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Analysis of Exceptionally Large Tremors in Two Gold Mining Districts of South Africa*

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Abstract—An investigation of ground motion, recorded using broad-band, wide dynamic-range digital seismographs, of large mine tremors from two South African mining districts with different geologic settings, reveals some essential differences in both seismic source and ground motion parameters. In the Klerksdorp district where the strata are offset by major throughgoing normal faults, the largest tremors, with magnitudes ranging as high as 5.2, tend to be associated with slip on these pre-existing faults. Moreover, the seismic source and ground motion parameters are quite similar to those of natural crustal earthquakes. In the Carletonville district, by contrast, where substantial faults do not exist, the large-magnitude tremors appear to result from the failure of relatively intact rock and cause seismic stress drops and ground motion parameters higher than normally observed for natural shocks. Additionally, there appears to be an upper magnitude limit of about 4 in the Carletonville district. Detailed analyses of an exceptionally large event recorded locally from each of these districts serve to highlight these contrasts.

Key words: Large mine tremors, source parameters, ground motion parameters, Klerksdorp mining district, Carletonville mining district.

Introduction

During March 1986 seven seismic stations were installed in and around the major gold mining districts of South Africa partly for the purpose of investigating the nature of high-frequency ground motion from unusually large mine tremors as recorded at both local and regional distances (Figure 1). GEOS digital event recorders (Borcherdt *et al.*, 1985) were installed at four surface sites within the mining districts that account for the majority of mine-induced seismicity in South Africa. At the GEOS stations three components each of ground acceleration and velocity are recorded digitally at a rate of 200 samples per second for each channel;

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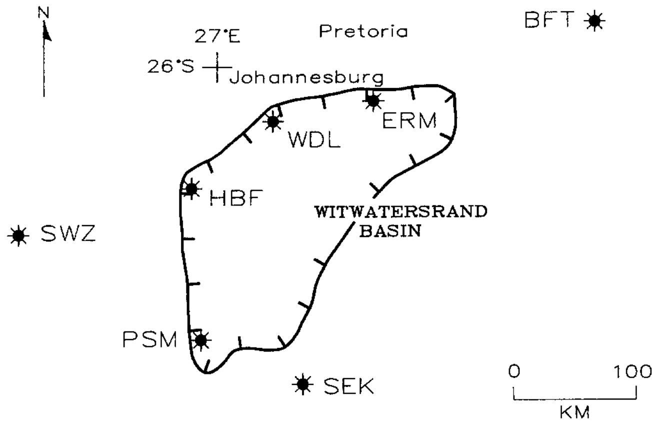

Figure 1
USGS seismic network in and around the major gold mining districts of South Africa. ERM, WDL, HBF and PSM denote GEOS stations and SWZ, SEK, and BFT comprise the regional SDCS stations. Stations WDL and HBF are within the mining districts of Carletonville and Klerksdorp, respectively.

each channel has a dynamic range of 96 dB. Regional seismic coverage of the mine tremors is provided by the SDCS stations (Special Data Collection System) manufactured by Teledyne-Geotech. At these stations, three short-period components of ground motion plus the long-period vertical are continuously recorded digitally at 20 samples per sec. As presently configured the useful bandwidth of the short-period system is from 1 to 6 Hz and for the long-period from 0.06 to 0.02 Hz; the dynamic range for each channel is 72 dB.

The goal of this project is to record and analyze all mine-induced events of magnitude 3 and greater. These events are of interest for several reasons. For example, with applications to nuclear test ban treaty verification, this data set can further our understanding of the nature of high frequency radiation from small-to-medium sized earthquakes. Another objective is to gain insight regarding the exact nature of exceptionally large mine tremors and their relation to both the mining operations and the geological setting. Progress toward this second objective is the subject of this report.

