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Total seismicity, and the application of ESS analysis to mine layouts*

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SYNOPSIS

A simple method for the application of excess shear stress (ESS) analysis to the mining of planar reefs is examined. The potential for seismicity associated with mining is expressed as the calculated increase in ESS on a regular grid of points 50 m above the reef, and is compared with observed seismicity around a deep-level, relatively geologically-undisturbed gold mine.

Thirty regions were studied, involving over 2000 seismic events with magnitudes greater than 1,5 on the Richter scale and associated with almost 2 million square metres of stoping. The total seismicity, measured either as the number of seismic events or as the total radiated energy, correlated more closely with changes in ESS than with ERR. The incidence of rockbursts also favoured the ESS model. Correlation coefficients of around 0,8 for seismicity and ESS indicated that the assumptions inherent in the method used are collectively reasonable.

The total seismicity in each region was found not to be strongly controlled by the presence of dykes and faults, although numerous individual seismic events were located close to such features.

SAMEVATTING

'n Eenvoudige metode vir die toepassing van 'n oormaatskuifspanningontleding (OSS) op die ontginning van vlakriwwe word ondersoek. Die moontlikheid van seismisiteit wat met mynbou geassosieer is, word uitgedruk as die berekende toename in OSS op 'n reëlmatige ruit van punte 50 m bokant die rif, en vergelyk met die waargenome seismisiteit om 'n diepmyn wat geologiese betreklik onversteurd is.

Daar is dertig streke bestudeer wat meer as 2000 seismiese gebeurtennise met 'n grootte van meer as 1,5 op die Richterskaal behels en met byna 2 miljoen vierkante meter afbouing geassosieer is. Die totale seismisiteit, gemeet as die getal seismiese gebeurtenisse of as die totale uitgestraalde energie, het beter met veranderinge in die OSS as met die energievrystellingtempo (EVT) gekorreleer. Die voorkoms van rotsbarstings is ook ten gunste van die OSS-model. Korrelasiekoëffisiënte van om en by 0,8 vir seismisiteit en OSS het getoon dat die aannames wat inherent in die metode is, gesamentlik redelik is.

Daar is nie gevind dat die aanwesigheid van gesteentegange en verskuiwings die totale seismisiteit in elke streek sterk beïnvloed nie, hoewel talle individuele seismiese gebeurtenisse naby sulke gesteldhede voorgekom het.

Introduction

Short-, medium-, and long-term goals are set for mine-wide seismic networks in South African gold mines. Firstly, rapid and reliable locations of the source of seismic events currently provide valuable information; secondly, the identification of areas of anomalous seismicity is a valuable aid to mine planning; and, thirdly, research on seismic data results in improved tools that can be used for these short- and medium-term objectives.

The use of seismic data for mine planning depends strongly on the ability to predict, in a quantitative manner, the total seismicity likely to result from each mining situation. Quantitative modelling of total seismicity and rockburst incidence is a major problem in the planning of deep-level mines. This problem is directly addressed in this paper for mining in a geologically less-disturbed area.

The design of stoping layouts to minimize the incidence of seismic events and rockbursts is one of the strategies for combating the rock-pressure problem in deep-level mining. A reduction of volumetric closure through the use of strike stability pillars in longwall mining has been found to reduce total seismicity and rockburst damage[1]. The energy release rate (ERR), which is related to volumetric convergence, is now routinely used in the planning of mining layouts in the Carletonville area and in the East Rand, where geological features have not had a controlling effect on mine layout and where longwall mining is practised. In contrast, seismicity has been found to be less strongly related to ERR in the geologically complex Klerksdorp and OFS Goldfields, where scattered mining is practised.

A new parameter, the excess shear stress (ESS), is being explored as an indicator of potential for seismicity in faulted ground[2]. This paper analyses seismicity around Blyvooruitzicht Gold Mine during a period of six years in terms of ERR and ESS. An earlier description of mining at Blyvooruitzicht was given by Ortlepp and Spottiswoode[3]. Geological features at Blyvooruitzicht have caused relatively minor deviations from the original planarity of the Carbon Leader Reef, the reef that was mined during the period considered here.

The relating of individual seismic events uniquely to individual stopes or geological features is a difficult, if not impossible, task. In this paper, seismicity at Blyvooruitzicht is dealt with in 30 seismogenic regions, which are clearly defined clusters of seismic locations over periods lasting from two to six years are investigated.

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ERR and Inelastic Rock Deformation

Rock deformation around an advancing face normally takes place in a stable manner: larger seismic events (those that account for the bulk of the radiated energy and rockburst damage, say $M > 2$) are only irregular features interrupting the development of regular fractures ahead of the face. (The term *stable* can be somewhat misleading in this context because the rock is continually fracturing and expending energy.)

Brummer and Rorke[4] proposed a classification of fracturing around advancing stope faces that was based on observations made by themselves and others in a variety of mining situations. At up to 10 m ahead of the face, shear slip takes place along steeply dipping mining-induced fracture planes, followed by vertical-induced tensile fractures at about 1 m ahead of the face. In addition, horizontal shear displacement takes place along bedding planes in an attempt to move rock out into the stope, and results in dilatation of the rock mass.

