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Shengzao Chen
Elliot Lake Laboratory
January 1991

Mining Research Laboratory

CANMET Special Report
SP 91-2E

Cat. No. M38–15/91–2E
ISBN 0–662–19236–2

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Shengzao Chen*

ABSTRACT

A further analysis on source parameters for thirty-seven mining-induced seismic events at Quirke Mine, Elliot Lake, Ontario, has been carried out to study the self-similarity assumption in scaling law of seismic spectrum for mining-induced microearthquakes, and to understand the focal mechanism in the mine. Evidence from high P-wave energy in a ratio E_p/E_s of 5% to 30%, and about 80% of the events with E_s/E_p <10% support the statement that most of the events for the data set in the mine are most likely to be candidates for nondouble-couple focal mechanisms. They are also characterized by low stress release, especially low apparent stress under the limit of 0.2 $\Delta\sigma$, and a low total seismic energy. For the same seismic moment, the total energy values vary within a range of 10 KPa to 200 KPa of apparent stress, which agrees with data from the Heinrich Robert Mine in Germany. Also it is found that the Gutenberg-Richter energy evaluation fits very well with the combined data set of magnitudes for Quirke Mine (0.7 to 2.3 Mn), and for Heinrich Robert Mine (1.2 to 2.3 M_L). For the same total seismic energy, the apparent stress is limited by 80 GN.m and 800 GN.m of seismic moment. The observed stress drop is dependent on the seismic moment, which implies a breakdown in scaling law for events induced by mining. An analysis of peak particle velocity and acceleration presents the evidence for seismic attenuation over the fractured zone above the rockburst area in the mine.

Key words: Waveform analysis; Source parameters; Focal mechanism; Rockburst.

*Post Doctoral Fellow, Elliot Lake Laboratory, CANMET, Energy, Mines and Resources Canada, Elliot Lake, Ontario, visiting from State Seismological Bureau, China.

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INTRODUCTION

By means of waveform analysis and velocity inversion, we delineated the failure zone at the Quirke uranium mine in Elliot Lake, Ontario, which does not spread to the adjacent Denison Mine (Chen and Hedley, 1990; Chen, 1990). On comparing with the Heinrich Robert Mine (HRM) in Germany (Gibowicz et al., 1990), we found the possible existence of nondouble-couple mechanism rockbursts at Quirke Mine, and a geological interpretation has been made. Here we go deeper into the discussion of focal mechanism and the similarity assumption for microseismicity in the mine. More new scaling relationships on dynamic ground motion will be added.

Some authors have noticed the influence of the geological setting on stress drop magnitudes (Rautian et al., 1978), and have pointed out the importance of depth, and the role of the tectonic context in scaling relationships (McGarr, 1984, 1986). Feignier (in press) even emphasizes correcting for the geological and rock mechanics influence on source parameter magnitudes. The question is exactly how the corrections will be made, and this will be discussed in the following pages.

Alternatively, in my opinion, for the special purpose of studying geological and rock mechanics properties, we should not, and do not even have to, eliminate the effects which include anelastic attenuation, because it is these effects that reflect the real tectonic and mechanical features of rock mass in the rockburst area. Undoubtedly, if corrections could be made properly and completely, we should see smooth scaling relationships; for geological purposes, however, we will see nothing on the parameters. This looks the same as gravity inversion in which we use different processing methods for different purposes, e.g., for someone studying regional structures on a large scale, the local anomalies have to be removed; but for the purpose of local structure study, the local anomalies are needed.

The similarity assumption, defined by Aki (1967), emphasizes that small and large seismic events have the same rupture process. This implies a scaling law between the power of spectral density and fault size for earthquakes of various magnitudes. This relationship is assessed by stress drop evaluations which should be independent of seismic moment and source size if similarity holds. For large and moderate earthquakes, this feature has been verified by innumerable studies (e.g., Kanamori and Anderson, 1975), but for microearthquakes ($M < 3$) many departures from this relationship have been observed, showing a dependence of stress drops on seismic moments while the source size remains roughly constant (e.g., Fletcher et al., 1986; Dysart et al., 1988).

In Quirke Mine, mining-induced rockbursts took on a role of microseismicity, with magnitudes ranging from 0.7 to 2.3 Mn (Table 1). These data analyses are of critical significance in the discussion on the scaling law and focal mechanism of microearthquakes.

Table 1 - List of rockburst events in Quirke Mine
(Events 1 through 18 recorded using accelerometers)

Event (No.)	Date	Time	Magnitude (Mn)	Event (No.)	Date	Time	Magnitude (Mn)
1	27/03/87	00:01:05	0.7	20	28/08/87	03:35:00	1.6
2	16/04/87	18:26:06	1.1	21	28/08/87	07:40:51	1.4
3	17/04/87	14:39:56	1.2	22	28/08/87	07:53:48	0.8
4	17/04/87	15:27:59	0.7	23	29/08/87	07:46:55	2.3
5	18/04/87	02:51:50	1.4	24	04/09/87	15:36:07	0.8
6	19/04/87	07:19:05	0.7	25	05/09/87	19:03:07	0.9
7	19/04/87	09:41:17	1.7	26	06/09/87	07:58:33	1.2
8	25/04/87	13:04:27	0.8	27	06/09/87	07:59:20	0.9
9	26/04/87	23:50:41	0.7	28	09/09/87	06:22:28	1.2
10	29/04/87	01:13:24	0.8	29	08/10/87	17:04:06	1.4
11	02/05/87	15:47:27	0.7	30	15/10/87	00:50:53	1.1
12	02/05/87	16:58:45	0.8	31	24/11/87	07:16:55	2.1
13	06/05/87	04:48:34	0.7	32	24/11/87	18:45:45	1.8
14	07/05/87	20:06:14	1.1	33	24/11/87	18:50:46	0.8
15	07/05/87	20:47:54	0.7	34	29/11/87	07:29:29	1.8
16	09/05/87	07:33:01	0.7	35	18/12/87	23:51:14	1.9
17	17/05/87	05:44:26	0.8	36	19/12/87	09:43:07	1.0
18	21/05/87	17:46:38	1.0	37	09/12/87	22:03:24	1.7
19	28/08/87	01:07:54	0.9				

SEISMIC MOMENT AND SOURCE SIZE

The low frequency level (plateau) Ω_o of the spectrum is directly related to the seismic moment M_o:

$$M_o = \frac{4\pi\rho c^3 R\Omega_o}{F_c} \qquad \text{Eq 1}$$

where, $\Omega_o = \sqrt{\Omega_{SH}^2 + \Omega_{SV}^2}$ for S-waves, ρ is the density of the source material, c is either the P-wave velocity α, or the S-wave velocity β, R is the hypocentral distance, and F_c accounts for the radiation pattern of seismic waves. A free-surface correction was omitted. The constants in Equation 1 were chosen as $\rho = 2.7$ g/cm^3, $\alpha = 5940$ m/s, $\beta = 3600$ m/s, $F_\alpha = 0.39$, and $F_\beta = 0.57$ (Chen and Hedley, 1990).

For the 37 events shown in Table 1, we have $M_o^p = 0.93\ M_o^s$ which is close to 1, implying proper calculation for the moments, even though a few of the values for S-waves seem to be higher than those for P-waves.

Estimates of the source size are heavily model-dependent. The radius r_o of the circular fault is inversely proportional to the corner frequency f_o:

$$r_o = \frac{K_c c}{2\pi f_c} \qquad \text{Eq 2}$$

where, K_c is a constant dependent on the source model. In Quirke Mine seismicity studies, the source size has been estimated using Brune's (1970, 1971) and Trafunac's (1972) models for which $K_\beta = 2.34$, $K_\alpha = 1.97$. The ratio $r_o^p/r_o^s = 0.94$ which is close to 1 indicates more consistent results for r_o calculation from f_o^p and f_o^s, implying the accepted estimates for the corner frequencies.