Before describing this progress, however, we should note a few of the advantages to undertaking an investigation of this sort in and around the gold fields of South Africa. The principal reason, of course, is that the mining operations give rise to a remarkably high level of seismicity in very confined areas, with magnitudes occasionally exceeding 5 (e.g., FERNANDEZ and VAN DER HEEVER, 1984). For instance, we note that during May 1986 we analyzed 22 tremors of $M \geq 3$, 18 of which occurred within hypocentral distances of 5 km of GEOS station WDL (Figure 1). There is nowhere else in the world where, at any given time, one could count on recording anything approaching such a concentration of seismicity in this magnitude range. This level of seismicity is almost entirely due to the mining. As assessed by McGARR (1985), for example, underground operations within the Klerksdorp district, comprising four large mines, serve to raise the level of seismicity by nearly four orders of magnitude relative to its natural level, which is quite low throughout South Africa due to the stable tectonic setting. Thus, there is little chance within a mining district of confusing an induced tremor with a natural earthquake. Another advantage is that seismic location networks operated by the mines can determine hypocenters very precisely in all three spatial coordinates. These location networks include numerous underground borehole recording sites above and below the mining levels.

This report focuses on the differences observed in the nature of seismicity between the Carletonville and Klerksdorp mining regions. These differences in seismicity appear to be related at least partly to differences in geological setting, an observation which had been broadly recognized before the present study commenced and, in fact, provided some of the motivation for it. Specifically, mining areas for which the strata are offset by major faults experience occasional tremors whose maximum magnitude is much greater than the largest tremors in gold fields with only small fault offsets. Moreover, it appears that the major faults are directly implicated in the generation of the exceptionally large tremors as evidenced by underground observations at localities where the faults intersect the mine excavations. For the two mining districts to be compared here the respective maximum local magnitudes are observed to be 4.0 and about 5.2, and so the effect under discussion is not subtle.

In addition to the maximum magnitude differences, however, routine analysis has revealed numerous other contrasts in the nature of both seismic source and ground motion parameters. In essence, for events of fixed magnitude, those involving slip across major pre-existing faults have much larger source dimensions and more extended ground motion time histories than tremors whose hypocenters are located in rock that has suffered only minor faulting. Additionally, levels of ground motion, considered to be potentially damaging, are observed to be lower for the events associated with major faults than for those located in relatively pristine rock.

Currently, the role a pre-existing geological fault plays in influencing the seismic character of mine tremors is not at all clear. Possibly the presence of major faults reduces the large-scale bulk strength of the rock mass relative to other mining areas in similar strata that have not undergone substantial faulting. Alternatively, the irregular mining geometries, associated with the major faults, may have more influence than the faults themselves on the nature of the seismic deformation.

Comparison of Klerksdorp and Carletonville Tremors and Geology

The geological structure of the strata comprising the Klerksdorp gold field (Figure 1) is quite complex in that the gold-bearing reef, at an average depth of about 2.3 km, is offset by a number of northeast-striking normal faults to form a series of horsts and grabens. Offsets across these major faults are typically several hundred meters, which gives rise to a relatively complicated mine geometry (GAY *et al.*, 1984). An extensive seismic location network (SCHEEPERS, 1984; VAN DER HEEVER, 1984) was installed in this gold field starting in 1971 partly with a view to investigating the relationship between the exceptionally large tremors and the major throughgoing faults.

In contrast, the geological structure of the Carletonville mining district is simple in that the strata are hardly offset at all by either faults or intrusive dykes (e.g., SPOTTISWOODE, 1984). Most of the mining in this region takes place at depths between 2 and 4 km, with the deepest operations occurring in the Western Deep Levels Gold Mine, where one of the GEOS units is sited (Figure 1). Although the unusually severe rockburst problem at Western Deep Levels has been attributed to the extreme depth of mining here (e.g., TANTON *et al.*, 1984), we shall review some observations that serve to reiterate the conclusion drawn by MCGARR (1984a) that the seismic hazard measured in terms of total seismic deformation does not depend appreciably on depth of mining. That is, mining at depths of 4 km does not lead to larger tremors than the same amount of mining at 2 km, for example.

To illustrate a few aspects of the seismic differences between the Klerksdorp and Carletonville gold fields we now review in some detail the analysis of an exceptionally large event recorded from each mining area (Table 1, Figures 2 and 3). The figures illustrate the component of ground motion transverse to the ray path so as to focus attention on the pure shear wave, which nearly always is the most important phase in terms of seismic hazard at small hypocentral distance. While due to space limitations we focus here on one component of one event recorded at each site, it is stressed that the observations made here apply to the general data set.

