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Seismicity associated with deep-level mining at Western Deep Levels Limited

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Synopsis

During the past five years, several research projects on the causes of mining-induced seismicity have been carried out by the Rockburst Research Department at Western Deep Levels Limited. This paper summarizes the results of these investigations.

Several types of mining-induced seismic events are addressed, and models of their mechanisms are presented. It is shown that most of the seismicity results from mining in geologically disturbed areas, and ways and means are discussed to reduce the seismic potential.

Stabilizing pillars, for instance, have been introduced to reduce stresses at the stope face and to alleviate the face-bursting problem. Facebursts still occur in areas of very low stresses, and pillars became the source of very large seismic events ($M>3$). At this stage, the understanding gained of pillar-associated events allows a review of current mining practices. Further, it makes possible an examination of the efficiency of measures to alleviate the effects of various seismically prone situations.

Samevatting

Daar is gedurende die afgelope vyf jaar verskeie navorsingsprojekte oor die oorsake van mynbougeïnduseerde seismisiteit by Western Deep Levels Limited aangepak. Hierdie referaat gee 'n opsomming van die resultate van hierdie ondersoeke.

Verskeie soorte mynbougeïnduseerde seismiese gebeurtenisse word ondersoek en daar word modelle van hul meganismes aangebied. Daar word getoon dat die meeste seismisiteit die gevolg is van mynbou in geologies versteurde gebiede en metodes en maniere om die seismiese potensiaal te verlaag, word bespreek.

Stabiliseringspilare is byvoorbeeld gebruik om spannings by die afboufront te verlaag en die probleem van frontbarstings te verlig. Frontbarstings kom nog voor in gebiede met baie lae spannings en pilare was die oorsaak van baie groot seismiese gebeurtenisse ($M>3$). In hierdie stadium maak die begrip van pilaarverwante gebeurtenisse 'n hersiening van huidige mynboupraktyke moontlik. Verder maak dit ook 'n ondersoek na die doeltreffendheid van maatreëls om die uitwerking van verskillende seismies geneigde situasies te verlig, moontlik.

INTRODUCTION

The gold mine Western Deep Levels Limited (WDL) is situated approximately 70 km to the west of Johannesburg. The mine extracts two gold-bearing reefs: the Ventersdorp Contact reef (between 1500 and 2500 m below surface), and the Carbon Leader reef (between 2300 and 3500 m below surface). The two reefs are inclined by about 20 degrees and are nearly parallel. Mining operations are carried out with the use of three shafts.

Seismicity is experienced as the major obstacle during mining operations at WDL. Approximately 700 seismic events ($M>0$), 80 per cent of which were located on the mine itself, are recorded by the mine's seismic network per month. The remaining 20 per cent are spread between the neighbouring mines of WDL. As mining operations extend laterally and advance deeper, aspects of mining-related seismicity did, and still do, attract interest. A number of papers describing detailed observations, and research efforts and results have been published[1-3]. The present paper builds on this expertise, and presents some results that, it is hoped, will contribute to safer mining operations.

HISTORICAL REVIEW

Generalizations are always a great help when a wide area of problems is addressed, even if the phenomenon of rockbursts is regarded as a very specific one. Although general trends are less informative, they allow a certain domain of interest to be split into categories, thus clarifying the different causes.

As seismicity levels are high in deep-level mining, a reasonable amount of data could be gathered and evaluated. The following paragraphs try to highlight some issues that are likely to be raised in many discussions regarding this issue.

Time

Most mining-induced seismic events are observed within 4 hours of a blast (Figure1). The rest of the seismicity is spread evenly over the remaining period of 20 hours. This observation does not allow any further conclusions. However, the distributions of the magnitudes during these two time spans show a remarkably different slope. Larger events ($M>2$) occur more often 4 hours after the blast than shortly after the blast, whereas most small events ($0<M<1$) are triggered during blasting operations or are released shortly thereafter.

The average weekday distributions demonstrate that all events ($M>0$) are evenly spread throughout the week (Figure 2). Similar seismicity levels are experienced from Mondays to Fridays. On average, Saturdays experience

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approximately half the seismicity of a normal weekday since production carries on only every second Saturday. The lowest seismic activity is experienced on Sundays, when no blasting operations are normally carried out.

More light can be shed on the problem from an examination of the distribution of larger events ($M>2$) during the week. Now, a slight increase between Mondays and Fridays becomes apparent (Figure 3).

Annual distributions (Figure 4) show no time-dependence of seismic activity, either for small or for large events.

