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Seismicity in the Welkom Area, O.F.S. (with special reference to the origin of the 1976-12-8 event)

Arnott, Frank Walter

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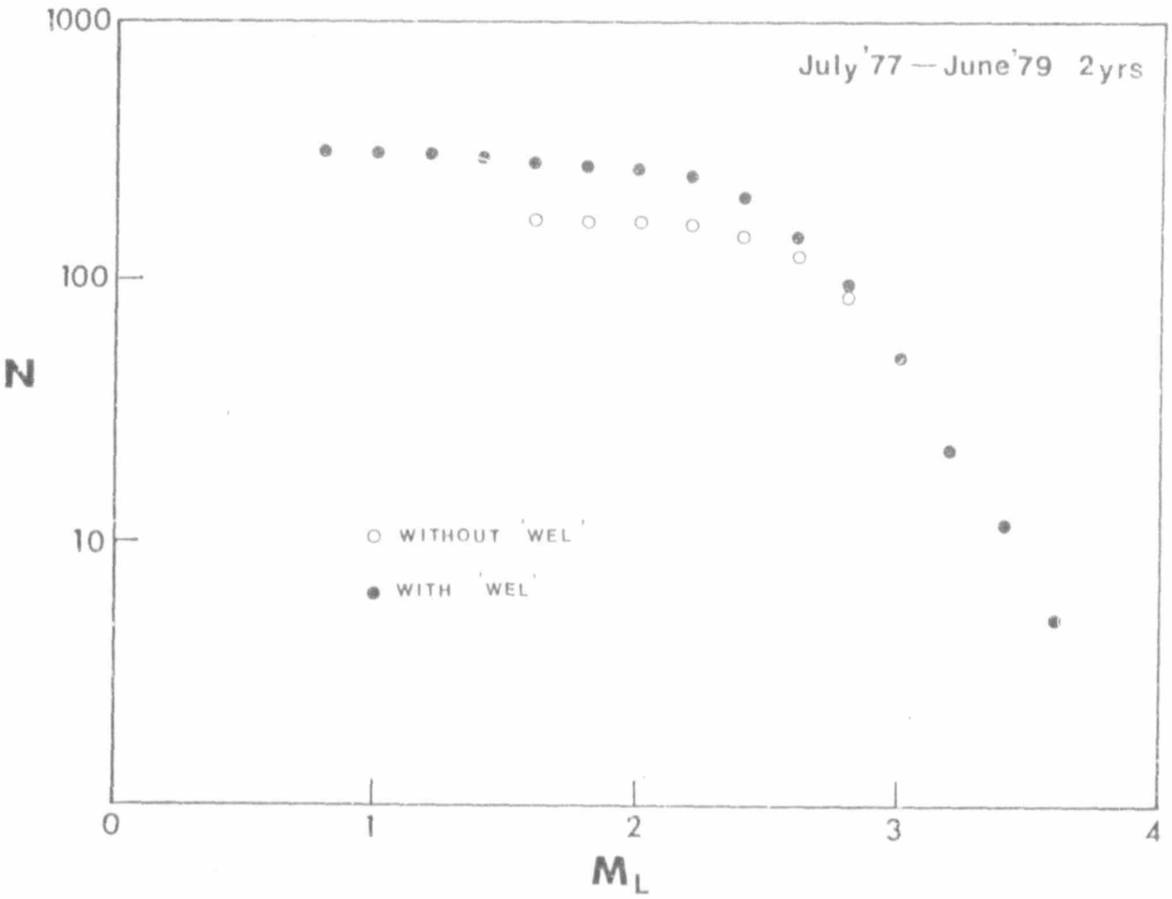


Figure 6.3 Log frequency of events greater than a particular magnitude for the G.S.S.A. records of events originating at Welkom. The data was obtained from the G.S.S.A. monthly seismic bulletins.

below surface or approximately 0.5 to 1 km below mining, which is inconsistent with the results of most other Witwatersrand mining districts. In these regions the seismicity has been situated principally in the hangingwall above the mined reefs which represents depths below surface of 3.2 ± 0.2 km at ERPM (McGarr, 1976b) 1.5 to 2.5 km for the northern Central Witwatersrand (Logie, 1949) and 1.4 to 1.5 kms at Harmony (Joughin, 1966).

In addition to the average seismicity situated approximately 1 km below mining, events were also well located down to 5 or 6 kms. Apparently, such deep seismicity has not been evident in other Witwatersrand mining districts, except at Klerksdorp. Results from the Klerksdorp array have shown that multiple events have occurred along fault zones down to a maximum depth below reef of 1.5 km, while individual events have been located at depths of 4.6 kms below surface (van der Heever, 1978).

6.2 Frequency of Seismicity

From curves representing the logarithm of cumulative frequency versus magnitude (Figures 6.2 and 6.3) comparisons between the two recording periods were made. These curves also provided from the respective seismic networks the threshold cutoff for the lower magnitudes, and the constants in the standard relationship $\log N = a + bM$ (Table 5), The values were obtained by linear regression analysis.

Included in the Geological Survey data, obtained from the monthly Bulletins, were events which had been recorded only at the seismic station "WEL". The magnitudes of these specific events were reduced by a factor of 0.7 to bring them into line with the mean magnitude

evaluations. The final curve of the combined events (solid dots in Figure 6.3) was not influenced significantly by this additional data, an important consideration in subsequent analyses (Section 6.4).

TABLE 5 Linear Regression Analysis

Source of Data	a	b	Regression coefficient	Observation period (days)	Magnitude limit (lower)	(upper)
Geological Survey	5.66	-1.35	0.96	730	2.6	3.6
BPI (Dec)	2.00	-0.70	0.96	29	0.6	2.4
BPI (July)	2.80	-1.03	0.98	23	0.6	2.4

A direct comparison between the Geological Survey and BPI curves was not completely justified because of the inequality of the time intervals. Over a period of one year Harmony Mine had values of 4.4 and -1.2 for a and b respectively (McGarr, 1971b) which are in agreement with the values from the South African Geological Survey records for one year in the Welkom area (a = 4.1, b = -1.3). The values obtained from the BPI magnitudes were distinctly different; however, these values agreed with the ERPM study where "a" ranged from -1.68 to 2.79 and "b" from -0.59 to -0.63 (McGarr and Wiebols, 1977), similarly the "b" value from Klerksdorp (-0,95) was in close agreement, but "a" was much higher (Van der Heever, 1979). The variation in network coverage and application of different time intervals greatly influences comparisons of these constants. This feature was well demonstrated by "b" values of -1.4 and -0.9 obtained from two broader studies at ERPM (Hodgson and Cook, 1970 and Maher, 1967). Therefore, the above comparisons should be viewed with caution, but in general the overall results are in agreement.

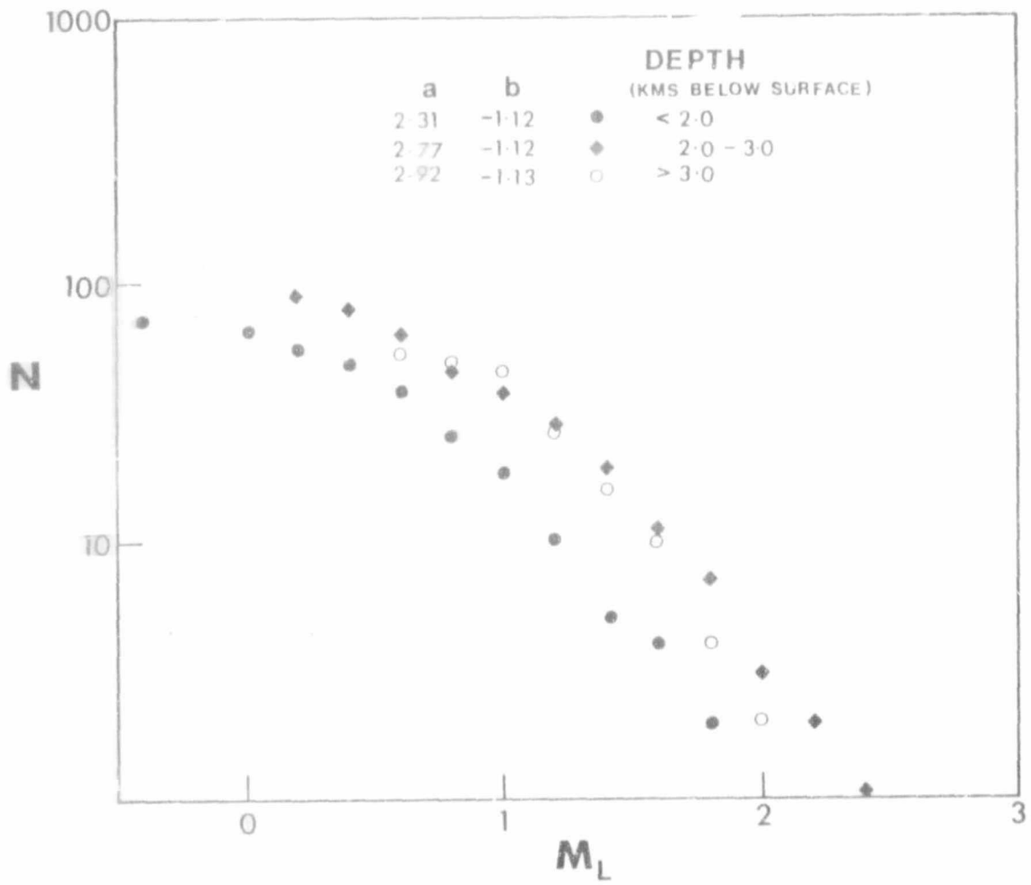


Figure 6.4 Variation of the log frequency of events above a particular magnitude range as a function of depth. The events are all those recorded in December, January and July by the B.P.I. network at Welkom.

Returning to the two periods of recording at Welkom, a closer examination of the two constants was made possible by the assumption that both the increase in time and volume of rock monitored, had a relatively limited influence on the results. This was a reasonable assumption because of the overall number of December/January events was considerably lower than those that had occurred during July. A decreasing "b" value has been suggested from laboratory microfracture studies to be indicative of an increase in ambient stress (Scholtz, 1968). Such a change was evident for July and the question therefore arises; were these results indicative of stress build-up after the main event in December? McGarr (1976a) argues against the possibility that a changing value of "b" reflects stress adjustments particularly around the order of 100 bars which has been the suggested level for mining localities. Using tilt measurements from ERPM he also related the "a" value to the strain rate, $\dot{\varepsilon}$, such that $a = \log \dot{\varepsilon} + 7.23$; where "a" represents the level of a particular magnitude range for a constant locating volume or network. This analysis assumed that the stress changes occur aseismically. Applying this observation to the Welkom data for which an increase in the value of "a" is observed for July, there was once again evidence of an increased level of stress subsequent to the December/January period.

