Effect of face fracturing on shear wave coda quality factor estimated from acoustic emission events

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ABSTRACT

The dependency of the quality factor derived from S wave coda (Q_c) on frequency is analysed in order to understand the effect of fracturing ahead of a mining stope. Micro seismic events recorded using acoustic emission sensors in a mining environment were used in the analysis. Acoustic emissions due to rock extraction were compared to those due to fault slip. The comparison is done by considering the ray paths of the two groups of events. The ray paths of the face events pass through fractured rock around the mining stope while those due to fault slip pass thought competent rock, away from active mining. Q_c was computed from averaging events from the two groups and normalising by the number of events. It was found that the Q_c dependency on frequency follows a power law. For face events, the power law is given by $Q(f) = 0.06f^{0.99}$ and $Q(f) = 0.003f^{1.58}$ for fault slip events. Q_c derived from face events was found to be lower than that derived from fault slip events. The degree of dependency which is given by the power law exponent was found to be lower for face events. The low dependency value is interpreted as the effect of fracturing ahead of the mining stope. The degree of dependency was found to be comparable to those found for natural earthquakes. This suggests scale invariance of the power law since the results obtained from acoustic emission events are comparable to those derived from natural earthquakes.

Key words: Acoustic emissions stope fracturing, S-wave coda quality factor.

INTRODUCTION

Ore deposits in South African gold mines are of a tabular nature. Although the rockmass deformation is largely elastic, stable and unstable fracturing around the deep stopes can be caused by the high stress concentrations ahead of the stope face. The stress concentrations result in characteristic patterns of fracturing (Figure 1, from Jager and Ryder, 1999) which have been recently studied in terms of their geometry and morphology (Van Aswegen and Stander, 2012). The face fracture development ahead of the stope face is associated with the generation of micro-seismicity. The fractures ahead of the stope act as scatteres of the seismic wave partitioning the energy into reflections and refractions which are recorded as coda waves. This process is a combination of intrinsic and scattering attenuation.

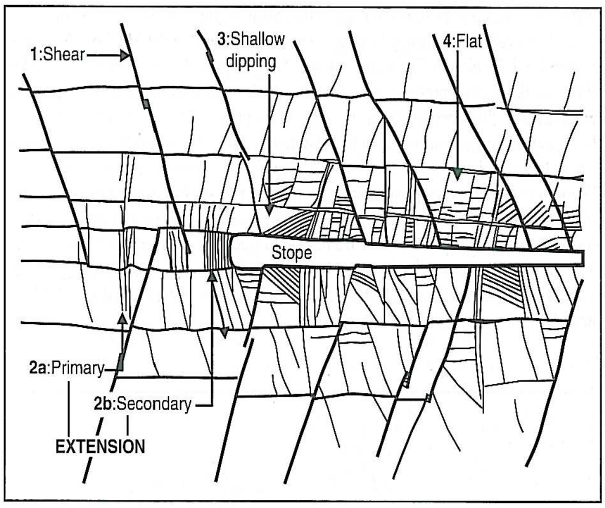

Figure 1. Characteristic fracturing around deep tabular stopes (from Jager and Ryder, 1999).

Scattering attenuation tends to shift energy from the main arrivals into the coda tail. Attenuation of the seismic waves is described by the dimensionless quantity *Q*, called the quality factor. The quality factor is a parameter which is frequency dependent and its dependency takes the form;

$$Q(f) = Q_0(f) f^n \quad (1)$$

where $Q_0(f)$ is a constant and *n* is the scaling exponent with values varying from 0.4 – 1.1 in the frequency range of 1 – 30 Hz (Ryder and Jager, 2002). *n* represents the degree of power law dependence. The high frequency dependency of micro seismicity associated with fracture development is analysed by evaluation of the decay of the shear wave coda (Q_c) with time.

METHOD AND RESULTS

Acoustic emission network of Cooke 4 shaft.

