

# Measuring the size of mining-induced earthquakes: a proposal

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## ABSTRACT

The Richter or local magnitude scale ( $M_L$ ) has been used, with some modifications, to measure the size of earthquakes since 1935. It has long been recognised that this single-number representation of a multi-dimensional phenomenon is inadequate and cannot fully describe the energy released by an earthquake or the displacement caused by it. The high stresses encountered in deep South African gold mines induce numerous mining-related seismic events. Large databases of good quality data make it possible to identify and quantify the effect of various factors on estimates of the size of the events, principally source effects (various failure mechanisms), path effects (especially geological inhomogeneity), and the unequal radiation of energy with azimuth. We propose that three parameters that give insight into the damage potential should be routinely reported: (i) Area of the source ( $m^2$ ), which is easily derived from the relatively stable Moment parameter, (ii) Energy per unit area of the source ( $KJ/m^2$ ), derived from model-based source parameters, and (iii) Azimuth of strongest shaking (degrees).

**Key words:** Seismic magnitude, spectra and source parameters.

## INTRODUCTION

Earthquake magnitude is one of the most widely used parameters in seismological practice, but is particularly prone to misunderstanding, even by seismologists. In the eight decades since a local magnitude scale ( $M_L$ ) was proposed by Richter (1935), many other definitions have been offered, using a variety of wave types or features of the seismogram. However, none has received world-wide endorsement for routine use. The major international agencies continue to apply the tables and monograms of Gutenberg and Richter (1956), as recommended by the Committee on Magnitudes in 1967 (NMSOP, 2012). We believe the primary reason for this lack of consensus is that a single number magnitude remains inadequate in specifying completely the multi-faceted failure source of earthquakes.

Mining-induced seismicity generally occurs at depths shallower than 4 km and with  $M_L < 5.5$ . Most seismically-active mines are equipped with seismic monitoring systems with sensors located within 5 km of the hypocentre. The risk of damage or injury is greatest within 1 km of the source. The shaking produced by an  $M_L 2$  natural earthquake is barely perceptible on the surface as the source is typically several kilometres deep. However, a  $M_L 2$  mining-related event may cause severe damage to underground workings situated in or close to the near field. Therefore, the quantification of co-seismic deformation ( $M_c$ ) and energy ( $E$ ) of mining-related events requires more sensitive recording and analysis than is common for natural events.

## QUANTIFYING EARTHQUAKES

### Natural earthquakes

**Magnitude.** The seismic ‘magnitude scale’ was originally proposed by Charles Richter as a measure of the size of an earthquake independent of the place of observation. His method was based on a procedure suggested by Kiyoo Wadati of Japan, which measured the amplitude of earth motion as recorded on a seismogram (Richter, 1935). The Richter or local magnitude scale ( $M_L$ ) is defined as

$$M_L = \log A - \log A_0$$

where  $A$  is the maximum trace amplitude recorded at a given distance, and  $A_0$  is the zero magnitude at the same distance.  $A_0$  is calibrated to 1  $\mu m$  recorded on a standard seismograph located 100 km from the epicentre, with the zero arbitrarily fixed to fit the smallest earthquake recorded in 1935. Richter (1935) identified some limitations to his scale:

1. It was, strictly speaking, only “local” for southern California. It required the use of a Wood-Anderson short-period seismograph, and was only applicable for  $3 \leq M_L \leq 7$  at distances  $> 25$  km and source depths of about 15 km.
2. The mechanism of shock production is not always the same and could be a source of error;
3. Energy was radiated unequally with azimuth, depending on the strike and orientation of displacements. Changes in geological structures along the wave path added to inaccuracy.

4. A method with numbers that referred directly to shock energy measured in physical units would be preferable.

Many other magnitude scales were proposed (NMSOP, 2012), including:

Surface-wave magnitude:  $M_S = \log_{10}(A/T) + S$   
 Body-wave magnitude:  $m_b = \log_{10}(A/T) + S$   
 Unified magnitude:  $M = M_S - m_b = a(M_S - m_b)$   
 Duration magnitude:  $M_D = B \log_{10}(\tau) + CR + D$   
 Energy magnitude  $M_e = 2/3 \log_{10} E_S - 2.9$  and the  
 Energy relation  $\log E = 11.8 + 1.5M$

where  $A$  is maximum displacement in  $\mu\text{m}$ ,  $T$  is the period of displacement in seconds i.e.  $(A/T)$  is particle velocity,  $S$  is an empirical correction function for the depth of the event and hypocentral distance ( $R$ ) of the station,  $\tau$  is duration time,  $E_S$  is shear wave radiated energy,  $E$  is total radiated energy in ergs and  $B$ ,  $C$  and  $D$  are calibration parameters.

