4. DATA ACQUISITION

4.1 Seismic Network

The two periods of seismic recording were carried out using different network configurations (Figure A1 - 2, Appendix 2). During the period 11 December to 21 December 1976, seven stations were deployed, five on surface and two underground at a depth of 1.3 km below surface, in the Western Holding Mine. These two underground stations were placed either side of the Dagbreek fault. However, due to many malfunctions the station on the eastern side of the fault did not provide any records. At the end of December, four stations were taken out leaving in operation a set of three surface stations which were finally removed on the 9 January 1977.

For the second phase, the network again consisted of seven seismic units, however, these were used to monitor a larger area than the December array. The period of operation was from the 6th to the 28th July 1977. The reason for this expanded coverage was to gain more information on events that had been located to the north and south of the area of the previous study. This, however, could not be achieved fully, because of two restrictions; a broader array with an equivalent number of stations would decrease the location accuracy, and a comparison of the seismic activity between the two recording periods could not be easily obtained from the arrays monitoring different volumes. In order to reduce the first restriction the number of underground stations was increased to three and in addition a satellite seismometer was deployed some 1.5 to 2.0 km away from the parent station. This scheme produced an additional monitoring locality without the need for further recording equipment. During the operation of the July network it was also planned to investigate how local sites affected the levels of recorded ground motion. This was achieved by moving a single

SEISMOMETER STATIONS

TABLE 3

NAME	LOCATION	MINE COORDINATES			DATE ON	DATE OFF
		+ X m	+ Y m	Z m		
Surface						
Agulhas	50 Agulhas Street Daagbreek	+7080	+7060	-451	12 Dec 6 Jul 25 Jul	10 Jan 14 July 28 Jul
Bashee	43 Bashee Street, St. Helena	+11520	+10220	-449	8 Jul	28 Jul
Church	79 Kerk Street, Doorn	+10070	+6100	-468	12 Dec 6 Jul	10 Jan 28 Jul
Toronto	160 Toronto Road, Naudeville	+11200	+8770	+472	11 Dec	9 Jan
Jasmine	9 Jasmyn Street, Jim Fouche Park	+9110	+560	-462	11 Dec	21 Dec
TDS	Western Holdings, Rock Mechanics Department	+7620	+10320	-468	12 Dec	21 Dec
Temporary Surface						
Anmercosa	Anmercosa House	+9850	+8130	-468	7 Jul	8 Jul
UBS	United Building Society	+9910	+7910	-468	14 Jul	16 Jul
Romeo	257 Romeo Street, Bedelia	+10280	+9340	-468	16 Jul	18 Jul
Tempesthof	Tempesthof Flats, Tempest Road	+10180	+8950	-468	19 Jul	20 Jul
St. Andrews	St. Andrews School St. Helena	+11540	+11020	-468	22 Jul	25 Jul
Utopia	Utopia Flats, Tempest Road, Daagbreek	+8140	+7970	-460	25 Jul	28 Jul
Underground						
Daagbreek East	Western Holdings, No. 2 Shaft, 43 Level, East of Daagbreek Fault	+8495	+8890	-1776	13 Dec	21 Dec
Daagbreek West	Western Holdings, No. 2 Shaft, 43 Level, West of Daagbreek Fault	+8780	+9936	-1776	13 Dec	21 Dec
Daagbreek West	Western Holdings, No. 2 Shaft, 43 Level, West of Daagbreek Fault	+8610	+9170	-1776	8 Jul	23 Jul
	Western Holdings Satelite	+8610	+9170	-1776	8 Jul	23 Jul
President Brand	President Brand Mine, No Shaft, 48 Level	+11200	+6410	-1457	7 Jul	21 Jul
	President Brand Satelite	+12125	+5418	-1457	7 Jul	21 Jul
Welkom Gold Mine	Welkom Gold Mine, No Shaft, 30 Level	+3849	+5948	-1334	6 Jul	23 Jul
	Welkom Gold Mine Satelite	+3849	+5948	-1334	6 Jul	23 Jul

station to various sites for a period of two to three days at a time. The selected sites were those that had differing degrees of structural damage related to the event on the 8th December. The coordinates of these temporary stations and their period of operation are summarised in a portion of Table 3 which provides a complete summary of the participating station coordinates and period of operation for the arrays during December, January and July.

4.2 Station Installations

Each site was equipped with a BPI portable seismic station (Green 1976; Green 1979), and a three component set of Electrotek 1 Hz short period seismometers (EV17 series). Electrical power to the system was supplied by one 12 V or two 6V lead acid batteires, which were continuously trickel charged at all the sites were a 250V source was available. The output of the three seismometers was recorded at a low and high gain setting. These gain settings separated by 16 to 20 d_B depending on the ambient noise level. Typical levels of gain were '2' (x 1.45) for the low gain and '5' (x 55.5) or '6' (x 177) for the high gains. In this way six seismic data channels were recorded in AM mode, analog format onto a ten track magnetic tape. Two of the remaining tape tracks were used for time records, one from the systems internal clock and the other a radio output tuned to the Standard Time transmissions on 5 and 10 MHz which provided an absolute time reference. For instances where radio reception was unobtainable, such as the underground stations, an additional time standard was recorded to provide relative correlation between records. This was provided by a portable non-thermostated crystal clock which was recorded on two seismic channels during a station service. Besides these 'daughter clocks' other additional information recorded during the installation of the equipment included seismometer polarization taps and an internal calibration of 0.5 Hz at 1V peak to peak. Using 35 cm tape reels at a transport speed of 2.5 mm per second a maximum of 10 days unattended recording was possible. However, service visits were made far more frequently in order that the inoperative periods due to malfunctions could be kept to a minimum and the daughter clocks could be recorded as often as possible. All the above information along with changes in time codes, errors and other problems were noted in a log book kept at each station, which later proved invaluable in translating the tapes at the BPI.

A number of criteria had to be considered in the choice of the recording site. Some of the prime considerations were, complete coverage of the Daagbreek fault in the region of Welkom, minimum cultural noise, security of equipment, minimum inconvenience to property owners, and a 250 voltage source. These restrictions proved difficult to satisfy at times, security being one of the major problems. Generally, the surface stations were housed in an outbuilding or storeroom, while the seismometers were buried outdoors at some distance from the room, at the same time being kept away from any potential noise source. Some of the temporary sites proved exceptions to this, at Anmercosa, St. Andrews and Utopia the equipment was installed in basements with the seismometers placed on the concrete floor away from the tape recorders, while at UBS the seismometers were placed on the ground under the floor of the main offices, entrance being obtained via a trapdoor. A caravan was used at the Tempesthof site for security purposes. The underground stations were locked in storerooms when security posed a major problem while the seismometers were placed directly onto the floor rock which in all cases consisted of quartzite. The underground satellite seismometers were always horizontal East-West components, and were connected to the parent station by twisted blasting cable hidden along the mine pipes and cables. These were recorded on the remaining two channels of the system at high and low gains.

4.3 Operation Difficulties

Various problems were encountered which led to the loss and deterioration of some of the records. Some of these have been well documented in other studies (Green, 1979), however, at Welkom the principle contribution to the detioration in record quality was the high level of electrical noise. The source of this 50 Hz mains pick-up was from the combination of the seismometers, particularly when associated with wet or humid conditions and the power supplies. The effect of water on the seismometers was clearly demonstrated by the stations at Jasmyn and Welkom Gold Mine. Heavy rains caused the claysoil at the Jasmyn site to become water-logged resulting in a high amplitude 50 Hz signal, while in contrast the underground site which was situated in a disused and therefore dry haulage produced a very clean set of data. In an attempt to reduce this anticipated problem during the July survey the seismometers were kept as dry as possible, and isolation transformers were placed in series with the 250 V supply line and the power supplies. In some instances, for the required effectiveness it was found necessary to use two transformers in series. Underground a third source of electrical pick-up was the length of cable carrying the signals from the satellite seismometers. This in turn created an additional problem in that pre-amplifiers could not be used to match the line impedances because of the already poor-signal to noise ratio. Even the use of blocking capacitators did not adequately alleviate the situation.

Cultural noise, although only of a secondary consequence, due to its intermittent occurrence still resulted in the loss of some events. On surface its origin was due to the approach of people (children) and animals towards the vicinity of the seismometers, while underground the passage of trains, ventilation doors closing and general mine activity created noisy records.