Brummer[5] modelled rock deformation ahead of the face by using a series of parallel seam elements adjacent to one another along the reef plane. The elements push one another towards the face in response to normal and shear stresses acting on their top and bottom contacts, equivalent to the bedding-plane slips reported by Legge[6]. Using reasonable deformation characteristics for the elements and frictional properties on the bedding planes, Brummer found that simulated rock failure begins at a distance ahead of the face similar to that observed underground, and that the ERR is exactly accounted for by fracturing and slip plus the amount of strain energy contained in the block of ground actually removed at the face. In deep-level gold mines, the last component is very small. The energy balance in Brummer's model will be obtained for any rock behaviour that includes strain softening. *The 'need' for seismicity and rockbursts to accompany energy changes associated with volumetric convergence as expressed by Cook[7] thus disappears.*

Fig. 1 is a section through a longwall face showing locations of seismic events with Richter magnitudes between 1 and 2 that were studied in detail by Spottiswoode[8]. The use of a joint hypocentral-location procedure to reduce scatter in the locations resulted in a relative location accuracy of better than 25 m, and clearly illustrates that seismic events of this magnitude are located typically about 50 m from the reef horizon in the hangingwall or the footwall. On the assumption of circular source regions, source radii of the events in this study were also of the order of 50 m. Fig. 1 also illustrates that the seismic source mechanisms are compatible with shear slip on steeply dipping fault planes, induced either geologically or by mining. Other studies have found that numerous seismic events are located at even greater distances from the reef horizon (e.g. Van der Heever[9], Arnott[10]).

The arguments against the existence of a causal relationship between seismicity and ERR at advancing faces can be summarized as follows.

(1) Stable fracturing ahead of the face can account for all the compulsory gravitational energy released by mining.
(2) To account for the irregular occurrence of the largest events, the rock has to store energy for long periods (months or years) before releasing the energy through seismicity.
(3) Large seismic events often occur remote from the source of energy change, the advancing face.

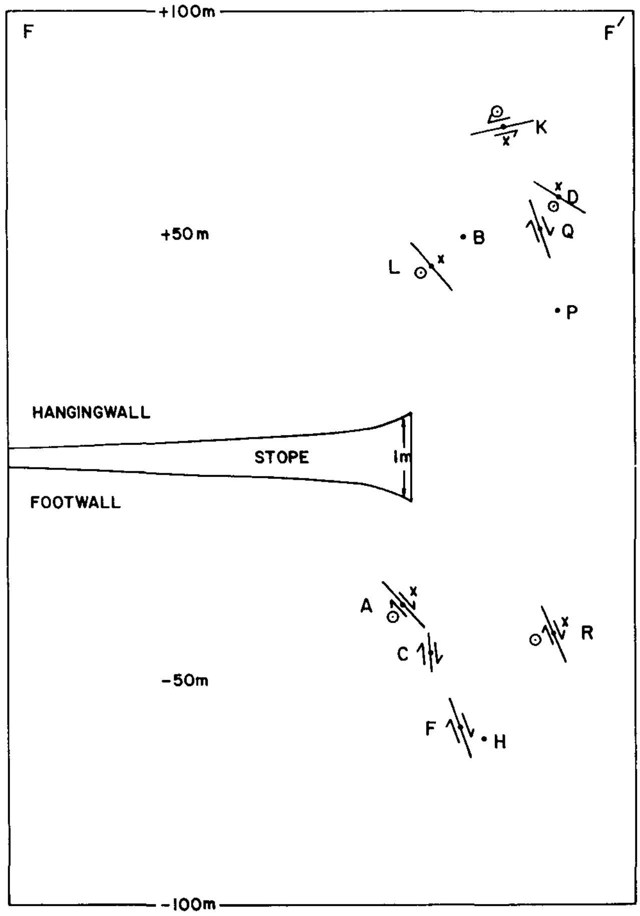


Fig. 1—Section through a longwall face indicating locations and seismic source mechanisms of seismic events with Richter magnitudes from 1 to 2

Points (2) and (3) above would require the transfer of energy to an energy 'store' before being released, a difficult scenario to justify. The value of ERR as a measure of the depth[11] and intensity of face-induced fracturing is not questioned here, and intense face-induced fracturing can lead to hangingwall conditions that are difficult to support.

McGarr[12] and McGarr and Wiebols[1] have contended that volume change (ΔV) under certain conditions such as mining results in a quantifiable amount of seismicity, expressed as the total seismic moment ($\Sigma M_0 \approx G\Delta V$), and found that the data from some areas at ERPM agreed closely with this relationship. While the 'need' for seismicity to account for ERR does not apply, McGarr's equation may provide an upper limit on the total, long-term seismic moment.

Stress Changes around Tabular Excavations

Stresses around the edges of tabular excavations have long been recognized as reaching values potentially well in excess of the rock strength, and seismic events located close to the face have been ascribed to violent rock failure[13].

