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ABSTRACT

In March 1977, a novel macroseismic system was installed above Rio Algom's Quirke Mine near Elliot Lake, Ontario Canada. To date, the system has measured in excess of 40 seismic events in the range of 0.7 to 2.3 M_N. Signal analysis of the captured events in both the time and frequency domain supports other evidence that an area of the mine has failed through to surface. Relationships between seismic energy and magnitude for events located close to the array are in close agreement with South African experience. Seismic moments determined for given magnitudes are generally lower than those obtained in South Africa, but agree with results from earthquakes in the Canadian Shield. Stress drop values are in line with those obtained elsewhere.

Key words: Rockbursts; Signal analysis; Source mechanisms.

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ANALYSE DES FORMES D'ONDES DES ÉPISODES SISMIQUES DUS À L'EXPLOITATION MINIÈRE ENREGISTRÉS DANS LA MINE QUIRKE DE LA RIO ALGOM

T. Semadeni*, P. Rochon* et J. Niewiadomski**

RÉSUMÉ

En mars 1977, un nouveau système macrosismique a été mis en place au-dessus de la mine Quirke de la Rio Algom près d'Elliot Lake (Ontario) Canada. Jusqu'à présent, le système a enregistré plus de 40 épisodes sismiques variant de 0,7 à 2,3 M_N. L'analyse des signaux pendant les épisodes captés à la fois dans le domaine du temps et dans le domaine de la fréquence appuie d'autres indications selon lesquelles une zone de la mine s'est effondrée depuis la surface. Les relations établies entre l'énergie sismique et la magnitude dans le cas des épisodes ayant eu lieu près du réseau de sismographes concordent bien avec les résultats obtenus en Afrique du Sud. Les moments sismiques déterminés pour des magnitudes données sont généralement inférieurs à ceux qui ont été obtenus en Afrique du Sud, mais ils concordent avec les résultats obtenus pour des séismes dans le Bouclier canadien. Les valeurs d'amortissement des contraintes concordent aussi avec les valeurs obtenues ailleurs.

Mots clés : Coups de toit; analyse des signaux; mécanismes relatifs à la source.

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INTRODUCTION

Rio Algom's Quirke II mine is located 15 km north of Elliot Lake, Ontario, Canada. Gently dipping uranium bearing quartz conglomerate reefs are mined using room-and-pillar methods approximately 500 m below surface. The progressive failure of a section of the mine has been well documented by Hedley (1984), and is shown in Figure 1. Observation of surface water in the area together with an attempt at diamond drilling confirms that the fracture zone has migrated to surface.

In March 1987, a macroseismic system, developed by Noranda under CANMET contract, was deployed on surface to measure the seismicity associated with the expanding failure zone. The sensors are located in shallow boreholes in an array which encompasses approximately 0.5 square kilometers (Figure 1). The monitoring system has been designed to record events in the range 0-2.5 M_N. Seismic waveform signals from these sensors are being analyzed to gain a better understanding of the causes and mechanisms of rockbursts, and to monitor the spread of seismic activity at both Quirke and Denison mines.

INSTRUMENTATION

The instrumentation used to monitor seismicity at Quirke Mine has been described by Labuc et al (1987). Briefly, it consisted of 5 triaxial ADR-711 (Kestle, 1983) accelerometers during the period March 1987 to June 1987, at which time a number of lightning strokes destroyed the sensors. The sensors were subsequently replaced with Geospace GS-40B 8 Hz geophones with a sensitivity of 0.27 V/cm/sec, and a case to coil motion capability of 0.18 cm.