Related to the above electrical noise sources from the power supplies was the unpredictable discontinuity of the supply battery voltage. Along with the well known difficulty of tape transport malfunctions this was the major cause of total data loss. Its influence was greatest during the December period when old batteries were used which could not hold a charge on some or all of their cells; a consequence of the method of storage. The only solution was to replace the unreliable batteries with new ones; in this way, operation in the January and July periods was far more dependable. Other equipment malfunctions such as magnetic tape stoppage and entanglement and failure of electronic units were corrected whenever possible. When repairs were not possible to such essential items as clocks, replacements were flown from the Bernard Price Institute of Geophysical Research (BPI) in Johannesburg.

Finally, the down-time of the recording system both underground and on surface was increased further by human interference. This did not only stop the operation of the system but also meant that the clocks had to be reset and re-correlated with the rest of the network. This occurred more frequently at the underground sites and since only one underground visit could be made per day corrective action was only achieved at maximum rate of every three days.

4.4 Calibration Blasts

To ascertain the accuracy of the location techniques, confirmation of the assumed phase velocities was required. This was achieved in the standard manner of detonating explosives at a pre-selected underground site. Two instantaneous 50 kg blasts were released at the localities and times below:

+X	+Y	+Z	Mine	Time
+11438	+ 6760	-1457	President Brand Mine	12th July 18:57
+ 9781	+10210	-7778	Western Holdings	13th July 16:04

The locations were provided by the mine survey departments and had an accuracy of ± 3 meters. The exact time of detonation was obtained by placing a small vertical geophone ten meters from the charge. The output of this geophone was attached by means of a temporary cable to two of the horizontal seismometer inputs at the recording station. The daughter clock was also recorded immediately after the blast in order to guarantee correlation with the rest of the network.

The 50 kgs of Amon gelignite* used for each blast produced an energy release of 210 mJ which in terms of magnitude would be equivalent to a -3.0 event. Thus, it was not surprising that the first blast was only registered on the records from Western Holdings, President Brand and Church Street, and the second blast from Western Holdings and Church Street. In both cases the Church Street record being of very low amplitude and only located because of its known time of occurrence. Admittedly, this

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Footnote*

This explosive is manufactured by AECI who give it an energy rating of 4.20 mJ/kg; which according to their report has a higher rating than AMFEX and TNT by a factor of 10% and 20% respectively.

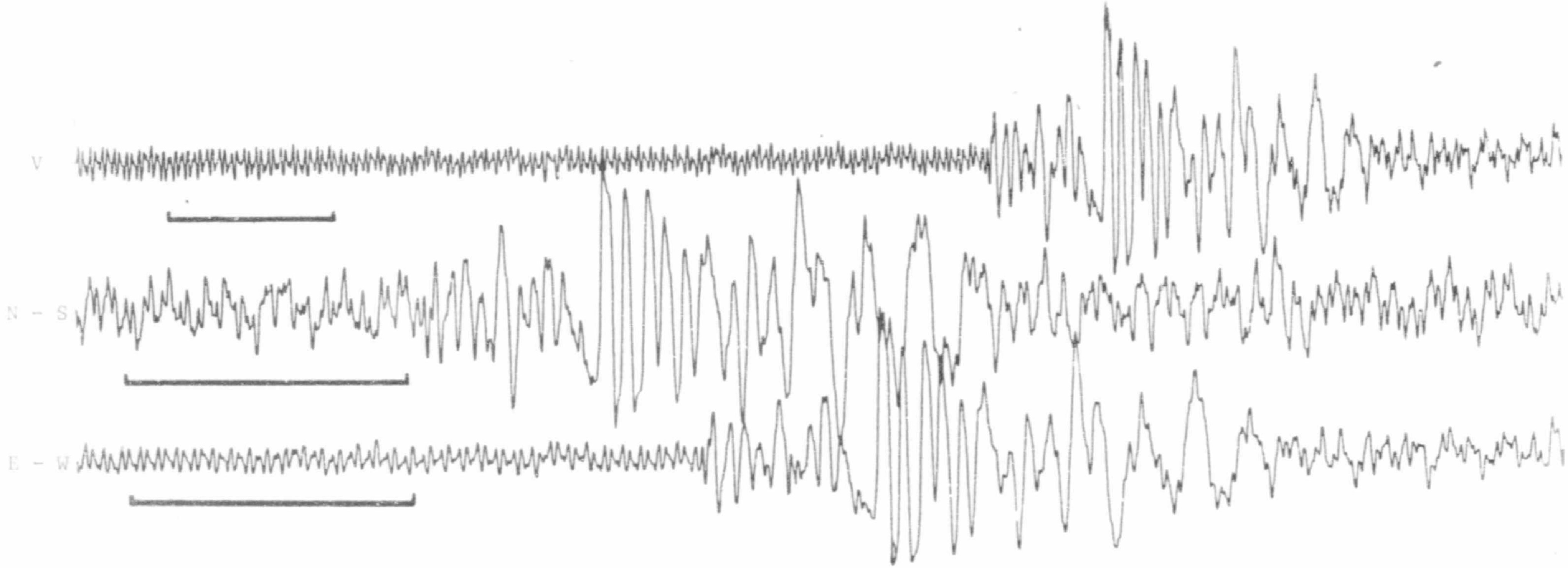

Figure 4.1 The digitized arrivals for the event on the 14 December at 16h56 at the Church Street station. The three ground components are shown V:Vertical, N - S : North South, E - W : West-West at unity gain. The bars represent 0.5 seconds. The noise envelope is representative of a moderate level due to $50H_z$ pick up. Filtering was applied to these records.

was an oversight in the study, however it had to be realized that very large detonations would be required to provide an energy level capable of detection, particularly, by the surface stations. Making the unrealistic assumption that conversion of explosive energy to rock strain is a 100% efficient the smallest located seismic events ($M_L = -0.5$) would be equivalent to 5 tons of explosives.

4.5 Primary Data Processing

Before interpretation and analysis of the field data could commence the relevant information on the analog tapes had to be transcribed into an alternate format. Two forms of data capture were possible, the first as light traces on ultra-violet sensitive paper, used for time domain analysis such as locations, magnitudes, energy content and first motion studies and the second onto 9 track IBM compatible tapes as digitized data for use in a computer for frequency domain processing. The 'replay' system used to obtain these additional records is described fully by Green (1979) and examples of the records from the digital recordings are shown in Figure 4.1. Events were identified by monitoring one of the seismic channels through an audio amplifier and at the fast replay speed of 150 x the field recording speed. Once an event had been selected it was recorded onto the photo-sensitive paper at a speed of approximately 60 mm per second of field recorded time (tape speed = 25 x, paper speed = ± 630 x). In this way a time resolution of 0.015 seconds was obtainable from the hard copies. The amplifier gains of the replay system were set for each event in order that the channel overlays on the paper records was not excessive and at the same time allowing for about ± 0.5 mm resolution when reading the maximum peak to peak amplitudes. The linear electronic filters were also used to reduce some of the high frequency noise.

Time Correlation

As each event was recorded onto paper its approximate arrival time and date, as provided by the Vela coded 100 Hz time marks, was written on a time log sheet. These logs provided information of the intervals between events which then enabled the events on stations where clock failure had occurred to be identified. An example where tapes had no recorded clock was from the site at Bashee Street, although, it had appeared to be functioning during the station services. Once all the tapes had been replayed equivalent events were correlated from different stations by using the above time logs; initial matching not always being possible due to incorrect increments in some of the station time codes. Having identified all the events the only remaining task before locations could be obtained was to apply the relative daughter clock corrections and when available the absolute radio corrections. In this way with an accuracy of 1×10^{9} seconds per day for the temperature controlled crystal clocks (field packages) and 1×10^{6} seconds per day for the unovened crystal clocks (daughter clock), the reading accuracy of the arrival times and seismic periods were well within the 0.015 seconds provided by the selected replay speeds.

