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Effect of the Rock Properties on Mining-induced Seismicity Around the Ventersdorp Contact Reef, Witwatersrand Basin, South Africa

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Abstract—The Ventersdorp Contact Reef is characterised by a variety of different rock types that are found above and below the reef in different mining areas. These variations in the host rock type have been classified into six main geotechnical areas. Knowledge of the difference in seismicity related to these geotechnical areas could influence the design of deep level stopes and optimise the support systems.

In this study, the total seismicity was evaluated using the relationship between the cumulative seismic moment and volume of convergence. In total 300,000 seismic events, occurred at Deelkraal, Elandsrand, East Driefontein, Kloof and Leeudoorn mines. Kloof and Leeudoorn gold mines were divisions of Kloof Gold Mine Co. Ltd. Mponeng was previously called Western Deep Levels Ltd.-South Mine.

The seismicity generated in areas with different mining conditions and geology has been compared. Special attention was paid to evaluate the difference in seismicity associated with different geotechnical classifications. The following variations were found: (i) geotechnical areas with *soft (Westonaria) lava* hangingwall and *quartzite-conglomerate* footwall are less active than the geotechnical areas with *hard (Alberton) lava* hangingwall and *quartzite-conglomerate* footwall at East Driefontein, Kloof and Leeudoorn Mines, (ii) geotechnical areas with *soft lava* hangingwall and *Jeppestown Shale* footwall are less active than geotechnical areas with *soft lava* hangingwall and *quartzite-conglomerate* footwall at East Driefontein Mine, (iii) geotechnical areas with *hard lava* hangingwall and *quartzite-conglomerate* footwall and *hard lava* hangingwall and *Booysen's Shale* footwall at Western Deep Levels-South Mine do not indicate differences in the associated seismicity, (iv) the variations in the properties of the different types of quartzite forming the footwall at Deelkraal, Elandsrand, Mponeng, East Driefontein and Kloof Gold Mines do not appear to influence the level of seismicity.

Key words: Mining-induced seismicity, rock properties, convergence, deep-level mining.

Introduction

The ventersdorp Contact Reef (VCR) is one of the most important orebodies in the Witwatersrand Basin and is located in its northern and northwestern parts. The Reef separates the predominantly sedimentary Witwatersrand lithologies from the

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volcanic Ventersdorp Supergroup. The combination of three footwall and two hangingwall types of rocks results in delineation of six geotechnical areas across the orebody (ROBERTS and SCHWEITZER, 1999). Quartzite, conglomerate and shale are the major rock types forming the footwall. Jeppestown shale and Booysens shale, however, have different geological and rock engineering properties, and therefore have been considered independently. Volcanic rocks of the Westonaria ("soft lava") and Alberton ("hard lava") formations are the major hangingwall types. The following abbreviations were used in the classification of the geotechnical areas: *SL* – soft (Westonaria) lava; *HL* – hard (Alberton) lava; *QC* – quartzite-conglomerate; *JSH* – Jeppestown Shale; *BSH* – Booysens Shale.

Mining-induced seismicity around deep level stopes is known to depend on the following factors: (i) the amount of mining; (ii) method of rock excavation – mining method; (iii) the geological and rock features; (iv) virgin stresses acting on the rock mass.

Various techniques have been suggested for quantifying the amount of seismicity and identifying the influence of these factors on total seismicity. MCGARR (1976) showed a close relationship between seismic moment and volume of convergence of the mined-out area. The volume of convergence can be calculated from the sequence of mining and the principal stresses, and compared to the amount of seismicity. This technique was applied by MCGARR and WIEBOLS (1977). The cumulative volume of convergence is also closely related to Energy Release Rate (ERR), the most widely used criterion for design of mining layouts in the South African gold mines.

Following this lead, the mining-induced seismicity was analysed based on the ratio of cumulative seismic moment ($\sum M_0$) to the volume of convergence (ΔV_E). It was also anticipated that there might be a variation in mining-induced seismicity associated with the geotechnical classifications. In summary, the aim of this study was to investigate this concept.