Signals from the sensors are frequency modulated, multiplexed and sent along fibre optic links to a central location where the signal is converted from optical to electrical, demultiplexed, filtered and then digitized by a

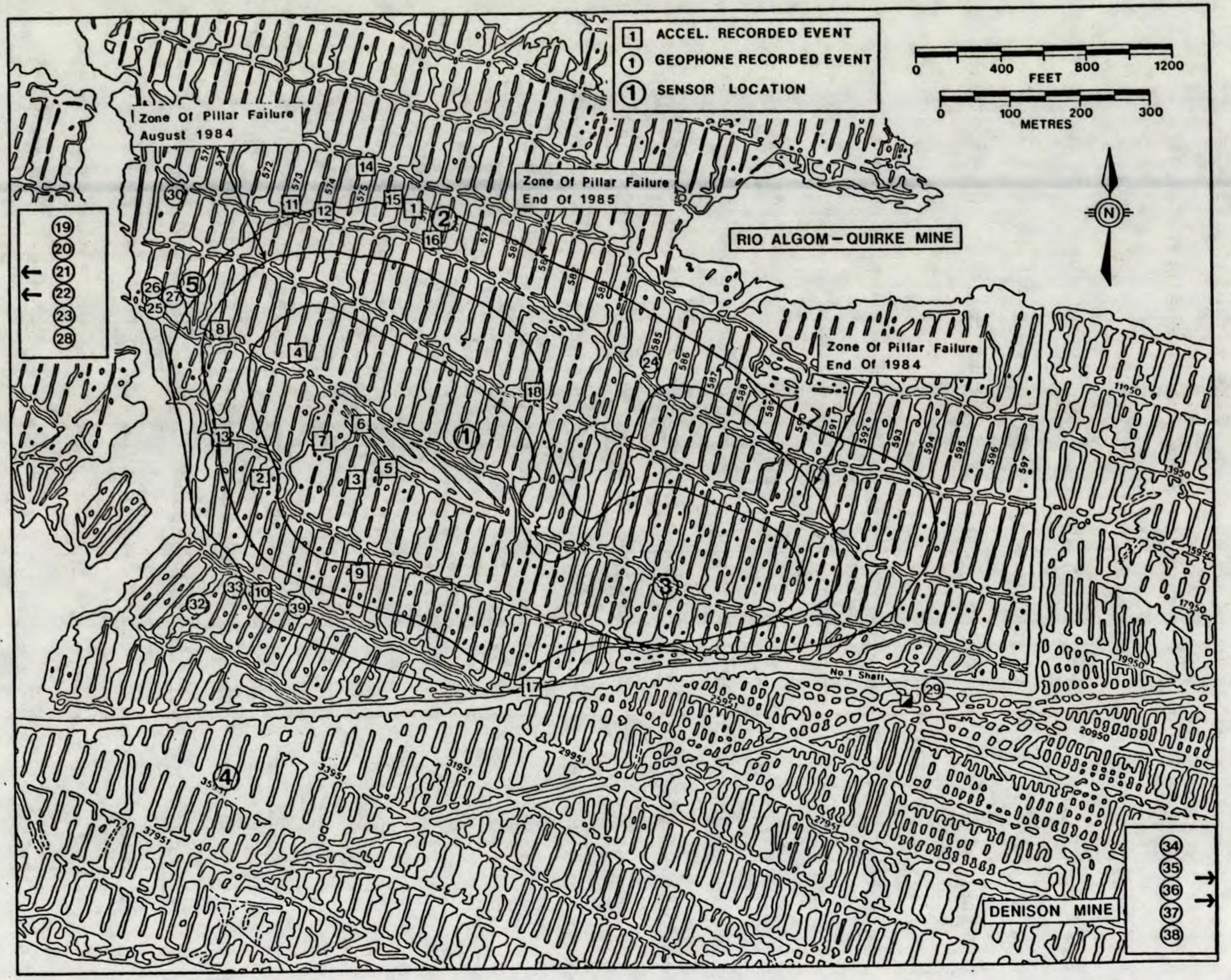


Fig. 1 - Plan view of Quirke Mine showing extent of failed zone, sensor and seismic event locations.

minicomputer at 1,000 points per sec for 0.8 sec, including an 0.2 sec pretrigger. Events are considered valid and are saved if 9 of the 15 channels (3 of 5 sites) exceed a preset trigger threshold. The 15 channels of data are then stored in ASCII format as one file to allow for later interactive analysis on the minicomputer. Time and frequency domain analysis of each channel can be effectively achieved using custom software developed in house.