Digitization

The second form of data preparation was only undertaken after all possible events had been located. Selected events based on clarity of records , locality and the type of information required were digitized at a sampling rate of 640 samples per second. Although this was very high in relation to the frequencies of interest (0 - 50 Hz) it was implemented so that short time intervals could be used for determining the frequency spectrum without the need for additional interpolation of the data. The frequency response of both the replay and record system for the two types of magnetic tape used (Scotch 3M* '888' and '871') was more than adequate for this frequency window, (Figures 4.2 and 4.3). The digitizing rate was controlled by the internal oscillator and the phase lock loop because of greater ease and reliability of operation. Each seismic channel required, was recorded at a gain setting which would prevent saturation (a maximum signal ± 5 V) and was filtered to reduce 50 Hz noise. The data was then transferred with the removal of any unnecessary blocks to a standard label tape on an IBM 370/158 computer, which could then be read by application of the fortran subroutine 'READT' in any main programme requiring a specified number of samples from different event files. The standard label tape format is provided in Appendix 2. During the transfer the first data block was always scanned for a constant harmonic component of noise. This was achieved with the subroutine 'MAINS' (Appendix 3) and in this way it was hoped to remove a high percentage of the 50 Hz noise. This was not always successful.

*3M is the trade name for the Minnesota Mining and Manufacturing Co. U.S.A.

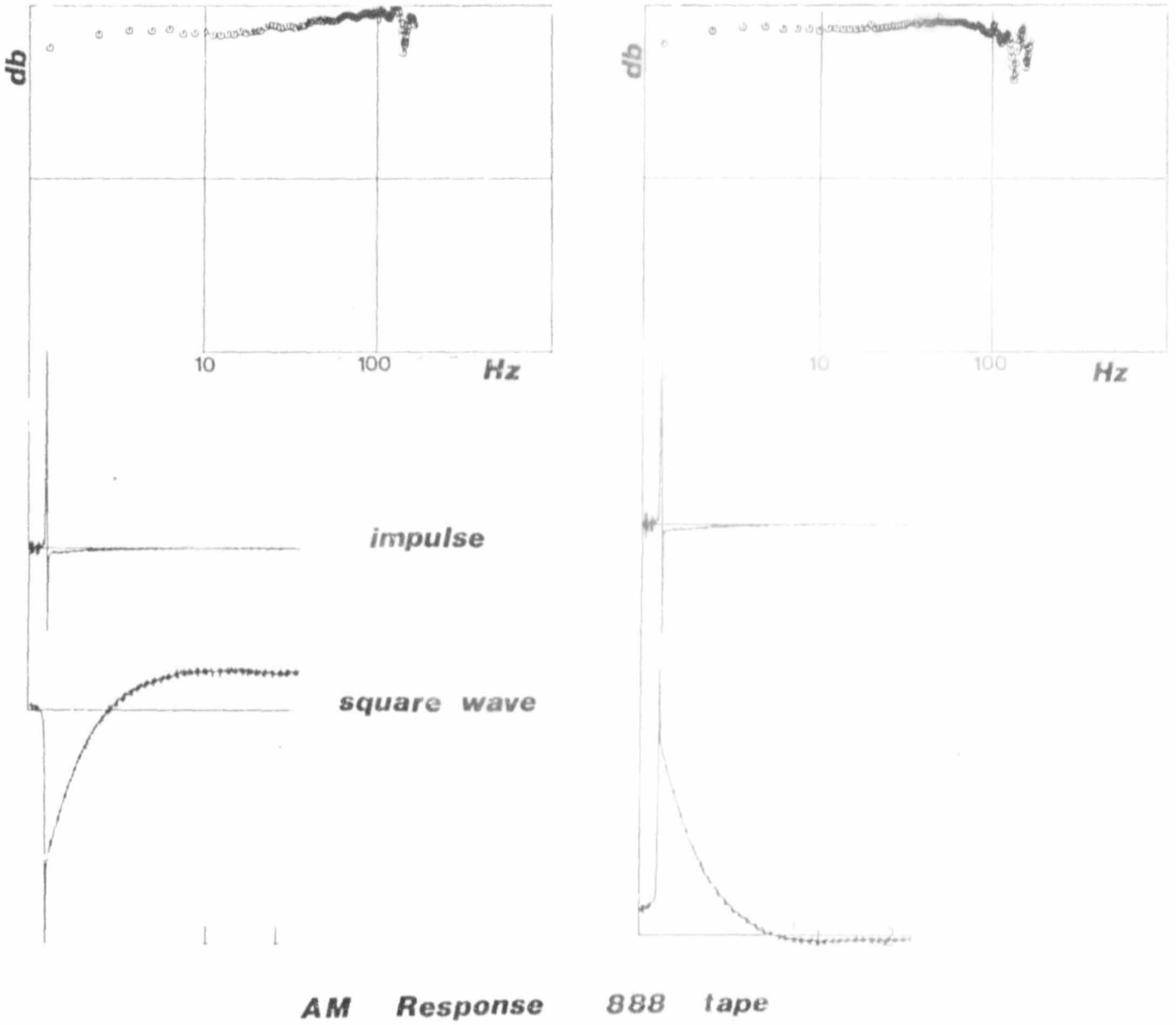

Figure 4.2 AM System Response for Type 888 Tape; 3M (Green 1979)

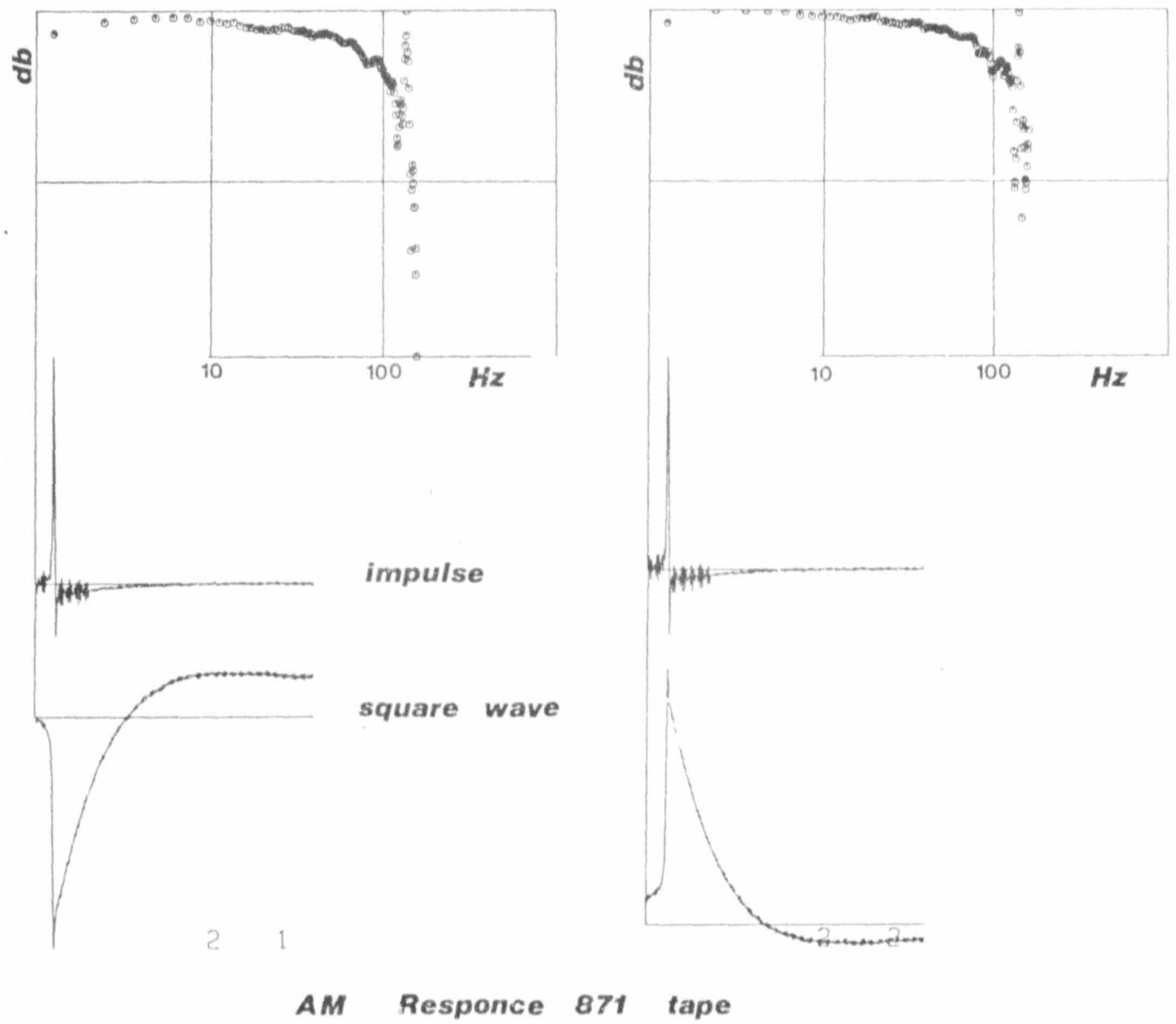

Figure 4.3 AM System Response for Type 871 Tape; 3M (Green 1979)

5. LOCATION AND MAGNITUDE DETERMINATIONS

Because both the location and magnitude are regularly referred to during the assessment of the seismic activity, it was important to ascertain the degree of confidence in these two parameters for any particular event. This is done in the subsequent sections by first outlining the method of calculation and then discussing the probable sources of error.