Method of Analysis

Mining of deep-level hard-rock deposits results in seismicity and occasionally rockbursts. The seismic energy released was empirically related to the volume of convergence by MCGARR (1976). This relationship can be expressed as:

$$\gamma_E = \sum M_0 / G \Delta V_E \ , \tag{1}$$

where $\sum M_0$ is the cumulated seismic moment, G is an average modulus of rigidity of the rock types involved (for the example given below G was taken as 3.01×10^{10} N/m^2), and ΔV_E is the volume of elastic convergence due to mining. In this paper we calculated M_0 from the local magnitude M_L using the HANKS-KANAMORI relationship (1979):

$$\text{Log } M_0 = 9.1 + 1.5\, M_L \ . \tag{2}$$

Generally the γ_E parameter varies between 0 and 1 and represents the level of seismic activity due to mining. This factor is, however, meaningful only for seismogenic areas for which the measured seismicity can be confidently associated with a certain volume of convergence.

Large-scale elastic stresses around deep tabular mining excavations can be efficiently estimated using the Boundary Element Method (BEM) (CROUCH and STARFIELD, 1983; RYDER and NAPIER, 1985). In this analysis, a two-dimensional mesh represents areas that have been mined at any stage. Displacement Discontinuities (DDs) representing convergence and ride between the hanging- and footwalls are calculated by iterating with Successive Over Relaxation (SOR) until the open mined-out areas carry no normal or shear stress.

The total volume of convergence across a mine can then be easily obtained from summation of all the DDs. To obtain localised contributions to the changes in the volume of convergence (ΔV_E), it is convenient to use the Energy Release Rate (ERR), defined in the mining context as:

$$ERR = \sigma D/2 \ , \tag{3}$$

where σ is the stress before an element is mined and D is the convergence between the hanging- and footwall after the element is mined. As the *ERR* represents the energy released (or stored) per area mined (SALAMON, 1984) and we are dealing with linear elasticity, its calculation should not be a function of the path taken between any two mining layouts. Indeed, we have found that our code satisfies this condition and the equivalent value of ΔV_E is then determined using:

$$\Delta V_E = \sum \sigma_i D_i / \sigma_v \ , \tag{4}$$

where summation occurs over all elements mined in any area and time, and σ_V is the virgin stress before mining.

The error in the calculation of ΔV_E is principally controlled by the accuracy of representing the area mined. For N elements mined in any step the error in estimating ΔV_E therefore varies as $\sqrt{1/N}$. In our studies, $N > 100$ and therefore the error in ΔV_E was less than 10%.

The time interval used when calculating the volume of convergence due to mining corresponds to that used for the selection of seismic data in each seismogenic area, from which the cumulative seismic moment is also generated. In this approach, seismogenic areas associated with consecutive mining steps may clearly overlap (the term "mining step" has been defined here as a certain amount of mining over a certain period of time). The calculation of the volume of convergence was performed using a computer program which calculates ΔV_E from step-wise mining as described by SPOTTISWOODE (1988, 1999).

The digitised mine outlines were used to prepare a pattern to describe the history of mining of the reef on a coarse scale of 64 by 64 elements. Digitising was done by hand from mine plans, as suitable digital data were not available. The solver then used the percentage-mined description on each element to obtain better resolution when each element was enlarged to form 16 (4 by 4) elements, bringing the "problem" size to 256 by 256 elements. Each element was then approximately 10 m on a side, allowing the simulation of area with reasonable accuracy across areas 2.5 km by 2.5 km. Element sizes of 10 m or less were required to provide sufficient accuracy for stresses on typical pillar sizes of 40 m and more. Typical values measured for the Witwatersrand quartzite were used: Young's modulus $E = 70$ GPa and Poisson's ratio $v = 0.2$.

Each mine was divided into seismogenic areas. These were chosen based on the pattern of seismic locations, mining steps and local geology so that we could search for differences in behaviour among areas.