Figure 2 illustrates the east-west component of ground motion due to an event of moment-magnitude (HANKS and KANAMORI, 1979) 4.0 located 2.4 km north of GEOS station WDL (Figure 1) and at a depth of 2 km. The peak acceleration of 0.45 g is considerable and the S pulse is quite simple in appearance (Figure 2a). Integration of the acceleration trace yields the velocity time history (Figure 2b), which also has an impressive peak value of 6.7 cm/s. Note, incidently, that the peak in velocity precedes that in acceleration in time. Thus, the peak acceleration is not associated with the leading edge of the S pulse, nor, presumably, the initiation of rupture.

A second integration yields the ground displacement trace (Figure 2c) from which the spectrum of displacement amplitude is calculated. As seen in all three versions of the ground motion, the major vibrations occur over a time of roughly 0.2 s, and this is reflected in the spectrum (Figure 2c), which shows a low-frequency plateau $\Omega(0)$ and a high-frequency asymptote (where the spectrum decays according to f^{-3}) separated by a corner-frequency of 6 Hz.

Table 1

Source and ground motion parameters.

Event	Date	R, km	Depth, km	M_0, dyne-cm	$M(M_0)$	r_0, m	$\Delta\sigma$, bars	$R\underline{v}$, cm^2/S	$\rho R\underline{a}$, bars	Mine	District
2321149	20 Aug. 1986	3.18	2.04	9.53×10^{21}	4.0	236	317	1.64×10^6	296	Driefontein	Carletonville
3171111	13 Nov. 1986	6.24	0.94	1.62×10^{22}	4.1	708	20	3.57×10^5	84	Buffelsfontein	Klerksdorp