5.1 Location Techniques

Utilizing both compressional and shear wave arrival times the locations were obtained with the aid of a computer programme that was based on the method of reducing the square of the distance residuals, (Lomnitz, 1977). The final location representing the complete hypocentral determination. The original programme written by Spottiswoode (1979) used an iterative least squares procedure as formulated by Seidel's method of successive approximations. For 'n' arrivals the resultant set of linear equations

$$\widetilde{A}\widetilde{x} = \widetilde{b}$$

where $\widetilde{A}$ = n x n positive definite symmetric matrix storing the partial derivatives of the distance residuals;

$\widetilde{x}$ = 4 dimensional row vector, containing the solution parameters of the new distance and origin time residuals;

$\widetilde{b}$ = n dimensional column vector containing the previous estimates of each distance residual;

was solved by applying the subroutine LEQTIP, a member programme of the

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International Mathematical and Statistical Library (Appendix 3).

The original programme incorporated a single velocity model, which had been developed for the underground seismic array at ERPM. From the geological considerations of the Welkom area it was apparent that a more complex model was necessary, particularly for ray paths directed towards the surface stations. Ideally, this model should have contained three velocity layers representing the Karoo, Ventersdorp and Witwatersrand Supergroups. However, due to the complexity introduced by faulting, the Ventersdorp was omitted from the model, the effect of this will be discussed in the error analysis. The subroutine 'TRAVEL' contained a numerical approximation of the resulting two layer velocity model, (Figure 5.1). Refractions at the Karoo-Witwatersrand interface were accounted for by applying the velocity ratios in the location process. Clearly for the underground sites this was not required.

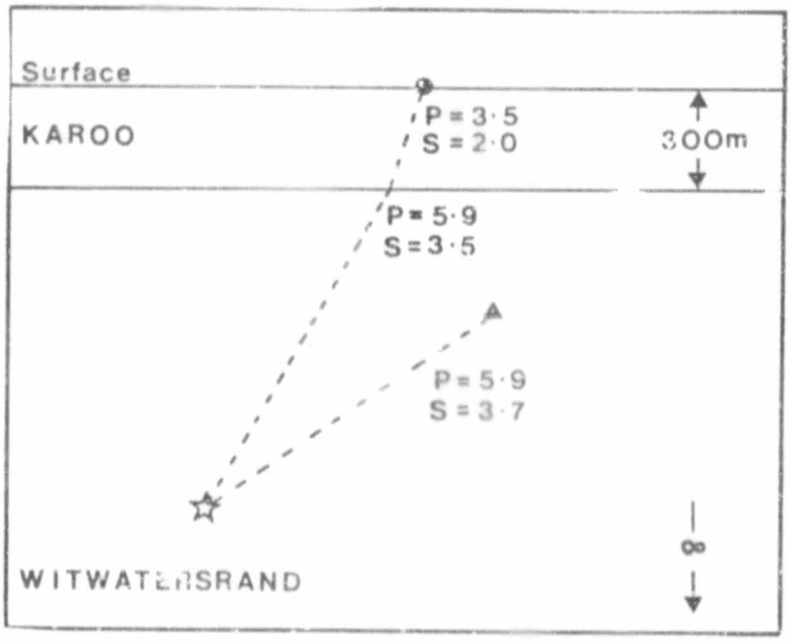

Figure 5.1 Velocity Model used in the location programme. Triangle represents an underground recording site, the dot a surface site. Velocities are in Km /sec.

Conditions imposed on the locations were minimal. The minimum hypocentral depth allowed was 500 meters below datum (100 meters below surface), oscillatory locations were multiplied by a damping factor after eight iterations, and events with a total squared distance residual of 10 meters were considered located. An assessment of the location accuracy was possible from a number of different parameters, the principal one being the final time residuals for each of the arrivals. These were examined individually for evidence of inconsistent initial values. This was done in the form of the statistical variance.

$$\text{Variance} = \{ \sum_{i=1}^{n} (\text{time residual}_i)^2 \} \; / \; (n-4)$$

It is important to recognize that the variance represents only the degree of confidence in the initial arrival times and it is not an error estimate of the location. That is, the variance provides the deviation about a mean location, which is not necessarily the true location. Unreliable locations were also indicated by a resultant high number of iterations, frequent attempts by an event to locate above ground surface and lastly how well the total distance residual converged. Comparisons were made between locations with or without suspected unreliable arrival times. The inclusion of P-S time intervals were also used for comparison. P-S time intervals were utilized when no relative clock corrections were available for any particular station.

In order to obtain further information from the recordings carried out during the early part of December a programme was developed to yield approximate locations from events recorded by only one or two stations. The direction of the event was estimated by the analysis of the polarization and amplitude of the first arrival. This process used curves which provide the incident angle at a free surface (Gutenberg, 1944). The distance along this ray path was then determined from the P-S interval, while all the necessary correction to the incident angle were applied for the refraction at the Karoo-Witwatersrand interface. The success of this exercise was dependent on the clarity of the first arrivals together with the resolution of the amplitude on all three ground components. In practically all cases these constraints were found to cause a considerable amount of scatter and even events previously well located by the conventional location process (LOC4) failed using this technique. For this reason this procedure was not followed up.

5.2 Location Errors

Errors in the location can originate from a number of factors. The principal contributions are considered in the following section and where possible test data has been included to provide the probable limits to the respective errors.

5.2.1 Timing Accuracy

Selecting the correct arrival and being able to determine its precise time is of considerable importance in obtaining a correct location. Employing the resolution of 0.015 secs that was available from the replay and assuming a maximum P velocity of 5.9 km/sec, a restriction of 90 meters accuracy was imposed upon all the event locations. This is the accuracy that was theoretically obtained for arrivals with clearly defined onsets. Good clear onsets were not observed for some of the arrivals and greater inaccuracies must thus result. The high level of noise was one of the principal reasons for this source of error, whilst in other instances emergent arrivals, malfunctioning seismometers, multiple events and saturated signals contributed to the problem. For such doubtful arrivals a relocation was generally carried out with the exclusion of the uncertain data.

5.2.2 Station Disposition

When deploying a seismic network, a wide geometric variation is generally available. During other investigations it has been observed that the configuration of the seismometers can maintain a significant influence on the location accuracies. From results obtained from test blasts and numerically constructed sources Shapiro and Bath (1977) determined a best possible configuration for small networks. They concluded that to obtain the greatest accuracy the disposition must provide a circular hemispherical locating volume. In addition, Milner and Harding (1972) concluded that large errors are incurred when applying the linear least squares location method to stations that are coplanar. Thus the implementation of underground sites during these studies resulted in minimised errors. The actual spread or volume contained by the array is also very significant since this controls the path length that has to be traversed by the seismic energy wave. For an event within the bounds of an array, the location error increases with the path length, this is accepted in quantitative terms as the location accuracy being typically 5% of the station spread. This implies that for the utilized arrays with an average surface spread of 6 km the minimum error in an epicentre determination can not be less than 300 meters.