The seismic deformations in a particular mining region for a given time period could also be statistically described by a Gutenberg-Richter frequency-magnitude relationship express as:

$$\text{Log}\, N = a - bM \ , \tag{5}$$

Where N is the total number of events with magnitudes M or greater; M is the local Richter magnitude and a and b are constants. The constant b, widely known as a b value, is of interest as it is controlled by the ratio of the number of smaller events to the number of larger events in a given area.

A minimum magnitude of $M_{\min} \geq 0.5$ was used in this study to calculate the b value for each seismogenic area using the maximum likelihood method of AKI (1965). Therefore, both parameters γ_E and b value could be related to rock properties which tended to seismic deformations during the process of relaxation.

Data

The seismic data from six VCR mines have been accumulated and processed. In total, the data set comprises 300,000 seismic events recorded underground by either the Integrated Seismic Systems (ISS) – AngloGold and Gold Fields of South Africa (GFSA) from 1983 to 1996. Mining plans with a scale of 1:1000 and 3-monthly face positions for Deelkraal, Elandsrand, Mponeng, East Driefontein, Kloof and Leeudoorn mines were processed. The average depth of mining at each of these mines was more than 2000 m below the surface.

The local magnitudes for the larger events $M_L \geq 2.0$ supplied by each mine were compared to those reported by the South African Geological Survey (SAGS). The average and the standard deviation of the magnitude residual for each of the mines is given in Table 1.

Table 1

Residual of the local magnitudes and magnitudes calculated by South African Geological Survey

Mine	Seismic network	Number of events	Magnitude range	Magnitude residual ($M_{MINE} - M_{SAGS}$)	
				Average	Standard deviation
Deelkraal	GFSA	10 000	0.0 to 3.9	−0.35	0.44
Elandsrand	ISS	70 000	−2.0 to 3.8	0.03	0.21
Mponeng	ISS	80 600	−2.0 to 3.7	−0.06	0.29
East Driefontein	GFSA	3 200	−2.1 to 3.9	−0.11	0.20
Kloof	GFSA	32 400	−2.0 to 4.0	−0.14	0.31
Leeudoom	ISS	90 000	−2.5 to 3.7	0.05	0.25

The magnitude residuals were then used to adjust the magnitudes recorded by the mine network before applying equation (2). The magnitudes reported by GFSA networks were also corrected for the bandwidth limitation (4.5 Hz to 200 Hz) of their recording system. This correction improved the magnitude values in the lower part of the magnitude scale and removed considerable curvature in the frequency-magnitude plots for $M_L < 1.0$.

After a preliminary analysis including quality evaluation, spatial and temporal distribution in terms of the face advance and digitising of the mining plans, the seismic locations were referred to the corresponding mining steps defined by quarterly face positions. The entire mining area of each mine was divided into seismogenic sub-areas using location pattern, depth profile, time intervals and local geology. Parameters of seismicity such as γ_E and b value were calculated for each of these subdivisions. Comparative analysis was done on the seismicity over entire mine areas and on the seismicity associated with the different geotechnical classifications.

Results and Discussion

Two of the mines, East Driefontein and Kloof, contained the most complex combination of diverse lava in their hangingwalls and were therefore chosen for detailed study. The seismicity of these mines is discussed below in detail.

East Driefontein Mine

The distribution of the seismic events with local magnitude $M_L \geq 1.0$ is shown in Figure 1a. It can be seen that there are several clusters of seismic events around areas with active mining. Increased seismic activity is observed in the southwestern part of the mine where the seismicity was formed by mining of three reefs: VCR, the Main Reef and the Carbon Leader Reef.