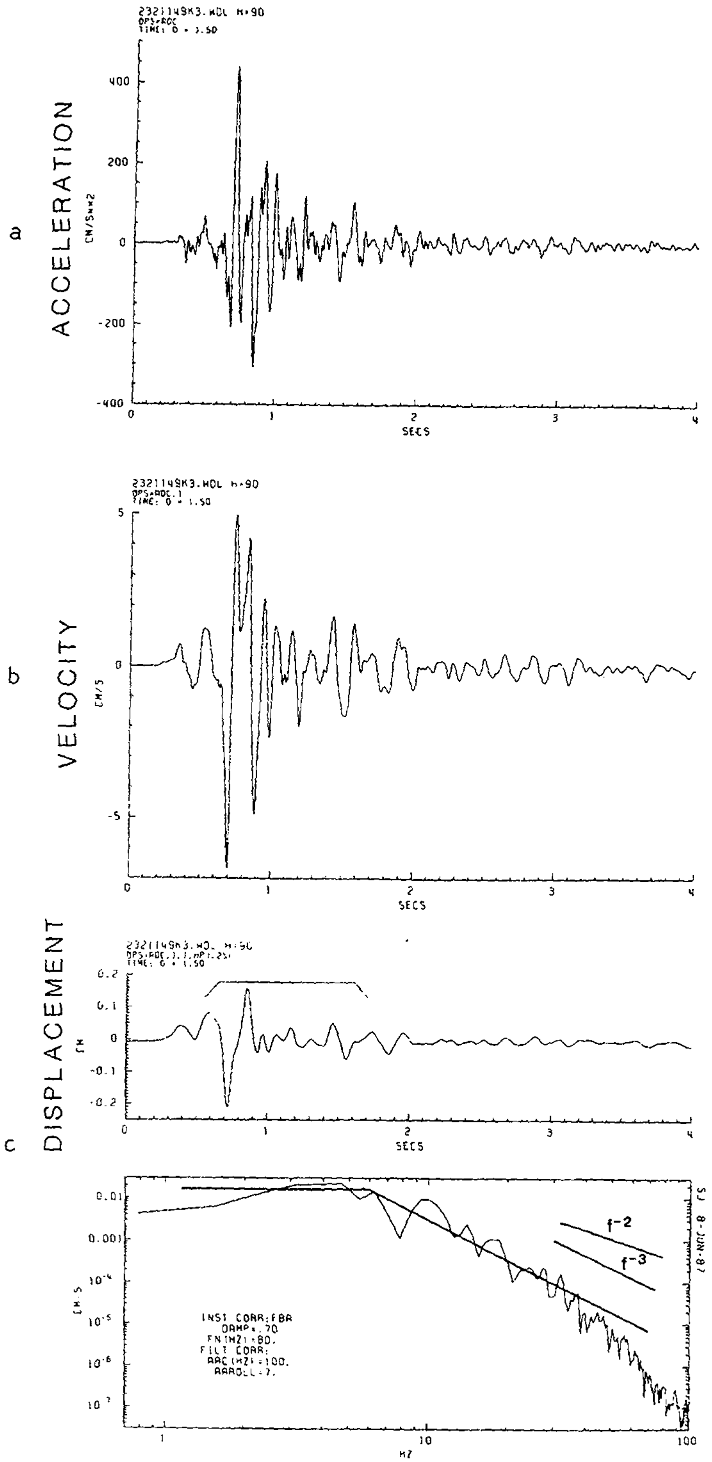

Figure 2
East component of ground motion from event 2321149 recorded at GEOS station WDL. (a) Acceleration, (b) velocity, (c) displacement and displacement amplitude spectrum.

Seismic moments, M_0, were calculated for both the P and S waves using (BRUNE 1970, 1971)

$$M_0(c) = \frac{4\pi\rho c^3 R|\Omega(0)^c|}{F(c)} \tag{1}$$

where for the P waves $c = \alpha$, the P wave velocity, and $F(\alpha) = 0.39$ (SPOTTISWOODE and MCGARR, 1975) whereas for S waves $c = \beta$, the S wave velocity and $F(\beta) = 0.57$. ρ is density, R is hypocentral distance and $|\Omega(0)|$ represents the vector sum of the low-frequency spectral plateau for P or S as would be recorded in a whole space; that is, the effect of the free surface has been taken into account. For the situations considered here, $\rho = 2.9$ gm/cm^3, $\alpha = 6$ km/s, and $\beta = 3.8$ km/s. The values of M_0 listed in Table 1 are geometric averages of $M_0(P)$ and $M_0(S)$, which for each of these events agree to within a factor of two. Seismic moment can be related to a moment-magnitude $M(M_0)$ scale (HANKS and KANAMORI, 1979), which is calculated from

$$M(M_0) = (2/3)\log M_0 - 10.7\,. \tag{2}$$

The source radius r_0 is estimated from the S wave corner frequency $f_0(S)$ (Figure 2c) according to (BRUNE 1970, 1971)

$$r_0 = \frac{2.34\beta}{2\pi f_0(S)} \tag{3}$$

and for event 2321149 the result is about 236 m (Table 1). M_0 and r_0 can then be used to estimate the seismic stress drop $\Delta\sigma$ (BRUNE, 1970) from

$$\Delta\sigma = \frac{7}{16}\frac{M_0}{r_0^3} \tag{4}$$

and for event 2321149 the result of 317 bars is exceptionally high by normal earthquake standards. Generally the stress drop is observed to fall within the range of 1 to 100 bars (e.g., HANKS, 1977; MCGARR *et al.*, 1981).

In addition to the seismic source parameters, the ground motion parameters $\rho R\underline{a}$ (e.g., HANKS and JOHNSON, 1976; MCGARR *et al.*, 1981) and $R\underline{v}$ (e.g., MCGARR, 1984b) are routinely determined and those for the events discussed here are listed in Table 1. $\underline{a}$ and $\underline{v}$ represent the vectorially summed peak acceleration and velocity as would be recorded in a whole space. The peak acceleration parameter for event 2321149 of 296 bars is quite high, especially for an event at a depth of only 2 km (MCGARR, 1984b). The peak velocity parameter for this event is also exceptionally high for an event of $M(M_0)$ 4.

Event 3171111, one of the largest events recorded locally, to date, during this project, was located 6 km east of GEOS station HBF in the northwestern portion of the Buffelsfontein mine where a major northeast striking fault has been mapped. Its ground motion presents quite a contrast (Figure 3) to that of event 2321149