Data from the previous five years (1986 to 1990) support the time dependence on a small scale. When the two mining horizons, VCR and CLR, were separated and only the larger events ($M>3$) were considered, the following observation was made: most (70 per cent) large events occurred on the VCR *4 hours after the blast*, contrary to large events on the CLR, which tend to occur mainly (70 per cent) *within 4 hours* of the blast. Hence, as one would expect, inelastic processes, which also result in an excessive amount of closure, take place faster at greater depth (CLR) than at intermediate depth (VCR). The process that leads to the final occurrence of larger events is governed by the time-dependent behaviour (creep) of the rockmass surrounding underground excavations. The time-dependent deformation of the rockmass should therefore be given more attention in modelling exercises.

Although numerous tests have been conducted on rock samples, very little is known about the time-dependent characteristics of the rockmass.

A more detailed study[5] on seismicity related to blasting versus seismicity not related to blasting, which tried to exclude effects brought about by dykes and faults, has confirmed the time dependence.

Space

Most seismic events occur in close proximity to the reef horizon[6] (less than 50 m from the reef). It can be noticed that larger events ($M>3$) show a tendency to occur in the footwall rather than in the hangingwall. Factors that contribute to this asymmetry are not systematic mislocations (most events $M>1$ are located around the reef horizon), owing to the existence of pillar foundation and abutment failures. However, some large events were also observed on WDL that originated from very deep or abnormally shallow areas. So far, the deepest large event ($M>3$) was located in a shaft pillar 400 m below the projected level of mining. Obviously, the point where the event originated fell into the zone where the changes in stress due to the surrounding mining excavations were substantial.

Nevertheless, a few other exceptions, such as failure of the rockmass along the sidewalls of abutments, have been noticed.

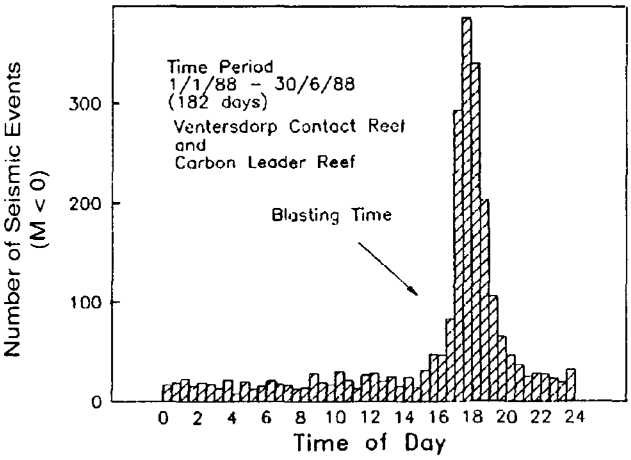


Figure 1—Diurnal distribution of mining-induced seismicity[4]

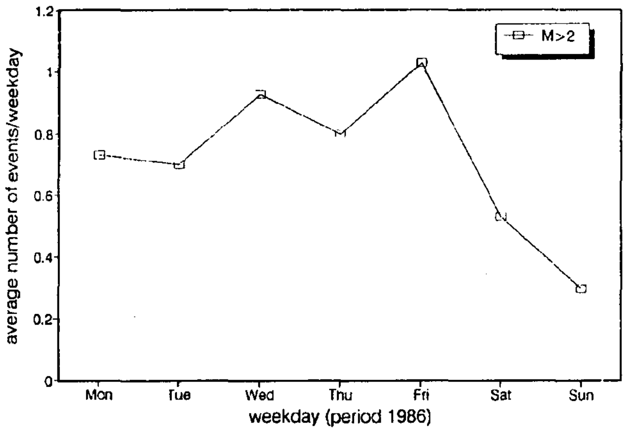


Figure 3—Weekday distribution of larger events ($M>2$)

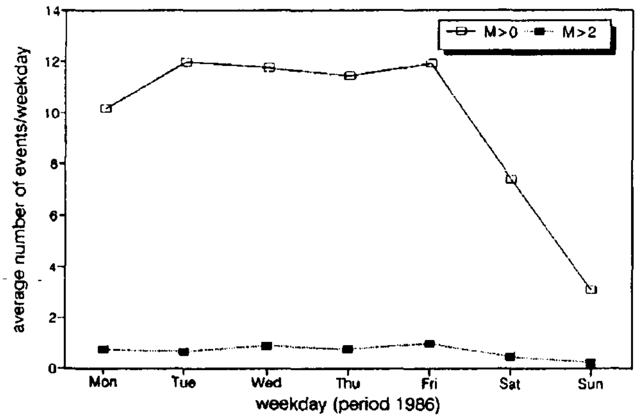


Figure 2—Weekday distribution of seismic activity ($M>0$)