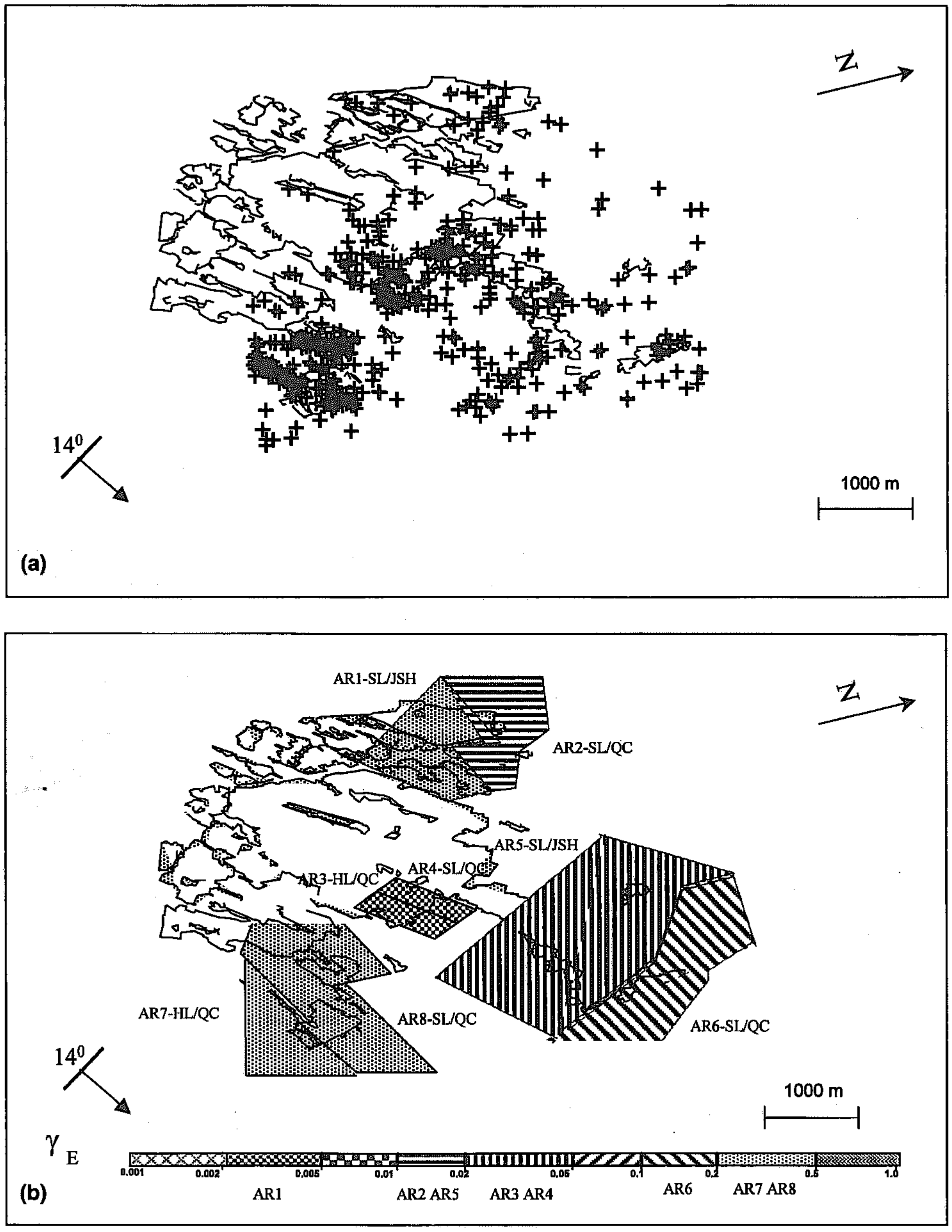

Figure 1
East Driefontein Mine: (a) hypocentral map for seismic events with local magnitude ($M_L \geq 1.0$); (b) mining induced seismicity γ_E for areas corresponding to different geotechnical classifications.

East Driefontein Mine contains the largest variety of geotechnical classification of the local VCR mines. Eight seismic areas were identified at East Driefontein and