Similar trends with respect to depth were also investigated. This was achieved by evaluating the two constants "a" and "b" from the magnitude frequency curves representing different depth ranges and the full 50 days of recording (Figure 6.4). The middle depth range represented the principal seismic zone. From the three levels examined, no change in "b" was observed, however the values of "a" indicated that there

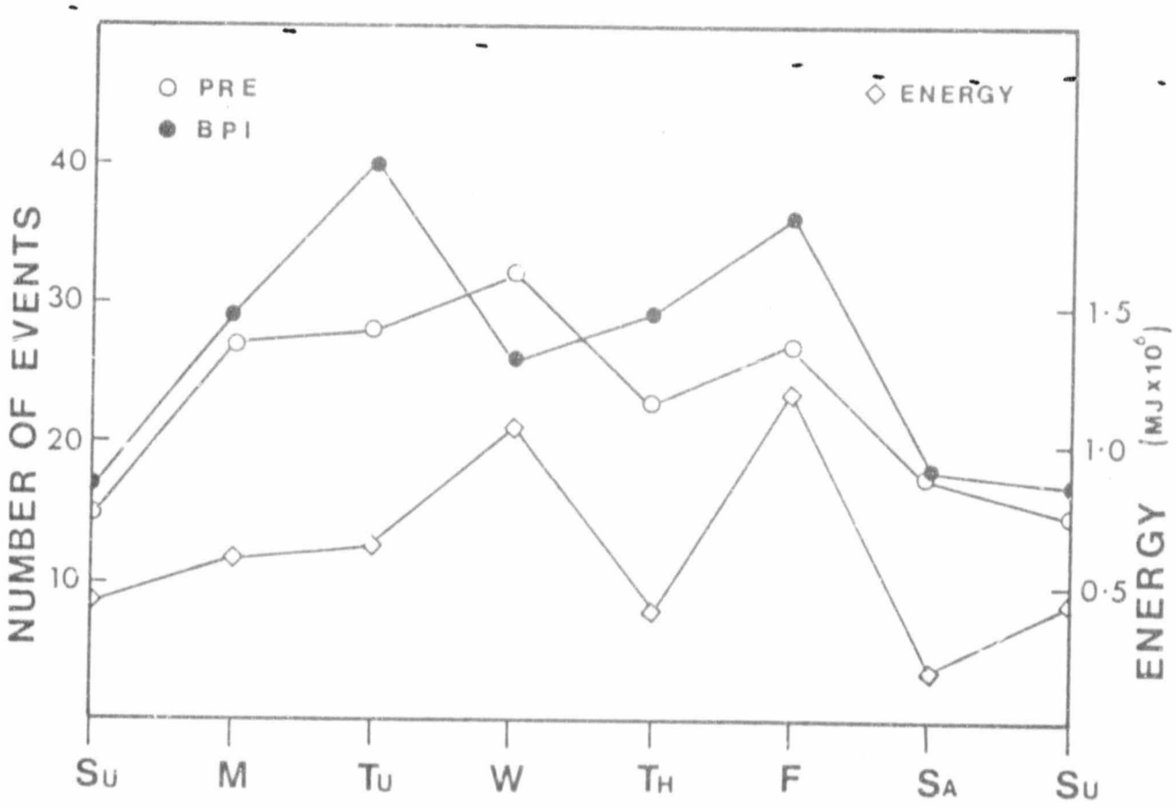


Figure 6.5 Daily variation of Welkom seismic levels expressed in terms of energy, open squares and number of events circles.
BPI data represents a magnitude range of -0.5 to 2.7
Pretoria data (GSSA) represents a range of 2.0 up to 5.4.

...an increase in strain rate at depths shallower than 1,5 Km below ...face, below which no further variation occurred.

... Aftershock Activity

The shocks represented as solid symbols in Figures A1 - 8, 10 and 12 demarcate events occurring during the 12th to 14th December. The number of those events was very low and they were not confined to any specific locality. Thus, since the main shock was followed by a few large events which occurred only during the subsequent first two hours (Appendix 2), it was apparent that the major aftershock sequence had been of a very short duration. Clearly, therefore, earlier installation of the recorders would have improved the understanding of this aspect, particularly in helping to define the source area of the main event. An inverse decreasing energy release during December 1976 to July 1977 (Figure 3.3) suggests a longer aftershock sequence; however, because this data represents seismicity from the whole of the O.F.S. goldfields it cannot be considered ...sparate of any trend at Welkom.

... Daily Seismic Activity

Referring back to the low magnitude threshold for the different seismic networks and time intervals (Figures 6.2, 6.3 and Table 5), it was apparent that to a first approximation events recorded by the SAGS network were representative of high energy or magnitude releases on a daily or hourly variation. Similarly, with a slight overlap, the BPI records represented the equivalent lower magnitude fluctuations.

The daily variation (Figure 6.5) for the complete range of seismicity

was an increase in strain rate at depths shallower than [illegible] surface, below which no further variation occurred.

6.3 Aftershock Activity

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6.4 Daily Seismic Activity

Referring back to the low magnitude threshold for the different seismic networks and time intervals (Figures 6.2, 6.3 and Table 5), it was apparent that to a first approximation events recorded by the SAGS network were representative of high energy or magnitude releases on a daily and hourly variation. Similarly, with a slight overlap, the BPI reversals represented the equivalent lower magnitude fluctuations.

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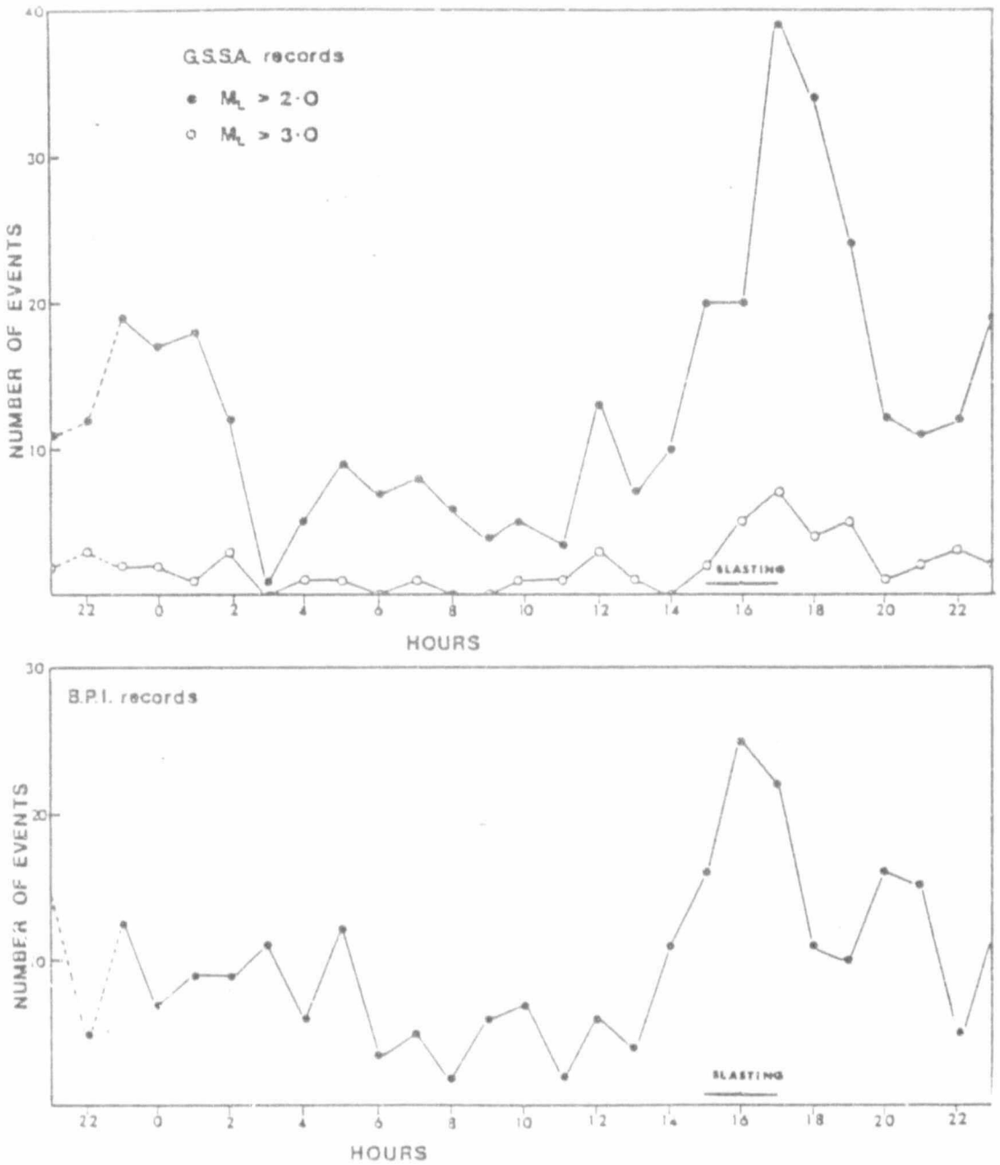


Figure 6.6

Hourly variations of the number of events located at Welkom from the BPI records (M_L = -0.5 to 2.7) and the GSSA records (M_L = 2.0 to 5.4)

was characterized by the decrease over weekends which is experienced by all mining districts. This demonstrates an influence from mine activity on the rate of seismicity. During one week, a single peak has been common at most of the other districts. At Welkom this was not observed instead two maxima occurred. The first high magnitude peak was delayed by one day with respect to the lower magnitudes equivalent peak. There was no noticeable shift in the second peaks; this could have been a result of the 24 hour sampling interval, so an examination of the hourly variation was appropriate (Figure 6.6). Once again correlation with mining activity is evident, with the maximum number of events taking place during the interval 1500 to 1700 hours, the blasting time for the different Welkom mines. For the larger events there was a delay of about an hour after the final blasting time. This delayed peak was also preceded by a smaller step representing approximately the same number of events and time of day as occurred for the low magnitude peak. A second smaller and broader maximum occurred three hours after the above blasting maximum for the smaller events and five hours later for the larger events (Figure 6.6).