Reference to magnitude is provided by the Eastern Canada Telemetered Network down to Nuttli magnitudes of 1.5, while a seismograph operated by CANMET eleven km away from the mine provides magnitudes down to 0.7 using an empirical scale developed by Rochon and Hedley (1987).

Event locations are determined using an ElectroLab MP-250 source location system operated by Quirke Mine. The vertical axes from the five surface sensors of the macroseismic system are in the process of being connected to the MP-250 to augment its underground array, thus increasing the accuracy of source location in the vertical direction.

DATA ANALYSIS

Digitized signals from each axis of each sensor were analyzed to determine parameters such as first motion, P- and S-wave arrivals, peak particle velocities and seismic energy. Following this, analysis of source parameters using the model of Brune (1970, 1971) was completed in the frequency domain. All analyses were done interactively using colour graphics with operator input from a mouse.

PEAK PARTICLE VELOCITIES

Peak particle velocities of measured seismic events have been analyzed by Hedley (1988). Results indicated that measured velocities were considerably lower than those measured in South African gold mines for comparable magnitudes and distances. Seismic signals were found to attenuate at a rate proportional to $R^{-1.6}$ as compared to $R^{-1.0}$ in South Africa. This was attributed to the fractured nature of the rock mass between the sources of seismic activity and the sensor array.

SEISMIC ENERGY

The energy radiated by a seismic source in the form of P- or S-waves is given by Cook (1964) as:

$$E_C = 4\Pi \rho C R^2 \int V_C{}^2 \, dt \qquad \text{Eq 1}$$

where, ρ = density (2700 kg/m^3)

C = α or β the compressional or shear wave velocity

R = distance from sensor to source

V_C = ground velocity of P- or S-wave.

If the measuring seismometers are oriented along mutually perpendicular axes, the total seismic energy may be computed as the sum of each component.

Due to the close proximity of most events to the sensor array, there was very little P- and S-wave separation and it was assumed that most of the energy would be contributed by the S-wave. The velocity term C was thus kept constant at 3.6 km/s during the summation of the complete waveform. The sum of energy in each of the components was determined to obtain an energy value for each site. Upon examination of these values, it became apparent that the energy values determined at each site varied widely for a given event. Site No. 1 generally reported high values, while site No. 2 generally reported low values. Results obtained at Site No. 1 remain unexplained. If anything, it was expected that Site No. 1 would produce low values due to being located directly above the failed zone. Site No. 2 may produce low values due to the fact that it is the only site to be located in a limestone rock unit. Sites located closest to the event generally reported higher energy values. These results indicate that the rock mass, through which the waveforms must propagate, deviated from the linearly elastic behaviour upon which Equation 1 is based.

Energy values shown in Table 1 were obtained as an average of energy determined at each site after the highest and lowest values were discarded. No energy values have been obtained as yet from accelerometer events due to inconsistencies encountered during integration. Seismic energy values are shown in Figure 2 as a function of magnitude M_N ($M_N = M_L + 0.3$). For comparison purposes, a line given by Gutenberg and Richter (1956) is plotted along with the results from this study. Results obtained from rockbursts by Spottiswoode and McGarr (1975) were found to lie along this line. Note that all data points from this study fall below the line. The relatively low energy values can be attributed to insufficient window length of 0.8 sec, which caused some of the waveform to be missed, and deviation from linearly elastic behaviour which caused attenuation. These assumptions are further supported if the data is grouped according to distance from the array. Events recorded from greater than 2,000 m away lie along a line of much flatter slope than events located closer to the array. The change in slope and intercept of the trend lines indicate that both attenuation and chopping of waveforms are occurring.

SEISMIC SOURCE PARAMETERS

Seismic source parameters were determined for shear waves of each event at each of the 5 stations, and on each axis of data. Thus, 15 values of corner frequency and plateau were determined for each event. Plateau values were combined as vector sums (McGarr et al. 1987) while corner frequencies were averaged to provide one number for each parameter at each site. Results considered to be valid for each site were then averaged to obtain final results. Using the final corner frequency and plateau values, source parameters such as seismic moment, source radius, and stress drop, were calculated for each event. These values are shown in Table 1.