The South African National Seismograph Network uses the original Richter definition with constants calibrated for local conditions (Saunders, 2010):

$$M_L = \log_{10}(A) + 1.075 \log_{10}(R) + 0.00061R - 1.89 + S$$

**Frequency-magnitude relationship.** Gutenberg and Richter (1956) noted that there was a power law statistical relationship between the number of events and their magnitude,

$$N = 10^{a-bM}$$

where  $N$  is number of events having a magnitude  $>M$  and  $a$  and  $b$  are constants.

**Moment.** Aki (1966) proposed the use of scalar seismic moment  $M_0$  (Nm) to measure earthquake size:

$$M_0 = \mu AD$$

where  $\mu$  is rigidity,  $A$  is the area of fault rupture surface and  $D$  the average displacement.  $M_0$  is independent of the dynamics of the rupture process and measures the amount of slip on a fault and the size of the area that slipped.  $M_0$  is estimated from the low frequency limit of the displacement amplitude spectrum. Hanks and Kanamori (1979) defined the relationship between  $M_0$  and moment magnitude ( $M_W$ ):

$$M_W = 2/3 \log_{10} M_0 - 6$$

**Radiated energy and stress drop.** The frequency spectra of seismograms were also used to derive model-based calculations of radiated energy ( $E$ ) and stress drop ( $\Delta\sigma$ ), the most commonly used models are those of Brune (1970) and Madariaga (1976).

The above techniques continue to form the basis for the study of tectonic earthquakes and have been transferred to the study of mining-induced seismic events since no systematic differences had been found (McGarr, 1984). This includes estimations of magnitude, source parameters ( $M_0$ ,  $E$  and  $\Delta\sigma$ ), and statistical or probabilistic hazard quantification where fractal sets exhibit self-similarity (Gibowicz and Kijko, 1994).

## Mining-related earthquakes

**Magnitude.** Monitoring of induced seismicity in South Africa began in 1910, the first underground system installed in the 1950s, and the first permanent networks in the late 1960s. Generally, magnitude calculations have followed international trends. The advance of digital technology since the mid 1990s has led to an increase in the sensitivity of seismic monitoring, and the quantification of source parameters became routine. This has resulted in most South African mines now using a local magnitude  $M_L$  derived by a weighted average of  $M_W + M_e$ , as proposed by Gibowicz and Kijko (1994). Inconsistencies between magnitude and damage on South African mines and the recognition of multiple failure mechanisms prompted the use of regional calibration constants for the different mining districts. By 2004 the equations were as follows:

$$M_L = A \text{Log}(E) + B \text{Log}(M_0) - C$$

Carletonville:  $0.272 \log(E) + 0.393 \log(M_0) - 4.630$

Klerksdorp:  $0.263 \log(E) + 0.333 \log(M_0) - 3.612$

Welkom:  $0.275 \log(E) + 0.433 \log(M_0) - 5.124$

The constants  $A$ ,  $B$  and  $C$  were later changed to:

$$M_L = 0.344 \log(E) + 0.516 \log(M_0) - 6.57$$

for application in all of the mining areas. They are currently used by a number of mines using the IMS system, including all of the mines in the study area (Stankiewicz, pers. com. 2011).

**Source and damage mechanisms.** Different failure mechanisms within mines have long been recognised. The Handbook on Rock Engineering Practice (Jager and Ryder, 1999) describes two main types of events ('crush' and 'shear'), and describes, in greater detail, various source mechanisms:

- Strain bursts - explosive failure of a few square meters of the "skin" of the excavation;
- Face parallel bursts - shear ruptures ahead of the stope face, events can be up to M 3 but usually less;
- Pillar or remnant bursts - dynamic failure of the pillar with magnitude from M 0.5 to M 2.5;
- Pillar foundation failure - creating a new shear ruptures with M generally  $< 3.5$ ;
- Slip on geological structures - such as faults and dykes. The magnitude can be up to M 5.

**Frequency-magnitude relation.** A bi-modal distribution was noted in Polish mines with a change in 'b' slope at about  $E > \log_{10} 7.5$  ( $\approx M 2.5$ ). It was suggested that this was the mixing of random variables generated by different mechanisms (Kijko et al, 1987). A similar change at about  $M_L > 2.6$  was also observed in Klerksdorp (Ebrahim-Trollope, 2001).