Assuming low level seismic or aseismic deformation was in evidence from the evaluation of "a", then the time delays and broader peaks associated with the larger events could be a result of aseismic stress transfer to regions below mining. This may have occurred particularly in the zone between the Arrarat fault and the Enkeldoorn dyke while in the same way the second peaks just before and after midnight could represent secondary adjustment by neighbouring faulted blocks and structures to the changing stress conditions of this initial seismic zone or block

(There is no pg. 75)

6.5 Multiple and Coincident Events

From the list of events (Appendix 2) it can be seen that a number of events originated within a restricted locality during a very small time interval. The majority of these multiple events (70%) were associated with the Arrarat fault-Enkeldoorn dyke wedge of seismicity. Area coincident events usually numbered two to five events in a time interval of between 4 to 13 hours. In most instances, the largest event of a series occurred at or towards the end of the sequence and there were very few examples of migration to an increased depth as had been observed at Klerksdorp (van der Heever, 1978). Exceptions were in sequences 32, 33 and 34 and 101, 102 and 103; the latter also having the largest event first. The general trends in the coincident and multiple events therefore supported a delay of the larger events similar to that, that occurred in the hourly seismic variation. In this way they provided only limited evidence for non-elastic stress transfer, postulated in the previous analysis.

7. FOCAL MECHANISMS AND STRESS CONDITIONS FOR THE WELKOM REGION

7.1 Focal Mechanism Determinations

Despite the limited data available for the main event there existed the possibility that a source mechanism could provide a broader understanding of the locality of the event and the stress conditions, prevailing at that time. Such a mechanism was obtained (Figure 7.1) and to aid the investigation further composite source mechanisms were constructed for events recorded by the BPI network (Figures 7.1 and 7.2) The restriction against obtaining solutions for individual events was due to low numbers of clearly defineable arrivals which prevented reliable definition of nodal planes. Events selected for any one composite solution were restricted to specific geological localities, that is regions where tight clustering or distinctive planar events were observed in relation to the major structures. In addition a composite solution was constructed from events located in close proximity to the Basal Reef, this representing the seismicity most likely to have been associated with mine activity.

Although it is more popular to represent the focal sphere by an equal area lower hemisphere, stereographic projection, the first motions from this study were plotted on an equal angle upper hemisphere projection. This was partially because of the geometry of the ray paths, with respect to the seismometers, but also to enable direct comparisons with focal mechanisms constructed in the same manner for ERPM (Spottiswoode, 1979). Only compressional first motions recorded by vertical seismometers were evaluated and in all cases the ray paths were assumed to be linear.

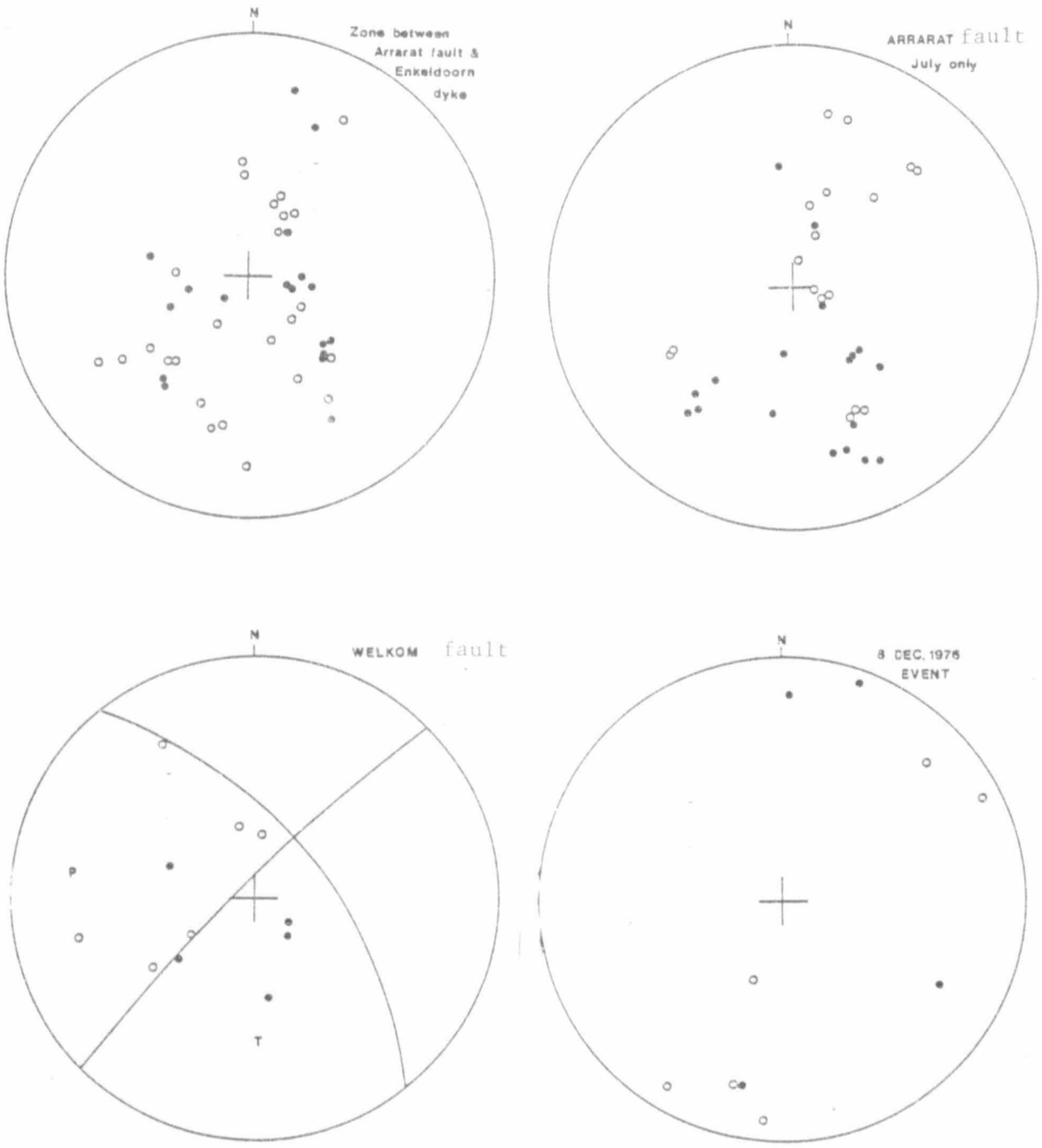


Figure 7.1

Three composite source mechanisms from B.P.I. located events, and source mechanism for the 8 December 1976 event.

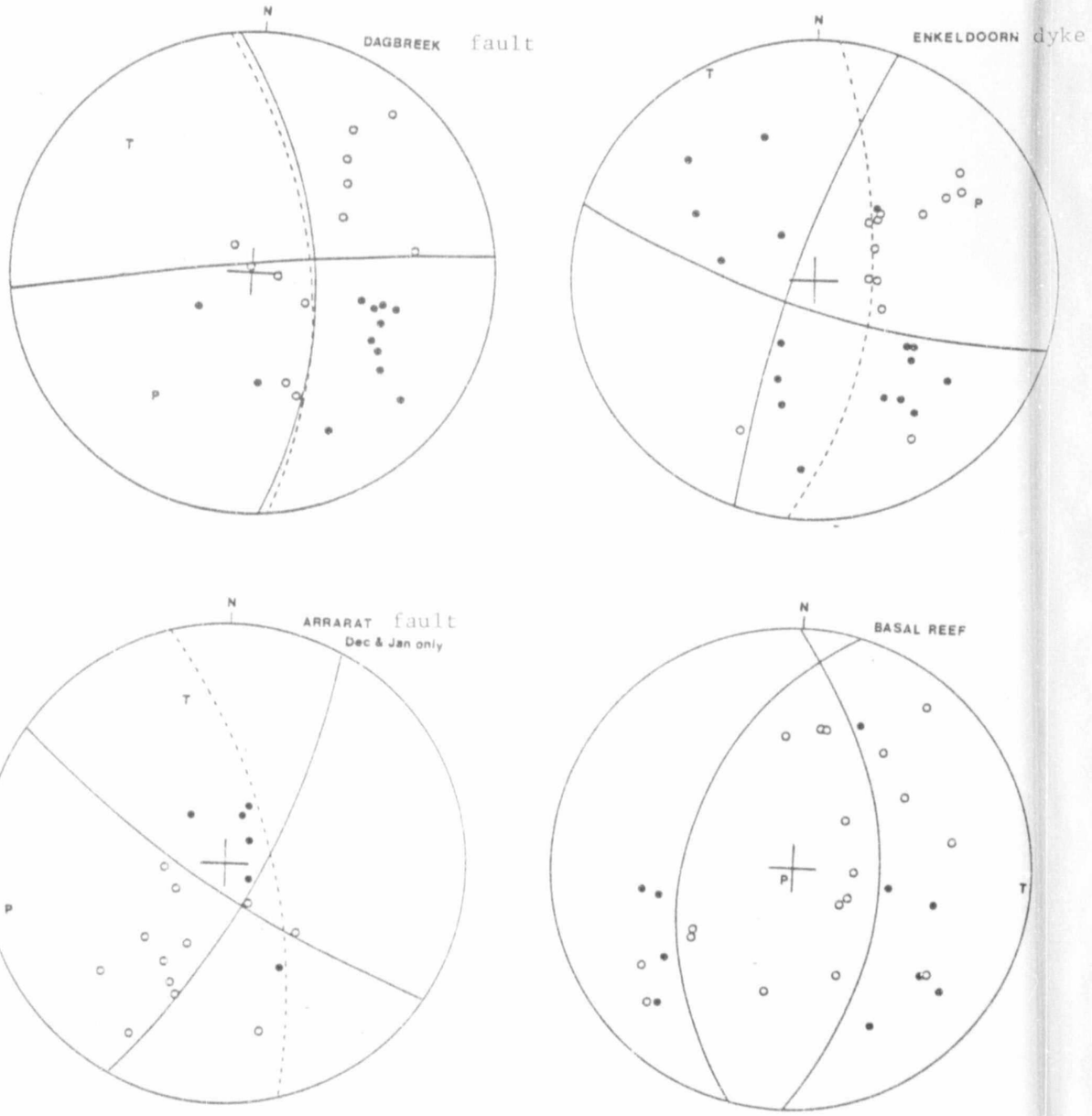


Figure 7.2

Composite source mechanisms from B.P.I. located events .
Dashed line shows mean position of fault or dyke plane.

For the main event first motions were read from short period vertical component records, which were obtained from the South African and Zimbabwe national seismic networks and also from WWSSN stations which had recorded the event at more distant localities. Although long period records are more satisfactory because their longer wavelengths are less susceptible to scatter; no long period plot was adopted as too few clear arrivals were evident from the available records. The respective extended distances were calculated for a curved surface by computer, according to the formula presented by Thomas (1965), and the angle of incidence was obtained from Tables (Pho and Behee 1972) The resultant first motions were also plotted on an equal angle, upper hemisphere projection by positioning them at the antipode of their position on the lower hemisphere. This projection was based on the assumption that the focus is a point, about which exists central symmetry.