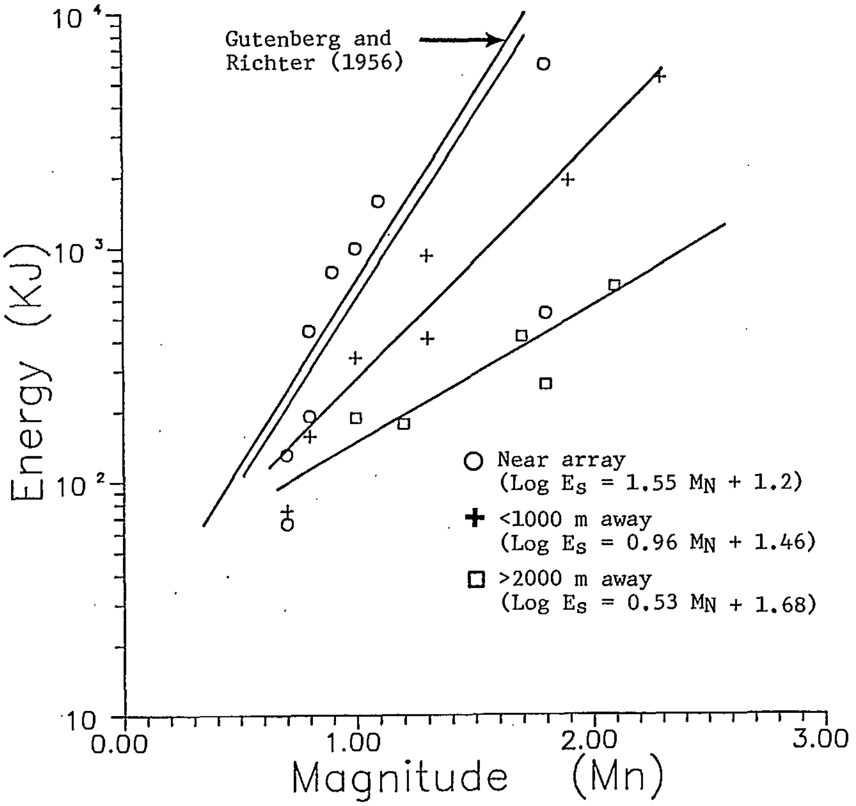


Fig. 2 - Effect of distance from a source to array on energy-magnitude relationship.

Table 1 - Summary of results of waveform analysis.
Events 1 through 18 recorded using accelerometers.

Event	Magnitude (M_N)	Energy (KJ)	Seismic Moment (GJ)	Corner Freq. (Hz)
1	0.7		72	28
2	1.1		330	23
3	1.2		415	25
4	0.7		95	23
5	1.4		615	25
6	0.7		100	23
7	1.7		663	22
8	0.8		367	23
9	0.7		114	25
10	0.8		230	25
11	0.7		191	25
12	0.8		450	21
13	0.7		230	29
14	1.1		265	26
15	0.7		54	26
16	0.7		64	24
17	0.8		200	23
18	1.0		350	25
19	0.8	155	168	32
20	1.9	1913	720	31
21	1.3	410	413	25
22	0.7	78	138	30
23	2.3	5200	2166	18
24	0.7	66	159	26
25	0.8	444	370	30
26	1.1	1570	296	33
27	0.8	190	296	29
28	1.0	340	334	30
29	1.3	920	588	25
30	1.0	995	516	25
31	2.1	680	800	19
32	1.8	5975	1108	25
33	0.7	130	190	25
34	1.7	417	526	21
35	1.2	176	314	17
36	1.8	520	786	14
37	1.0	188	310	16
38	1.8	260	339	19
39	0.9	790	566	24

Pertinent equations and an example of a waveform, and its associated spectral density are shown in Figure 3.