A network of Acoustic Emission (AE) sensors was deployed to monitor seismicity associated with fault slip and face fracturing. Mining at the level of the experimental site takes place at a depth of about 1000 m below surface where the shaft pillar is being extracted. The sensors are distributed in a 3-dimensional configuration around the Zebra fault to monitor seismicity associated with the fault slip. The network consists of 24 AE sensors covering 1 – 40 kHz and seven tri-axial accelerometers. Four of the seven accelerometers have a flat frequency response up to 25 kHz, while three have a flat frequency response up to 10 kHz.

Evaluation of Q_c

The amplitude spectrum of coda waves as a function of time is expressed by the following relation;

$$A(f) = A_0(f) t^{-1} \exp(-\pi f t / Q_c) \quad (2)$$

where $A_0(f)$ is the source spectrum, *f* is the frequency and *t* is the travel time. Q_c is evaluated by considering the regression fit through the coda decay envelope of a seismogram fitted at different frequency bands (Aki and Chouet, 1975).

In this work, the following procedure is used to estimate the dependency of Q_c on frequency:

1. Band pass filter raw seismograms using different centre frequencies f_c,
2. Extract S-coda from the band pass filtered seismograms and compute its envelope,
3. Apply a sliding window through the envelope. In each window, determine the time at the centre of the window t_c and the root mean square of the envelope,
4. Fit a linear regression through $\ln(A(f)t_c)$ *vs* t_c where the slope of the regression is given by $\pi f_c / Q_c$, and
5. Use the slope to estimate Q_c at f_c then average over many events.

Figure 2 (which is given at the end of the paper) shows an example of the raw trace and its band pass-filtered version. A centre frequency of 500Hz was used.

To evaluate Q_c and its frequency dependency, two types of event groups are considered and compared using an AE sensor (PL1201). The first group of events are those associated with the fracture development ahead of the stope face. The second group of events are those associated with fault slip on a fault plane. The two groups of events are characterised by their difference in ray paths. The fault slip events which are located away from mining excavations have their ray paths passing through competent rock. Ray paths of events locating in the fracture zone, on the other hand, pass thought highly fractured rock. Previous studies (Spottiswoode, 1993; Churcher, 1990; and Cichowicz and Green, 1989) have found much lower *Q* values in the fractured region ahead of the mining excavations.

The waveforms were band pass filtered with the following centre frequencies; f_c = 100 Hz, 200 Hz, 300 Hz, 400 Hz, 500 Hz, 600 Hz, 700 Hz, and 800 Hz. The frequency bands were $f_c \pm \Delta f$, where Δf = 50Hz. A 1ms S-coda windows were used. Within the coda window, a sliding window of 0.2 ms and a sliding increment of 0.05 ms was used. The effect of the coda window length was investigated by repeating the analysis using coda window lengths of 0.5 ms and 2 ms. The window lengths did not affect the results. Following the procedure outlined previously, the regression fits which had correlation coefficients less than 0.8 were rejected. The average magnitude and hypocentral distance of face events were -2.8 and 68 m respectively. For fault slip events, the average magnitude and hypocentral distance were -3.4 and 79 m. Since the Q_c values represent an average over a number of events, Q_c values are normalised by the number of events averaged. Tables 1 and 2 give the results obtained for face and fault slip events respectively. At higher centre frequencies the fault slip events were fewer. This is because these events had slightly complex S-coda resulting in some events being rejected by the correlation coefficient criterion.

Table 1. Normalised average Q_c values of face events with coda length of 1 ms at different centre frequencies.

# events	f_c(Hz)	average Q_c	stdQ_c	stderrQ_c
24	100	6.1	1.2	0.2
24	200	10.7	1.4	0.3
24	300	15.9	2.1	0.4
24	400	21.0	2.6	0.5
24	500	26.7	3.8	0.8
24	600	33.8	10.6	2.2
24	700	36.1	4.7	1.0
21	800	50.8	16.1	3.5

Table 2. Normalised average Q_c values of fault slip events with coda length of 1 ms at different centre frequencies.