Figure 1 shows the relationship between r_o^p and r_o^s for 37 events observed at 5 sites in the mine, and describes the variable values of about 15 to 120 m for P-waves, and around 30 to 90 m for S-waves. The average values from 5 sites for each event range from 32 to 104 m for P-waves, and 39 to 73 m for S-waves, respectively. Its average radius from P- and S-waves range from 45 to 90 m, which is less than those of 70 to 180 m from Heinrich Robert Coal Mine (HRM) in Germany (Gibowicz et al., 1990).

In source scaling relationships, describing the way the source dimension increases with increasing seismic moment, there is growing evidence of a breakdown in similarity for small earthquakes with a seismic moment below 10^4 to 10^5 GN.m, i.e., a marked decrease of stress drop with decreasing seismic moment (e.g., Hasegawa, 1983; Archuleta, 1986; Chun et al., 1989). Another manifestation of the apparent breakdown in similarity is the divergence of the scaling of peak acceleration and ground velocity from that expected from theoretical considerations following similarity relationships (McGarr, 1986).

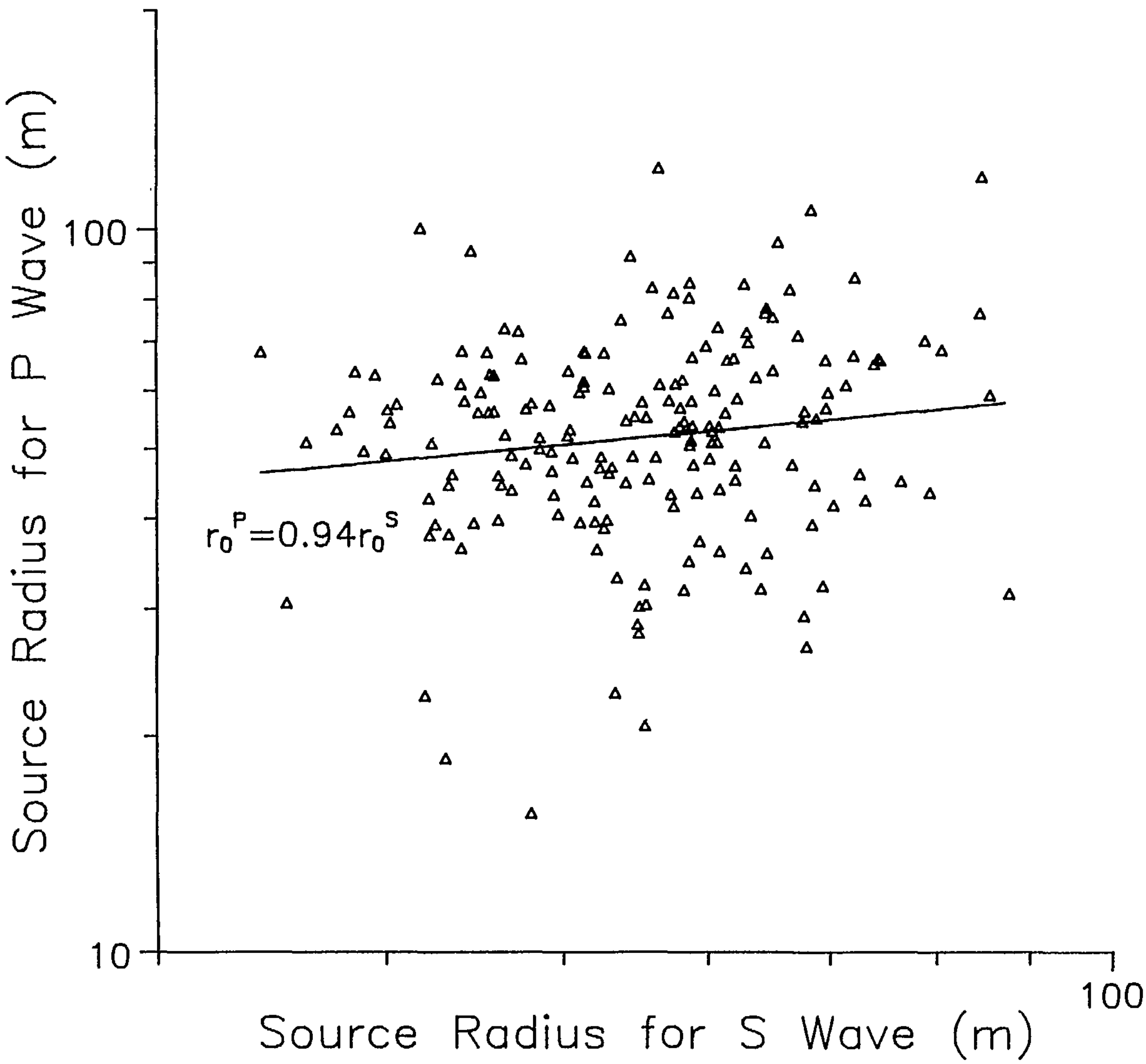

Fig. 1 - Source radius r_o^P versus r_o^S.

The evidence for scaling relations for our data set in Quirke Mine, shown in Figure 2, appears to be of the same nature with a smaller moment of 51 to 2022 (i.e., 10^1 to 10^3) GN.m., and also indicates that stress drop is moment-dependent. Seismic moment versus source radius is bounded by the contours of constant stress drop from 100 KPa to 5 MPa. This result is similar to that of the moment 10^2 to 10^3 GN.m from the HRM, a coal mine in the Ruhr Basin, Germany (Gibowicz et al., 1990), which is integrated into the same figure.

The most convincing evidence of the breakdown in the scaling relationships for small earthquakes can also be found from other studies of mining-induced seismicity. A stress drop decrease with decreasing seismic moment has been definitely observed for small mine tremors with the moment from 10^2 to 10^4 GN.m in the Polish copper mines (Gibowicz, 1985), and in the western deep level gold mines in South Africa (Bicknell and McGarr, 1988; Cichowicz et al., 1988).

Numerous studies ascribe this departure from similarity assumption to a source effect, involving either an upper limit to the radiated frequency, that is the presence of a characteristic fault length, or a dependence of stress on the seismic moment (e.g., Aki, 1987, 1988; Madariaga, 1987). Other authors explain the change in spectra scaling as anelastic attenuation effect, or any process that limits high frequencies, so-called bandwidth effect (e.g., Hanks, 1982; Fletcher et al., 1986). Boore (1986) has shown that a moment-independent filter that attenuates high frequencies, regardless of their origin, produces marked changes in the scaling expected from the usual analysis of self-similar models. In addition, a site effect was also pointed out to explain this phenomenon (Frankel, 1982; Malin et al., 1985; and Peppin, 1985).

In our case at Quirke Mine, the observed corner frequencies range well within the considered frequency bandwidth. The recorded pulses are simple and clear, signal-to-noise ratio is sufficiently high even for the smallest events, and the hypocentre distances are small. Therefore, source effects and attenuation effects seem to play the most important role in the present case. However, the attenuation is negligible due to the close proximity of most events to the sensor array (Semadeni et al., 1988), and the attenuation effects will be considered as a feature of the failure zone for the purpose of this paper.

SEISMIC ENERGY OF P- AND S-WAVES

The radiated seismic energy of either P-waves, Ep, or S-waves, Es, can be estimated directly from the integral J, expressing the energy flux of P- or S-waves:

$$E_c = \frac{4\pi\rho c R^2 J}{F_c^2} \qquad \text{Eq 3}$$

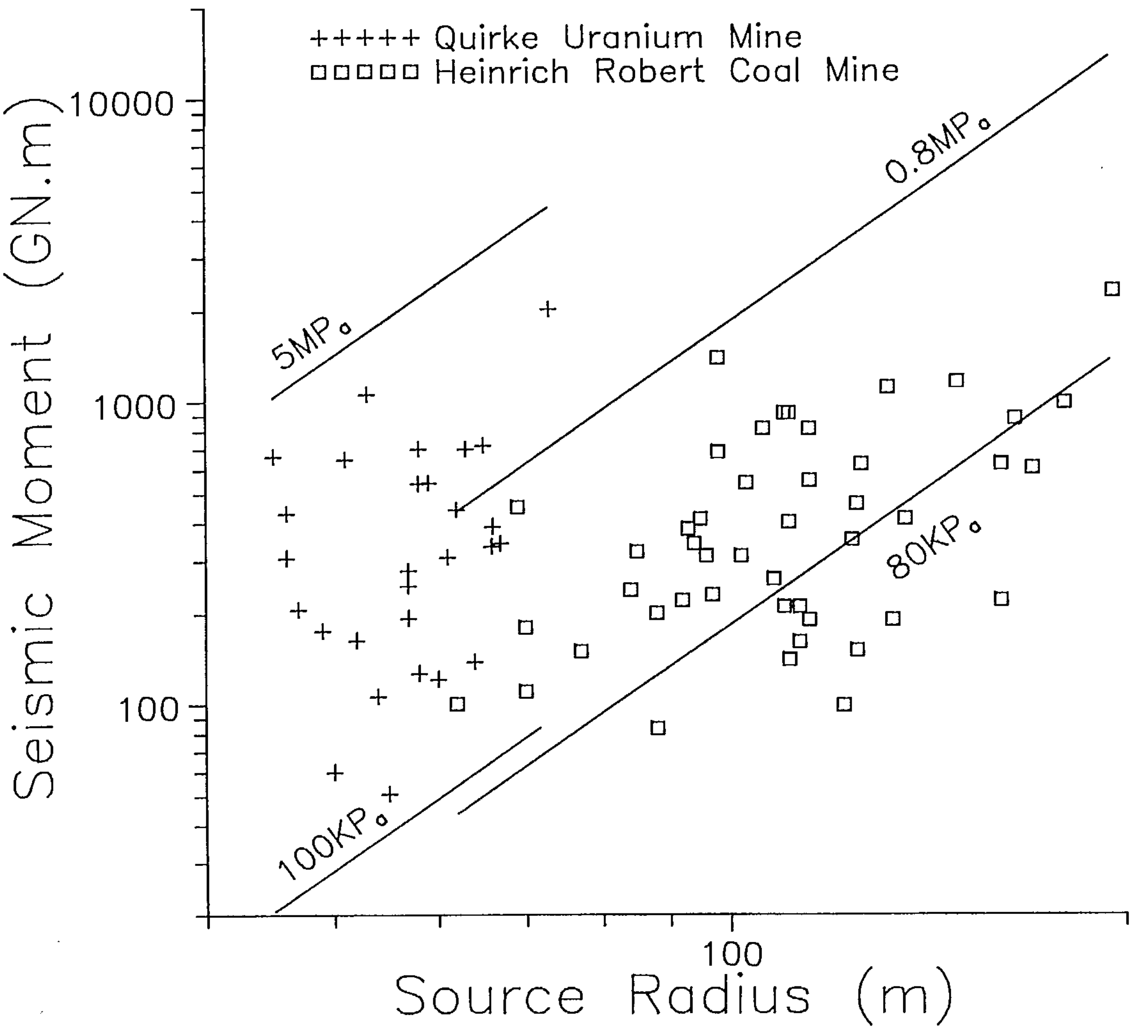

Fig. 2 - Seismic moment versus source radius. The straight lines show contours of constant stress drop.

where, $J = \int^{T} c\, V_c^2\, dt$, in which V_c is the ground velocity of P- or S-waves, c is α or β, i.e., P- or S-wave velocity.

The loss of energy from attenuation is accounted for in the calculation of the energy flux, even if it was ignored due to the close proximity of most events to the sensor array. If the measuring seismometers are oriented along mutually perpendicular axes, the total seismic energy may be computed as the sum of each component.

Figure 3 shows the relationship for E_p and E_s, where two contour lines of constant E_p/E_s ratios are measured at 5% and 30%. The ratio of S-wave to P-wave energy ranges from about 1.5 to 30. For 77% of twenty-six events at Quirke Mine, this ratio is less than 10; 19% are between 10 and 15. From a total of 37 events in Table 1, we have the percentages of 78% for $E_s/E_p < 10$, 14% for $E_s/E_p = 10$ to 15, 8% for E_s/E_p greater than 15. There are two unexplained too high ratios of 38 and 48 for events 16 and 15, respectively, which are close to site 2 at the north margin of the failure zone in the mine. Generally, the higher fraction of P-wave energy, and the high ratio of E_p/E_T, 22% (Chen and Hedley, 1990), are similar to those from the coal mine (HRM) in Germany (Gibowicz et al., 1990), where the ratio E_s/E_p ranges from 1.5 to 30, and two thirds of them are less than 10.

The total seismic energy (E_T) against seismic moment, shown in Figure 4, indicates that the energy values are bounded by lines of constant apparent stress of 10 KPa to 200 KPa, and therefore, the energy for a given seismic moment varies by a factor of 20. This result also agrees with that from Gibowicz et al. (1990), although the shear modulus μ is different at two mines, a higher μ value of 30 GPa for Quirke uranium mine being displayed. When modelling the distribution of E_T versus M_o at the coal mine in Germany, we find low values of μ of about 11 GPa, implying a different geological and mechanical background relative to Quirke Mine.

The Gutenberg-Richter seismic energy relationship, $\log E = 9.9 + 1.9\, M_L - 0.024\, M_L^2$ (Gutenberg and Richter, 1956) was used for energy evaluation in Figure 4. In some cases, this relationship provides highly underestimated values of the energy (e.g., Boatwright, 1984; Gibowicz et al., 1990). On combining our present result at Quirke Mine with that in the coal mine, as mentioned, these energy estimates fit in very well with those obtained by the Gutenberg-Richter relationship. This means the Gutenberg-Richter relationship could be covered by a wider range of magnitudes for rockbursts. As shown in Quirke Mine, the magnitudes range from 0.7 to 2.3 Mn, and in the coal mine from 1.2 to 2.3 M_L in the Richter magnitude scale, which are about 0.3 Mn higher than those in Nuttli's magnitude.

The evidence from natural earthquakes that the energy in P-waves is a small fraction of that in S-waves indicates the ratio E_s/E_p ranges between 20 and 30 (e.g., Boatwright et al., 1984). Although no systematic differences have been found so far between mining-induced events and natural earthquakes, and most