Figure 4a presents a plot of seismic moment versus corner frequency. Contour lines of constant stress drops of 100 kPa, 500 kPa, and 5,000 kPa were generated by combining Equations 2 and 3 from Figure 2 to yield:

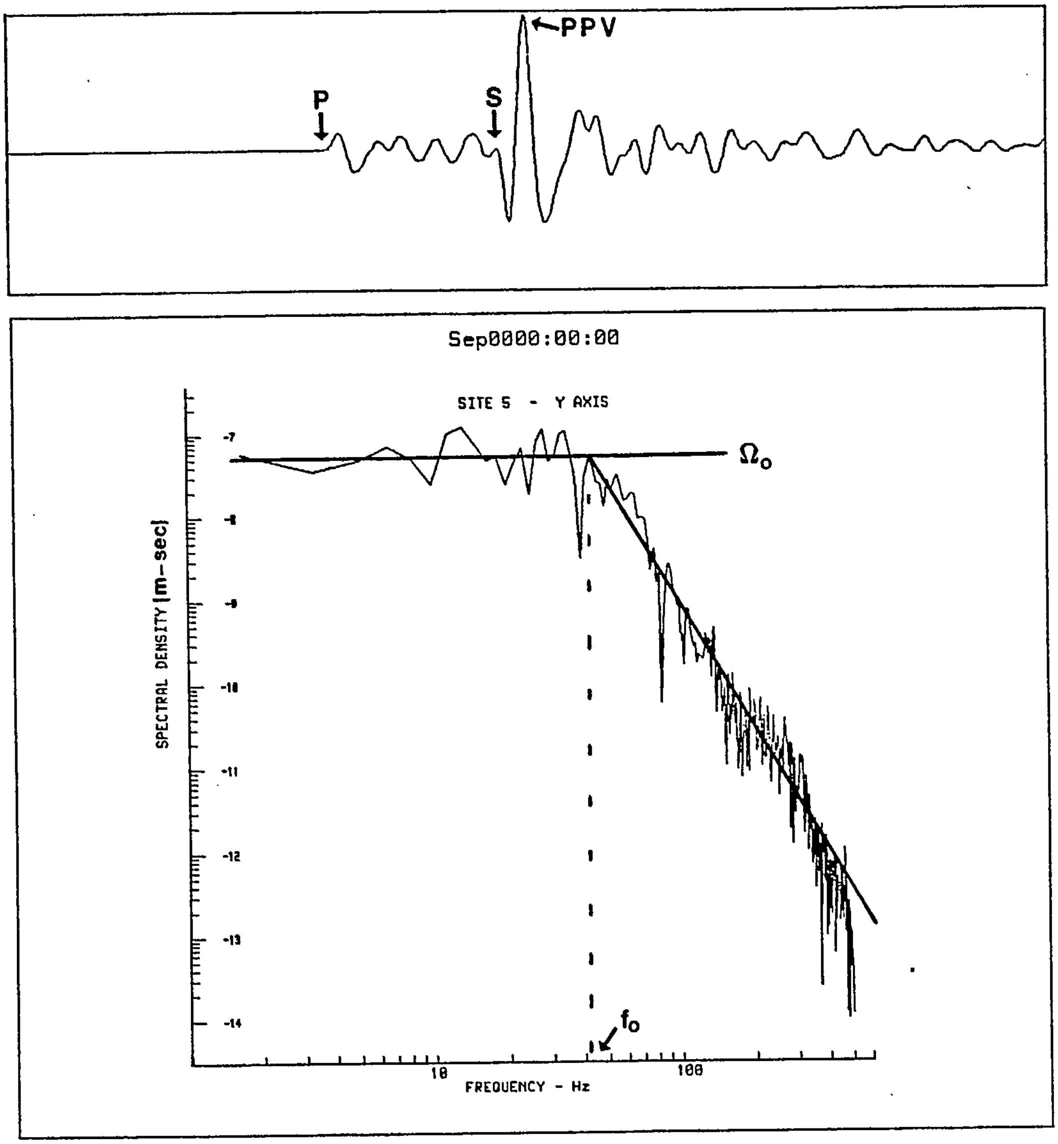
$$\text{Log Mo} = \log \frac{16}{7} \Delta\sigma - 3 \text{ Log } \frac{2\Pi fo}{2.34\beta} \qquad \text{Eq 2}$$

Hanks (1977) in analysing earthquakes originating from Southern California, determined that the vast majority of earthquakes yielded stress drops in the range of 100-100,000 kPa, and that there was no consistent variation of stress drop with seismic moment. These results were obtained for Mo values in the range of 2×10^2 to 2×10^{11} GJ.