5.2.3 Depth Estimates

The depth parameter is recognised as the most unstable variable of any hypocentre determination. There are essentially two approaches for finding a hypocentre; find the best epicentre at various constrained depths (Shapiro and Bath, 1977) or locate the hypocentre directly treating depth as a fourth unknown (Engdahl and Gunst, 1966). The latter technique has been reported by Freedman (1968) to be more reliable since, by restricting the depth, they observed that there was a tendency for the incidence of divergent solutions to be higher. This of course does not guarantee a reduction in the overall depth error, and although the complete hypocentre was determined in a single operation by the programme LOC4 the maximum errors were still observed as occurring in the depth estimates. These conditions manifest themselves primarily in the unstable locations such as those events outside of the network. A first approximation to the error in the depth determination can be expressed;

$$\frac{\text{maximum error in epicentre}}{\text{Sin } \theta \ / \ 2}$$

where θ is the angle formed at the epicentre, by two stations and the event. Clearly with large distances this error becomes infinite; however, for this study where θ was typically 90° errors of the order of 550 meters are suggested.

5.2.4 Initial Location Estimates

To commence the iterative procedure of the location programme an initial estimate of the hypocentre had to be made. Shapiro and Bath (1977)

TABLE 4 VELOCITY CALIBRATIONS AT DIFFERENT WITWATERSRAND GOLD MINES

Area	V_p	V_s	V_{ps}	V_R	Reference
Central Rand	5,64	3,37		0,60	Logie (1949)
Pretoria to Heidelberg	5,9	3,56	8,98	0,60	Gane et al (1956)
Harmony, OFS*	5,79 (5,57 to 5,73)	-	-	-	Joughin (1966)
	-	-	9,15	-	Maher (1972)
ERPM	6,0	3,8	10,36	0,63	Spottiswoode (1980)
ERPM *	(5,8 to 6,1)				McGarr et al (1975)
Western Deep Levels,* Carletonville	(5,92 to 5,93)	3,74	10,14	0,58	Heunis (pers. comm. 1978)
Klerksdorp	5,67	-	-	-	van der Heever (1978)

* These velocities have been determined using calibration blasts.

report that this estimate has a considerable influence on the ability of an event to locate, so in order that it could be accounted for test runs were undertaken. The December events were repeatedly relocated, each set of relocations using a different initial estimate. Through this procedure it was observed that the only marked effect occurred when the initial depth value was too shallow (less than 600 m below surface). Under these conditions divergent solutions were obtained for a large number of previously located events, with one exception when a previously unlocated event was able to converge on a solution. No other variations were observed from these changes. This suggests that the non-linear least squares method and/or the constrained depth determinations, as used by Shapiro and Bath (1977) are more vulnerable to the initial estimates.

5.2.5 Velocity Structure

The geological structure beneath Welkom can be represented by various crustal models each increasing in complexity from that provided by the simple model in Figure 5.1. Representation of very detailed structures is not only difficult to achieve numerically but is also unlikely to be significant within the bounds introduced by other errors such as the timing accuracy. However some of the assumptions that have been applied with respect to the more gross features require assessing in terms of their influence on the hypocentre errors.

Guided by some of the earlier values determined for P velocities (Table 4) a velocity of 5.9 km/sec was selected for the Witwatersrand Sediments in the Welkom area. The accompanying S velocity of 3.5 km/sec was then selected so that the resultant PS velocity was also consistent with other determinations.

Prior to the calibration additional confirmation of these velocities was obtained by relocating the December events over a range of P velocities (5.6 to 6.1 km/sec) and S velocities (3.4 to 3.8 km/sec). For these data which was derived from several stations and differing ray paths the greatest internal consistency was provided by velocities between 5.9 to 6.0 km/sec and 3.5 to 3.6 km/sec respectively. The actual values being closer to 5.9 km/sec and 3.5 km/sec. The results of the calibration blasts were limited, however they showed that these velocities were correct for the surface stations but indicated a slightly higher shear velocity at the underground sites. Although it was not possible to obtain a specific value for this S velocity a value of 3.7 km/sec satisfied this condition without violating the earlier constraints.

Further evidence on the reliability of these velocities was obtained by examining the consistency of the origin time and the velocity ratios (V_s/V_p). This checking was achieved by plotting the P-S time interval as a function of the P travel time, the velocity ratio being given by the resulting slope. From approximately 100 events and recordings at different stations (Figure 5.2) two not too dissimilar trends were evident. These were distinguished as being due to the underground sites and the surface sites respectively, however, by linear regression analysis both yielded velocity ratios of 0.60 (coefficients of determination = 0.95). A value of which agreed with the ratio of 0.60 obtained for the Central Witwatersrand Goldfields, (Logie, 1949). Considering this as the medium value the ratios of the actual velocities used for the Witwatersrand Sediments (0.59 and 0.63) represent a maximum 5% deviation.

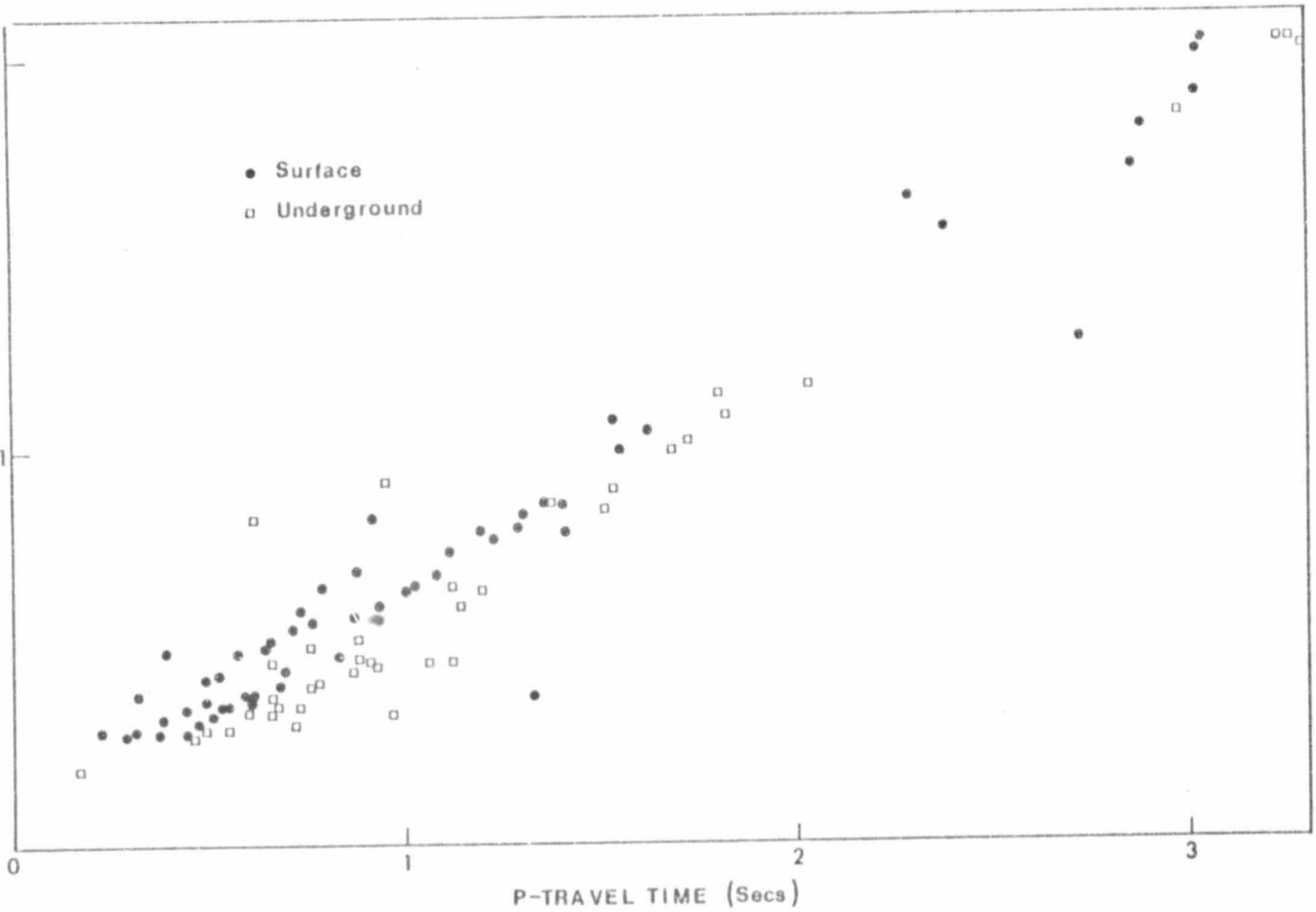

Figure 5.2 Ratios of time intervals for events recorded at Welkom

The Karoo sediments have a markedly different velocity to the underlying Precambrian sediments and lavas. For these Karoo sediments a value of 3.5 km/sec and 2.0 km/sec was assumed for the P and S velocities respectively. Because a relatively thin layer of these sediments was in evidence discrepancies in the velocity values were not critical to the overall errors. Notably the velocity ratio for the Karoo (0.57) did not cause any significant deviation to the estimate of the Witwatersrand velocity ratio for the surface stations in figure 5.2. The Ventersdorp lavas were omitted from the velocity structure because the errors introduced by attempting to represent the complex lateral and vertical discontinuities by a simple layer would have been greater than those resulting from its complete omission. An initial estimate of the error introduced by this omission can be attained by considering the velocities through the Ventersdorp as representative of a deviation from the Witwatersrand velocities. Using a compressional velocity of 6.3 km/sec for the lavas (van der Heever, 1979) a resultant deviation of 0.04 secs is observed. This deviation can be expressed as;