Where possible the P wave compressions and rarefractions were separated by two orthogonal planes and the centres of the resultant two uppermost quadrants were indicated by P and T. P representing the compressional axis and T the tensional exis, these however do not necessarily represent maximum and minimum principal stress directions (McGarr and Gay, 1978). Double couple displacement vectors, the dip as determined from sections + X8000 and + X10000 (Figures A1-10 and 12), and the average strike of the associated geological structure have also been plotted on the stereo projections.

7.2 Observations

The seven composite mechanisms could be separated into those that showed a relatively random scatter of dilations and compressions (Figure 7.1)

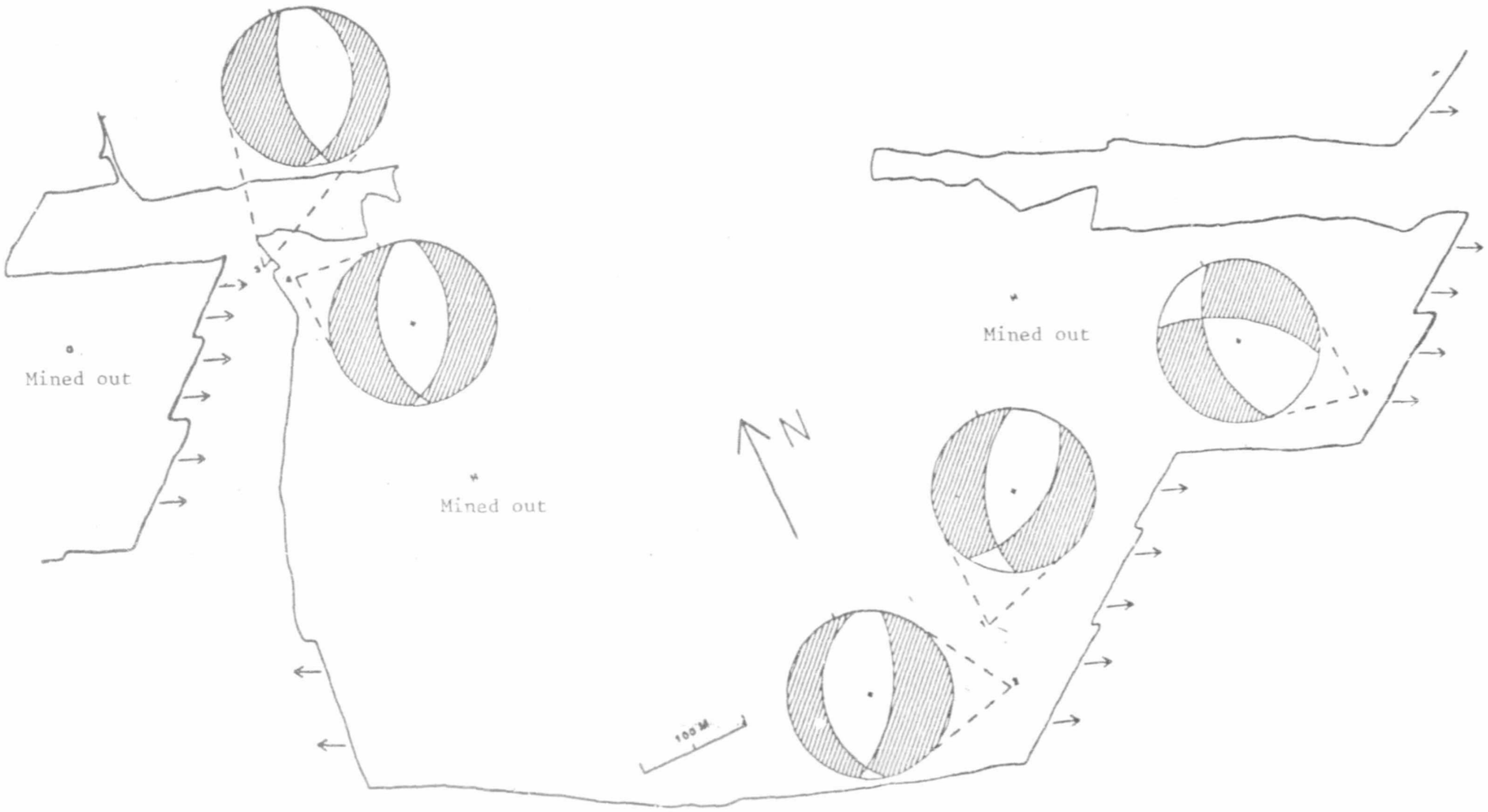


FIGURE 7.3

Map of East G and H slopes of ERPM with the face positions during March 1972. Arrows indicate the direction of face advance for faces being mined at the time. Five seismic events are plotted together with their source mechanisms. Hatching indicates quadrants of compressional first motions. (Spottiswoode 1979)

and those which provided reasonably well defined nodal planes (Figure 7.2). Misplaced first motions, as could be expected were common to all the solutions. These could be attributed to three main causes, velocity inhomogeneity in the source region, incorrectly selected events and change in the attitude of the geological structures. Besides the low number of data points the changing dip, for example 72^{o}E to 52^{o}W between geological sections + X8000 and + X10000, was mainly responsible for the poorly defined nodal planes from the Welkom fault. The random scatter observed for the Arrarat fault during July was unexpected particularly in relation to the December-January observations. This result can probably be attributed more to the incorrect correlation of events with structure; particularly as the grouping of these first motions closely resembled the distribution for the zone between the Arrarat fault and Enkeldoorn dyke. The randomness in this latter area resulted principally from different hypocentral sources. The comparitively well defined nodal planes in Figure 7.2 suggested further that inhomogeneities in the velocity structure had only a minor influence on the composite plots.

The most striking feature of the nodal plane solutions (Figure 7.2) was a distinctive right lateral strike-slip mechanism for the geological structures and normal faulting for the mining environment. The maximum vertical stress and normal fault displacements obtained for the mining levels were in agreement with mechanisms for events close to advancing faces at ERPM, (Figure 7.3) (Spottiswoode, 1979).
At ERPM the nodal planes were also parallel to the advancing faces, however, this result did not occur at Welkom. Instead the nodal planes were perpendicular to the east-west striking longwalls. At Harmony

(Joughin, 1966), Western Deep Levels (Hallbauer, 1967) and ERPM (Spottiswoode, 1979), a high percentage of dilational first motions have been observed, this has also been true for the source mechanism from the mining environment at Welkom.

The strike-slip mechanisms obtained for the three geological structures suggested nodal planes which were similar in attitude to the average strike and dip obtained for the structures at the geological sections + X8000 and + X10000. This was particularly pronounced for the Dagbreek fault. The inferred maximum principal stress for these structures was always orientated approximately NE-SW. This could only have been effective if clockwise rotation of the intermediate faulted blocks had taken place. As the events used for the composite mechanisms for geological structures were all located below mining an important feature was the occurrence of completely different mechanisms at depth in relation to those at the shallower mining levels.

No unique nodal planes were possible for the main event (Fig. 7.1) because of an inadequate distribution of stations. Although both normal and strike-slip mechanisms were possible, strike-slip was more predominant. Superimposed on the other solutions, the agreement with the Enkeldoorn dyke was very close, whilst least agreement could be associated with the mechanism from the mining levels. Assuming then that the main event represented a strike-slip right lateral movement the previous orientation of the maximum principal stress is still maintained.

7.3 Ambient Stress of the O.F.S. Goldfields

The focal mechanisms from the above tectonic structures present evidence

for a maximum principal stress operating perpendicular to the strike of

boundary of the central horst

was also observed (Chapter 2) that a maximum compre-

similar direction during the final tec-

trend, which generated the strike-slip

normal faults. No recent in-situ stress

from the Welkom area. The nearest results

mine at a depth of 1.5 km. In

stress was recorded and this observation

from many other Witwatersrand goldmines

consistent with the focal mechanism observed at

kms below surface) at Welkom. Exceptions

stress have also been recorded. At both Evander

and Durban Roodepoort Deep in the West Rand maximum

orientated (Gay, 1975).

McGarr and Gay (1978) report that it has been observed that there is a

in the directions of horizontal and the principal stresses.

attributed to complexity of the geological structures and also

tectonic stresses. Residual stress can be generated by either

isostatic variation (McGarr and Gay, 1978; Gay, 1979).

a thermal origin is clearly possible as there are numerous dykes

, including the Enkeldoorn dyke. Evidence for isostatic

riations can be obtained from a consideration of the isostatic

omalies. From the isostatic anomalies over southern Africa

Gough, 1939); it is apparent that the Welkom region is

over a local zone of compensation. To the north and east however

anomaly suggests a region of low order under compensation or

while to the west and south-west a smaller

circular -10 mgal anomaly implies the converse. Thus, it appears that Welkom is situated on a localised hinge zone with a NW-SE strike. Evidence of this hinge zone was also reported from Landsat imagery (Chapter 2). This hinge zone broadly correlates with the strike of the major normal faults. Thus, if it represents the remains of major crustal movement in a vertical sense it could be evidence for the residual horizontal stresses which are apparent at present.

8 FREQUENCY SPECTRA AND SOURCE PARAMETERS

A considerable amount of valuable information has been obtained from the study of both earthquakes and mine tremor body wave spectra and from these studies the associated source parameters (e.g. Douglas and Ryall, 1972; Smith et al., 1974; Spottiswoode and McGarr, 1975; Gibowicz and Cichowicz, 1977; Fucik and Rudajev, 1979; Fletcher, 1980). In order to gain a deeper insight into the mechanisms of events in the Welkom area it was decided to evaluate and compare displacement spectra obtained from this local seismicity with that from the other studies.

8.1 Processing and Spectral Determinations

Thirty-one events were selected for digitization. They were chosen as representing the variations observed for magnitude depth and the major geological provinces, particularly those which had been used in the focal mechanism analysis. Where possible all the events were digitized from the Church Street records so that a "standard" reference could be established. For the purpose of comparing different sites, some of the events from five other surface stations and one underground station were then digitized. After the digitization (outlined in Section 4.5), all relevant data blocks from the standard label tape "ARFWEL" were plotted. These plots were then used to select the appropriate 0.4 second sections from each of the events. This sample window was equivalent to a sample count of 256. Some events had a short duration and this window was too long, however, the time interval could not be shortened without increasing the fundamental frequency of the window. The programme 'SPEC' developed by Spottiswoode (1975; 1979) was then used with modifications to obtain the P wave spectra from the vertical component records and the

S wave from the corresponding horizontal components.