McGarr et al. (1981) and Spottiswoode and McGarr (1975) present source parameter results for a number of mine tremors at the ERPM Mine in South Africa. For any given Mo value in the range of 10^1 to 10^5 GJ, most events fell between constant stress drop lines of 500 kPa and 5,000 kPa.

Our results for Mo between 2×10^1 to 2×10^3 GJ are in agreement with the aforementioned earthquake results, but deviate from South African experience in that a number of events yielded stress drops of less than 500 kPa, but greater than 100 kPA. These events are either events of low magnitude (approximately 0.7) produced from the failed zone, or were events produced at Denison Mine in excess of 2,000 m from the array. These data have probably been corrupted by propagation effects such as attenuation and scattering, to yield low corner frequency and plateau values.

Figure 4b presents results of plotting seismic moment versus magnitude. Hasegawa (1983) determined the illustrated trend line of Log Mo = 0.94 M + 1.32 from in excess of 100 seismic events occurring in eastern Canada in the magnitude range $0.9 \leq M_N \leq 4.2$. The best fit line through the present data is



Seismic Moment: $Mo = \dfrac{4\Pi C^3 \rho R\ \Omega_o}{Fc}$ Eq 1

Source Radius: $Ro = \dfrac{2.34\beta}{2\Pi fo}$ Eq 2

Stress Drop: $\Delta\sigma = \dfrac{7Mo}{16ro^3}$ Eq 3

c = α or β the compressional, or shear wave velocity

ρ = density (2700 kg/m^3)

R = distance from sensor to source

Ωo = Spectral density plateau

Fc = radiation pattern factor = (0.57)

fo = corner frequency

Fig. 3 - Typical waveform with associated displacement spectral density illustrating peak particle velocity, P- and S-wave arrival, first motion, corner frequency and plateau.

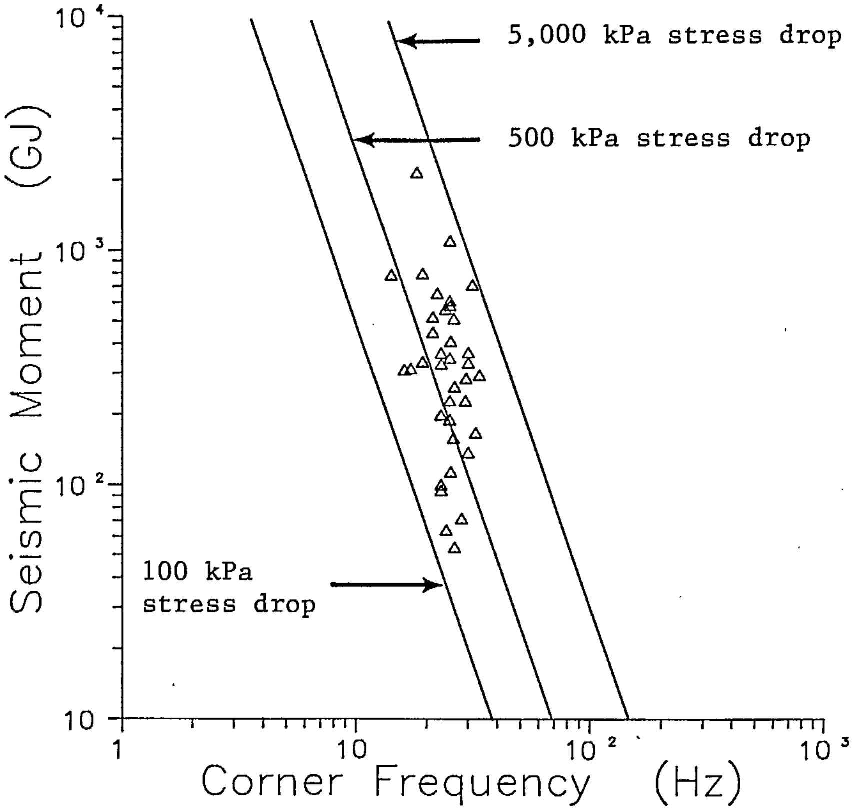


Fig. 4a - Lines of constant stress drop plotted on seismic moment versus corner frequency illustrate that all events fall between 100 kPa and 5,000 kPa stress drop.