Table 2

Seismic parameters for selected seismogenic areas at East Driefontein Mine

Area name	Geotechnical class	Time period	Number of events	M_{max}	γ_E	b value
AR1	SL/JSH	JUL 88–AUG 94	62	2.1	0.003	0.77 ± 0.10
AR2	SL/QC	MAY 90–OCT 94	65	2.2	0.01	0.82 ± 0.10
AR3	HL/QC	MAY 89–DEC 93	93	3.0	0.05	0.64 ± 0.07
AR4	SL/QC	JAN 90–OCT 94	153	2.5	0.04	0.80 ± 0.06
AR5	SL/JSH	JAN 93–OCT 94	223	2.7	0.03	0.91 ± 0.06
AR6	SL/QC	MAR 93–OCT 94	59	2.9	0.13	0.79 ± 0.10
AR7	HL/QC	JAN 88–MAR 93	50	2.7	0.49	0.53 ± 0.07
AR8	SL/QC	JAN 88–OCT 94	1479	3.2	0.55	0.78 ± 0.02
	Standard deviation				0.22	0.12

associated with the following geotechnical areas: *HL* hangingwall and *QC* footwall; *SL* hangingwall and *QC* footwall; and *SL* hangingwall and *JSH* footwall (Fig. 1b).

Seismic activity for several adjacent areas with different geotechnical classifications, *SL*/*JSH* and *SL*/*QC*, manifests differences in γ_E with the *SL*/*JSH* area being less active. The areas with *SL*/*QC* display lower seismic activity when compared to adjacent areas with *HL*/*QC*. However, the differences in γ_E values in this portion of the mine are small. They seem to be influenced by mining of Main Reef and Carbon Leader Reef in proximity to the VCR. The summary of the results is given in Table 2.

A brief discussion of b values will follow below.

Kloof Mine

The location of the seismic events with local magnitude $M_L \geq 2.0$ is shown in Figure 2a. Most of the events were related to the areas with active mining while others were associated with areas highly stressed by previous mining. On average, the southern part of the mine shows higher seismic activity, by factor of two, when compared to its northern part. The smaller mining spans in the northern part apparently played an important role in reducing the level of seismicity. Smaller spans have lower *ERR* and therefore less convergence. The resulting lower values of ΔV_E per area mined therefore do not adequately account for the benefit of smaller spans.

Kloof Mine is a complex of several different geotechnical classifications; *HL* hangingwall with *QC* footwall, and *SL* hangingwall with *QC* footwall occur most widely. A total of 11 seismogenic areas were delineated in such a way that each area contained a single geotechnical classification. The position of the areas and distribution of the γ_E are illustrated in Figure 2b.

Two pairs of adjacent seismogenic areas for geotechnical classes of *SL*/*QC* and *HL*/*QC* located in the southern and northern portions of the mine indicate differences in the level of seismicity. The areas with *SL*/*QC* are less active than the areas with *HL*/*QC*. The summary of the results is given in Table 3.