The spatial relationship of seismic locations to stress changes was studied by McGarr *et al.*[14]. Considering the

Mohr–Colomb failure envelope used by Cook[13] to describe the failure of Witwatersrand quartzites, they looked at

$$F = \Delta\sigma_1 - 6\,\Delta\sigma_3, \quad (1)$$

where $\Delta\sigma_1$ and $\Delta\sigma_3$ are respectively the maximum and minimum stress changes induced by mining. They found that most seismic events were located where F was between 100 and 300 MPa

Ortlepp and Spottiswoode[3] considered

$$F = \sigma_1 - 6\,\sigma_3 \quad (2)$$

calculated from the total elastic stresses above a longwall face. Without stabilizing pillars, it was found that $F > 0$ over large areas ahead of advancing longwalls. With the introduction of stabilizing pillars, σ_3 increased sufficiently in their vicinity for $F > 0$ to occur only between the pillars, and then less extensively than was the case without pillars.

Mohr–Coulomb failure can perhaps be more usefully viewed in terms of the shear stress, τ, acting on a plane trying to overcome the shear strength, c_o, and frictional resistance. Hepworth and Diamond[15] used the term *excess shear stress*, defined as

$$\tau_e = |\tau| - (c_o + \mu\sigma_n), \quad (3)$$

where μ is the coefficient of friction and σ_n is the normal stress acting across the plane; $\tau_e > 0$ then indicates that the rock must fail. When the rock has failed, c_o will drop to zero and μ will change from the static to dynamic coefficient of friction. The presence of numerous geological weaknesses with $c_o \approx 0$ in the rockmass argues for the consideration of the rockmass as a whole as having zero cohesion.

Ryder[2] describes the concept of ESS in detail, and Napier[16] provides examples in which it can be used to assist mine planning by reducing shear slip and, thereby, seismicity and rockbursts. Napier shows that the mining of a reef offset by faulting can lead to high values of ESS, and that these values depend strongly on the proximity of stoping to the fault. The amount of shear slip required to relax the ESS to zero is even more dependent on details of mining. These papers discuss some of the difficulties inherent in the application of the ESS in actual mining situations.

In contrast to the ERR, which is a scalar quantity dependent only on mine geometry and the position on the face at which it is determined, ESS is a tensor quantity that varies in three dimensions, and is thus much more difficult to evaluate.

Determination of ERR and ESS

Stoping at Blyvooruitzicht Mine takes place principally on the Carbon Leader Reef at depths between 1000 and 2500 m below surface. The reef across the property is unusually planar, with no geological faults displacing the reef by more than 40 m. The mine layouts were modelled by the use of a MINSIM type of simulation in which the mine consisted of a grid of points arranged as 256 columns and 166 rows. Each point represented a block of reef 30 m by 30 m that was either mined out or solid. This area included portions of adjacent mines so that stress induced from these areas was also considered. The six years from June 1979 to June 1985 inclusive were simulated in 25 mining steps, representing mining at three-monthly intervals. Convergence in the mined-out area and on-reef normal stress in the unmined area were calculated by the computer program REEFF using the displacement discontinuity method[17]. (REEFF operates on windows of 60 × 60 blocks within the overall area, each window being influenced by all the surrounding areas. Edge effects were almost eliminated by successively overlapping windows. More than 600 individual 60 × 60 areas were processed during this solution phase.)

All the seismic events with $M > 1{,}5$ located by the Blyvooruitzicht Mine Seismic System[3] were plotted together with mining outlines for three two-year periods: mid 1979 to 1981, 1981 to 1983, and 1983 to 1985. Thirty seismogenic regions were chosen, using time periods of 2, 4, or 6 years, and each region was associated with separate stoping areas. Fig. 2 shows mining and seismicity in part of the mine during the first period, June 1979 to June 1981, together with outlines of some of the areas chosen.

Major geological features as mapped on the standard 1:2000 mine maps are also represented in Fig. 2. For this analysis, the area of geology within each block was determined from outlines digitized from the 1:2000 mine plans. Most of these features are dykes. Faults were represented by fault loss on plan or, more usually, by the extent of overstoping. These indicators of geology are somewhat qualitative by nature, and it is beyond the scope of this paper to attempt an accurate quantification of geological features.

For each of the 30 seismogenic regions, the following mining and geological parameters were considered.

(1) Identification of each area by mining method based on the following classification.
   - (a) Longwall mining with a continuous face length of more than 200 m.
   - (b) Remnants that were mined out almost completely during the study period. There were two such remnants, both in the shallower areas of the mine, and each was mined by updip mining.
   - (c) Scattered mining where the spans did not exceed 200 m.
   - (d) Mini-longwall mining with a face length of about 180 m, either isolated or separated by well-established stabilizing pillars 45 m wide.

(2) Area mined (in 1000 m^2). The area mined was calculated from the number of grid blocks mined and is therefore given in multiples of 900 m^2. To reduce errors, a minimum of 15 grid blocks was mined in any region (Table I).