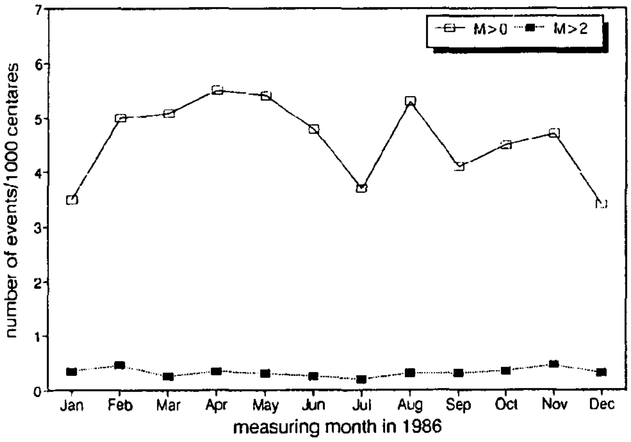


Figure 4—Annual distribution of seismicity

Production

The correlation of production with seismicity is meaningful only if a large range of data can be evaluated. Figure 5 shows the correlation between these two data sets for M>0 from the Carbon Leader reef. The correlation suggests a linear relationship between production and the number of events (M>0) during the same time intervals. This fact is not surprising since the amount of mining represents the amount of stress change that ultimately leads towards instability. The slope in Figure 5 (events versus centares) is often used in the industry to express seismicity levels taking account of the dependence of seismicity on the amount of production

Larger events (M>2) do not correlate with production—no relationship exists any more. Other factors than centares mined or volume extracted determine the stability of underground workings: rock properties, geological features, and mining geometry.

OBSERVATIONS

Shear-slip Events

It is common knowledge that most of the very large seismic events (M>3) in the vicinity of mine workings occur along geological features—62 per cent on WDL (Figure 6). This fact is also reflected in the seismic behaviour of the four major gold-mining districts in South Africa. Not only do they experience dissimilar levels of seismicity, but their individual maximum expected magnitude also differs[7]. On the assumption that the magnitude of an event is directly related to the seismic moment[8], which itself describes the extent of the rupture area, mining regions with faults of large throws (larger than 100 m) are expected to release much larger seismic events than other regions where faults are not regarded as an obstacle to mine planning and longwall mining can be carried out. It should be noted, however, that no stringent relationship between the seismic moment and the magnitude exists; otherwise, the stress drop would be identical for all seismic events.

Seismic observations have shown that faults of minor throw (less than 10 m) are also able to release events of larger magnitudes (M>3), but have never so far exceeded a magnitude of 4,2 on WDL.

The following paragraphs document some larger events and try to explain their mechanisms.

Fault Slip

The classical type of a seismic event constitutes slip along a plane of weakness (fault or dyke contact). Although slip along a discontinuity seems to be the simplest case of a mining-induced seismic event, the modelling of real rockmass behaviour has to allow for uncertainties such as varying friction properties and the geometry of a fault plane. The concept of excess shear stress (ESS)[9] describes the basic relationship between prevailing shear stress (T) and the dynamic properties of a fault plane:

$$ESS = T - \tan(a)*S_n,$$

where S_n is normal stress and a is the angle of internal friction.

Therefore ESS represents the cohesion, or intrinsic shear strength, along a fault that has slipped, particularly if a linear relationship between shear and normal stress (Coulomb–Navier) is assumed and no difference exists between the coefficients of the dynamic and the static friction.

Limitations and benefits arising from the application of the concept of ESS were already recognized at its introduction and later when a number of case studies were carried out[10–12]. Main reasons for the limited application of the ESS concept were the extreme sensitivity of ESS calculations to small changes (less than 20 per cent) in the ratio of horizontal to vertical stresses (k ratio, normally assumed to be 0,5) and the angle of internal friction.

Deviations from the planar geometry of a fault plane create additional problems. Suddenly asperities (areas of higher friction) occur at places where excess shear stresses would be negative if the undulation of the fault plane were not accounted for. Indirect proof of the ESS concept was found during a monitoring exercise involving the Brand fault in Welkom[13]. The fault plane was modelled extensively, all the available survey data being taken into account. Stress calculations along this surface revealed an area of positive ESS (which was associated with a seismic event M>1 but small displacement). The distinction between seismic and aseismic deformation (creep) is substantial in this context. At this stage, emphasis is laid on the detection of asperities[14] that exist along fault planes to delineate areas of potential seismic activity.

