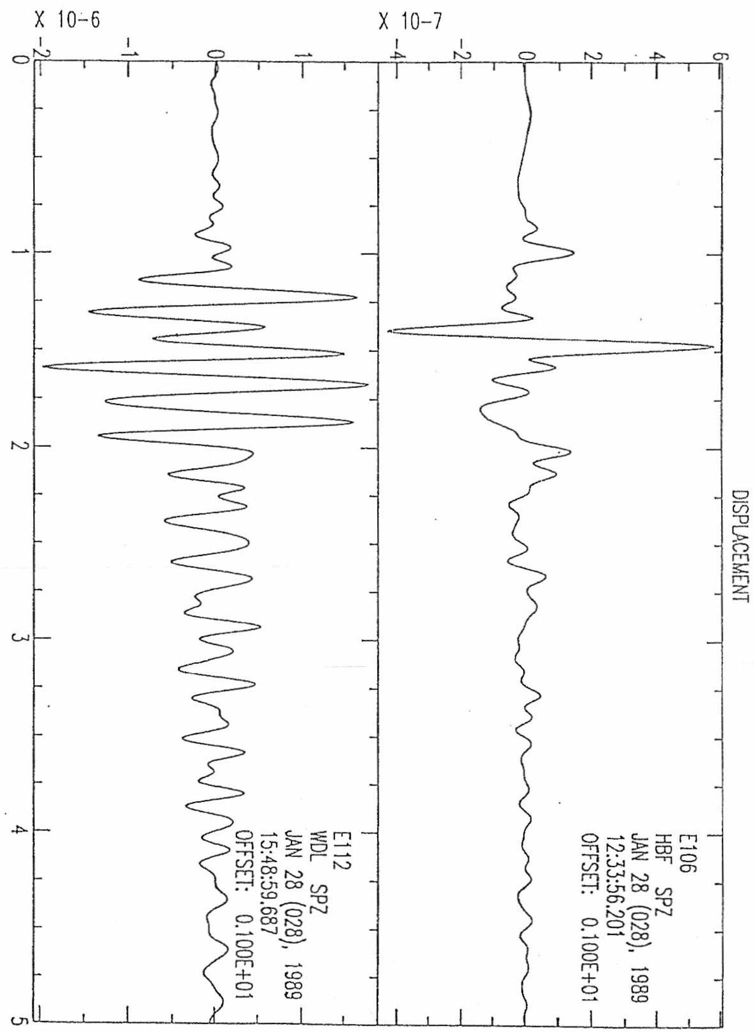

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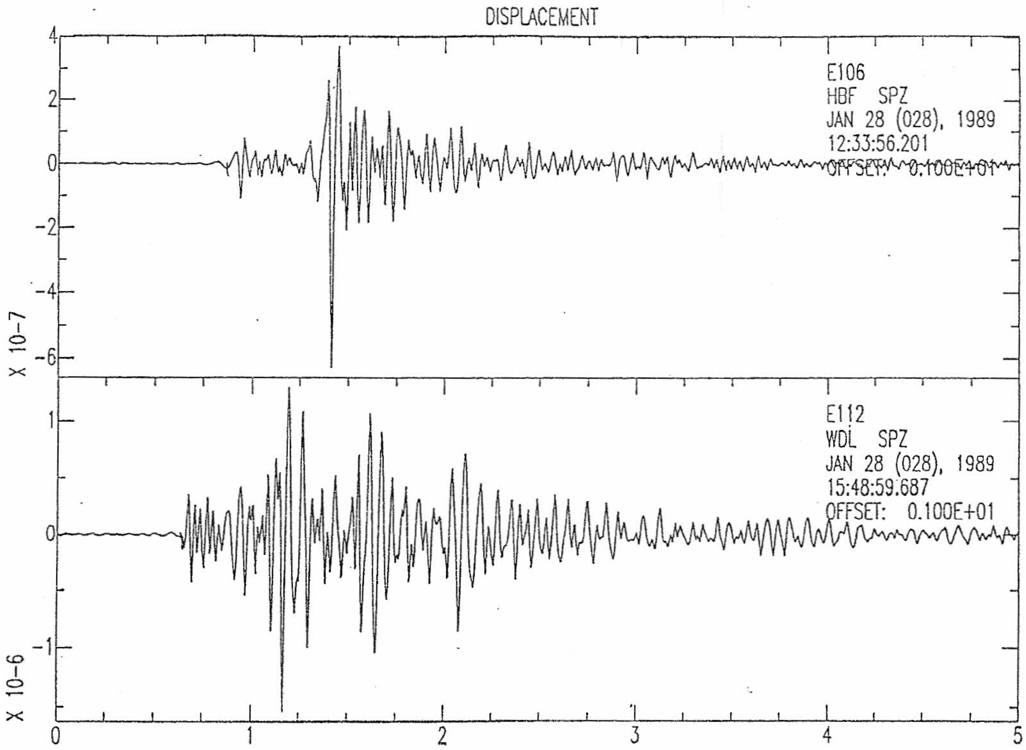
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FIGURE 8.