(3) ERR in MJ/m^2. The average energy release rate was calculated from

$$ERR = \tfrac{1}{2}\,\sigma_n D_n, \quad (4)$$

where σ_n was the average normal stress acting on all the grid blocks to be mined during a mining step, and D_n was the average elastic convergence of these blocks after mining. This calculation is somewhat different from the procedure normally used with MINSIM-type programs but provides average values of ERR that do not depend on the size of the mining steps or the order in which a region is mined out: rules

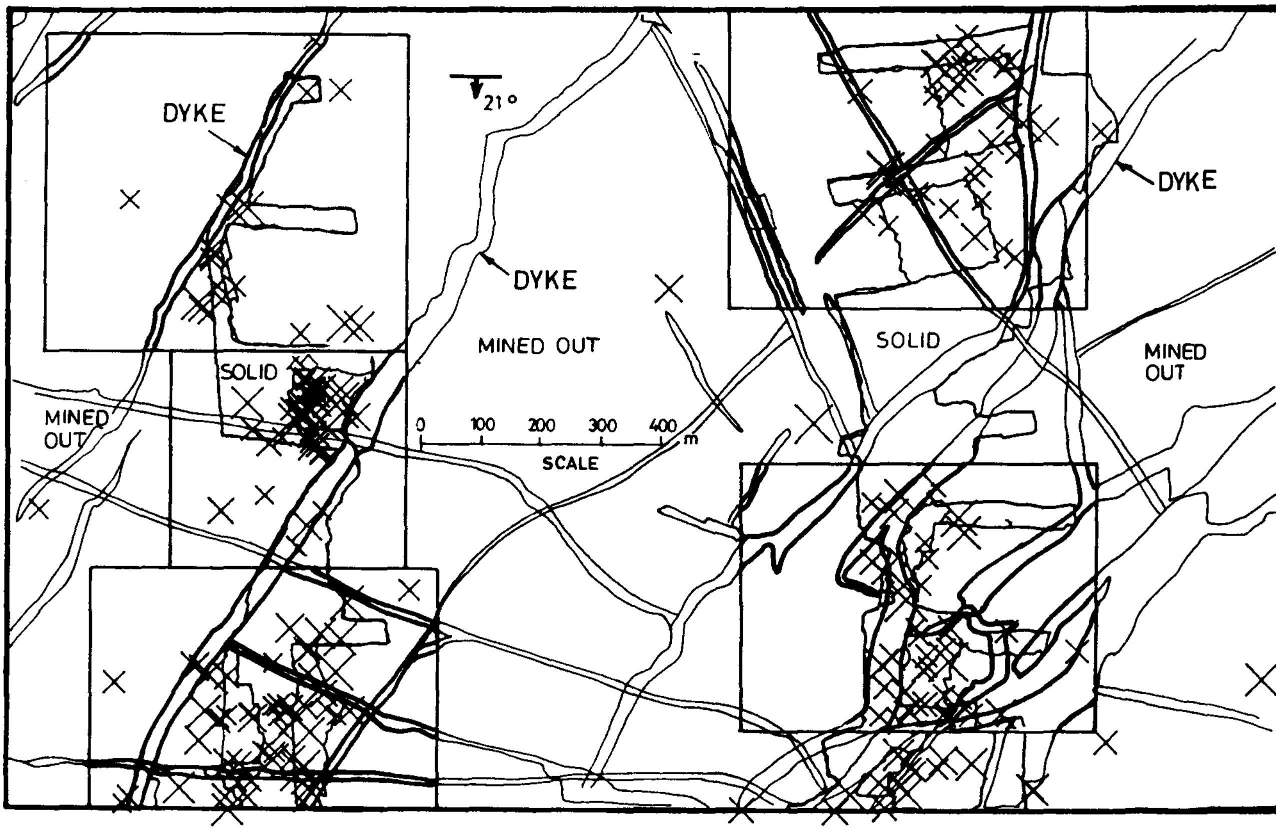


Fig. 2—Part of Blyvooruitzicht Gold Mine showing face outlines during June 1983 and June 1985, seismic events with Richter magnitudes of more than 1,5, five of the seismogenic regions featuring in this paper, and prominent geological features

TABLE I

MINING AND SEISMICITY PARAMETERS FOR 30 REGIONS

Mining method	Area m^2	ERR MJ/m^2	$\Sigma\Delta\tau_e$ MPa	P_g	N $10^{-3}\ m^{-2}$	ΣE_s kJ/m^2	L_R $m/10^3\ m^2$
1	124,2	12,5	5,2	0,03	0,19	4,8	5,2
1	161,1	13,4	3,5	0,15	0,13	4,0	3,5
1	128,7	14,7	5,2	0,19	0,59	11,2	5,2
3	116,1	15,4	8,2	0,29	0,99	27,9	8,2
3	47,7	9,8	1,8	0,27	0,63	17,8	1,8
1	194,4	17,6	3,1	0,12	0,49	19,0	3,1
1	38,7	48,1	16,6	0,10	1,94	62,0	16,6
1	35,1	40,0	12,1	0,04	1,54	45,5	12,1
1	94,5	27,6	5,7	0,19	0,78	14,2	5,7
1	58,5	36,6	15,5	0,11	2,03	45,3	15,5
1	162,9	27,2	6,6	0,16	0,61	16,2	6,6
1	67,5	32,7	18,6	0,06	2,44	65,1	18,6
4	59,4	53,2	24,3	0,08	2,17	60,6	24,3
4	27,0	46,6	26,9	0,22	3,81	101,8	26,9
4	31,5	38,8	10,5	0,12	1,37	42,8	10,5
4	22,5	37,5	4,2	0,19	1,60	44,4	4,2
4	37,8	37,5	9,6	0,06	1,64	68,7	9,6
1	53,1	61,2	12,2	0,06	1,09	35,7	12,2
1	35,1	58,0	9,2	0,24	3,08	105,4	9,2
4	27,9	29,2	12,0	0,20	2,54	114,7	12,0
4	44,1	40,9	11,4	0,07	0,77	19,2	11,4
4	16,2	35,4	10,4	0,13	2,65	40,1	10,4
4	46,8	27,8	12,3	0,09	1,00	37,3	12,3
4	18,0	24,2	19,0	0,33	3,17	88,8	19,0
1	32,4	66,5	30,3	0,48	2,69	77,1	30,3
4	18,0	57,5	40,8	0,38	6,94	177,7	40,8
3	26,1	9,5	4,9	0,01	0,69	19,1	4,9
2	13,5	175,1	29,8	0,13	2,59	81,4	29,8
3	137,7	27,7	12,6	0,13	1,61	45,7	12,6
2	19,8	201,9	25,0	0,23	2,68	42,9	25,0