$$|dT| = \frac{H}{V_w^2} \, dV_w$$

where V_w is the phase velocity for the Witwatersrand and H the distance travelled through the lavas.

The time residual introduced on a normally incident ray for H = 1 km is 0.011 secs which is equivalent to an error of 65 meters or a maximum of 7%, the percentage error decreases the greater the actual volume of Witwatersrand (5.9 km/sec) material traversed. The complexities introduced by refraction and in some cases multiple refractions at the various Ventersdorp, Witwatersrand interfaces are also significant but these are difficult to access.

The influence of the source material is generally a well documented problem, as well as being evident in the P velocity variation from various calibration blasts (Table 4). Calibration blasts at ERPM revealed variations of 5% between paths through hanging-wall quartzites as compared with footwall quartzites and also for short path lengths through highly fractured rock (Spottiswoode, 1979). Unfortunately these factors could not be evaluated for the Welkom array as the calibration blasts were too small with respect to the dimensions of the array.

Omission of a non-uniform Ventersdorp lava sequence from the velocity model implies that the locations are dependant on P - S intervals and azimuths. In addition observations have been made which show a dependance of the time residuals on azimuth and hypocentral distance for relatively homogeneous media (Herrin and Taggart, 1968; Spottiswoode, 1979). Thus anticipating the occurrence of similar results for the Welkom region an examination of the time residuals was made for all the located events. The results however, showed no correlation with azimuth for any one station, although the influence of inhomogeneities in the velocities was indicated by an additional test location programme. Ten well located events were relocated after applying time increments of 0.02, 0.04, 0.06, 0.08, 0.1 and 0.5 seconds respectively to the recorded P arrival time for each station; a single increment being applied to only one station during any one location. From these results the variance was sometimes found to improve consistently for a number of events after inclusion of a specific time interval, at a particular station, for example at Utopia this was 0.06 secs. This method however, did not provide sufficient data to allow for station corrections.

5.2.6 Summary

From the criterion that has been discussed the overall error is clearly of a composite nature, but the total error does not represent an accumulation of all the individual values. The main contribution is derived from the geological or velocity model which from the above analysis does not appear to present an error greater than the accepted 5% of the total network dimension. The largest contribution to the error was due to exclusion of the Ventersdorp lava from the velocity model. However, by setting the Karoo depth to 300 meters, thinner than the true value for many areas, compensation was partially achieved. By considering the velocity of the Karoo and Ventersdorp to be 5.9 km/sec, then 1 km of the faster Ventersdorp medium would be equivalent in time to 240 meters of the slower Karoo. Errors in the model were also indicated by the P-S time intervals in Figure 5.2. Ideally, these should have been zero for a zero P-travel time, instead 0.08 secs was observed for the surface stations and -0.03 secs for underground. This larger surface station error reflects the influence of the approximations used in the velocity model.

From the above considerations it is safe to assume that the total error in any hypocentral location was never greater than 500 meters. This value having been based on 5% of the network dimension and the contribution due to the uncertainty in the depth estimates. Additional confirmation of this value was provided by the test location programme, which had utilized different velocity ranges. From all the events examined the maximum variation observed for any one location was [illegible] meters, 180 meters and 280 meters for the X, Y and Z coordinates respectively. It is also important to note that this overall error of 500 meters is only applicable to the region of the network, events that occur to the south and north of the survey region are associated with far larger error estimates

5.3 Relocation of the 8 December 1976 Event

An attempt was made to re-estimate the location of the main event as well as some of the later shocks which had been located by the South African Geological Survey (SAGS). The technique that was to be employed was the method of joint epicentral or hypocentral determination (Douglas 1967). This procedure required a master event, however examination of the SAGS monthly seismic bulletins revealed that no suitable event had been located concurrently by the national network and the BPI network. A total of nine possible events with local magnitudes greater than 2 occurred during the December, January and July periods, two of which were associated with underground damage. Only one of these nine events had been located successfully by both networks, however due to its small size (M_L = 2.4) the geological survey location had relatively large errors and time residuals (-2.34 to 0.26 secs). Even after re-examination of the records no improvement was possible particularly as some of the first arrivals were too small to be identified with any degree of confidence. Thus, it was not possible to provide any additional information on the position of the main event by this relocation technique, from the available data.

5.4 Magnitude Determinations

The local magnitudes of the events recorded by the BPI networks were evaluated from the maximum peak to trough body wave amplitudes. These values of maximum ground velocity were then converted to local magnitude by a relationship developed by Eaton et al. (1970).

$$M_L = \log \left(1.03 \frac{X.T}{C_{10}} D^{1.7}\right) - \text{CONSTANT}$$

X : maximum trace amplitude in mm (peak to trough)

T : period in seconds of the wave with amplitude X

D : hypocentral distance

C_{10} : trace amplitude in mm (peak to trough) of a 10 µV RMS signal introduced into the seismic system in place of the seismometer

CONSTANT : 1.85 for horizontal component seismometers
1.60 for vertical component seismometers

The formula was based upon observational data from California using the same EV17 seismometers as this study and so of the constants used only the distance scaling factor of 1.7 may be in error for the present study. The equipment calibration factor C_{10} was dependant on the complete system so individual values had to be obtained for the different types of magnetic tape. These calibrations were carried out by K Jones (1978), who obtained a value of 113 x 10^6 for the 3M type 871 tape, which was taken as the standard value. For the 3M 888 type the calibration amplitude in the flat region of the response curve was found to be a factor 2.1 less than the standard value, so for events recorded on this magnetic tape a constant of 0.32 had to be added to the calculated magnitude. Normalization of the peak amplitudes at a replay and record gain of unity was also necess[illegible]stency of the signal amplitude between stations, however corre[illegible]re not possible for any variation between any of the recording systems because the recorded internal calibration was unfortunately always saturated. Hypocentral distances were obtained directly from the location as determined in the output of programme 'LOC4'. Where locations were not available, such as events in other mining districts the P-S velocities (as determined for the Transvaal by Gane et al. (1956)) were used to convert the P-S interval to distance. For single magnitute estimates a hand calculator programme was used and for the bulk processing the magnitudes were computed by the programme 'MAG' which also provided statistical estimates in the output (Appendix 3).

5.5 Magnitude Errors and Local Variations

The magnitude assigned to a particular event was taken as the average of the surface station estimates, the underground stations having been omitted because of their expected lower value. This was principally due to the absence of Karoo sediments, whose influence will be discussed later. From each of these mean values a standard deviation was determined which never exceeded 0.4 for the surface stations. This is in close agreement with values quoted for many international networks including the South African network (Adams, 197[illegible]).