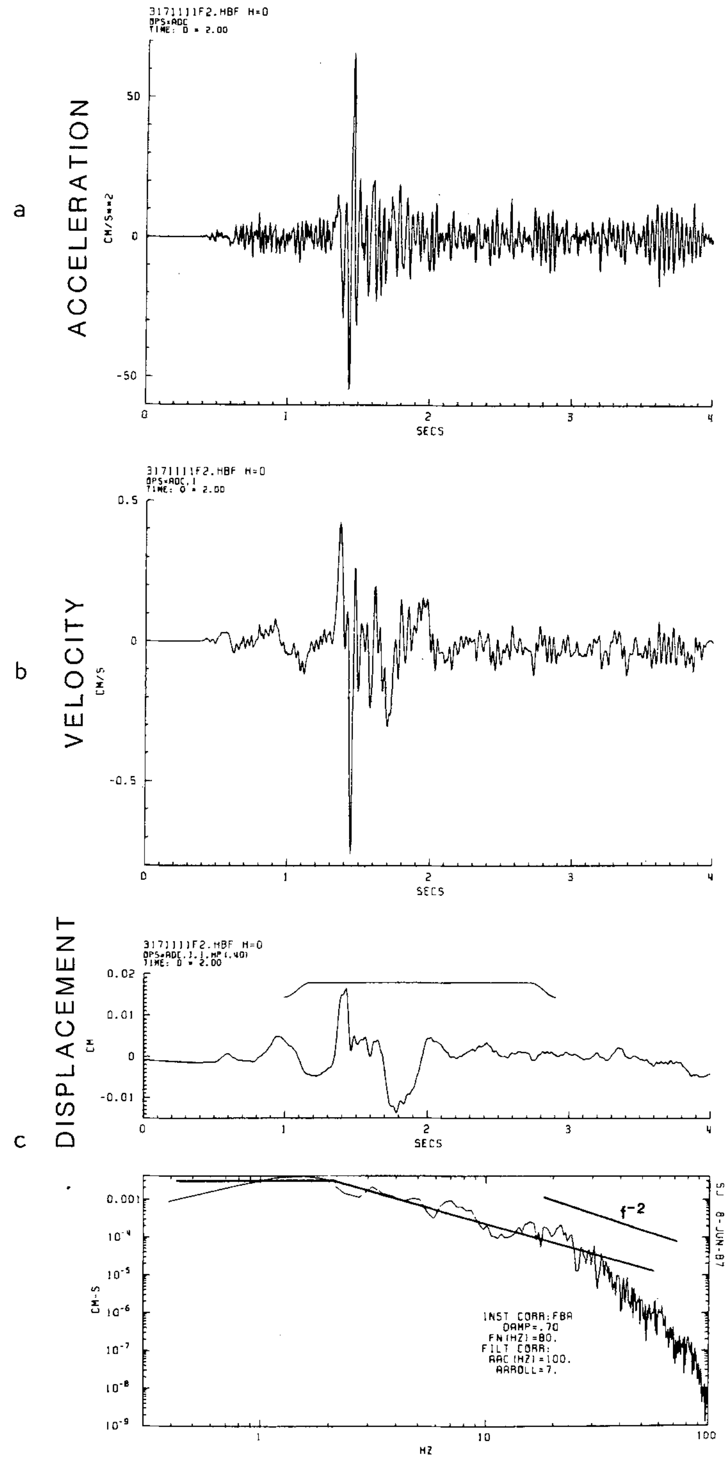

Figure 3
North component of ground motion from event 3171111 recorded at GEOS station HBF. (a) Acceleration, (b) velocity, (c) displacement and displacement amplitude spectrum.

(Figure 2). The peak acceleration of 3171111 (Figure 3a) is low compared to event 2321149 and the corresponding ground motion parameter, $\rho R\underline{a}$ (Table 1), which takes hypocentral distance into account, is only 28% that of event 2321149. The peak velocity of this event (Figure 3d) and its parameter $R\underline{v}$ (Table 1) are also quite small compared to those of the other event; $R\underline{v}$ for event 3171111 is about 22% that of the other tremor in spite of the fact that the magnitude of this Klerksdorp event is greater.

The most interesting comparison, however, involves the ground displacements and displacement spectra for the two events. In Figure 3c we see that the displacement time history of the *S* wave lasts approximately 0.7 sec, in contrast to that in Figure 2c, which, as noted before, lasts about 0.2 sec. The *S* wave corner frequency (Figure 3c) of 2.0 Hz, as geometrically averaged over the three components, is correspondingly low compared to that of event 2321149. In essence, then, the *S* pulse of event 3171111 is stretched out in time by about a factor of three compared to the large Carletonville event, but the peak displacement is lower, even taking geometrical spreading ($1/R$) into account (compare Figures 2c and 3c).