**E- $M_0$  relation.** A bi-modal distribution in the E- $M_0$  relation was observed in the Klerksdorp mining district. This was attributed to differences in the failure mechanisms: fracturing ( $M_L < 0.5$ ), and larger structural failure i.e. shear-ruptures (Ebrahim-Trollope, 1997).

Richardson and Jordan (2001) confirmed the  $E-M_0$  bimodal result in mines in the Carletonville district, and proposed two source models: (1) fracture events that nucleate under low normal stress with small process zones, and (2) events analogous to tectonic events that nucleate under near lithostatic normal stress, are friction controlled and characterised by process zones equal to critical patch size with a minimum magnitude of 0.

**Alternative measurements.** Over the past 30 years it has been shown that multiple emission sources and failure mechanisms exist and that these are reflected in seismic measurements. Therefore, they can be quantified seismically. In addition it was known that the effect of a  $M_L 2$  event in the Welkom mining district is significantly different to a  $M_L 2$  event in Klerksdorp or Carletonville, particularly in terms of type and severity of damage. A number of new proposals were put forward to quantify these differences:

- Violence Potential:  $V_{EM} = E/M_0$  where ( $V_{EM}$ ) is the potential violence of the event, ( $E$ ) is the energy released in Joules, and ( $M_0$ ) moment in (Mega Nm). (Burrows and Ebrahim-Trollope, 2004);
- Potency:  $P_s = 4\pi V_s R \Omega_0 / \Lambda_s$ : where  $\Omega_0$  - low frequency displacement spectrum,  $V$  - wave velocity,  $R$  - hypocentral distance and  $\Lambda$  - constants for P or S wave radiation pattern (Mendecki, 2005). Potency is essentially an alternate parameter to moment with SI units ( $m \cdot m^2$ ).

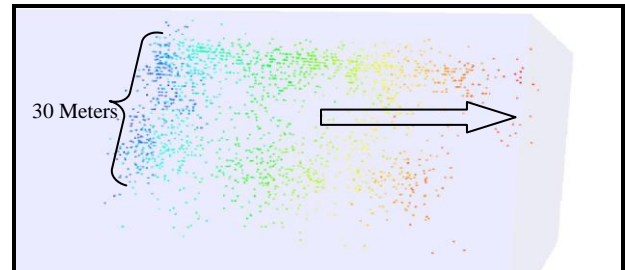
## SOURCE PARAMETERS AND FAILURE MECHANISMS

Ebrahim-Trollope is undertaking (as part of her PhD study) a systematic analysis of the relationship between source parameters derived from seismic measurements and the nature of the sources of seismic emissions (faults, pillars, abutments, tunnel development ends, etc), the physical failure mechanisms, and geological heterogeneities. This, in turn, impacts on all analyses that are based on source parameters. For example:

- Calculation of magnitude  $M_L$ ,
- Classification of hazardous structures,
- Statistical hazard assessment,
- Stability analysis, and
- Spatial and temporal changes in hazard.

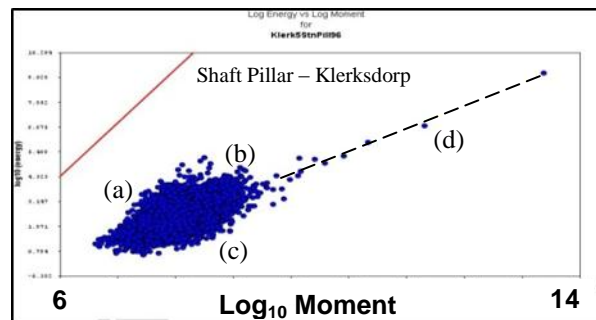
Harmony Gold Mining Company, operator of mines in all the major mining districts, have kindly made data available. All Harmony mines use the Institute of Mine Seismology (IMS) monitoring system. The monitoring sensitivity threshold in the study areas since 1995 is below  $M_L$  0.0 and in localised areas it is complete to  $M_L -2.0$ . Quality control consisted of ensuring the consistency of databases by recalculating and reprocessing data where necessary. The IMS processing and interpretation software produce between 6 and 20 parameters to describe the source. Some results are shown on Figures 1 to 5 and in Tables 1 to 3.

**Effect of geology.** A dense sensor network in the shaft pillar of a Klerksdorp mine allowed events to be located with sufficient accuracy to differentiate between fracturing in the hanging- and footwall (Figure 1). Slight differences in the  $E-M_0$  relation were ascribed to differences in the geology: the hangingwall consisted of siliceous to argillaceous quartzite, and the footwall of argillaceous to argillaceous conglomeratic quartzite.