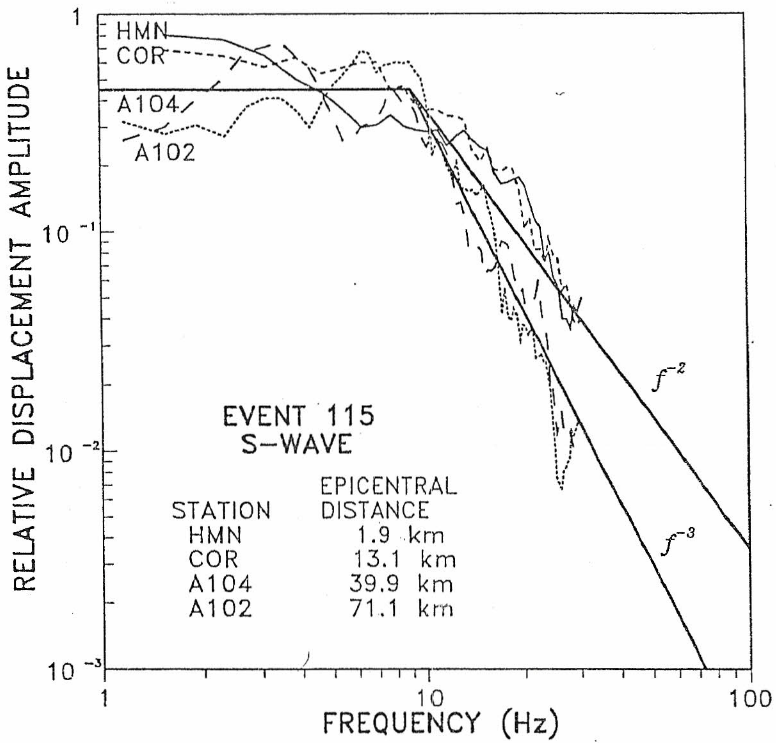

FIGURE 9.

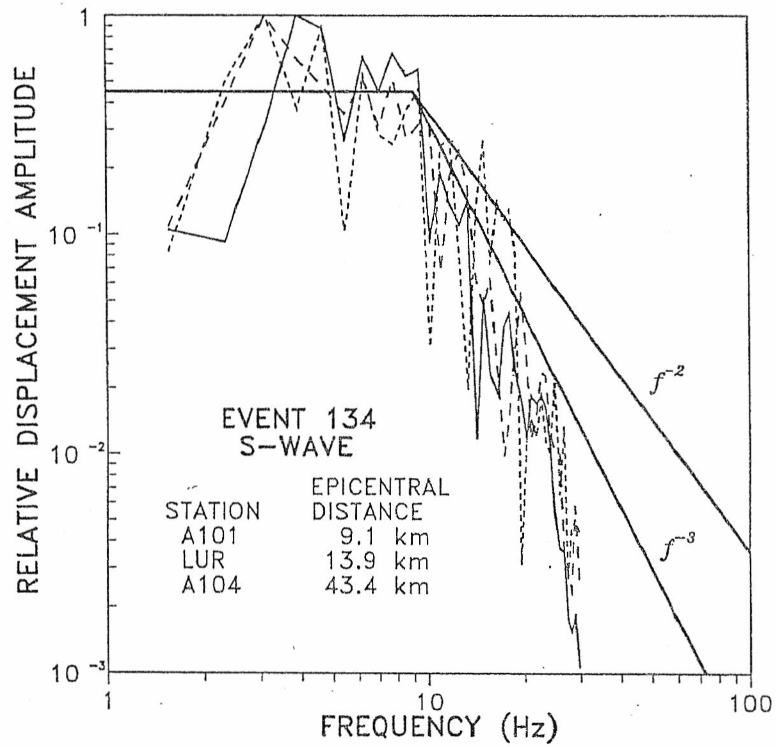

FIGURE 10.

CARLETONVILLE MINE TREMORS

EVENT:	E112	E134	E136
DATE:	28-Jan	30-Jan	30-Jan
TIME:	15:48:57	16:16:13	16:16:57
DEPTH (km):	2.937	1.897	3.277
MAGNITUDE:	1.4	1.4	1.4
SPECTRAL SOLUTION			
RUPTURE RADIUS (km):	0.15	0.12	0.11
MOMENT (10^{16} dyne-cm):	592	931	619
STRESS DROP (bars):	78	220	197
M(Mo):	1.8	1.9	1.8
INVERSION SOLUTION			
MOMENT (10^{16} dyne-cm):	321	1192	627
CLVD:	0.20%	0.40%	1.60%
% NON-DOUBLE COUPLE:	0.91%	1.97%	6.31%
STRIKE:	103°	343°	197°
DIP:	21°	11°	16°
RAKE:	331°	298°	27°

FIGURE 11.

KLERKSDORP MINE TREMORS

EVENT:	E115	E150
DATE:	28-Jan	31-Jan
TIME:	18:45:40	13:25:49
DEPTH (km):	2.335	2.566
MAGNITUDE:	2.4	1.7
SPECTRAL SOLUTION		
RUPTURE RADIUS (km):	0.17	0.072
MOMENT (10^{16} dyne-cm):	1025	81
STRESS DROP (bars):	955	93
M(Mo):	2.6	1.2
INVERSION SOLUTION		
MOMENT (10^{16} dyne-cm):	3697	84.8
CLVD:	0.60%	27.00%
% NON-DOUBLE COUPLE:	2.67%	85.53%
STRIKE:	191°	133°
DIP:	35°	45°
RAKE:	268°	249°

FIGURE 12.