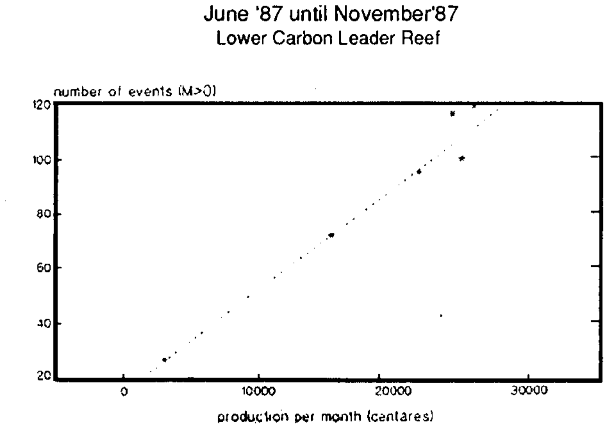


Figure 5—Seismicity (M>0) versus production

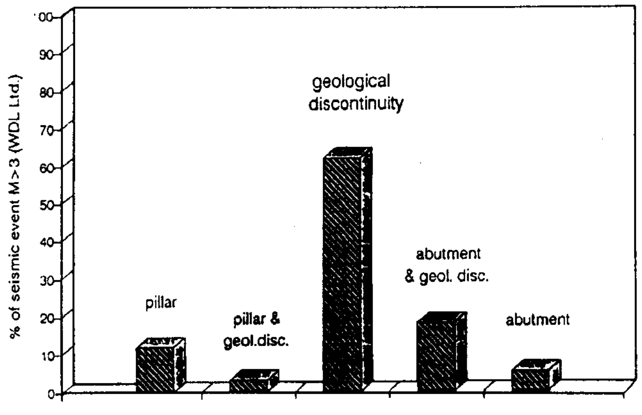


Figure 6—Large seismic events (M>3) and where they occur[6]

Slip along Dyke Contact

Dykes are the most common geological feature on WDL. Since the beginning of mining operations at WDL, some dykes have been recognized as potential hazards, which has led to the idea that some dykes are rockburst-prone and some are not. Seismicity associated with dykes was found at WDL to be mainly of a shear-slip nature. Not a single dyke that was mined during the past five years on WDL remained 'aseismic'. Mining through these features was always accompanied by an increase in the number of seismic events, and led to exceptionally large events (M>2,8), which do not otherwise occur near a stope face except in the presence of a fault.

Fairly often, a dyke is accompanied by dyke-parallel faulting or joints[15]. This increase in faulting or jointing tends to occur in the ultimate vicinity of the dyke—between 5 and 10 m from the dyke contact. This is the area where small rockbursts (facebursts) become more and more pronounced. Once the dyke contact has been sufficiently exposed (e.g. for 50 m), larger events (slip along the dyke contact) are likely to take place.

However, some dykes behave differently. Bushveld intrusives tend to bulge out in the footwall[16]. By the time mining operations reach the dyke contact on a reef, a large portion of the dyke shoulder in the footwall has been effectively overstoped (Figure 7). So far a number of events have been observed along the southside of the Peggy dyke contact deep in the footwall, 50 m before the actual dyke contact on the reef horizon was reached, indicating bulging of the dyke 100 m below reef. The extent of the 'shoulders' of some of the Bushveld intrusives has been confirmed by boreholes.

The classical case of a rockburst during which the stope face is ejected and a seismic event of small magnitude (e.g. M=1) is released still prevails inside the dyke since many dykes on WDL have been found to be inhomogeneous and jointed (e.g. the Xmas dyke). Rock properties within a dyke differ from one another, especially when the chilled zone of the dyke (fine-grained) or the centre of the dyke (coarse-grained) is examined (Figure 8).

However, these properties reflect only the general composition of the dyke, and not its strength, which is determined by the inhomogeneities of another nature: joint sets within dykes can be excessive, and can cause unstable situations identical to facebursts.

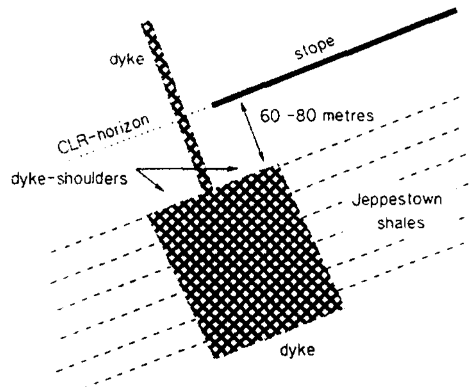


Figure 7—Bulging of Bushveld intrusive dykes

Abutment Failure

The sidewalls of longwalls (abutments) represent areas of stress concentration and are therefore prone to seismic activity at greater depth. In 1986, acoustic emissions were observed[17] before and after an event of M=3 occurred near an abutment approximately 2800 m below surface. After ten events (M >2,8) of this nature (July 1987 and July 1989)[18], some common features became apparent.