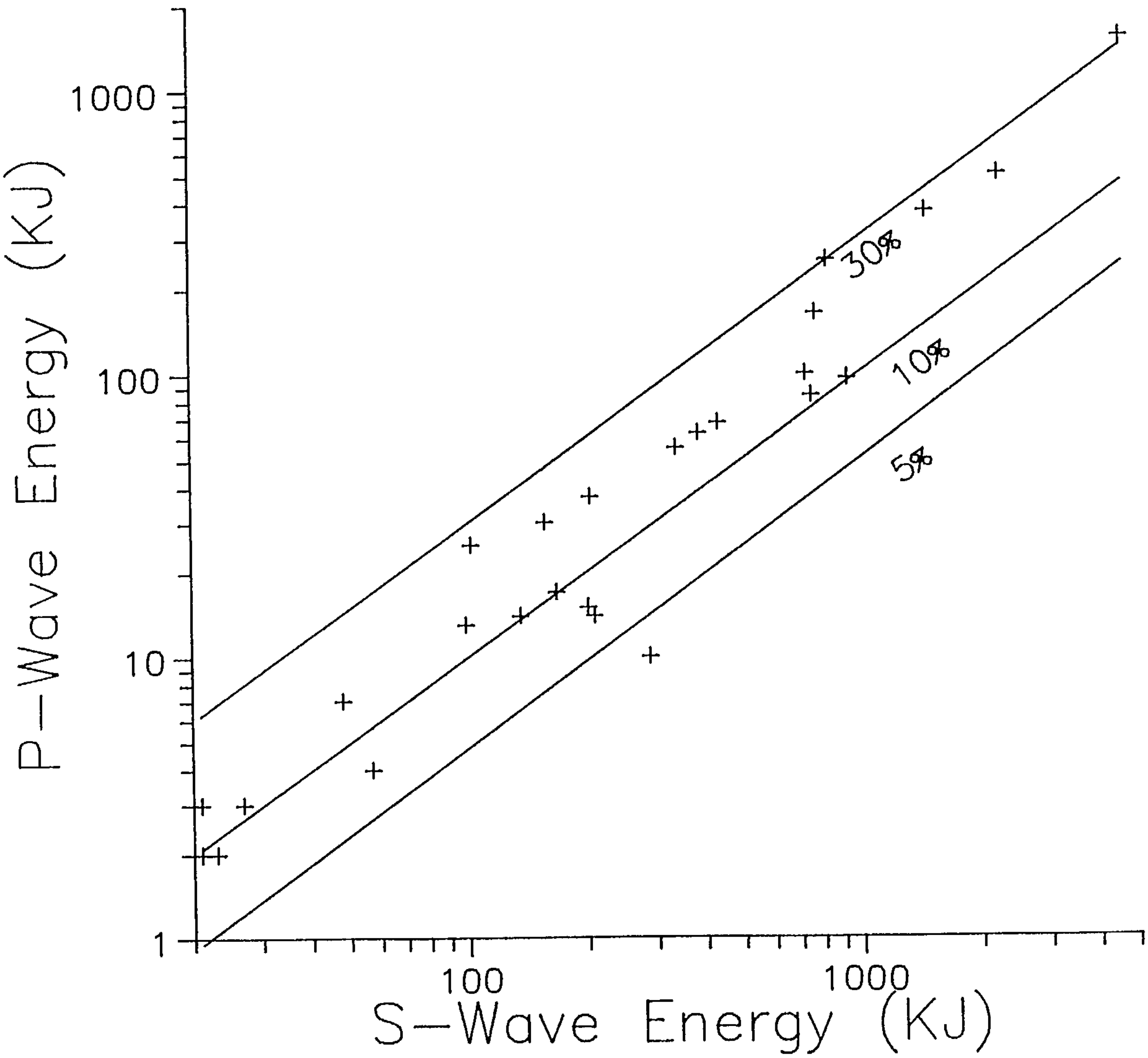

Fig. 3 - The relationship between P- and S-wave energy.

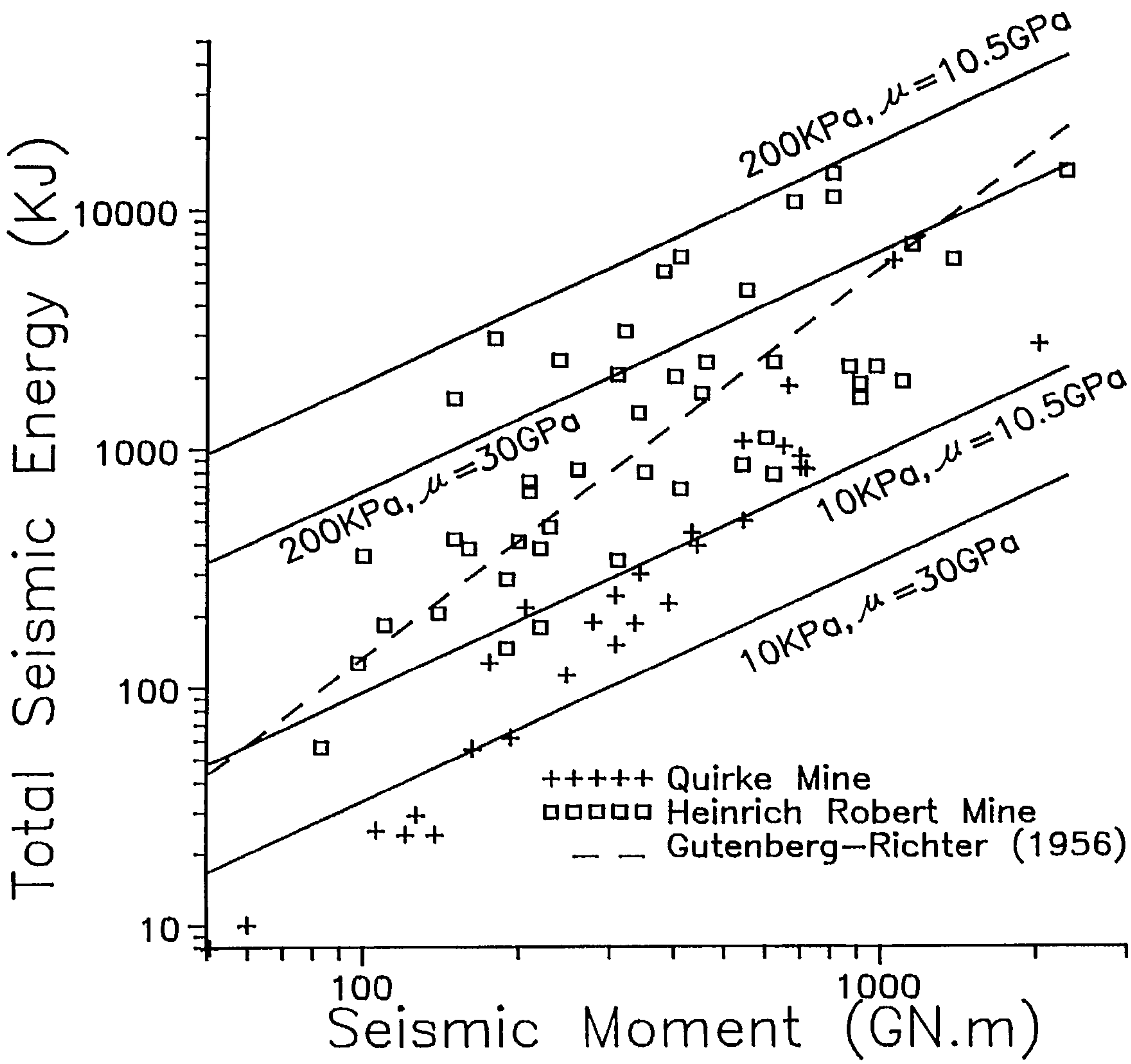

Fig. 4 - Seismic energy versus seismic moment. The lines of constant stress show the range of energy variation for a given seismic moment. The Gutenberg-Richter relation is indicated.

of what has been discovered about the mechanism of earthquakes can be applied to mine tremors, there is increasing evidence that other focal mechanisms than those of shear failure are possible (e.g., Rudajev et al., 1985). Compared with the report from the coal mine by Gibowicz et al. (1990), a similar conclusion could be drawn that the observed energy depletion in S-waves could possibly be explained by a nondouble-couple focal mechanism of some seismic events induced by mining, enriching the energy radiated in P-waves.

STRESS RELEASE ESTIMATES

Different estimates of stress release during earthquakes are in use at present. Two of them can be applied here: apparent stress, and the modified Brune (1970, 1971) stress drop, the so-called static stress drop.

Apparent stress can be expressed by:

$$\sigma_\alpha = \eta\bar{\sigma} = \frac{\mu E_q}{M_o} \qquad \text{Eq 4}$$

where μ is the modulus of rigidity at the source, η is the seismic efficiency, and $\bar{\sigma} = (\sigma_o + \sigma_1)/2$ is the average shear stress acting on the fault, i.e., efficient stress, in which σ_o and σ_1 are stress levels before and after the occurrence of an earthquake, respectively.
When a complete stress release is assumed, the stress drop can be calculated from the following relationship:

$$\Delta\sigma = \frac{7}{16}\frac{M_o}{r_o^3} \qquad \text{Eq 5}$$

which represents the uniform reduction in shear stress acting to produce seismic slip over the circular fault.

Figure 5 shows the apparent stress versus seismic energy, bounded by the lines of constant seismic moment in the range 80 GN.m to 800 GN.m, indicating a low apparent stress of no more than 200 KPa. For two data sets of E_s/E_p less than 10 and greater than 10, the apparent stress increases with seismic energy consistently at a slower rate than that expected from the contour lines of seismic moment. The best possible interpretation is that the seismic efficiency η, an undetermined but worth studying parameter, is actually smaller than usual because of the failure zone above the rockburst area in Quirke Mine, implying anelastic features of the fractured medium in the area.

The observed stress drop is dependent on the seismic moment within a limited range of source radius from 0.45 to 0.7 m (Figure 6). This clearly provides evidence for the breakdown in scaling relationships of self-similarity for small earthquakes, including some mining-induced seismic events in the mine.