Operational modifications to the programme were applied in the input and output sections. The subroutine READT was included so that any number of events could be accessed directly from tape and simultaneously processed while the plotting routine was also improved. Filtering capabilities in the frequency domain were made available but were never implemented (Appendix 3.). The constants and physical parameters included by Spottiswoode (1975) were not changed, but a new impulse response function necessary for the equipment's improved bandwidth (Figure 4.2 and 4.3) was included. End effects were removed by application of a Hamming cosine window. Corrections for the free surface were based upon a Poisson's ratio of 0.25, for which an enhancement of 2 was accounted for. Consistent evidence existed (Douglas and Ryall, 1972; Gibowicz and Cichowicz, 1977; Spottiswoode and McGarr, 1975) which confirmed that variations in the attenuation constant (Q) had no significant influence on the displacement spectra over small hypocentral distances, particularly when its value was below 200 Km. Shear wave birefringence and scatter were initially thought to be an important consideration because the straight ray paths available during the ERPM study were not realistic in the far field at Welkom. From the seismic records, however, it was evident that there was close agreement in the initial P wave signatures for the different ground components. In addition, the calculated seismic moments did not display any excessive variation and it was therefore assumed that scatter did not contribute any major influence, particularly in the near source region.

8.2 Displacement Spectra

The improvement in the recording equipment's low frequency response provided improved definition in the low frequency plateau regions for both P and S waves. This enabled the low frequency log spectral densities $\Omega(o)$ and corner frequencies f_o to be determined with more reliability (Figure 8.1 and Figure 8.2).

The corner frequencies had values generally below 13 Hz but values as high as 50 Hz were also noted. An important influence on the values was the filters used to remove 50 Hz noise. The analytical filter applied during transfer of data between digital tapes was essentially a phase filter so it was only significant at the dominant harmonic of the noise usually 50 Hz. However, the electronic filters applied during digitization were variable low pass filters, which could steepen the high frequency fall off of the spectral densities. In many instances slopes of up to -4 were obtained, although the mean value of -3.5 was relatively close to the values obtained for ERPM (Spottiswoode and McGarr, 1975). Accompanying these steeper gradients was the possibility of an increase in the corner frequencies, this however was only significant if the f_o value was of the order of 15 Hz and higher. P waves from the events 13 December 03h09 and 19 December 15h32 (Figure 8.2) clearly demonstrates this feature. The 19th December event had a corner frequency of 14 Hz whilst the 13th December tremor had a corner frequency of 6 Hz after applying a filter with a high cut-off of 100 Hz. In contrast using a filter with a high cut-off of 20 Hz the corner frequency for the 19th December event increased by 80% while the 13th December event remained within the tolerance of the computation. In practice the filters were only set at 20 Hz for a small number of records which contained excessive 50 Hz noise.

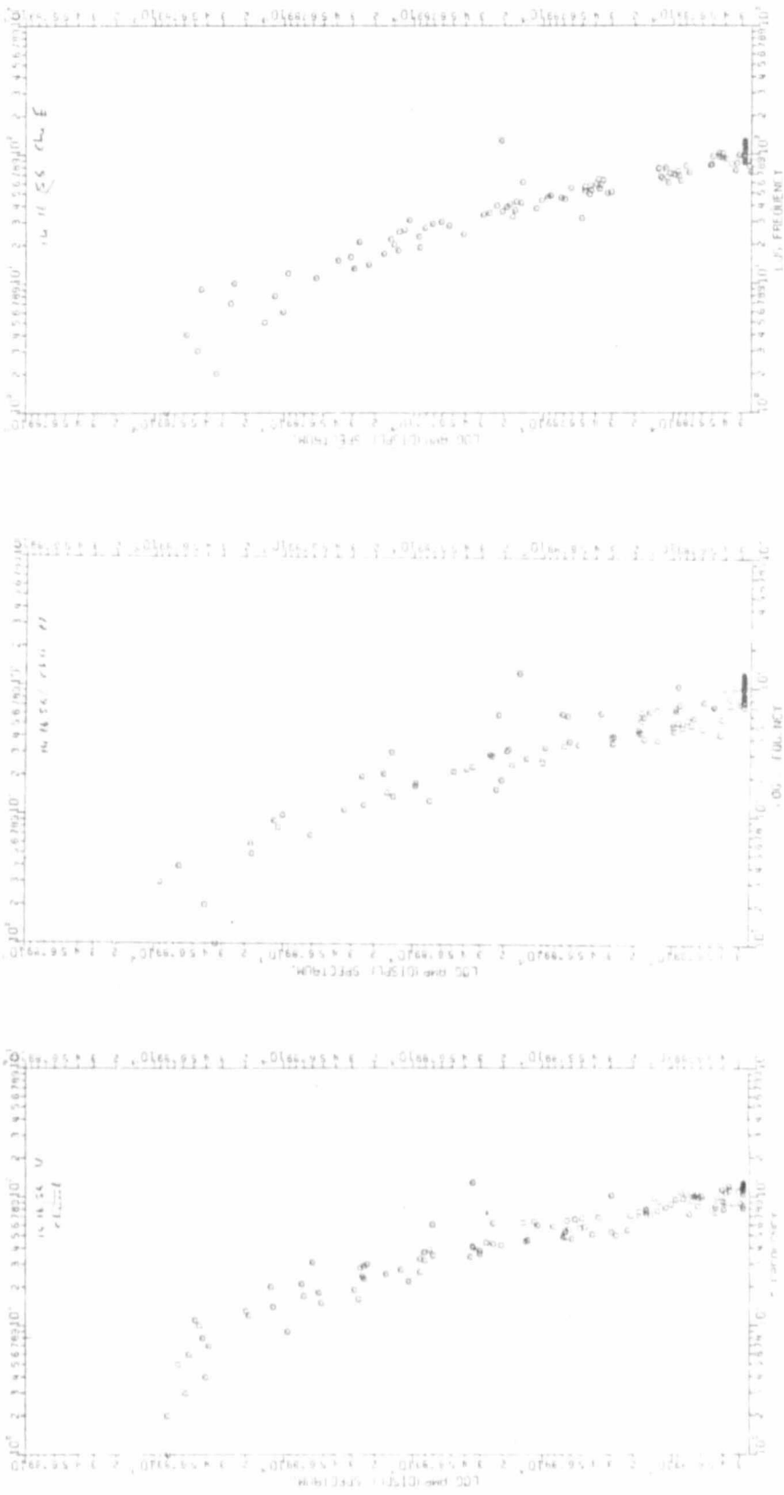
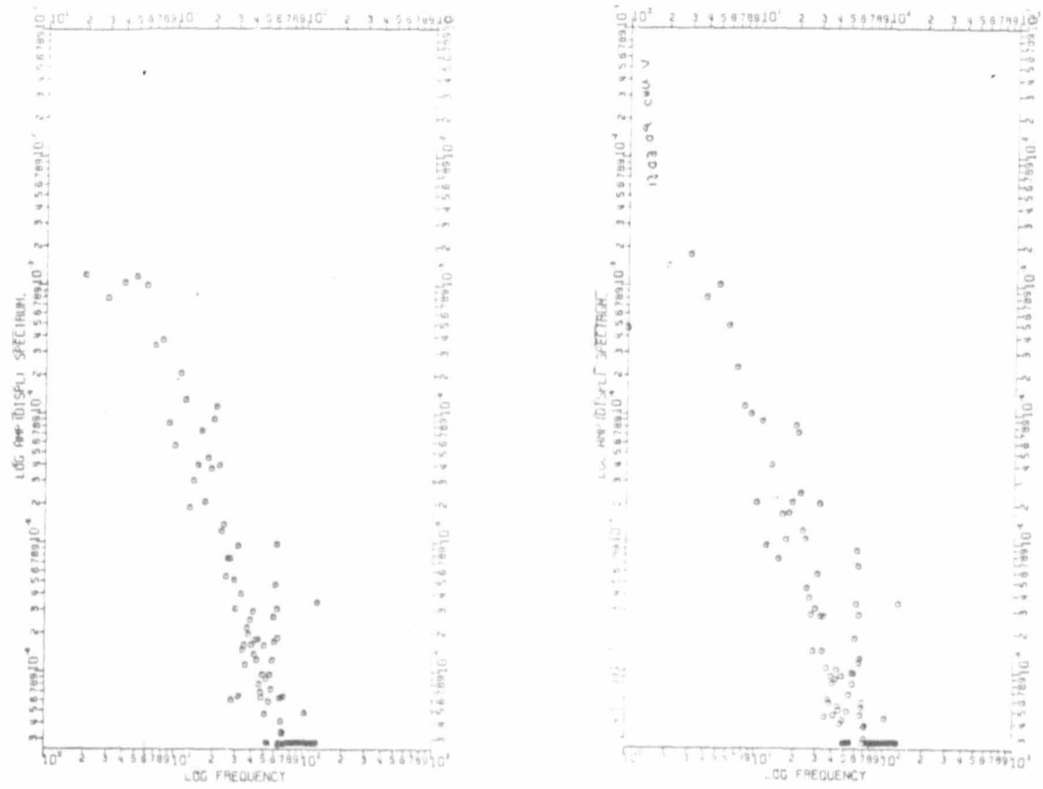
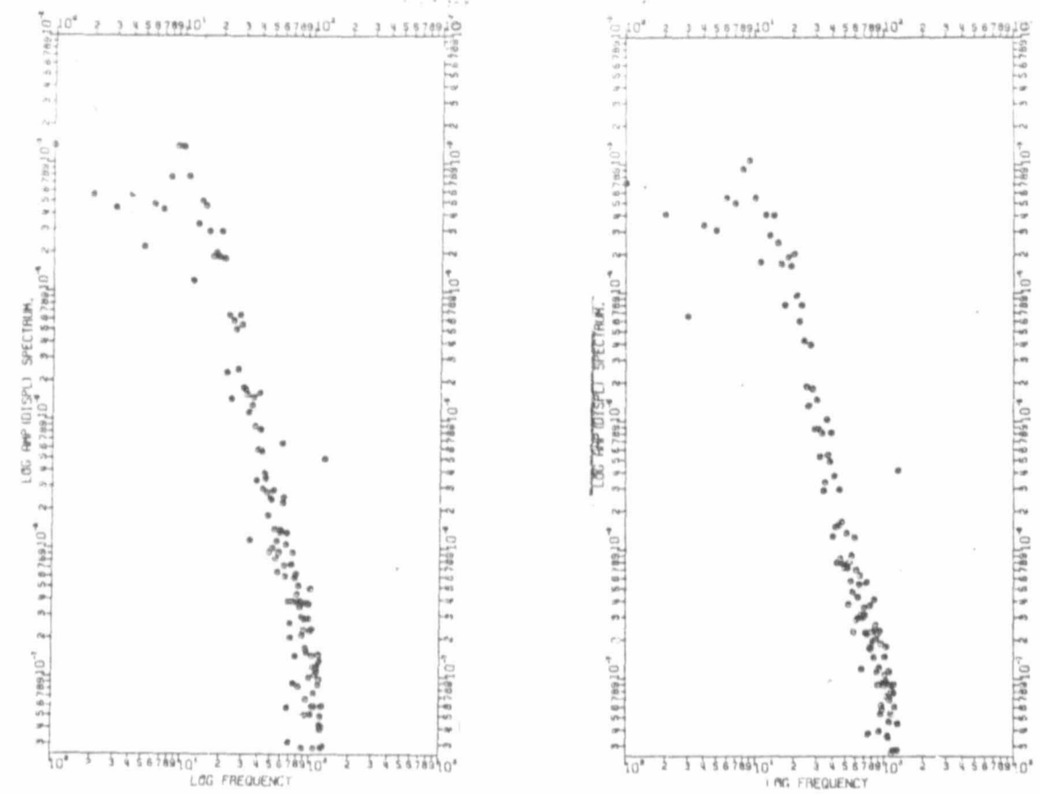