(1) First motions indicated footwall lift in the old mined-out area.

(2) Events occurred deep in the footwall (60 to 100 m below the reef) along the abutment between 60 and 100 m ahead of the new approaching longwall (which changed the mining geometry from an abutment to a pillar).

(3) Abutment failures tended to occur in the proximity of dykes or faults.

(4) The age of the abutment had no bearing on its seismic activity. (Age refers to the time span between the creation of the abutment and its failure.)

A mechanism that could explain abutment failure involves two stages (Figure 9). During the first stage, stress weakening might create unfavourable conditions. Extension fractures near the edge of the excavation continue as shear fractures into the rockmass, creating a large plane of weakness. At a later stage (Stage 2), the stress tensor rotates when the new longwall approaches, and shear slip is initiated. A fault or dyke intersecting the abutment can facilitate the strain release since it constitutes a potential plane of weakness. Only recently (1st January, 1991), slip along a dyke contact was initiated by an approaching longwall deep in the footwall (100 m below the reef) at the position where the dyke intersected an abutment.

Events Not Caused by Shear Slip

The question arises as to whether a non-shear-slip event can exist at all. On several occasions, even though their frequency is low, seismic events were observed that could not be explained by a double or single couple of forces. Sometimes all first motions of the geophones were dilatational, which indicates an implosive mechanism[19]. On other occasions, both types of first motions were observed—compressive and dilatational but, in a first-motion analysis, they could not be separated by a set of orthogonal fault planes. Both cases indicate an activation of more than one plane of weakness on a small scale (implosive, associated with a small magnitude) or on a large scale (compressive and dilatational first motions but cannot be separated by orthogonal planes—associated with

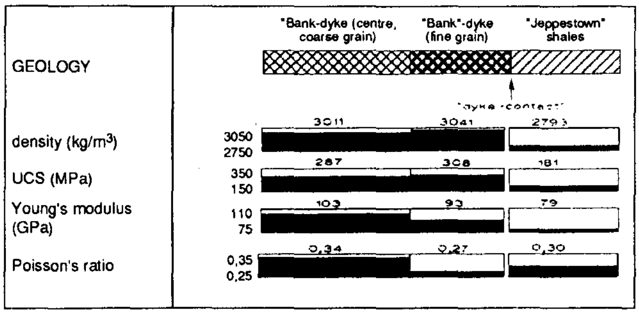


Figure 8—Rock properties near a dyke contact

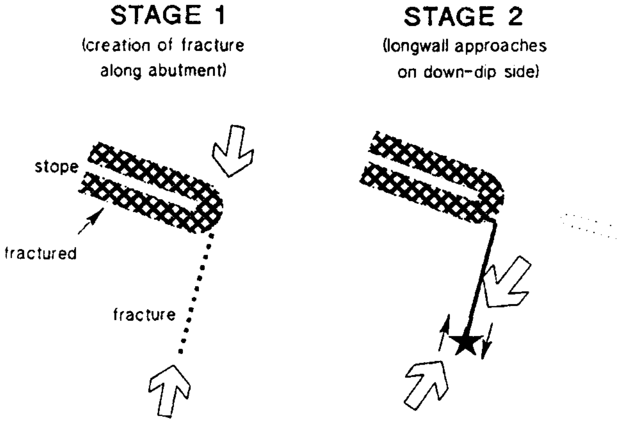


Figure 9—Proposed mechanism of abutment failure

an event of large magnitude). It should be noted that a seismic source with a shear dislocation of less than 80 per cent of the total displacement produces mainly dilatational first motions[20]. The interference of a fault with a stope would constitute such a scenario.

Implosive seismic events, based on first-motion observations, could therefore still result from shear failure of the rockmass, although a first-motion analysis indicates the opposite. This ambiguity can be resolved only from a determination of the seismic moment tensor.

Pillar-foundation Failure

Stabilizing pillars were introduced at WDL in 1980 to reduce stresses at the stope face and to limit the closure in the back areas. In the beginning, 20 m pillars at an extraction ratio of 85 per cent were left behind for this purpose. Extensive fracturing was observed along the up-dip side of these pillars, which was combated in 1985 by a change in pillar layout to 40 m pillars. As the extraction ratio remained the same (85 per cent), the span between the pillars had to be doubled. At the same time, the location accuracy of the seismic system at WDL was considerably improved by a change from automatic to manual locations, which allowed a consideration of geophone performance, thus avoiding wrong interpretations of the seismic signals. Since then, the seismic activity at the mine can be used to gauge the effectiveness of different mining layouts and support strategies. Monitoring the behaviour of stabilizing pillars became one of the main tasks, and remains high on the priority list of the mine's research team.