of conservation of energy are strictly followed.

(4) Total excess shear stress change per area mined ($\Sigma\Delta\tau_e$ in MPa). This parameter represents a simplified measure of the complex pattern of change in ESS around an advancing stope face and is central to the analysis in this paper. A detailed description and motivation follows.

Stress values at a mesh of points 50 m above each grid point of the 30 selected areas were calculated for each mining step. The distance of 50 m was based on the data shown in Fig. 1 and was therefore meant to represent likely foci for $M > 1,5$ events. Details of face shape become less important in the calculation of stresses with increasing distance from the stope, and a smoother and more accurate profile of stresses was obtained than if points closer to the reef horizon had been used.

The elastic-stress analyses presented by Ryder[2] suggest that shear slip should occur preferentially at an angle of about 60 degrees to the reef plane, an observation in agreement with locations and mechanisms of seismic events (e.g. Fig. 1). Also, an angle of 60 degrees was found in laboratory work to be a typical angle between shear-slip direction and confining stress[18]. It was assumed that, if the small effect of reef dip is neglected, seismicity at Blyvooruitzicht occurs only in response to vertical and horizontal components of stress, and ESS values were then calculated from these values.

Values of ESS are illustrated in Fig. 3 for a typical point as mining progresses. It can be seen that the ESS is negative some distance ahead of the face, and

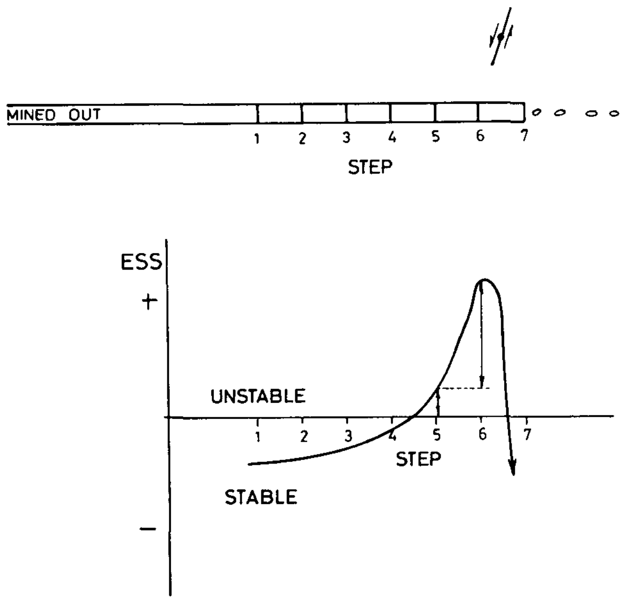


Fig. 3—ESS history of a typical point as it is undermined (increases in ESS during mining steps 5 and 6 are marked)

peaks sharply above the highly stressed area ahead of the face, and then decreases rapidly as the point becomes undermined.

The potential for slip is modelled here as the increase in ESS above zero, or above the ESS during the previous mining step, whichever is the greater. This increase is represented by $\Delta\tau_e$; $\Sigma\Delta\tau_e$ is then the sum of ESS changes during mining. So that data for different areas could be compared, this parameter was then divided by the area mined: as each point represents an area of 900 m^2, the dependence on grid size was reduced by multiplying by 900 m^2. ESS was calculated from c_o = 7,5 MPa and μ = 0,6 in equation (3).

(5) The proportion of total ESS change that occurred in geological structures (P_g). P_g is the proportion of geological features in the region considered, weighted by the value of $\Delta\tau_e$ at each point. P_g is not always equal to the proportion of geological structures present in the area mined, or the proportion of on-reef waste, since mining layouts are strongly affected by these structures.

Mining layouts in the vicinity of geological features at Blyvooruitzicht receive special attention: they are considered in the planning of stabilizing pillars, face shapes, and leads and lags[19].

Seismicity and Rockbursts Parameters

Seismicity and rockburst data for the 30 regions were collected for comparison with the mining parameters listed above, in the form of the following three quantities:

(1) the number of seismic events with $M > 1,5$ per 1000 m^2 of area mined;
(2) the total radiated energy per unit area (ΣE_s in kilojoules per square metre), the radiated energy in megajoules for each individual event being calculated from $\log E_s = 1,5M - 1,2$;
(3) the length of face per area mined that was affected by rockbursts (L_R in metres per 1000 square metres).