Figure 8.1 Examples of displacement spectra for the event 14 December 16h56



100 Hz Filter 20 Hz Filter

Event : 13 December 03h09, Vertical Component



100 Hz Filter 20 Hz Filter

Event : 19 December 15h32 Vertical Component

Figure 8.2

Two events showing the influence of the high cut off frequency and low pass filter on the displacement spectra.

8.3 Source Parameters

To retain uniformity with the majority of other studies the source parameters were calculated using the model proposed by Brune (1970 and 1971) for shear wave spectra, and the more generalized model by Hanks and Wys (1972) and Trifunac (1972) for compressional wave spectra. The formulae which determines the seismic moment, source dimension, stress drop and displacement for such a circular dislocation surface are described by Spottiswoode and McGarr 1975 and Spottiswoode 1979.

Although the seismic moment is not model dependant it is generally influenced by the radiation pattern, R (θ,ϕ,r); for the complex geology and different source mechanisms that have been observed at Welkom this presented a formidable problem. Noting the problems documented by Spottiswoode (1975; 1979) it was decided to utilize the same values that had been derived for ERPM. Realizing that this assumption would produce an error the decision to make Church Street the reference station for the spectrum and source parameters was accordingly taken. Church Street being centrally positioned with respect to the principal seismicity, provided the best site in that it was least influenced by the problems of an incorrect radiation factor. Scatter in the seismic moments did occur but a relative close grouping within the range 10^{16} and 10^{18} dyne. cm permitted analysis of the results to continue with some degree of confidence.

The source parameters for six mining environments and two tectonic microearthquake studies have been listed along with the Welkom parameters in Table 6; Brune's model was employed in all the studies except for Klando

TABLE 6 SOURCE PARAMETERS FROM STUDIES OF SMALL MAGNITUDE EVENTS.

Region	Locality	M_o dyne.cm	r_o meter	f_o Hz	$\Delta\sigma$ bars	ud cm	w^{-x} x	Reference
ERPM goldmine	Transvaal S. Africa	10^{18}-10^{21}	50-500	3-30	5-50	$1\text{-}10^{-2}$	3	Spottiswoode and McGarr, 1975
Upper Sileisa coal mines	Poland	10^{17}-10^{20}	30-190	~8	2-74	$1\text{-}10^{-1}$	2	Gibowicz and Cichowicz, 1977
Lubin copper mine	Poland	10^{18}-10^{19}	55-140	-	0.4-54	-	-	Gibowicz et.al., 1979
* Oroville small aftershocks	California, USA	10^{16}-10^{18}	31-110	10-68	0.1-26	-	2.7	Fletcher, 1980
Sunnyside coal mine	Utah, USA	10^{17}-10^{18}	77-90	10-14	0.2-9.6	10^{-2}	2	Smith et. al., 1974
Klando coal mine	Czhechoslo-vakia	10^{18}-10^{19}	8-78	-	0.19-0.28	-	2	Fucik and Rudajev, 1979
* Fiarview Park Microearthquakes	Nevada, USA	10^{18}-10^{19}	200-400	3-6	0.04-0.6	-	2	Douglas and Ryall, 1972
Welkom gold mines	OFS, S Africa	10^{16}-10^{18}	50-400	5-15	0.001-0.1	10^{-5}-10^{-6}	3-4	-

* Natural environments

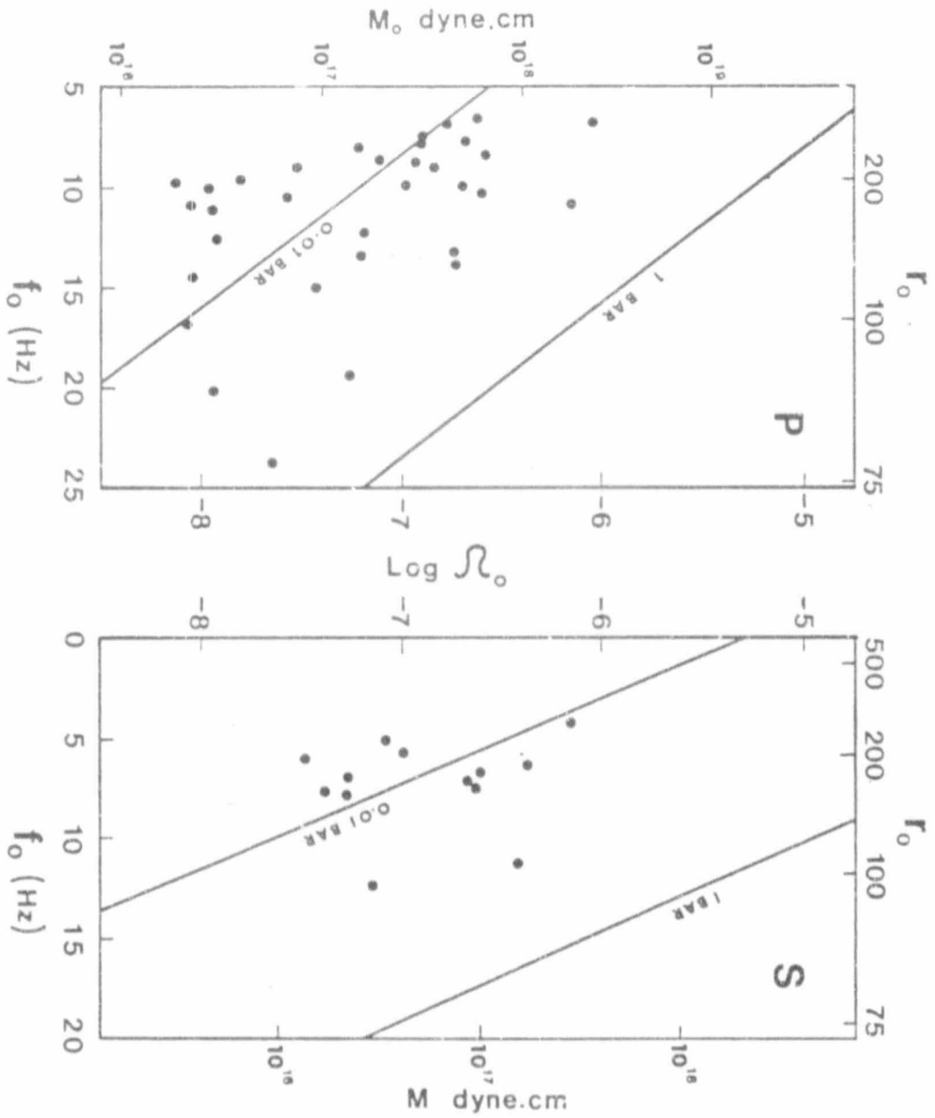


Figure 8.3 Ω_o as a function of f_o. The equivalent seismic moment and source dimension are provided on the opposite axis for a hypocentral distance of 3.0 kms.