Numerous investigations were carried out[21-23] to evaluate the efficiency of these regional support units and in terms of their seismic potential.

A research study[24] in 1989 revealed some typical features related to foundation failures. It was established that large seismic events along pillars are much less dependent on blasting time than their, mainly geology-related, counterparts (Figure 10). Another result indicated that the main deformation process along pillars takes place some distance (about 100 m) back from the stope face along the edge of the pillar, and recurs once a certain longwall advance has been accomplished[25]. Further, the width of pillars (between 20 and 60 m) was found to have no bearing on the magnitude of seismic events[26]. This result indicated that the common design criterion for pillars—the average pillar stress—is inadequate. Instead, shear stresses along a pillar's edge should be considered for pillar design, and numerous case studies should be carried out to establish a guideline for pillar design in deep mining.

Acoustic emissions observed from a foundation failure showed clearly that the seismic activity was concentrated along the edge of a pillar, while the core of the pillar remained more or less unaffected[25]. This observation explains why the magnitude of an event does not correlate with the width of pillars since the determining factor is the extent of failure along the edge of a pillar (which is independent of the width, the mechanism leaving the pillar core intact), and not across the pillar (dependent on width, the mechanism being of the crush type).

Some foundation failures could be interpreted definitely as shear-slip events; others could not. (Shear-slip events were observed along pillars that had been left along geological discontinuities, e.g. Wuddles dyke on the VCR.) Finally, based on all the seismic and underground observations, several models of foundation failures were postulated[25] (Figure 11).

When the performances of pillars on the shallower VCR horizon were evaluated[27], the effect of footwall geology was recognized to be of utmost importance. Two mining sections at the same depth (approximately 2200 m below surface) had been subjected to completely different seismic patterns. One section had been affected 16 times by foundation failures ($M>2,8$), while the other section experienced only one event of this nature during the same period (January 1986 to June 1989). The reason for this discrepancy was found in the foundation rocks of the reef: areas with quartzitic footwall rock formations experienced the highest seismicity levels along pillars. The other mining section is underlain by shales, which tend to deform plasticly and hence do not permit shear stresses to build up until they reach critical levels.

Crush

The intrinsic failure of a pillar has not been observed on WDL with the seismic network, but seismic events of moderate magnitudes ($M=1$ to 2) and implosive mechanisms (all the sensors surrounding the rockburst moved towards the source) have sometimes been observed. The damage pattern resembles itself in many cases, and it is

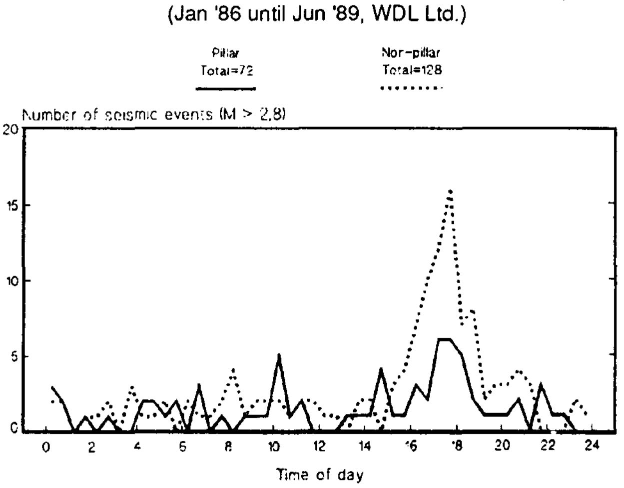


Figure 10—Diurnal distribution of large events (M>2,8)

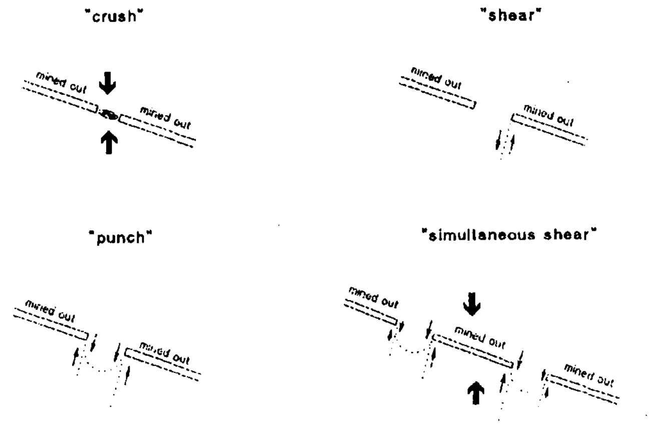


Figure 11—Proposed mechanisms of foundation failures

striking that this type of event, which seems to be very common on the VCR horizon, seldom occurs on the deeper CLR horizon. The word *faceburst* has been used in the past to describe and distinguish this seismic event from others that are related to different mechanisms (shear failure of the rockmass on a large scale). The following observations in connection with facebursts were made:

(1) facebursts occurred mainly on VCR (stoping width slightly higher than on CLR)
(2) control of the hangingwall was sometimes lost during previous blasts
(3) reef roll was sometimes apparent
(4) the magnitude averaged $M = 1{,}1$
(5) the energy-release rate was very low (less than 10 MJ/m^2).

A search for the causes of these facebursts gained momentum after these common factors had been detected. As a working hypothesis, the following two scenarios were adopted.

Scenario A

(1) Reef roll provokes drilling into the hangingwall.
(2) A fall of ground occurs during the blast, leaving the brow behind.
(3) An undercut is attempted to restore the stoping width.
(4) Stresses at the stope face are altered by the presence of the brow.
(5) A faceburst occurs as the result of excess shear stresses at the stope face (facilitated by the presence of joint sets and an increase in shear stresses ahead of the stope face due to the presence of the brow).

Scenario B

(1) The density of the joint set increases (e.g. while approaching a dyke).
(2) The stope moves from stable ground (joint spacing large) to unstable ground (reduced joint spacing).
(3) A faceburst occurs as the result of the reduced strength of the stope face (buckling of the stope face).

PRACTICAL IMPLICATIONS AND DISCUSSION

The classification of rockbursts assists in the adoption of proper counter-measures. Several categories of seismic events that lead to rockbursts have been identified according to their striking resemblance in terms of damage, seismicity, and existing mining configurations. It is hoped that the chart shown in Figure 12 can be of assistance when seismic problems occur in a mining environment for which only sparse seismic information is available. Once the cause of an event has been established, efforts can be concentrated towards the prevention or control of its effects.

The kind of seismic event that is created by slip along a plane of weakness (fault slip or slip along a dyke contact) can be 'controlled' by two means:

(a) stabilizing the feature (e.g. mining geometry), or
(b) de-stabilizing the feature (e.g. triggering blasts).

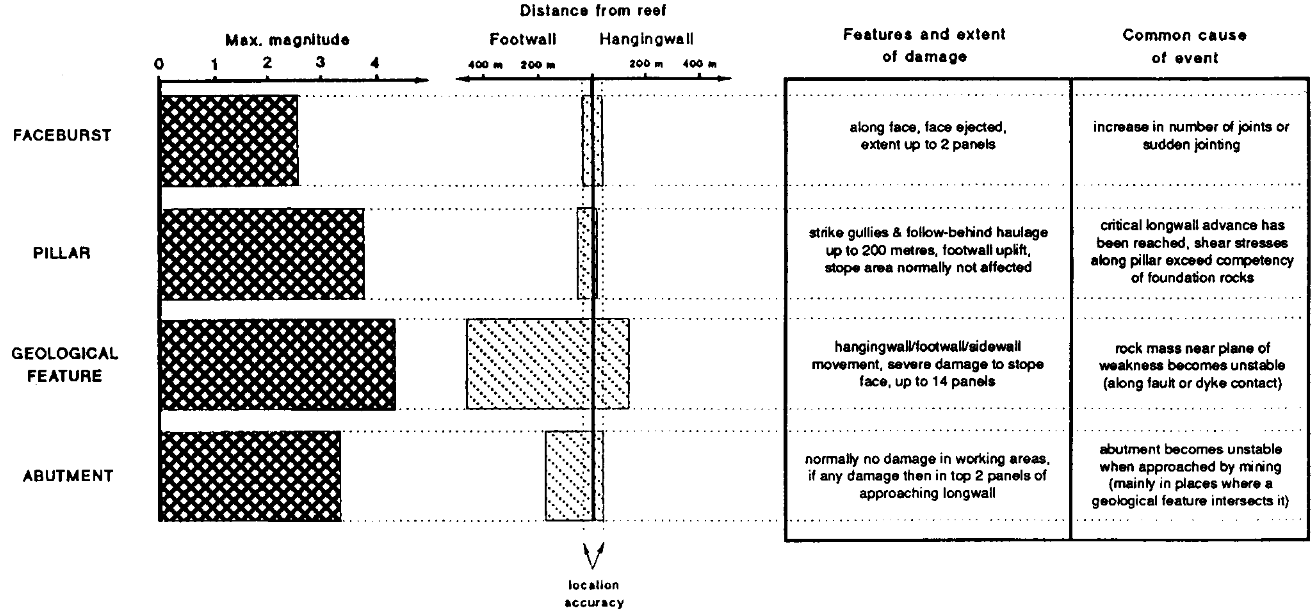
The first method involves proper orientation of the longwall shape when negotiating a geological feature. Bracketing the feature creates artificial asperities along the fault or dyke contact that help to stabilize the rockmass. Bracket pillars will certainly become seismically active, but at a later stage after mining has been completed in the feature's vicinity. Triggering is the most critical method since very little is known about the potential of initiated fault slip. Also, a balance must be found between the size, type, and pattern of the charge and the damage due to manmade fracturing of the rockmass that might call for additional support.