# events	f_c(Hz)	average Q_c	std Q_c	stderr Q_c
23	100	6.4	0.8	0.2
26	200	12.1	4.7	0.9
24	300	19.0	6.4	1.3
20	400	32.7	12.1	2.7
19	500	53.0	22.1	5.1
14	600	82.0	43.0	11.5
13	700	130.2	84.8	23.5
12	800	154.1	87.2	25.2

Figures 2 and 3 show the relationship between Q_c and f_c for face and fault slip events respectively.

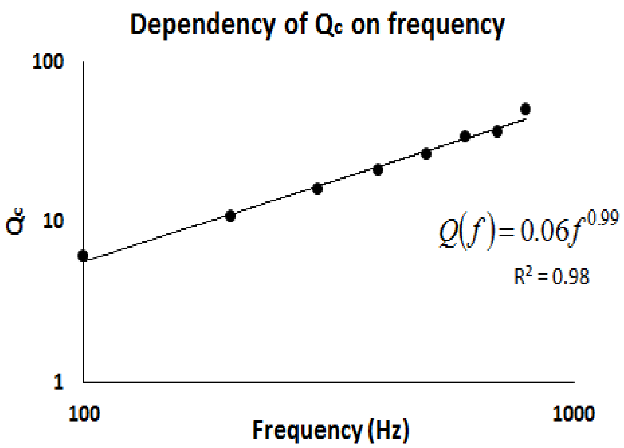

Figure 3. Dependency of Q_c on frequency for face events.

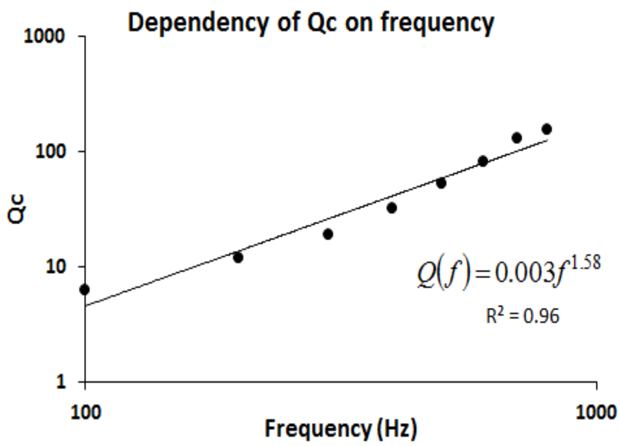

Figure 4. Dependency of Q_c on frequency for fault slip events.

The two figures suggest that Q_c has a power law dependency on frequency, as has been found by other studies of tectonic events (Brahma, 2012, Chung *et al*., 2009 and Mitchell, 1981). Analysis of the two groups of events shows a difference in the constant Q_0 and the degree of dependency n. The degree of dependency for face events was found to be $n = 0.99$, resulting in the relation: $Q(f)=0.06f^{0.99}$. For fault slip events, $n = 1.58$, resulting in the relation: $Q(f)=0.003f^{1.58}$. The lower degree of dependency suggests that fractures ahead of the stope face tend to reduce the dependency on frequency. In general the Q_c values for the face events were found to be lower than those obtained from the fault slip events.

The degree of dependency can be seen by noting the increase of Q_c with frequency for the two groups (Tables 2 and 3). The values of n that were obtained are similar to those obtained for natural earthquake studies (Brahma, 2012, Chung *et al*., 2009 and Mitchell, 1981). Obtaining similar results for n suggests a scale invariance of the power law frequency dependency.

CONCLUSIONS

The coda Q for shear waves was analysed for two groups of events. The first group was that of events in the fractured zone ahead of the stope face while the second group was that of events associated with fault slip. Normalised average Q_c values for both groups were found to follow a power law given by the relations: $Q(f)=0.06f^{0.99}$ and $Q(f)=0.003f^{1.58}$ for face and fault slip events respectively. Q_c values were found to be lower for face events. The lower degree of frequency dependency is attributed to the presence of fractures ahead on the mining stope. The difference in the Q_c values was found to increase with increasing frequency as a consequence of the different degree of dependency n. The similarity of n values of micro seismic events with other natural earthquake studies suggests scale invariance of the frequency dependency.