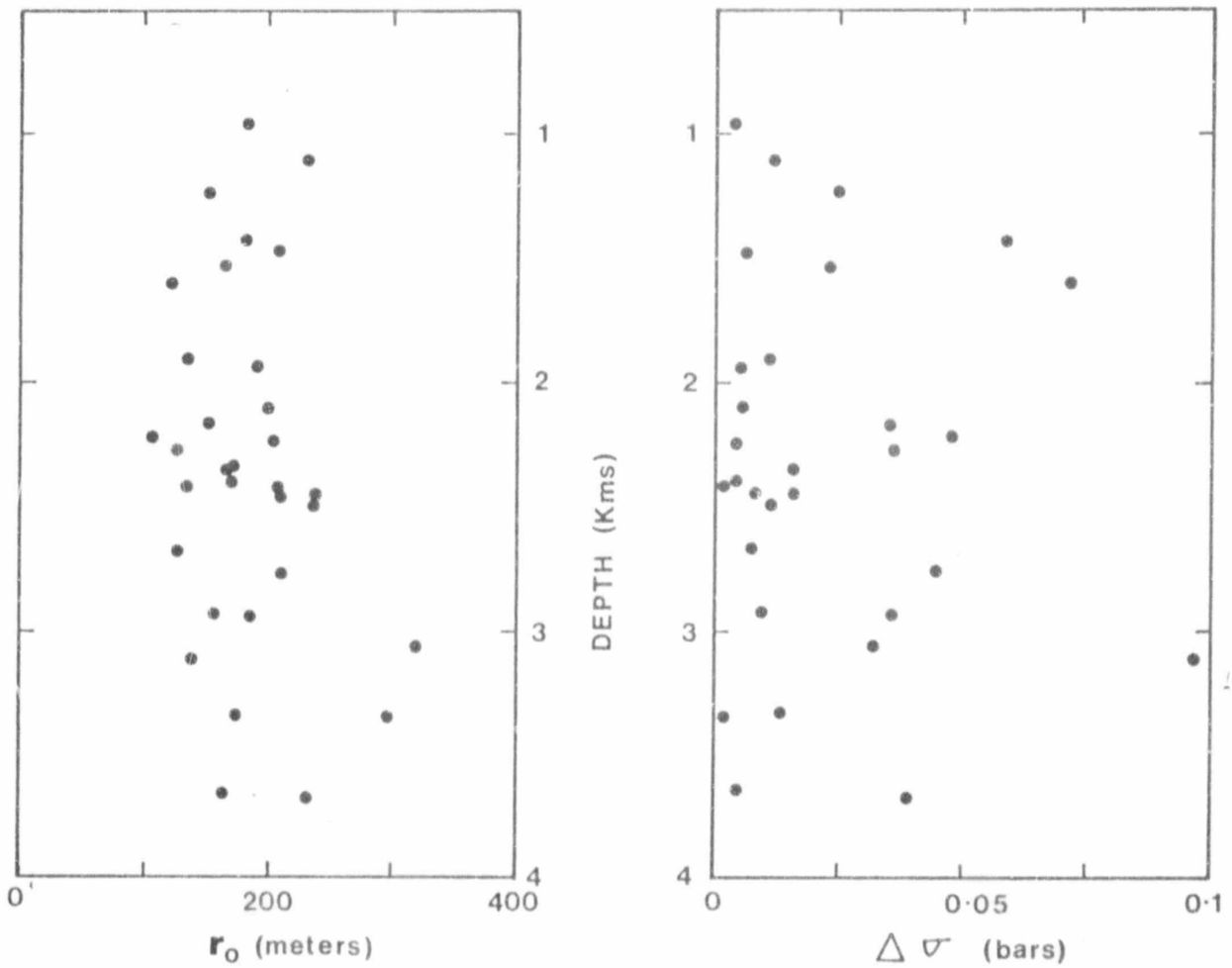


FIGURE 8.4

Variation of source radius and stress drop as a function of depth below surface.

coal mine. A comparison, therefore of the seismic moment, source radii and the corresponding corner frequencies showed the same broad ranges, ERPM representing the upper limit for both parameters. Significant differences were apparent for the stress drops. Welkom yielded values that corresponded to those experienced at Fair View Peak and Klando Coal Mine, while the maxima of these three did not exceed the lowest stress drops at Sunnyside Coal Mine, Lubin Copper Mine and Orville had stress drops in the range found for crustal earthquakes (Spottiswoode and McGarr, 1975).

The variation in source parameters and particularly stress drop has been related to difference in fault mechanisms (Lieberman and Pomeroy, 1970; Douglas and Ryall, 1972). The overall stress drops at Welkom are represented by plots of Ω_o against f_o for a mean hypocentral distance of 3 kms (Figure 8.3). Combined with the large source dimensions principally 125 to 200 meters, these low stress drops therefore imply that the source rock in the region of seismicity is of low strength which is consistent with the apparent high occurrence of fractures and faults. These stress drops, although lower than the value specified by Thatcher and Hanks (1973) are still comparable with stress drops associated with natural earthquakes because of the agreement with values obtained from the microearthquake study at Nevada and Oroville (Table 6).

The variation in depth of the stress drops and source dimensions suggests additional evidence for the existence of two relatively higher stressed zones beneath Welkom (Figure 8.4). Both these parameters displayed an apparent decrease between 1.8 and 2.1 kms below surface. It can be seen, however, that associated with this feature is an apparent bias generated

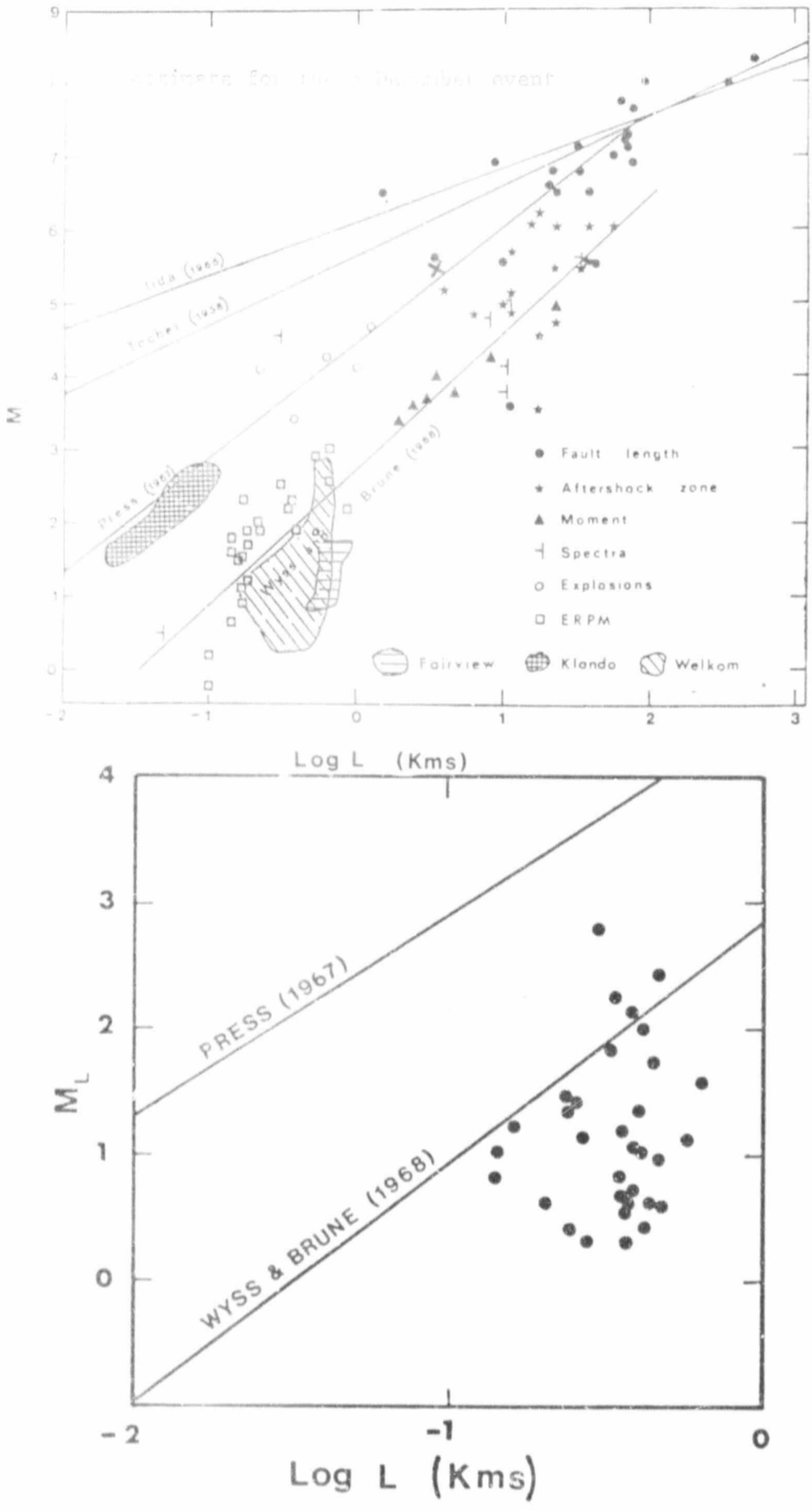


FIGURE 8.5

Local magnitudes as a function of source dimension ($L = 2r_o$). The lower figure is a detailed presentation of the Welkom data. Data from other studies obtained from (Spottiswoode and McGarr 1975, Liebermann and Pomeroy 1970, Fucik and Rudajev 1979 and Douglas and Ryall 1972)

by a minimum number of events that occurred at these depths, however this influence is not the entire picture because the low energy release in this same region also supports small stress changes (Figure 6.1). An increase in stress drop with depth has been observed for the Oroville aftershocks but in/that study no marked additional maximum occurred at the shallow depths (Fletcher, 1980). There is strong evidence therefore of induced stresses causing increased stress drops and source dimensions in the Welkom mining environment, which is situated at the same depths as the shallow stress drop maximum. The deeper maximum correlating with the increase in the natural tectonic stress changes which are also observed at Oroville. This aspect will be discussed in a later section.

Returning to the three studies which have displayed low stress drops, that is Klando, Fairview Park and Welkom, it is interesting to look at the comparisons of the source diameter and event size. Superimposing the data from these studies onto the same type of data presentation for earthquakes (Lieverman and Pomeroy, 1970) and mine tremors (Spottiswoode and McGarr, 1970) two distinctive areas were delineated (Figure 8.5). This plot clearly reflects the influence of the source model, used to obtain the parameters. The Klando coal mine study assumed a spherical source as had been proposed by Sharpe (1942), and is situated close to the empirical relationship of Press (1967) which correlates with data from explosions. In contrast the other studies assumed the circular source mechanism proposed by Brune (1970 and 1971) and they are thus in close agreement with the emperical relationship of Wyss and Brune (1968).

In Chapter 5 it was demonstrated that there was strong evidence for the enhancement of the energy levels in the surface Karoo sediments. The

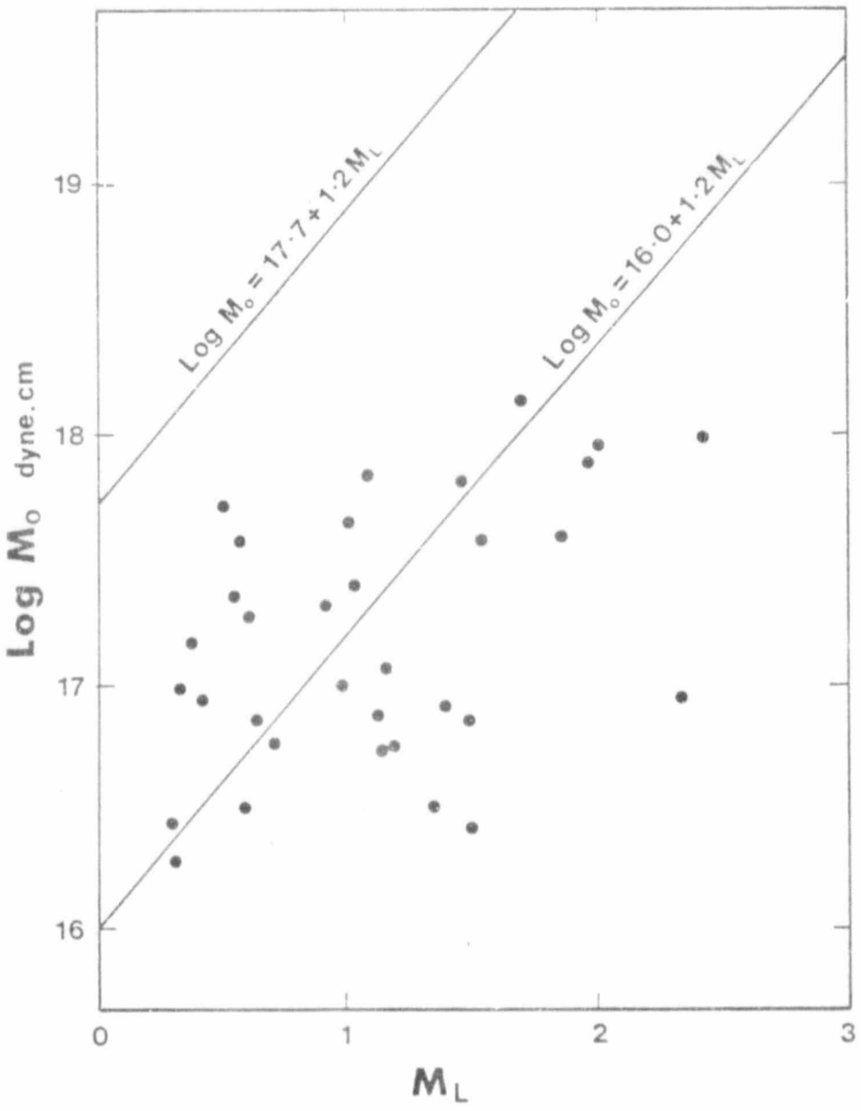


FIGURE 8.6

Moment as a function of Local Magnitude. The empirical relationship are those of Spottiswoode or McGarr (1975) log M_o = 17.7 + 1.2 M_L and the best fit to the Welkom data.