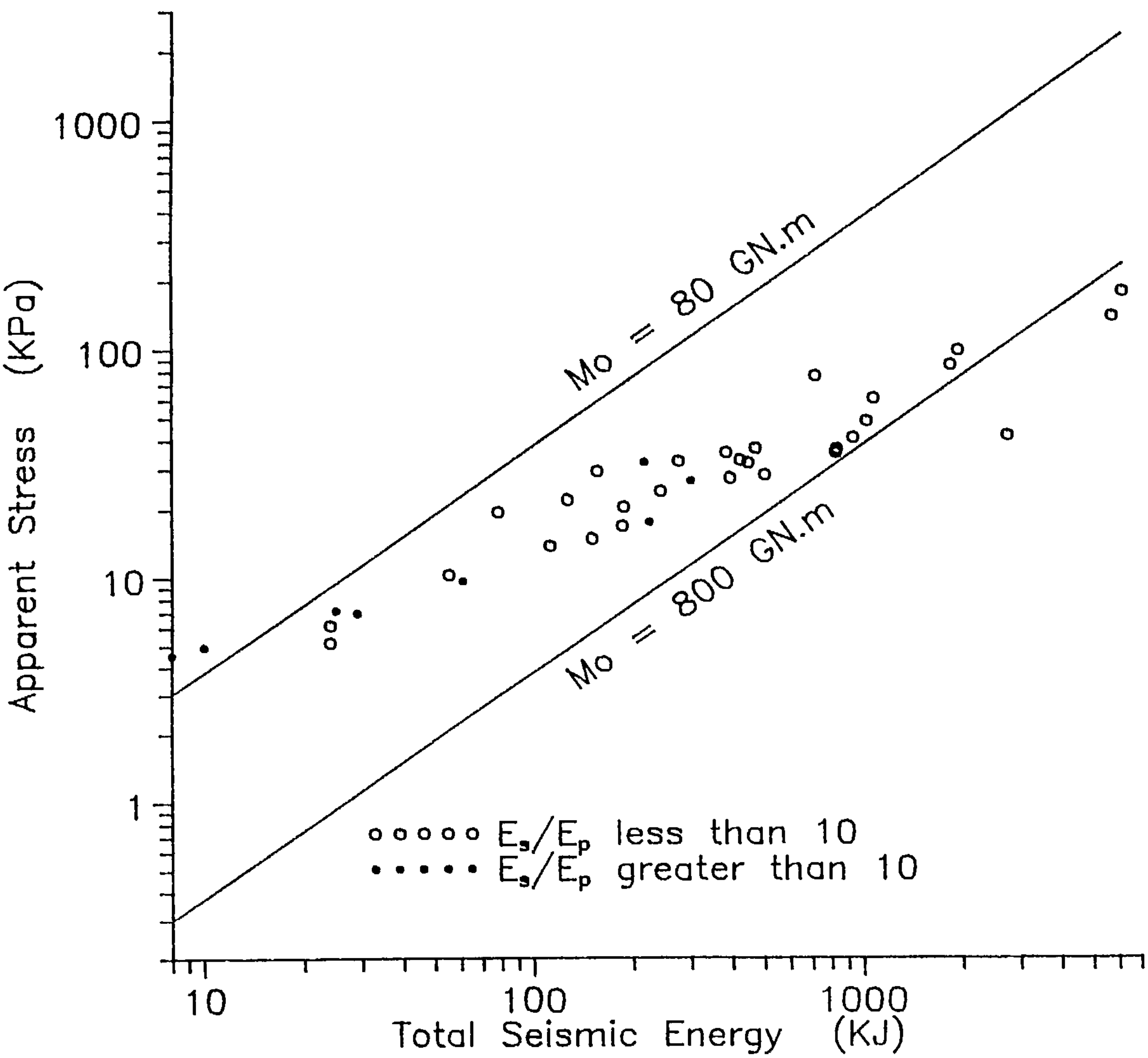

Fig. 5 - Apparent stress versus seismic energy, bounded by lines of constant seismic moment. Solid and open circles represent pure shear evens and those with a probable nondouble-couple mechanism, respectively.

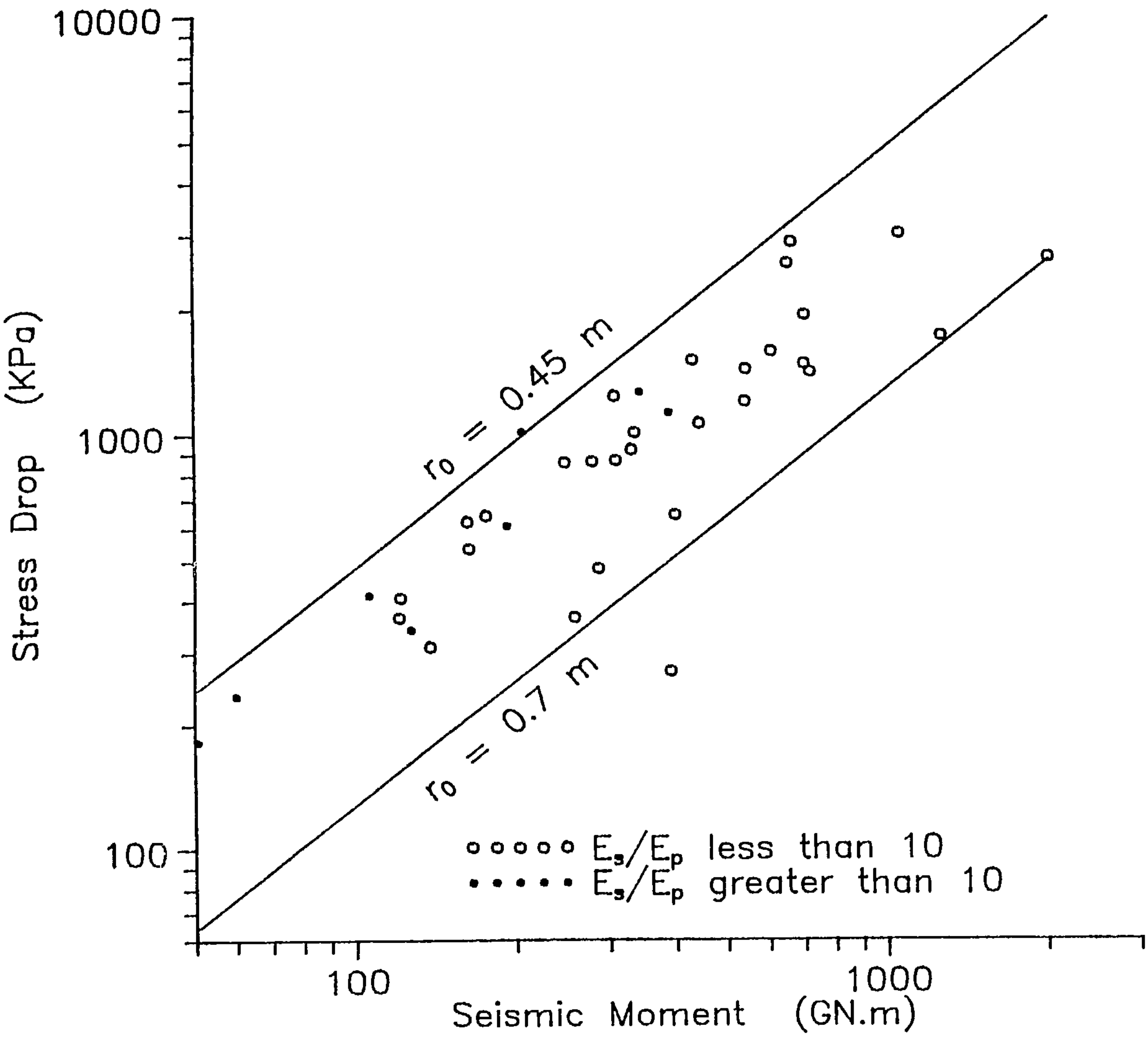

Fig. 6 - Stress drop versus seismic moment. The contour lines show constant source radii of 0.45 m and 0.7 m. For the open and solid circles see Figure 5.