In regard to (1), the magnitudes reported by the National Seismic Network of the Geological Survey of South Africa were used when available. Events with $M < 2,0$ were generally not located by the National Network, and those magnitudes were estimated locally by use of a magnitude scale that generally agreed with published magnitudes within 0,3 magnitude units. Plots of frequency versus magnitude indicated that almost all $M > 1,5$ events were recorded and located by the mine-wide network. Sensitivity in the centre of the network was somewhat greater than around the edges, and many smaller events had therefore to be excluded from the analysis. The system downtime was less than 5 per cent for each of the time periods considered.

During most of the time period considered, a system of rockburst reporting was in operation. Reports of 'potential' rockburst were sent to mine overseers following $M > 1,5$ seismic events that were located near active faces. Reports were returned indicating the extent of the damage, if any, and the projected delays in production. For this analysis, the length of the panels for which mining was delayed by one day or longer was considered, and these were added for all the reported rockbursts.

Quantitative assessment of rockburst damage is a problem area in studies of rock mechanics. A typical problem is that of unreported rockbursts, and, for various reasons, a proportion of reports were not returned. However, the rate of return of reports was generally well in excess of 50 per cent and increased with time as these reports have become integrated with the overall mine management[19]. As the return rate of the reports did not depend noticeably on the magnitude of the event, the report rate was corrected approximately by dividing by the return rate. Again, L_R was normalized by dividing by the area mined.

Mining, geological, seismic, and rockburst parameters as described above are listed in Table I for the 30 regions.

Analysis of Quantitative Seismicity

In Fig. 4, N, ΣE_s, and L_R are plotted against *ERR* and *ESS* ($\Sigma\Delta\tau_e$) for the 30 regions. For each plot, the regression line of Y on X is plotted. Each point was weighted by the area mined, and also by the return rate of rockburst forms for the L_R plots. The regression coefficient, R, is shown as an indication of the goodness of fit of the regression line. *ESS* was calculated from C_o = 7,5 MPa and μ = 0,6 in equation (3); μ = 0,6 was taken from Ryder[2] and c_o = 7,5 MPa was chosen empirically so that the seismicity was mostly closely proportional to *ESS*. The physical interpretation of this value of c_o will be discussed later.

All three measures of seismicity and rockbursting correlate more strongly with ESS than with ERR.

The two remnants were extracted with average *ERR* of around 200 MJ/m^2, but with the resulting seismicity no greater than in some regions with *ERR* of around 40 MJ/m^2. The regression lines are indicated for the 28 regions, exclusive of the two remnant areas, by dotted lines, with regression coefficients in parentheses. Even these regression coefficients are lower than those using *ESS* as the independent variable. Otherwise, the choice of mining method did not seem to affect the lines of best fit in Fig. 4. The use of *ESS* in particular seems to have