**Figure 1: Section through a shaft pillar showing the seismicity associated with the development of a 50m tunnel (marked by the arrow) in a Klerksdorp mine. The events are colour-coded according to time, showing the advance of the tunnel from left to right.**

**Identification of emission sources.** Three sets of fracture events are identified (Figure 2). Ensembles (a) and (b) have lengths of between 5m to 10m and are restricted spatially and temporally. Set (c) is low energy small events with lengths  $<25m$ . These have been interpreted as secondary extension fractures and occur more randomly in time, though spatially in the same area. Set (d) is larger events on faults.



**Figure 2 Klerksdorp: 500 x 300 m<sub>2</sub> shaft pillar**

Figure 3 shows  $E-M_0$  plots for a Carletonville mine. Three ensembles of events were identified. A multimodal distribution is evident, with both upper and lower limits of  $E$  and  $M_0$  being recognised for each ensemble. These are interpreted as different emission sources and show both parallel and steeper slopes of  $E$  versus  $M_0$ . The parallel slopes could be indicative of similar rupture physics but different rupture velocities and consequently different radiated seismic energies. A code of practice for the area identified emission sources as:

- Fault slip i.e. secondary shear rupture of a previously ruptured surface, controlled by friction;
- (bi) Abutment failure, particular where the abutment is intersected by small faults, and occasionally pillar

foundation failure i.e. primary shear rupture controlled by both nucleation, fracture and friction with an implosive ‘crush’ component;

- (b-ii) Stope face bursts i.e. explosive events that are controlled by nucleation and fracture of intact rock;
- Fracturing of intact rock ahead of the face that is nucleation-controlled.

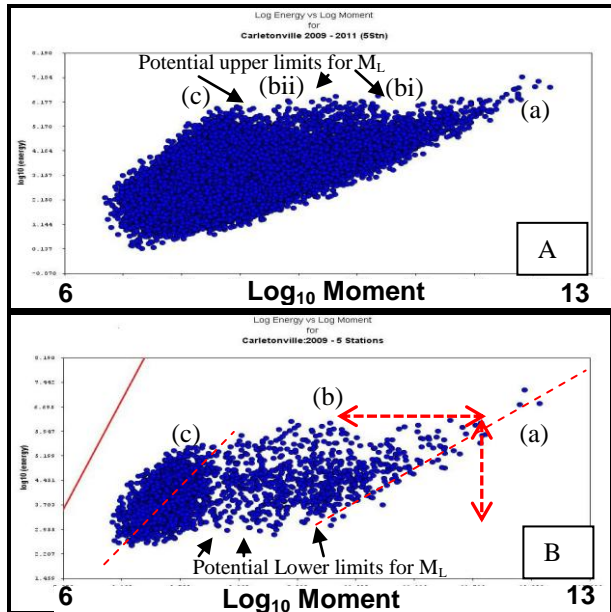


Figure 3: Carletonville Energy-Moment plot

**Self-similarity.** The high frequency spectral slope ( $f_c^{-\gamma}$ ) is indicative of self-similarity (Figure 4), which implies that stress drop and rupture velocity are constant, regardless of the size of the event i.e. the rupture process is constant. The shear rupture ensemble (a) and fracture of intact rock ensemble(c) (see Figure 3B) have slopes of  $f_c^{-3}$  and  $f_c^{-1}$ , respectively. Spottiswoode (1975) obtained a similar exponent for data from the Central Rand region. A spectral scaling of  $f_c^{-3}$  scales both  $M_0$  and  $E_R$  as  $x^3$ , thus scaled energy  $\bar{e} = E_R/M_0$  and will be constant (Walter et al., 2006). This example indicates self-similar behaviour within each ensemble, but not between them. Other results show similar slopes but with a constant shift.

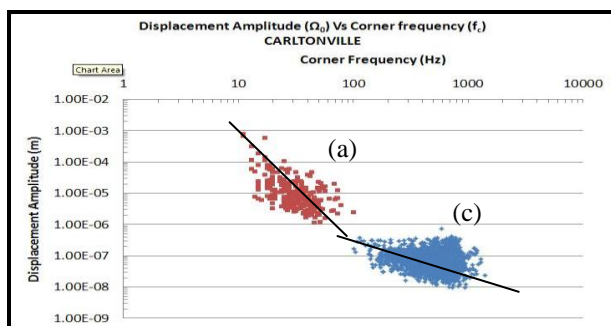


Figure 4: ( $\Omega_0$ ) versus ( $f_c$ ) for ensemble (a) and (c).