In comparison with the values of stress drop, all rockburst events in Quirke Mine are characterized by low values of apparent stress. For the same stress drop, the apparent stress varies within a limit under 20%, bounded by the contour lines of 0.02 to 0.2 as shown in Figure 7. This relationship is in good agreement with one of two data sets in the coal mine in Germany, which has a low ratio of σ_α versus $\Delta\sigma$, about 8% (Gibowicz et al., 1990: Figure 14), and is the most likely candidate for nondouble-couple seismic events.

Most events marked by open circles in Figures 5, 6 and 7 appear to have high ratios of P-wave energy over S-wave energy, and are characterized by a low total seismic energy for the same magnitude. For example, the same magnitude 0.7 events 4 and 6, marked by open circles, have a total energy of only 24 KJ, while for event 13, marked by solid circles, the total energy approaches 216 KJ.

In the coal mine in Germany, the most possible nondouble-couple events also have constant high ratios of corner frequencies for P- and S-waves (Gibowicz et al., 1990). In Quirke Mine, however, this corresponding relation is not clear enough to make a distinguishing mark between the two data sets shown in Figures 5 to 7. The disagreements, on comparing with others, could be attributed to the fractured nature of rock mass over the rockburst area in Quirke Mine.

PEAK PARTICLE VELOCITY AND ACCELERATION

Peak particle velocities (PPV) and accelerations (PPA) from waveform analysis for the events in Quirke Mine (Table 1), show the same trend for P- and S-waves with a slope of about 0.54. When combined, this relationship is clearer (Figure 8).

The relationship between PPV, distance, and magnitude can be expressed by:

$$\mathrm{Log}(RV)_p = 0.71\ Mn - 1.65 \qquad \text{Eq 6}$$

for P-waves in the mine (Figure 9). Combined with the relationship for S-waves, i.e., $\mathrm{Log}(RV)_s = 0.60\ Mn - 1.33$ (Chen and Hedley, 1990), they were developed for assessing damaged rock mass in the rockburst area, which is representative not only of Quirke Mine, but also of the adjacent Denison Mine and Creighton and Strathcona mines in Northern Ontario (Hedley, 1988).

Elastic theory predicts that the attenuation of the peak particle velocity should decay with distance from the source at a rate of R^{-n}. Therefore, an alternative method of analysis for the relationship between PPV, magnitude (M), and distance (R) can be expressed by $\hat{V} = L\left(\frac{R}{10^{M/3}}\right)^n$, where L is a constant.

Hedley (1988) gave this function as:

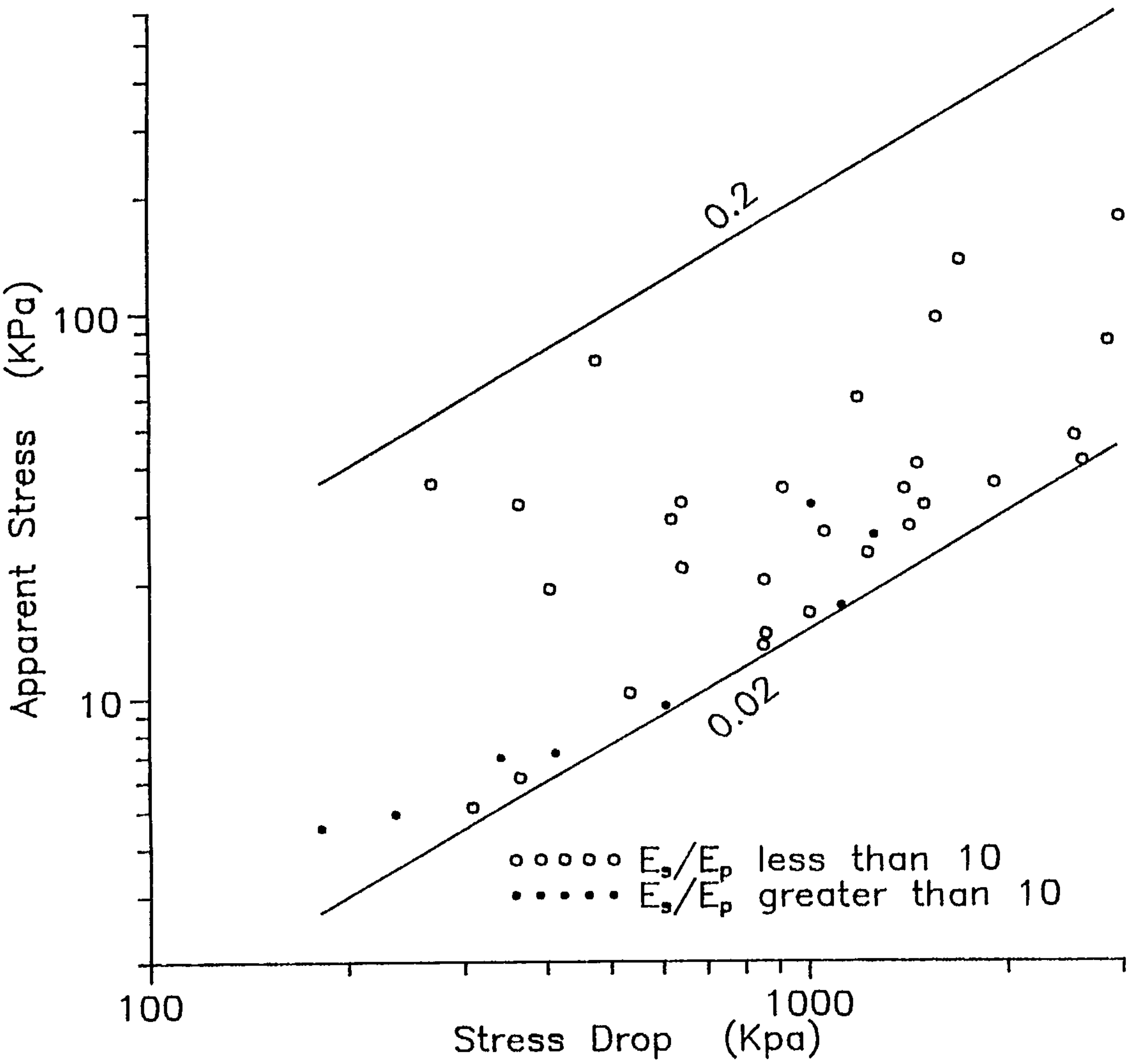

Fig. 7 - Apparent stress σ_α versus stress drop $\Delta\sigma$. The contour lines show the ratio $\sigma_\alpha/\Delta\sigma$. For the open and solid circles see Figure 5.