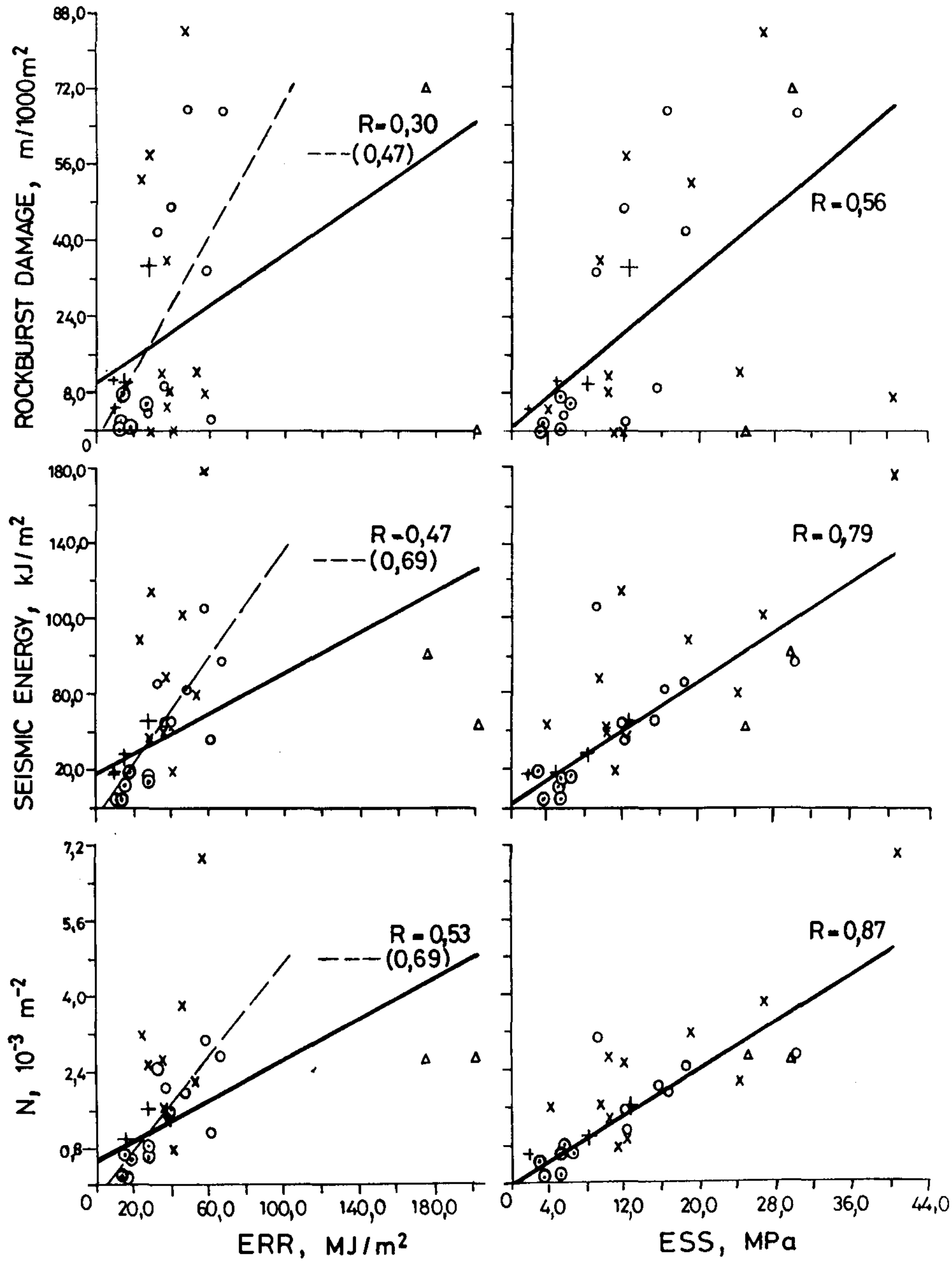


Fig. 4—Seismicity and rockburst incidence as functions of ERR and ESS, showing regression lines and coefficients. The dotted lines and numbers in parentheses apply to regions with ERR of less than 70 MJ/m²

accounted adequately for differences in span and face lengths, as well as the presence of stabilizing pillars.

Effect of Geological Features

Thorough assessment of the effect of geological discontinuities on mine seismicity requires quantification of many aspects of these features and their incorporation into suitable models of seismic slip. In this paper, it is assumed that dykes and faults, as traced from routine mine plans, had the effect of enhancing the seismicity by a constant factor, f. Total seismicity, for example N, was then related to ESS by

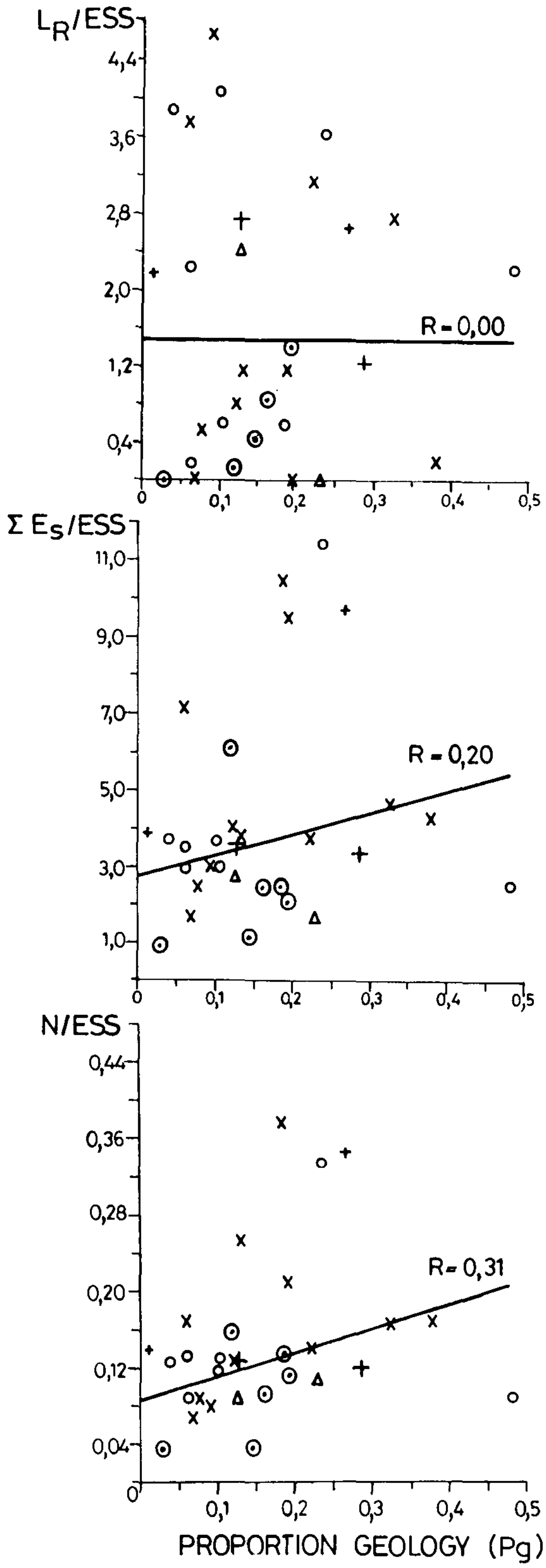
$$N = CONST \times ESS \times (1. + f \times P_g). \quad \text{.........} \quad (5)$$

In Fig. 5, N/ESS, $\Sigma E_s/ESS$, and L_R/ESS were plotted against P_g. Values of f = 2,9 and f = 2,0 were obtained for the effect of the geology on the number of seismic events and the total radiated energy respectively, based on rather poor correlation coefficients of 0,31 and 0,20. No correlation was apparent for L_R. As the contribution of dykes and faults to total ESS increase (P_g) was generally less than 25 per cent, geological features appeared to have increased the total seismicity by less than a factor of two.