Stope support can assist only in minimizing the damage (by reducing the extent of falls of ground), but cannot prevent the seismic event from happening. Backfill, for example, has been found not to be effective in controlling geological features (Figure 13). In practice, most panels, which advance through geological features, are not backfilled because the provision of sufficient hangingwall control by area support (packs) becomes imperative[28].

Although backfill does not seem to contribute towards the stability of excavations near faults or dykes, its potential in combating the foundation failure of stabilizing pillars is very high indeed. Backfill becomes more and more effective with increasing compression, which is the case in the back area, especially on the deeper horizon on the Carbon Leader reef. Backfill is expected to reduce the load on pillars, thus preventing the edges of the pillar exceeding the critical shear stress that would ultimately lead to foundation failure.

Abutment failures are not likely to be controllable, since their source region extends very deep into the footwall and trigger blasts become unpractical. Moreover, the mining geometry cannot be changed to prevent this type of event from happening. The only remedy is to accept that such an event is possible, and to avoid placing footwall developments near the intersection of an abutment and a dyke or fault. As this region is weakened by the presence of the geological feature, it is likely to fail when approached by a longwall.

The most effective counter-measure for crush type events, which affect small areas, could be de-stressing blasts. This method is critical because there is uncertainty about its viability and effect, and it demands the same attention as trigger blasts. Most encouraging would be a specialized blasting method that can be incorporated into the production blast pattern.



	Features and extent of damage	Common cause of event
FACEBURST	along face, face ejected, extent up to 2 panels	increase in number of joints or sudden jointing
PILLAR	strike gullies & follow-behind haulage up to 200 metres, footwall uplift, stope area normally not affected	critical longwall advance has been reached, shear stresses along pillar exceed competency of foundation rocks
GEOLOGICAL FEATURE	hangingwall/footwall/sidewall movement, severe damage to stope face, up to 14 panels	rock mass near plane of weakness becomes unstable (along fault or dyke contact)
ABUTMENT	normally no damage in working areas, if any damage then in top 2 panels of approaching longwall	abutment becomes unstable when approached by mining (mainly in places where a geological feature intersects it)

Figure 12—Categories of deep-mining-induced seismic events (based on data from WDL, 1985-1989)

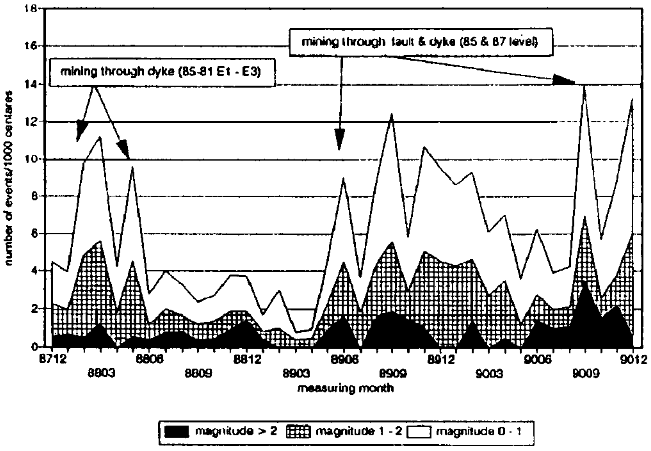


Figure 13—Seismicity of a backfilled mini-longwall at East mine

Seismic data can be used to monitor stress changes brought about by mining, thus indicating the true rockmass properties. By evaluating this information, the rock-engineering practitioner gains an insight into the local rockmass behaviour and can take appropriate action, such as intensified local support that minimizes the extent of falls of ground associated with seismic activity. When modelling is carried out, the time-dependent deformation of the rockmass should be taken into account.

Monitoring of the rockmass with all available means solves debatable questions as to whether regional support strategies satisfy our expectancies. Seismic networks can assist here as a monitoring unit on a large scale to delineate critical areas where additional steps need to be taken to ensure safe mining operations.

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