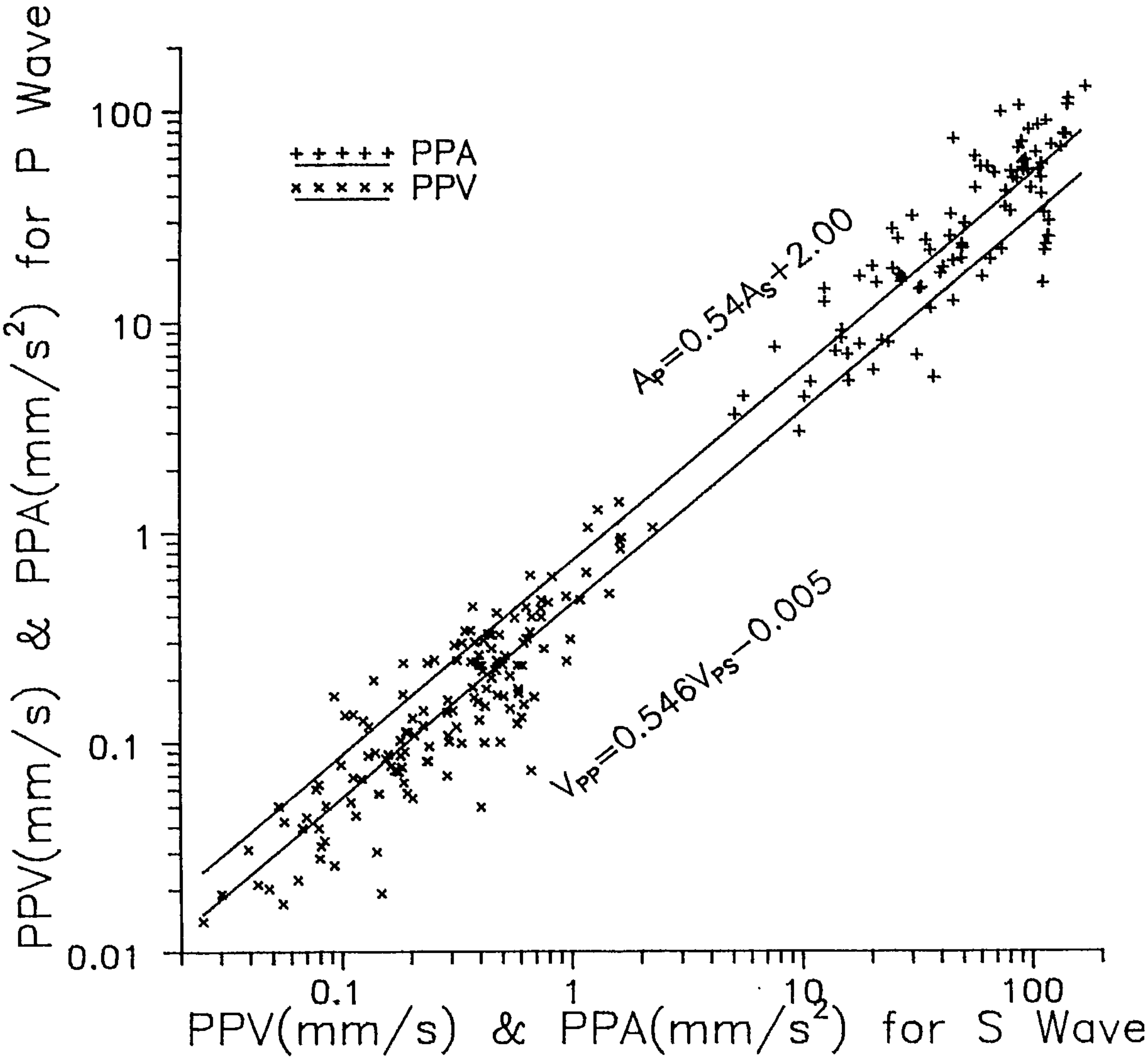

Fig. 8 - Peak particle velocities and accelerations for P- and S-waves.

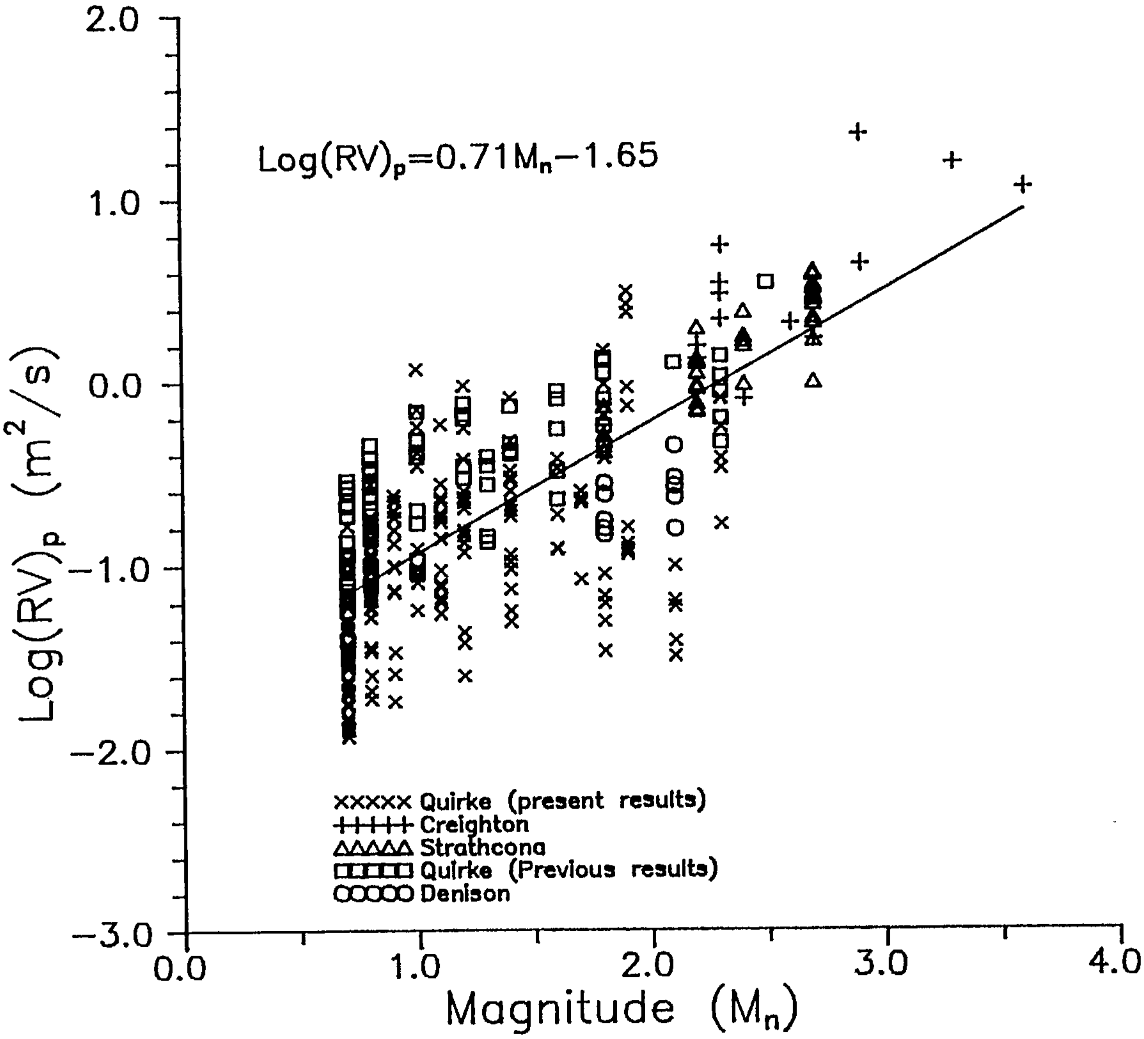

Fig. 9 - Scaled peak particle velocity as a function of rockburst magnitude, using a seismology format.

$$\hat{V} = 4000\left(\frac{R}{10^{M/3}}\right)^{-1.6} \qquad \text{Eq 7}$$

for the 25 events recorded at Quirke, Creighton and Denison mines. With the new PPV data presented here, this relationship is improved:

$$\hat{V} = 1823\left(\frac{R}{10^{M/3}}\right)^{-1.6} \qquad \text{Eq 8}$$

Figure 10 shows the peak particle velocity as a function of cube root scaled distance, which indicates the same attenuation factor of n = -1.6, only the constant L = 1823 is less than that in Equation 7.

At Quirke Mine, the hanging wall above the main rockburst area is extensively fractured through to surface (about 500 m at depth). Diamond drilling encountered a number of open cracks up to 15 cm wide which extend over a large area (Hedley, 1988). Measurement and analysis of the peak particle velocity and acceleration all provide evidence of seismic attenuation over the fractured zone above the rockburst area in the mine.

DISCUSSION

In physical definition, the seismic energy can be described as an integration, around the circular surface s_o enclosing the seismic source, of the energy flux from elastic seismic waves radiated during the duration of an earthquake (Koctpob, 1975).

$$E_q = -\int_0^{t_m} dt \int_{s_o} \tau_{ij} \dot{u}_i n_j ds \qquad \text{Eq 9}$$

where, t_m is the duration of the earthquake; τ_{ij} is the stress calculated from displacements of seismic waves using Hooke's law, indicating the difference between the variable stress tensor σ_{ij} and the initial stress tensor σ^o_{ij}, i.e., $\tau_{ij} = \sigma_{ij} - \sigma^o_{ij}$. This means that seismic energy is not individually dependent on σ^o_{ij} and σ^1_{ij}, but only on the variation of the stress tensor τ_{ij}.