Because the magnitude of the main event and immediate aftershocks were evaluated by the South African Geological Survey, it was appropriate to determine whether or not the BPI local magnitudes were consistent with these initial results. Previous seismic investigations which had utilised the same equipment and magnitude relationship as this study, were the Hendrik Verwoerd Dam seismicity investigation (Milner, 1975), the ERPM studies (Maher, 1972; Spottiswoode, 1980) and the Damara project, (Jones, 1978). All of these studies yielded magnitudes which showed a close agreement with the corresponding mean magnitude estimates by the SAGS. In particular Spottiswoode (1979) found that, for large events located at ERPM, the difference between the two methods of evaluation never exceeded

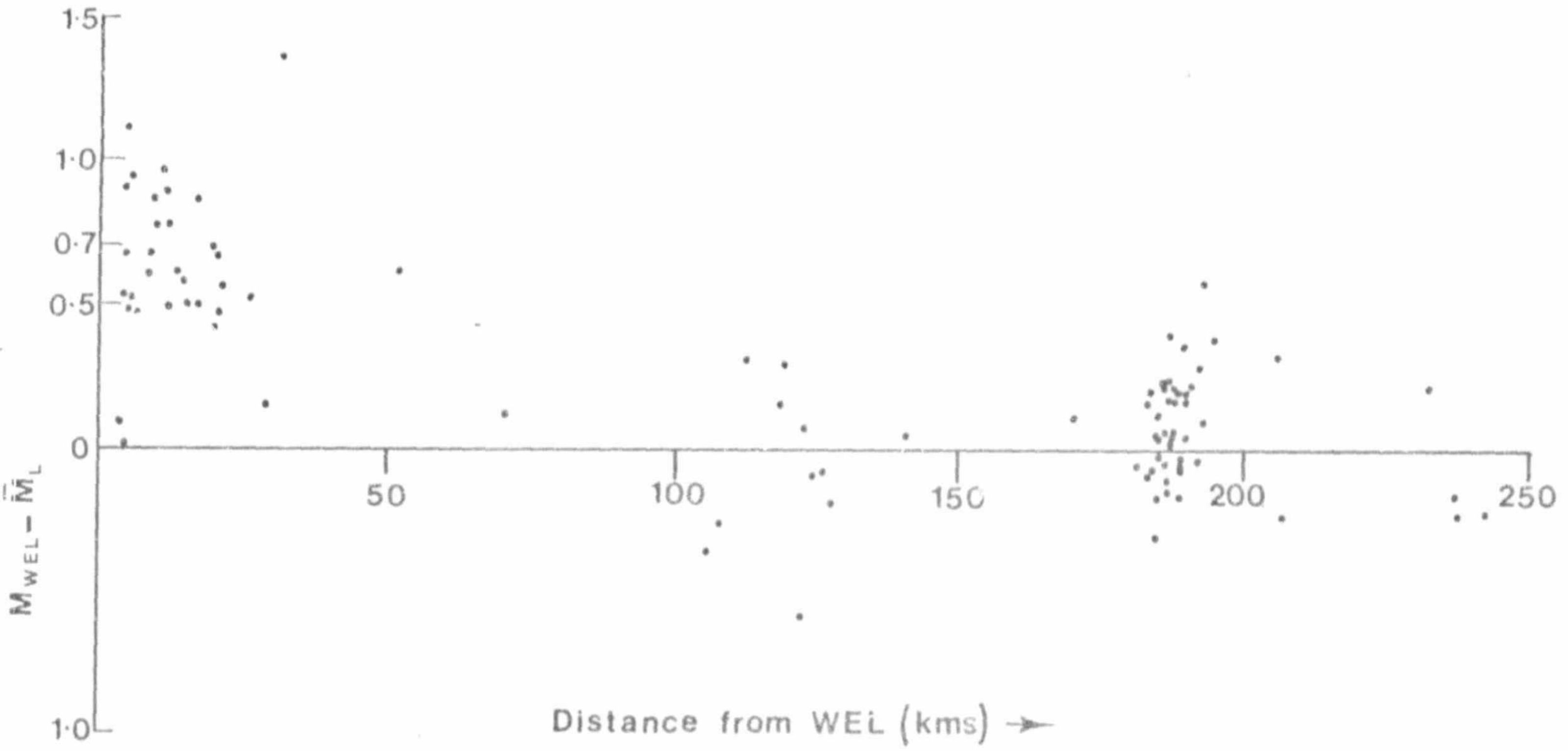

Figure 5.3 Local Magnitude differences of the SAGS Welkom station from the SAGS mean estimate; plotted as a function of epicentral distance from Welkom. (Recording period 10 months)

0.5. During December the Welkom network recorded a number of events that originated in the Transvaal mining districts and it was found that these events yielded consistently higher values of magnitude than those given by the National network. The mean value for the Welkom array was some 0.7 magnitude units bigger (sd 0.2) than that given by the National network. In contrast six large events; jointly located in the Welkom region by both networks did not show the same variation; instead differences between the two magnitude estimates were representative of those observed by Spottiswoode at ERPM. These observations suggested that the distance attenuation factor of 1.7, as adopted in California for distances up to 150 kms, was too high for distances of up to 200 kms in the Transvaal and Orange Free State. Contrary to evidence from the other previous BPI studies, in particular for distances up to 300 kms across Namibia 1.7 was well suited (Jones, 1978). An exception is also suggested from the study of blasts in the Western Province during 1964. From these data a slightly higher value of 1.8 was found to be more applicable (Green, unpublished).

"Enhancement" or the trapping of the surface energy was also an important consideration in these magnitude variations. Evidence of such an effect was provided by a vertical component seismic station "WEL". This station was installed at Welkom in July 1977, by SAGS. The magnitudes obtained from it and the corresponding mean value as published in the SAGS Bulletins were substracted, thus providing a difference for events at different distances from Welkom (Figure 5.3). The variation presented in the figure revealed a consistently larger magnitude that amounted to approximately 0.7 for the local events and 0.4 at the more typical deviation for the more distant events. It could be concluded from this evidence that a distinct energy magnification seems to be evident at Welkom.

In addition to the above features, magnitudes obtained from the BPI underground stations showed that this must principally be due to the unconsolidated Karoo sediments as the underground stations yielded consistently lower mean magnitudes. That is, for 158 located events the mean underground magnitudes were on average 0.7 (sd 0.3) less than the mean surface magnitudes.

6. DISTRIBUTION OF SEISMICITY

A total of 230 seismic events were located for December 1976, January 1977 and July 1977, which represents approximately 65% of the total number of locatable events recorded over those periods. It is noticeable from the list of events (Appendix 2) that the locations for July indicated a significantly higher level of activity than during December-January; 171 events in contrast to 59. These figures are not however due to an improvement in the location techniques or the quality of available records because the proportion of located events to the total recorded was only 4% higher for the July period.

6.1 Spatial Distribution

The total seismicity is presented in plan in the form of two overlays representing the recording periods of December-January and July, (Figures A1-6 and A1-7 in Appendix 1). Comparing this total seismicity with a plan of the active mining combined for both periods (Figures A1-3) a close correlation is observed in the horizontal distributions. This feature was given further emphasis by realizing that the scatter in seismicity to the north and south of the central region was principally due to large tolerances associated with hypocentres outside the seismic network (Figure A1-2).

Due to the complex structural geology (Figure A1-1) a detailed comparison with seismicity was not warranted and only general seismic trends are discussed. This discussion has been restricted to the region beneath Welkom because of the probable large location errors that may have occurred outside the network. The principal feature of the total seismicity was a wedge of intense activity bounded by the Enkeldoorn dyke and Arrarat fault that fell within the Enkeldoorn block. This is clearer in the geological sections which take into account variations in geological dips and depth of hypocentres (Figures A1-8 to 13). In relation to mining this zone was also one of the most active regions. This does not suggest that all mining was associated with seismicity as a relatively active mining region along the southwest boarder of Western Holdings is practically free of seismicity.

Besides the July increase, there were also some other significant differences between the two periods of seismicity. During December-January, minor seismicity occurred between the Arrarat and De Bron fault zones, whilst along the Dagbreek fault zone there was a marked absence of events; this was in complete contrast to July when the level of seismicity for these two regions was reversed. It must be noted however that an apparent increase in the activity during July in the southern region was once again partially influenced by the disposition of the seismic stations. An unusual feature of the central wedge of seismicity during July was the absence of large events ($M_L >$ 1.5), these larger events only occurred in issolation outside of this seismic wedge. Similar behaviour was not apparent for December and January.