Discussion

The choice of c_o = 7,5 MPa in the calculation of ESS was based on purely empirical considerations: namely, that it is convenient to state that seismicity should become zero as $\Sigma\Delta\tau_e$ becomes zero, as is shown in Fig. 4. This convenience was exploited in the investigation of the effect of geology on seismicity, as illustrated in Fig. 5.

Speculation about the meaning of this value of cohesion would be fatuous at this stage since it depends on a number of unrelated parameters, only one of which is the actual cohesion. Among these parameters are the k ratio (the ratio of horizontal to vertical stresses before mining takes place) and the rock deformation resulting



Key

O: Longwall mining with face length > 200 m	**Δ: Remnant extraction by updip mining**
Dotted symbols are used for the five larger longwall regions	**+ : Scattered mining**
	x : Longwall mining with face length < 200 m

Fig. 5—Seismicity and rockburst incidence normalized to ESS and plotted as functions of P_g. The symbols used are the same as for Fig. 4

from the seismic events that did occur. Biases in the calculation procedure are also to be expected. The correlation coefficients of around 0,8 relating seismicity to *ESS* suggests a robustness of the analysis used here that belies these apparent weaknesses.

The role of geological features in mining-induced seismicity can be divided into three categories, relating to triggering, increased seismicity due to material properties, and their effect on mine layouts.

Triggering

As a volume of rock is placed under stresses approaching the strength of the rock, fracture is most likely to originate at inhomogeneities and discontinuities. Compared with Witwatersrand quartzites, which are generally massive and homogeneous, dykes and faults provide ideal foci at which rupture can initiate. Even joints and veins provide more points of weakness than are present in massive quartzite. The surrounding quartzites would be considerably weakened by rupture within a geological feature, and fracturing can then penetrate and extend into previously unfractured rock.

Seismicity around a small longwall stope has been documented by Rorke[20], who found that seismic events with $M \approx 1$ clustered very clearly on a family of faults spaced 40 m apart and striking at an angle of about 60 degrees to the face. The source dimension of a seismic event of $M = 1$ is about 60 m (e.g. Spottiswoode[8]), so that fracturing should extend right across the quartzites between the faults mapped by Rorke. In addition, face-induced fracturing in deep-level stopes is not typically more intense near small geological features, such as faults, veins, or joints. It appears that rock deformation was not significantly more intense at the location (or foci) of the seismic events than in the surrounding rocks.

It is therefore suggested that discontinuities merely cause violent rock failure (seismicity) to originate somewhat further ahead of the face, where stress levels are lower (e.g. Fig. 3) than would be the case in massive quartzites. Triggered events are therefore expected to *reduce* the amount of seismicity that would *otherwise follow*.

The indication in Fig. 5 that the total face length damaged by rockbursts did not increase with an increase in geological features does, at first sight, seem strange. A possible explanation is that early triggering of rupture by geological features results in a greater distance of the event from the face.

Enhanced Seismicity

Factors such as the higher elastic moduli of dykes, the lower friction coefficients in fault zones, and residual stresses can result in greater co-seismic deformation within geological features than would occur in massive quartzites. In this regard, it has long been recognized that mining breast on to major geological features presents a direct rockburst hazard, and the avoidance of such a situation is currently a major consideration in mine planning.

The assessment of the actual increase in seismicity due to geological features poses difficulties that have not been sufficiently addressed. 'Normal' seismicity has to be quantified adequately before increased deformation with geological features can be measured. Fig. 5 shows an increase of only a factor of 2 or 3 within these features themselves. The net effect on the overall seismicity was that the more geologically disturbed areas, after corrections had been made for excess shear–stress change, were no more than twice as active seismically as less-disturbed areas. As mentioned above, the effect of geological features on the rockburst damage appeared to have been nil.

Layouts

Dykes and faults have had a profound effect on deep-level mining. An outstanding example of the association of geological features and mine seismicity is in the Klerksdorp and OFS Goldfields, where $M > 4$ seismic events are associated with faulting that has throws of hundreds of metres. As Napier[16] has shown, mining on both sides of these faults results in high ESS values, and considerable shear slip can result: the amount of slip is strongly controlled by the mining geometry. Considerable effort will be required to separate the effects on seismicity due to mine layouts from those due to fault properties.

Particularly in the scattered mining environment, dykes are often left intact and can become highly stressed remnants, seismically active and prone to rockbursts. Similar remnants of reef can also burst. Again, careful analysis is required to separate the effects of the mining layout from those of the material properties of the dykes.

Conclusions

Prediction of the total amount of seismicity and rockburst incidence, and planning to reduce these events, are among the more important problems in deep-level gold mining. The approach taken in the present paper to relate total seismicity and rockburst incidence to changes in ESS and to the effects of geological features in a relatively less unfaulted mine should be extended to more complex mining situations and to the application of mine planning.

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