In the calculation of Equation 9, waves reflected from the free surface of the earth are ignored, implying an assumption of infinite elastic medium of the earth. In the case of Quirke Mine, the fractured medium and anelastic attenuation will affect the energy values observed, resulting in lower values; even anelastic attenuation can be ignored at the shorter distances from events to sensor sites.

By the law of conservation of energy, ignoring the work of rock rupture for earthquakes, and assuming a mutual interaction between two surfaces of the fault, determined by frictional law, i.e., when the variation of σ_{ij} with time

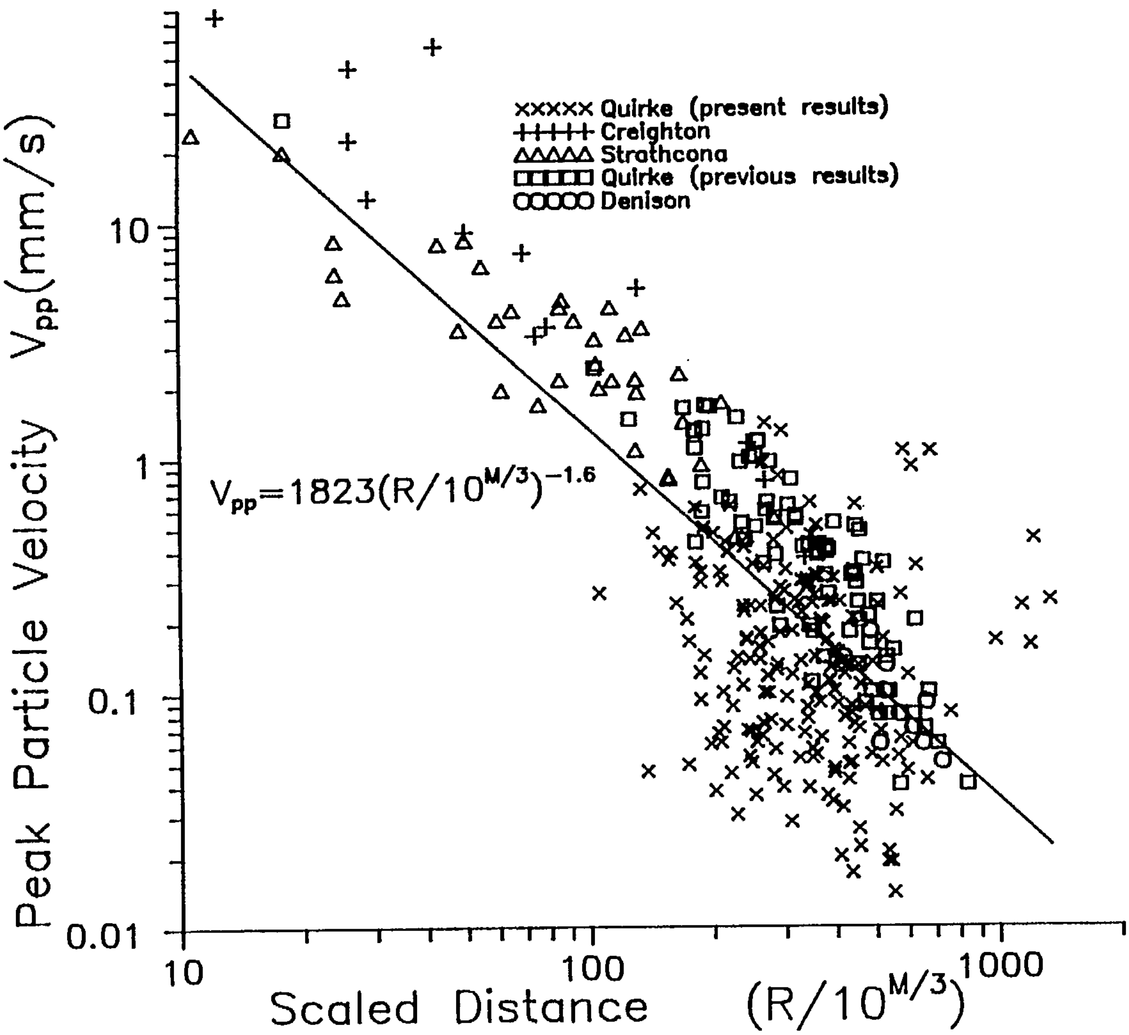

Fig. 10 - Peak particle velocity as a function of cube root scaled distance, using a blasting format.

is ignored, we can find an approximate equation for energy estimates,

$$E_q = \frac{1}{2\mu} \Delta\sigma M_o \qquad \text{Eq 10}$$

and, therefore, the apparent stress can be expressed by:

$$\sigma_\alpha = \eta\bar{\sigma} = \frac{1}{2} \Delta\sigma \qquad \text{Eq 11}$$

In this case the apparent stress is one half of the stress drop.

Actually, due to the microscopic inhomogeneity and non-smoothing on the surfaces of the fault, the stress on the fault should vary with time irregularly. In consideration with the loss of energy radiated from short-periodic waves, related to the radiational friction, and in using an average radiational friction stress expressed by the ratio of radiational loss versus seismic moment, the seismic energy can be written in the following form:

$$E_q = \frac{1}{\mu} (\frac{1}{2} \Delta\sigma - \sigma_r)M_o \qquad \text{Eq 12}$$

and, the apparent stress will be expressed by:

$$\eta\bar{\sigma} = \frac{1}{2} \Delta\sigma - \sigma_r \qquad \text{Eq 13}$$

where, σ_r is average frictional stress radiated.

From either of Equations 11 or 13, it can easily be seen that the apparent stress value is less than the stress release, or stress drop, and this difference is less than, or equal to, one half of the stress drop.

This analysis seems to be suitable in the case of Quirke Mine, where the low apparent stress under the contour line of 0.2 $\Delta\sigma$, as shown in Figure 7, implies a frictional stress in the amount of about 0.3 $\Delta\sigma$ if the shear mechanism could explain the events in the mine. However, the high ratio of P-wave energy over S-wave energy, lower total seismic energy, and an average high corner-frequency shift of 1.69 (Chen and Hedley, 1990), provides evidence that most of the events in Quirke Mine are likely to be candidates for nondouble-couple mechanisms in comparison with the coal mine in Germany (Gibowicz et al., 1990), even though some of the events show a smaller higher ratio of E_s/E_p as indicated in Figures 5 to 7.

I must emphasize the fractured properties in Quirke Mine, and recommend the use of observations on source parameters as an original characteristic of the failure zone. For this purpose, the corrections on geological or mechanical effects are not valid. In some cases, to reduce the scatter of source parameters in scaling relationships, the corrections have been done. Taking an average standard deviation of the whole data set as a reference, these referential values have been dedicated in a wide range, from 33% (Thatcher et al., 1973) to 50% (Tucker et al., 1973). In Feignier's (in press) result, this deviation is from 46% to 37.5% before and after the correction, with the same order of value magnitude. These larger deviations clearly show that it is extremely difficult to make a proper correction. More studies are still needed.

CONCLUSIONS

1. The stress drop observed in Quirke Mine is dependent on seismic moment, implying the breakdown in scaling relationships for small earthquakes, and especially for most of the mining-induced seismic events in the mine.

2. Higher ratio of P-wave energy versus S-wave energy (5%-30%), low stress release, and especially low apparent stress (under 0.2 $\Delta\sigma$) were common characteristics of all thirty-seven events at Quirke Mine in 1987. This reflects a specific anelastic feature of the fractured zone in the mine. An analysis of peak particle velocity and acceleration presents the evidence for seismic attenuation through the failure zone.

3. Evidence from further studies on source parameters supports the statement that the high P-wave energy events are probably events with a nondouble-couple focal mechanism. The descriptions of medium properties on procedure of earthquakes should be put in two ways, i.e., macroscopic smoothing, and microscopic inhomogeneity.

ACKNOWLEDGEMENTS

This paper was supervised by Dr. D.G.F. Hedley and Dr. R. Tervo. The author wishes to thank them and P. Rochon for reviewing the manuscript. M. Plouffe and all staff in the Laboratory are thanked for their cooperation. This study was funded by NSERC.

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