Variation in the hypocentral depths was of considerable significance in this study, so to view this to greater advantage three geological sections combined with seismicity were plotted. These seismic sections were projected from within 1 km either side of the profile line

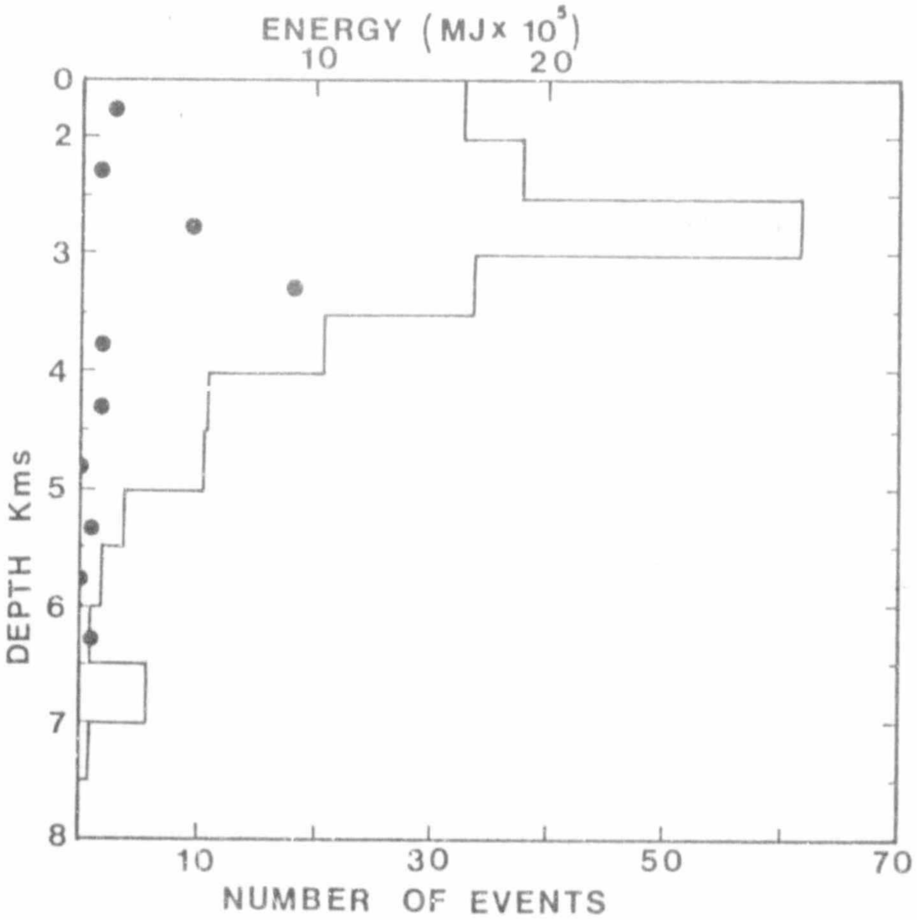

Figure 6.1 Cumulative energy (o) and number of events (Histogram) as a function of depth below surface at Welkom. Note: the summing interval is 0.5 Kms. except between 0 and 2 Km where it is 1 Km. Mining occurs between 1.0 and 1.5 Kms below surface.

(Figures A1-8 to 13). Their positions were chosen such that geological features along the north-south orientated strikes were relatively consistent across the zones of projection. The most striking feature of the variation with depth was the intense activity situated below the Basal Reef which represents the principal mining horizon. This aspect of the seismicity was still valid even if the events were to be made shallower by applying the maximum possible depth error of 500 meters. However, such an error was unlikely because of the close grouping, section + X8000. As previously indicated the principal region of this activity was well confined between the Enkeldoorn dykes and Arrarat fault, but in addition some events were also situated along and in the footwall of the Arrarat fault. It was not possible to position the mine related events to either the mine hanging or footwall as location accuracy did not provide sufficient resolution.

The Dagbreek fault and Enkeldoorn dyke displayed some marked contrasts with respect to the two recording periods. With the exception of a few minor events the region between and including these two structures was aseismic during December and January. During July, however, there was an increase of seismicity in the plane of both the Dagbreek fault and the Enkeldoorn dyke which is particularly apparent in section + X10000. Similarly, the region between them was slightly more active but it still did not equal the intensity of the neighbouring region of high seismicity.

A summary of the depth of the events in terms of frequency of occurrence and energy released is presented in Figure 6.1. From this diagram the maximum level of seismicity was situated at between 1.5 and 2.5 Kms.

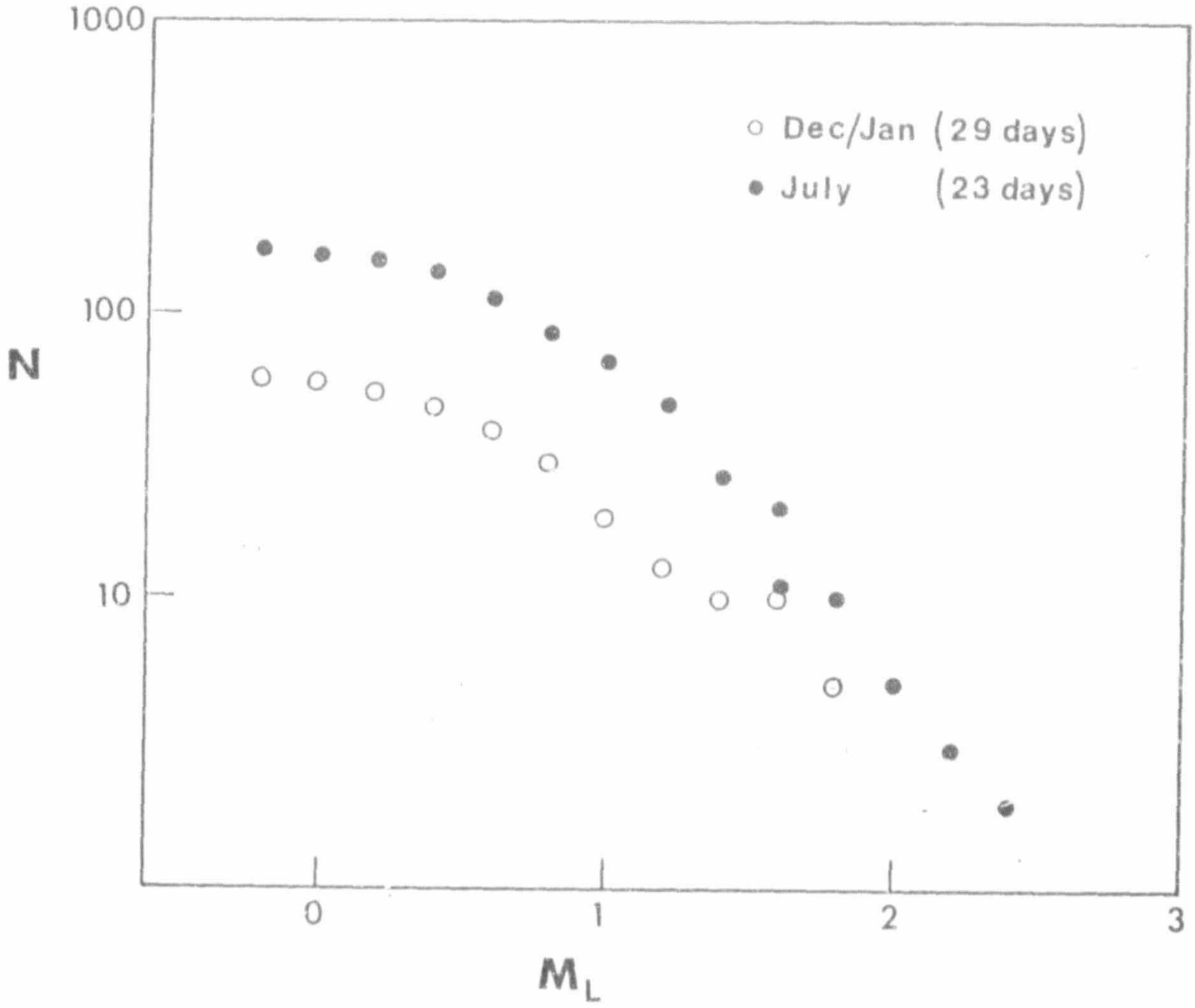

Figure 6.2 Log frequency of events greater than a particular magnitude. The events were recorded by the BPI stations at Welkom and the sampling interval is 0.2 magnitude units.

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