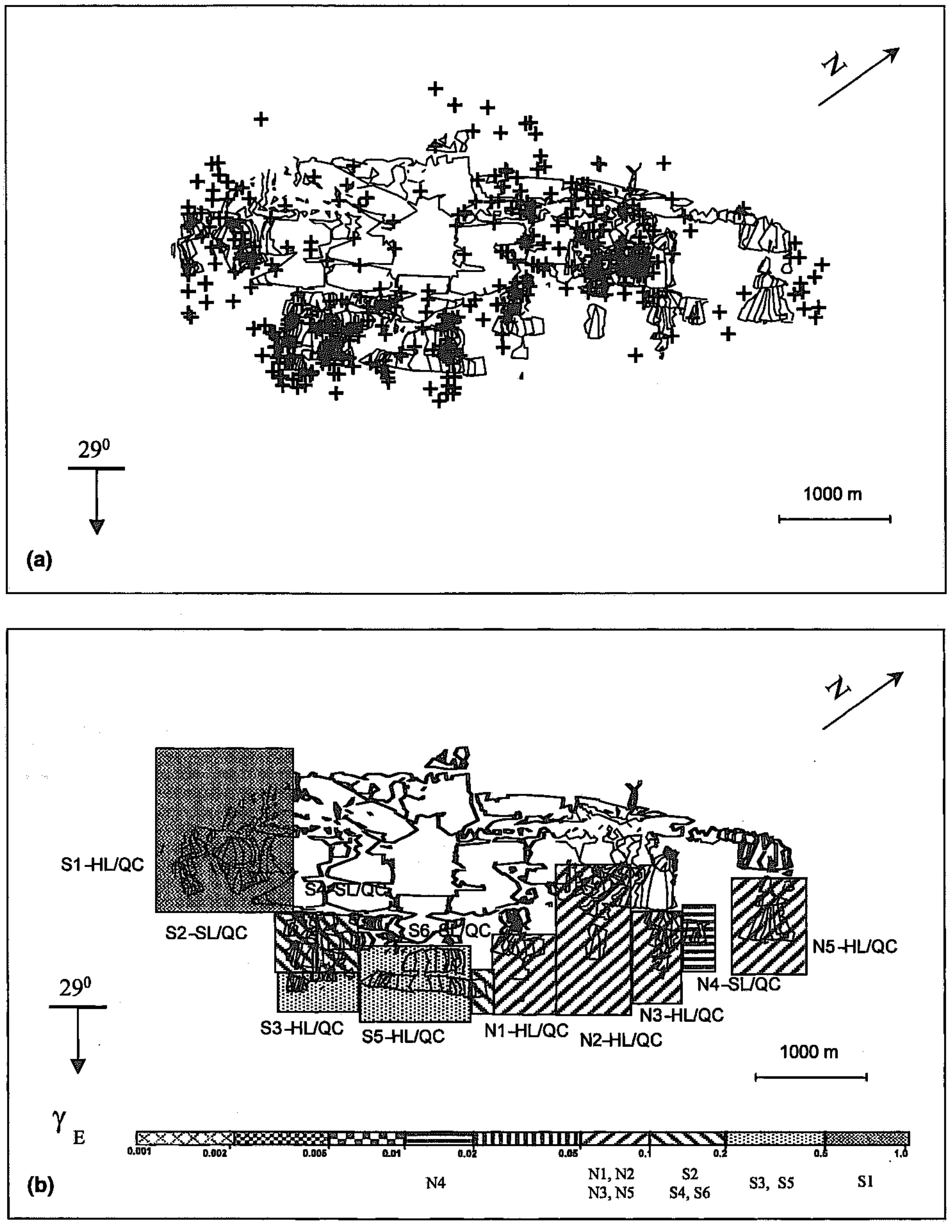

Figure 2
Kloof Mine: (a) hypocentral map for seismic events with local magnitude $M_L \geq 2.0$; (b) mining induced seismicity γ_E for selected seismogenic areas.

Figure 3 is a plot of the cumulative distributions of γ_E for the two hangingwall types, hard lava and soft lava overlying a quartzite-conglomerate footwall, analysed at East Driefontein and Kloof mines.

Table 3

Seismic parameters for selected seismogenic areas at Kloof Mine

Area name	Geotechnical class	Time period	Number of events	$M_{\max}$	γ_E	b value
S1	HL/QC	JAN 87–AUG 95	4100	4.0	0.57	0.87 ± 0.01
S2	SL/QC	JAN 87–AUG 91	720	3.3	0.12	0.85 ± 0.03
S3	HL/QC	JAN 90–AUG 95	550	3.0	0.23	0.69 ± 0.03
S4	SL/QC	JAN 87–AUG 91	1100	3.2	0.13	0.82 ± 0.02
S5	HL/QC	JAN 87–AUG 95	3520	3.8	0.21	0.76 ± 0.01
S6	SL/QC	JAN 93–AUG 95	85	1.9	0.13	0.99 ± 0.11
N1	HL/QC	JAN 90–AUG 95	1300	3.1	0.05	0.82 ± 0.02
N2	HL/QC	JAN 87–AUG 95	2850	3.4	0.07	0.86 ± 0.02
N3	HL/QC	JAN 91–AUG 95	390	3.2	0.07	0.78 ± 0.04
N4	SL/QC	JAN 87–AUG 95	190	2.1	0.01	0.86 ± 0.06
N5	HL/QC	JAN 89–AUG 95	240	3.5	0.09	0.76 ± 0.05
Standard deviation					0.15	0.08