**Radiated energy.** The energy radiated along the length and over the area of the source for a  $M_L$  0.0 and 1.0

event from ensembles (a), (b) and (c) for the Welkom area is shown in Table 1. For comparison, note that the energy radiated by a  $M_L$  2.0 and  $M_L$  3.0 event from ensemble (a) is 2.29 KJ/m<sup>2</sup> and 18.2 KJ/m<sup>2</sup> respectively. It can be seen that the energy radiated by a  $M_L$  0.0 and 0.9 event from ensemble (c) is about the same as the energy radiated by a  $M_L$  2.0 and 3.0 from ensemble (a), respectively. While the total area that experiences severe shaking (and hence exposure to hazard) is much less for ensemble (b) than for ensembles (a), the potential hazard in the near field is significantly higher.

TABLE 1: Energy/Length (J/m) and Energy/Area (J/m<sup>2</sup>) for events with different source mechanisms

$M_L$ Ensemble	0.0 (a)	0.0 (b)	0.0 (c)	1.0 (a)	1.0 (b)	0.9 (c)
Energy Log <sub>10</sub> (J)	4.33	4.65	5.24	5.97	6.07	6.43
Length (m)	30	24	7.5	58	34	15.8
Area (m <sup>2</sup> )	707	452	44	2642	908	196
E/L (J/m)	0.71 KJ/m	1.7 KJ/m	23 KJ/m	16 KJ/m	35 KJ/m	171 KJ/m
E/A (J/m <sup>2</sup> )	0.030 KJ/m <sup>2</sup>	0.085 KJ/m <sup>2</sup>	4.0 KJ/m <sup>2</sup>	0.352 KJ/m <sup>2</sup>	1.5 KJ/m <sup>2</sup>	14 KJ/m <sup>2</sup>

Significant differences in the energy radiated per given moment for different ensembles (i.e. emission sources) are shown. Self-similarity ( $f_c^{-\gamma}$ ) may exist within a number of ensembles but at different energy levels i.e. parallel slopes. This is attributed to different emission sources having the same rupture process, but with significantly different energies radiated. The slope of  $f_c^{-1}$  for fracture events suggests a different failure process.

### ALTERNATIVE PROPOSAL TO A ONE DIMENSIONAL SEISMIC MAGNITUDE

Local magnitude  $M_L$  on most mines is based on the average of  $M_W$  and  $M_e$  i.e. size and energy magnitude. This averaging blurs the importance of each of these parameters and consequently the potential hazard they may pose. The current single number local magnitude is deemed inadequate for measuring the size of induced events that affect the near field. It is proposed that ‘Size’ be reported together with magnitude and that it be quantified in at least three–dimensions:

1. The source area (m<sup>2</sup> or km<sup>2</sup>).
2. The Energy radiated per square meter by the source (J/m<sup>2</sup> or KJ/m<sup>2</sup> or MJ/km<sup>2</sup>) and
3. The azimuth of the station recording maximum energy radiated and by how much this differs to the average. This aspect of the study has not been fully quantified yet and it is preliminarily added to the proposal.

For example, consider three events:  
 $M_L$  1.0; 2642 m<sup>2</sup>; 0.352 KJ/m<sup>2</sup>; 238° (x 5).  
 $M_L$  2.0; 7854 m<sup>2</sup>; 2.3KJ/m<sup>2</sup>; 38° (x 3.5).  
 $M_L$  0.9; 196 m<sup>2</sup>; 14 KJ/m<sup>2</sup>; 97° (x 4).

The parameters quantify: (1) how much rock is moving, (2) the average rate of energy being radiated, and (3) the direction of increased radiation. Two other parameters for routine reporting could also be considered: (4) source length, and (5) peak particle velocity (PPV) at, say, 100 m. The PPV-distance would have to be empirically derived for each region.

## CONCLUSIONS

Notable limitations of the magnitude scale identified by Richter are caused by: inhomogeneity of the propagation of waves (i.e. geology); different failure mechanisms; and azimuthal variations in energy radiation. They remain significant limitations 80 years on and are intrinsic of a single number quantification of a multi-faceted event.

With the current state of digital technology seismic source parameters and their derivatives are calculated routinely and almost real time. This makes a multi-dimensional quantification and routine reporting of the size of mining induced events easily achievable.

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