These first-order differences are reflected in the source parameters (Table 1) which indicate that in terms of M_0, event 3171111, which is associated with a major fault on the basis of its hypocentral location adjacent to such a fault, and approximately 1 km above the mine workings, involved approximately 1.7 times as much seismic deformation as event 2321149. The low value of $f_0(S)$, moreover, indicated (equation (2)) quite a large source radius of 708 m. Thus, although the hypocenter was located about 1 km above the mining horizon, the large overall size of this tremor suggests that part of the seismic deformation included slip at the level of the mine workings. Finally, the stress drop of 20 bars (equation (3)) for this event is typical for earthquakes in contrast to the high stress drop of the Carletonville tremor (Table 1).

Concluding Discussion

From our description of these two largest events, it is clear that there are some substantial differences in the nature of the seismic deformation in the Klerksdorp and Carletonville areas. Moreover, it appears most likely that these differences are related to the presence of major throughgoing faults at Klerksdorp and their absence in the Carletonville district. Results of the present analysis suggest that the largest Klerksdorp events produce ground motion that is more similar to that of natural crustal earthquakes in extensional tectonic settings than do those near Carletonville.

Both the spectra and the seismograms themselves indicate that the 2321149 event, near Carletonville, generated a narrow range of frequencies relative to the 3171111 tremor. In comparing Figures 2c and 3c, it is clear that beyond the respective corner frequencies, the 2321149 spectrum falls off more rapidly with increasing frequency than that of 3171111. Specifically, for 2321149 the high-frequency asymptote diminishes as f^{-3} whereas for 3171111 the same asymptote decays according to f^{-2}, more in agreement with natural earthquake observations (e.g., ANDREWS, 1986).

This essential spectral difference is also clear on the velocity traces (Figures 2b and 3b) where we see that for 2321149 there is little apparent frequency content beyond about 10 Hz in contrast to the trace for 3171111 for which important contributions are present for frequencies ranging from roughly 2 Hz to 20 Hz. Assuming that the rupture area is inversely proportional to the apparent frequency (e.g., equation (2)), it is clear that the 3171111 event involved a more complex rupture process, one involving failure over a wide range of scales, extending downward from the inferred source radius of 708 m (Table 1). In the case of event 2321149, the rupture process appears to have been much simpler. In brief, then, the important ground motion for 2321149 is contained within quite a narrow spectral band compared to that of 3171111.

Just as the seismic stress drop of event 3171111 is typical for those of natural crustal earthquakes (Table 1), as was discussed already, it turns out that the ground motion parameters for this event are also quite compatible with results for natural events in contrast to the same parameters of event 2321149. To make this comparison, the parameters $R\underline{v}$ and $\rho R\underline{a}$ have been plotted in Figure 4 along with regression fits to natural earthquake data developed by MCGARR (1984b).

$$R\underline{v}/M_0^{1/3} \text{ (extensional)} = 10^{-4}(\text{m}^2/\text{s})(\text{Nm})^{-1/3}[3.00 + 0.69(\text{km}^{-1})z]$$

and

$$\rho R\underline{a}(\text{extensional}) = -1.08 \text{ MPa} + 3.06(\text{MPa/km})z$$

where z is depth in km and 'extensional' refers to an extensional tectonic state of stress. For the peak velocity parameter $R\underline{v}$, that for 3171111 is in close agreement with the earthquake regression lines for either 1 or 2 km depths; these regression lines, incidently, show the expected scaling of $M_0^{1/3}$. The peak velocity for 2321149, however, is above the 2 km regression line by a factor of nearly 3.

In the case of peak acceleration, the parameters for both events are above the regression fits to earthquake data for depths of 1 and 2 km but the agreement between the 3171111 parameter and the earthquake line is substantially better than for 2321149. Referring to Figure 2 of MCGARR (1984b), the peak acceleration of 3171111 is within the scatter of the earthquake data used to develop the regression fit but that for 2321149 would fall outside this range.