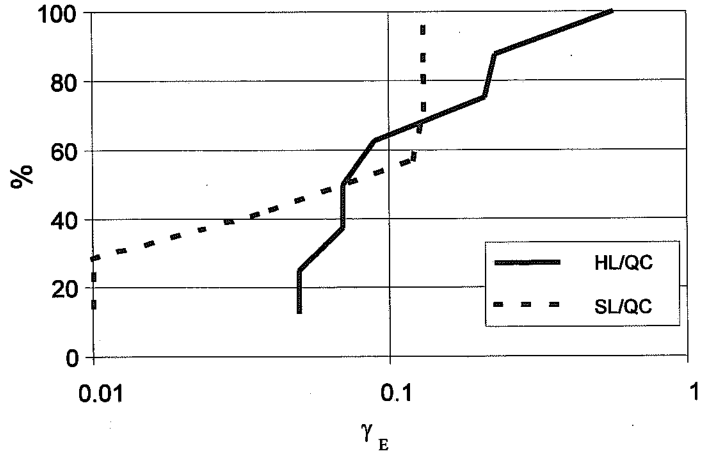

Figure 3
The cumulative frequency curves of the γ_E values calculated for areas with soft and hard lava hangingwall at East Driefontein and Kloof Mines.

It can be seen that the areas covered in hard lava were several times more seismically active, when normalised by ΔV_E, than the areas covered by soft lava. This result is in agreement with the conclusion of McGarr *et al.* (1975) who attributed the concentration of seismic events in the hangingwall to higher strength of hangingwall rocks in their study area.

In summary, the γ_E on two mines was found to be slightly higher for stronger hangingwall rocks and stronger footwall rocks, although the contrast in the values of γ_E are not statistically significant, with each population showing large deviations of their average, both in a linear and logarthmic sense (Table 4).

Table 4

Statistical evaluation of γ_E for seismogenic areas with hard lava and soft lava hangingwall types overlying a quartzite-conglomerate footwall

Geotechnical class	Number of areas	Linear		Geometric	
		Average	Standard deviation	Average	Standard deviation
HL/QC	8	0.168	0.177	0.115	2.40
SL/QC	7	0.081	0.058	0.052	3.34
SL/JSH	2	0.017	0.019	0.009	5.09
All areas studied	65	0.241	0.294	0.084	5.79

The deviations in the values of γ_E of factors of two and more are of great importance, as control of ΔV_E is achieved through leaving 15% or more of the ground behind as regional stability pillars. These pillars are typically designed with the objective of reducing seismicity by a factor of about three.

The conclusion of McGarr and Wiebols (1977) that seismicity at ERPM mine was reduced in accordance with the reduction in ΔV_E is not supported in this paper for the two mines studied. The large pillars (60 m wide) and the regular mining geometry at ERPM mine might have led to behaviour closer to ideal elastic. The mine layouts studied in this paper (Figs. 1a and 2a) were considerably more complex than the ERPM practice. Further work is underway to investigate whether these discrepancies can be attributed to non-linear effects.

An inverse relationship between γ_E and b values was pointed out by McGarr (1986). He commented "...it is of considerable interest to find out if there are any geological factors that may cause low values of γ_E and high values of b". Figure 4 shows the cumulative frequency curves of the b values calculated for areas with soft and hard lava hangingwall at East Driefontein and Kloof Mines.

In contrast with Figure 3, the graphs plotted on Figure 4 clearly indicated that the b values calculated for areas with soft lava hangingwall are higher then the b values calculated for areas with hard lava. Higher strength rocks can build up more strain energy before failure and then fail more violently. As low b values implies a high ratio of large to small seismic events and since the large seismic events cause most of the seismic deformations, the high γ_E values in the areas with hard lava are physically well supported.

The other mines studied: Deelkraal, Elandsrand, Mponeng and Leeudoorn have insignificant variations in terms of geotechnical classes. The variations of γ_E for these mines were summarized in Figure 5 and Table 4.