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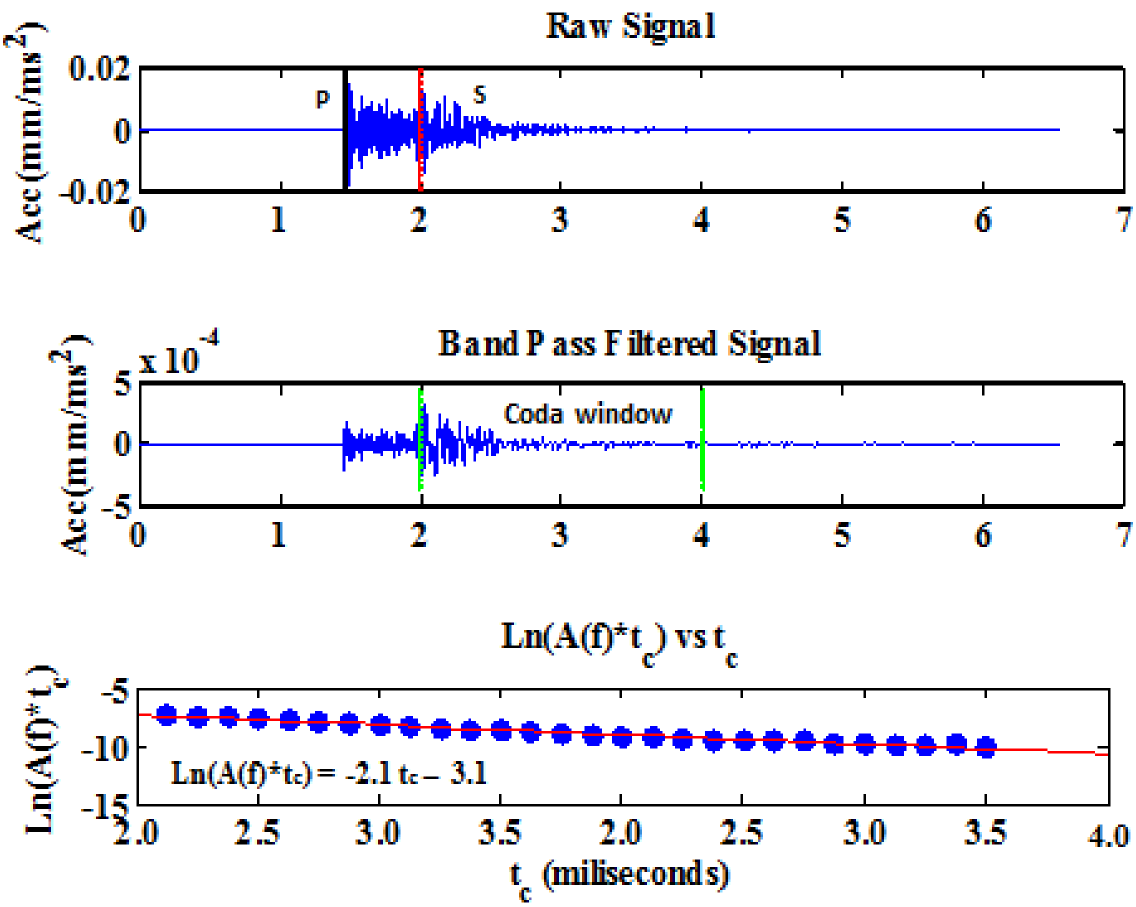

Figure 2. Raw trace with P and S arrivals shown (top). Band pass-filtered trace with a centre frequency of 500Hz. A 2ms S-coda window is also shown (middle). Linear regression fit (bottom).