empirical relationship log M_o = 17.7 + 1.2 M_L which relates seismic moment M_o to magnitude M_L for ERPM (Spottiswoode and McGarr, 1975) may therefore not be applicable at Welkom, since the ERPM data was derived from bedrock observations. Plotting the log seismic moment against magnitude for the Welkom data showed a wide scatter, however a linear trend was also present which could be described by the relationship log M_o = 16.0 + 1.2 M_L (Figure 8.6). Thus the slope was constant for both linear points, while there exists a displacement of -1.4 magnitude units for the Welkom data. This indicates that the differences can be attributed to the over-estimation in the magnitudes at Welkom and to a far less extent in correct seismic evaluation of the seismic moments, although there is evidence of this latter feature from the wide scatter of values.

8.4 Seismic Moment of the 8 December Event

Information pertaining to underground damage caused by the main event was available from an Anglo American Corporation report (1977) and mine plans showing the horizontal extent of this damage (Figure A1-4). A maximum displacement of 9.5 cm to 15 cm was estimated and the total area of underground damage beneath the surface locality of maximum intensity was 5.0 km^2. This represented a maximum source diameter 'L' of 2.25 km which plotted on Figure 8.5a against the magnitude of 5.4 compared well with the other data. Therefore by applying the above values to the volume change, a seismic moment of between 1.9 and 3.0 x 10^{23} dyne.cm was obtained from the relationship $M_o = \mu \Delta V$ (McGarr, 1976b). The modulus of rigidity μ being taken as 4 x 10^{11} dyne/cm. From this seismic moment a magnitude range was determined using the relationship of Spottiswoode and McGarr

(1975). The magnitudes obtained, were between 4.6 and 4.8 and were thus lower than the Geological Survey estimate of 5.4 for the main event. This suggests the source dimension could have been underestimated by applying the area of underground damage. This would be particularly true if the focus had been deeper than the mining levels. Stress drops of between 62 and 99 bars determined from the above values would therefore also be too large, which was further supported by the evidence that this is a low stress drop environment.

9 SEISMICITY AND ASSOCIATED DAMAGE

9.1 Structural Damage and 8 December 1976 Event

Structural damage associated with the main event was dispersed over most of Welkom, with a maximum centred on the western flank of the city centre. This maximum was evaluated at VII on the modified Mercalli Scale by the South African Geological Survey (1979), (Figure A1-5). The resultant isoseismals also converged on a region directly above the zone of maximum underground damage which emphasised the probability that this was the locality of the epicentre. The relationship of this central maximum to the subouteropping geological structures can be more readily seen on the geological section (Figure A1-12 and 13), than by comparing the structural geology and town plan, because of the varied geological dips.

The surface structural damage was diverse but in all cases it was typical of the type associated with high dynamic shear stresses. Many of the displacements of cracks, occurred in the north or south facing walls or structures, thus indicating that the principal component of the shear stress was orientated approximately east-west. This east-west maximum strain was clearly demonstrated in the United Building Society structure, an isolated rectangular brick building, (Plates 1, 2 and 3). At the end of the north-facing wall large sections of the wall had been displaced from the main body of the structure by as much as 1 to 2 cms, while on the east and west faces no major cracks were evident. Similarly, at Anmercosa House, not far from the United Building Society, panel cracking was observed between the ground floor, south facing windows, a typical indicator of shear motion which, in this case was once again in an east-westerly direction (Plate 4). The extent of the damage between neighbouring buildings was not always

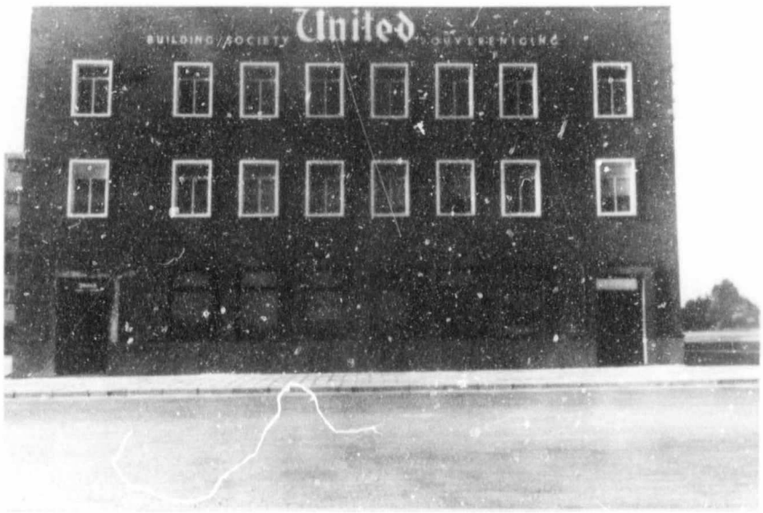


PLATE 1

U.B.S. shows isolation of building from other structures. Damage in corners of north facing wall.



PLATE 2

U.B.S. north facing wall, east corner, displacement at level of door lintel and mortar cracks.

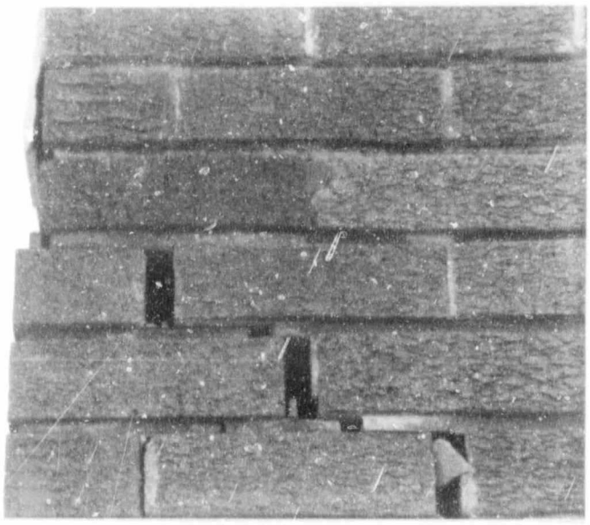


PLATE 3

L .S. north facing wall, displacement on western corner.

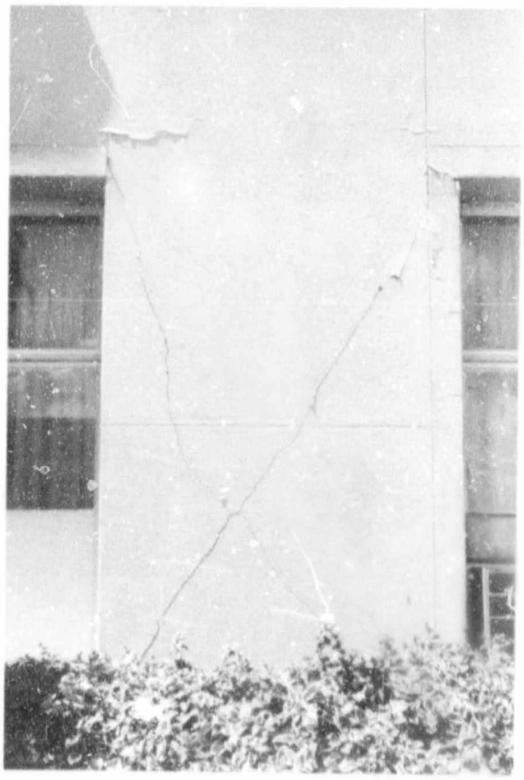


PLATE 4

Anmercosa House : panel cracking between ground floor windows (south facing).



PLATE 5

Collapsed Tempesthof flats with a relatively undamaged 7 storey block of flats in the background. (Courtesy 'Star')



PLATE 6

Tempesthof flats showing post office with microwave tower to the left and the Civic Centre clock tower in the distance, right.

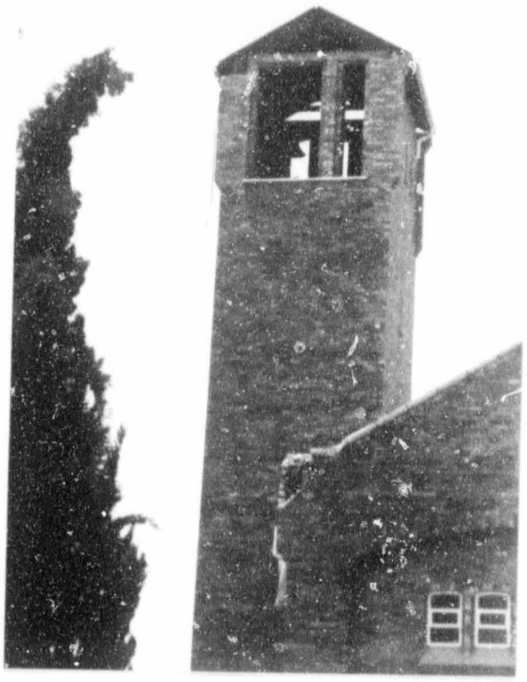


PLATE 7

Convent bell tower showing damage from fallen masonry



PLATE 8

Jan Hofmeyer School. East facing wall completely collapsed.

Author Arnott Frank Walter
Name of thesis Seismicity In The Welkom Area, O.f.s. (with Special Reference To The Origin Of The 1976-12-8 Event). 1981

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