Returning now to the question of the effect of mining depth on seismic hazard, at this point we can at least say that this factor does not play an important role in producing the largest magnitude events. Between April and November 1986, for example, there were five events in the Carletonville area that were assigned moment

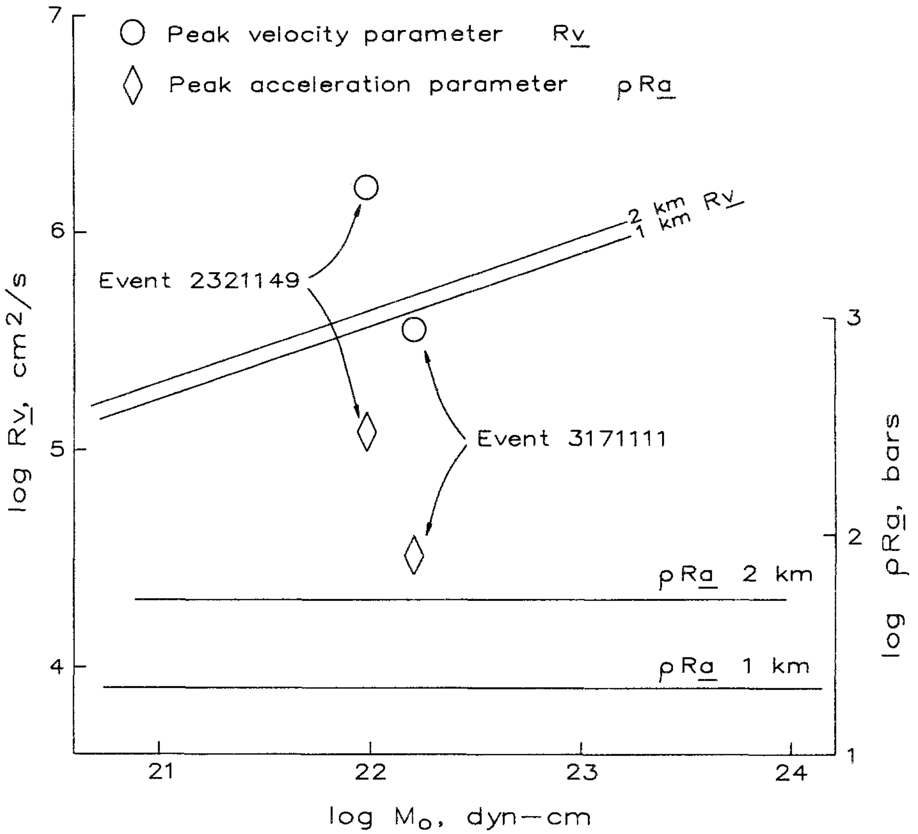

Figure 4
Peak velocity and peak acceleration parameters for events 2321149 and 3171111 compared to expectations based on observations of natural earthquakes (McGarr, 1984b), for depths of 1 and 2 km.

magnitudes of 3.9 or 4.0; as mentioned before, events of $M(M_0) > 4.0$ have not been observed in the Carletonville district. Of the five events, four of them, including the three of $M(M_0)$ 4.0, had hypocentral depths near 2 km. One of the two events assigned a magnitude of 3.9 was located at at depth of 3.1 km. Hence, in the Carletonville area, at least, mining depth does not seem to be the controlling factor influencing the overall amount of seismic deformation. This observation is consistent with results relating integrated seismic deformation to mining (McGarr, 1984a). Hypocentral depth of the mine tremors does probably influence the ground motion parameters for peak velocity and acceleration. This has been shown to be the case for earthquakes (McGarr, 1984b) but this will be the subject of another report.

We conclude by noting that there is a significant contrast in large magnitude seismicity between the Carletonville and Klerksdorp districts. Mining near Carletonville produces a great many events in the magnitude 3 to 4 range each month whereas in the Klerksdorp district it is rare to record more than a few of $M(M_0) > 3$. For instance, from the beginning of May to the end of October 1986, 22 events of $M(M_0) \geq 3.5$ were recorded in the Carletonville district. During the same period 4 such events were recorded in the Klerksdorp mining area, 2 of which had magnitudes well in excess of 4. In terms of seismic deformation, however, the few very large events at Klerksdorp produce a greater total seismic moment than do the somewhat smaller but more numerous tremors near Carletonville. During the May through October 1986 period, for example, the integrated seismic deformation at Klerksdorp was approximately 50% larger than that estimated for the tremors near Carletonville, taking all events of $M(M_0) \geq 3.5$ into account.

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