Considerable effort and expense is applied to reduce the volume of convergence by leaving pillars. Therefore, γ_E should have the same values for all seismogenic areas. However, Figure 5 shows significant scatter in γ_E values. This indicates factors other than the country rock type might significantly contribute to the formation of

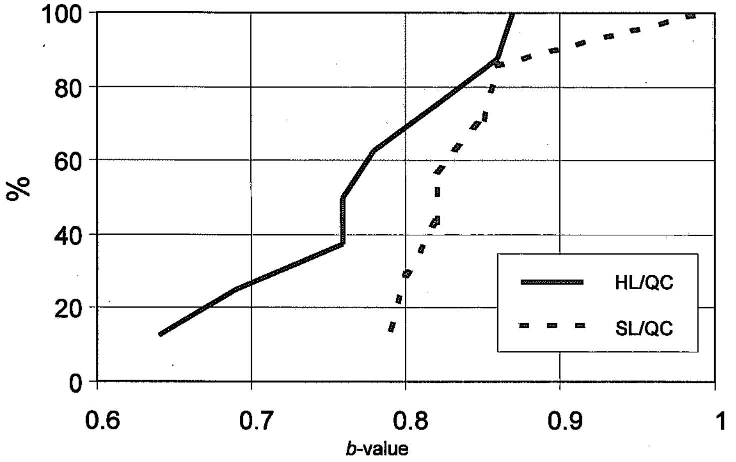

Figure 4
The cumulative frequency curves of the b values calculated for areas with soft and hard lava hangingwall at East Driefontein and Kloof Mines.

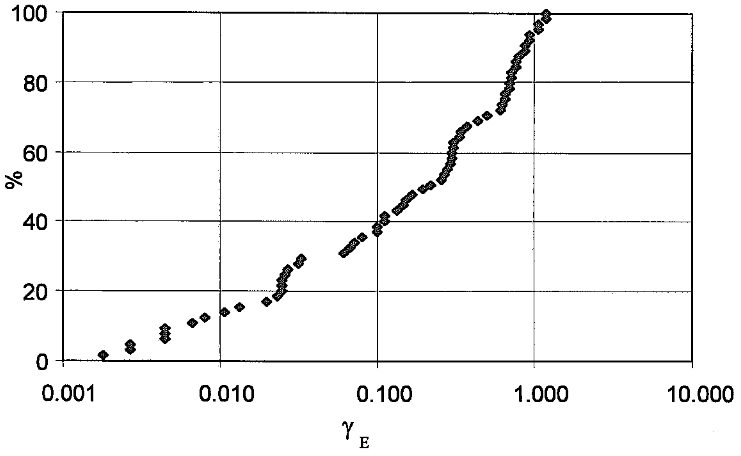

Figure 5
The cumulative frequency curves of the γ_E values calculated for all areas at Deelkraal, Elandsrand, Mponeng and Leeudoorn mines with hard lava hangingwall and quartzite-conglomerate footwall.

γ_E. For example, the stope spans at Kloof seemed to have some control on γ_E. In addition, as suggested by MILEV *et al.* (1995), "inherited" seismicity of previously mined-out areas might also provide an important control on γ_E values. Although the large scatter observed in γ_E places considerable doubt on the value of convergence control as currently practiced. Further research on this topic is ongoing. The b values also show a significant spread, from 0.53 to 1.72, throughout all areas and this indicates that changes in the mine production strongly effect seismicity.

Conclusions

There appeared to be some control of rock types on the ratio γ_E between the cumulative seismic moment and the volume of convergence across two mines that reflected the most variation in country rock types.

- The γ_E in areas with soft lava in the hangingwall was about 50% of γ_E where only hard lava was present.
- The γ_E was less for areas with shale footwall.

Conclusions drawn from a larger set of six mines were:

- The γ_E was lower in areas of lower span.
- Different types of quartzite footwall did not appear to influence γ_E.
- The standard deviation of a factor of 5.8 in all the 65 selected areas, for which values of γ_E were measured, is higher than the factor-of-three benefit expected from leaving pillars.

More accurate models are needed for estimating the anticipated level of seismicity around deep tabular mining.

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