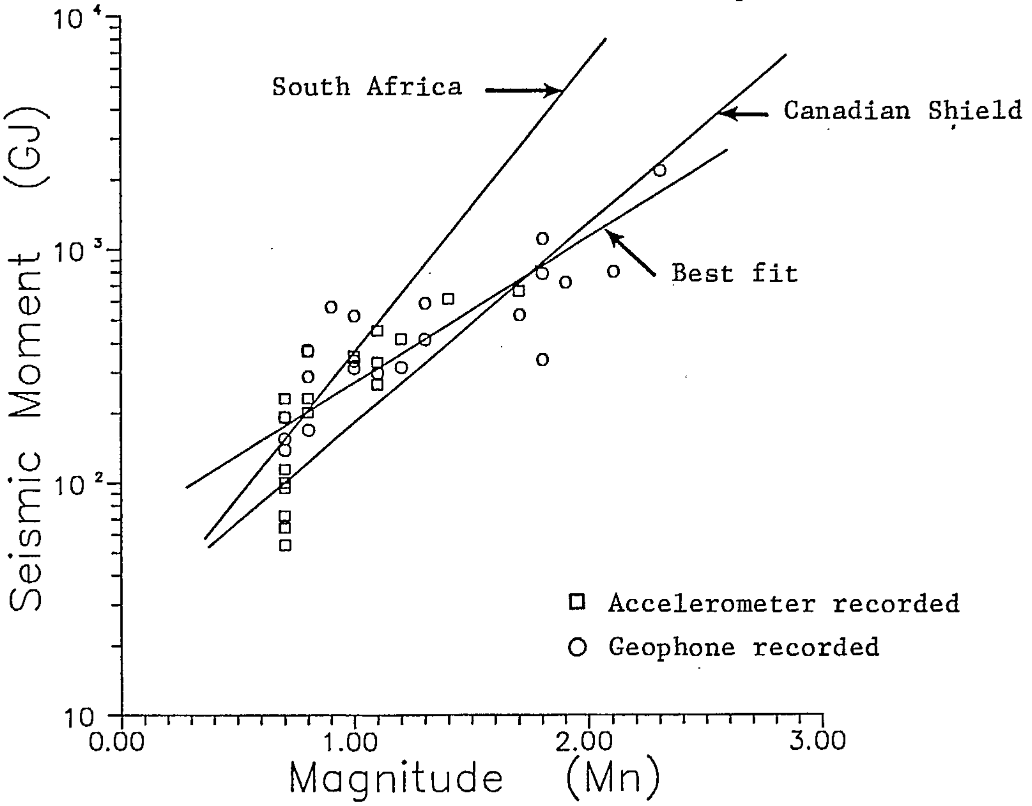


Fig. 4b - Seismic moment - magnitude relationship compared with South African gold mines and Canadian Shield results.

of lower slope and higher intercept (Log Mo = 0.62 M + 1.79), and reflects the insufficient time window of 0.8 sec. As magnitude increases so does event duration, and thus as magnitude increases error is introduced by the fixed 0.8 sec window. The effects of this error are seen in reduced plateau levels as some of the low frequency energy produced by the event is missed. For comparison purposes, South African results determined by Spottiswoode and McGarr (1975) are also shown.

CONCLUSIONS

The first of a series of macroseismic systems has been successfully installed at Rio Algom's Quirke II Mine near Elliot Lake, Ontario. Preliminary analyses indicate that results generally agree with those of previous workers. Any differences which do exist can be accounted for and are generally attributed to the fractured nature of the rock mass over the failed area of the mine and/or to insufficient digitizing window length. The window length is currently being increased to 1.5 sec to ensure that complete seismic waveforms will be recorded.

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