Deep Mining 07 — Y. Potvin (ed)
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https://papers.acg.uwa.edu.au/p/711_11_Wienand/

# Planning and Practice of Remnant Pillar Mining — A Case Study

**G.A. Wienand** *Driefontein Division, Gold Fields Mining, South Africa*

**R.I.L. Ferreira** *Driefontein Division, Gold Fields Mining, South Africa*

## Abstract

*The extension of the life of some shafts by mining extractable, accessible and economically viable remnant pillars, has become much of a necessity. The geotechnical investigation into the potential for successful extraction of these pillars is crucial, and is approached in a multi-disciplinary manner.*

*This case study outlines the mining methodology, and relates the initial investigation to the practical experience of extracting a 8000 m$^2$ remnant pillar in a tabular reef at 1600 m depth, at the Thabelang "Let's be happy" Shaft of Gold Fields' Driefontein mine.*

## 1 Introduction

The auriferous tabular conglomerates on the rim of the Wits Basin in South Africa have been mined for many decades, the deeper levels of which are now approaching some 3500 m below surface. The mining of in-stope remnant pillars has become an increasing occurrence, particularly in the older shafts, where the orebody has been extensively depleted.

A feasibility study of mining one such pillar – the so-called 18-23 Carbon Leader Reef pillar – assesses the geotechnical environment, underground conditions, historical seismic data and its limitations, the seismic hazard relative to other mining areas, probabilities of reoccurrence of seismicity, mining design options and numerical simulations. An initial phase of mining, which amounts to 50% extraction of the pillar, considers local geology and mining geometry, and the stope support practice. Health and safety information provides a feedback loop during operations. A planned secondary phase, amounting to 85% extraction, considers in-situ observations, seismic behaviour of prior mining and updated numerical modelling.

Special precautions endeavour to maintain rigid adherence to obligatory specifications, improve rock face and hangingwall conditions through pre-conditioning blasting, limit the daily production to a single shift, introduce dynamically-capable support at the stope front, control the rate of advance, enhance seismic sensitivity and location accuracy by augmenting the regional seismic coverage with the installation of additional ground motion sensors, and log the real-time seismic response to production.

This paper does not test new mining, monitoring or assessment methodologies or hypotheses; rather, it uses well-established concepts in routine applications, and presents an experience in remnant pillar extraction.

## 2 Pre-mining feasibility of pillar extraction

A glossary of terms describing local mining terminology is appended (Appendix A).

### 2.1 Old information

A number of pillars, favourably identified from positive consideration of geotechnical extractability, accessibility and economic viability, were earmarked for extraction. A search for pertinent information regarding the reasons for the remnant being formed was then attempted. In the case of the 18-23 pillar (i.e. located on 18th level, 23rd crosscut), no documentation was readily available: old records appear to be non-existent, as the last mining in the vicinity of the pillar took place in 1973, and only a little information could be inferred from stoping plans. The pillar is situated between the 18-23 and 18-24 cross cuts, the latter of which intersected reef in June 1957. Mining between raise lines was conducted in a 'scattered' layout, due to its flexibility and applicability at medium (1600 m) depth (Jager and Ryder, 1999). The eastern side ledging of the 18-23 raise was measured in May 1966. The ledging to the east of the 18-23 raise was not completed. The overstoping of the 18-24 crosscut to the west of the 18-24 raise was measured in February 1973.

Meetings were arranged with ex-employees who were acquainted with past mining operations. These meetings were fruitful in identifying areas where 'old gold' could be found but delivered no information as to the reasons for leaving the 18-23 pillar.

## 2.2 Geotechnical environment

The 18-23 pillar is situated in the narrow single seam Carbon Leader Reef (CLR). The strike of the tabular reef is approximately 700, with an average dip of 230. The pillar is isolated within a faulted expanse of old mining. It has a fractured outer skin and its intermittent extraction is linked to a brief history of recorded seismicity.

### *2.2.1 Stratigraphy of the immediate CLR hangingwall*

The behaviour of the Carbon Leader hangingwall is dominated by the presence of the Green Bar horizon. This is a green coloured chloritoid shale which is generally 1.5 m thick, located 1.0–1.5 m above the top of the reef contact, with a uniaxial compressive strength (UCS) of 140–170 MPa. At the bottom of the Green Bar there is normally a weak parting plane sometimes associated with a thin sheared vein quartz layer. The quartzites above and below the Green Bar are typically strong and brittle (UCS of 180–220 MPa), but the weak parting at the base creates a potentially unstable beam and falls of ground can occur up to this parting if the beam is broken due to blasting and stress fracturing ahead of the stope face.

The top of the Green bar is a gradational sedimentary contact and does not act as a plane of weakness, although failures up to this top contact have been known to occur.

### *2.2.2 Stratigraphy of the immediate CLR footwall*

The footwall of the Single Band CLR consists of quartzites (also with UCS of 180–220 MPa), with minor grit and conglomerate bands. Some of these bands, which include the North Leader, can be mineralised but are not payable reefs. The footwall is typically a strong and brittle rock mass that does not cause significant strata control problems.

The original 18-23 pillar (post-1973) is triangular in shape, with the base on strike and an apex on the down-dip side. The pillar measured just under 8000 $m^2$ at a depth of 1.6 km below surface.

Access to the pillar was gained through the rehabilitation of the 18-23 crosscut and reef drive. Subsequently, a shallow follow-behind footwall drive was developed to improve access to the pillar.

## 2.3 Underground investigation

The underground investigations to the 18-23 pillar were accomplished with input from a multi-disciplinary task team, including Rock Engineering, Safety, Ventilation, Geology and Production personnel. In order to gain access to site, the ventilation seals were broken to allow fresh ventilation to enter the 23rd crosscut. Only when the Ventilation department had declared the crosscut free from noxious gases, was the rest of the team granted entrance to examine the condition of the crosscut and reef drive. The required remedial actions were discussed and recorded, for inclusion in the financial feasibility study. The access-ways to 18-23 were found in fairly good condition, considering the length of time elapsed since traffic ceased. Due to deterioration, all the sets had to be re-cribbed, but only a few set legs needed replacing. The crosscut was top-cut vamped, and the rail tracks had been removed. New tracks were installed, together with new air and water piping and electrical cabling.

## 2.4 Seismic hazard

Stresses, stress fracturing and the rockburst hazard are normally moderate for mining at medium depth (1000–2250 m) in narrow tabular excavations (Jager and Ryder, 1999, p. 30). Remnants, by virtue of their nature, will experience higher stress levels with diminishing size, also dependant on the mining spans and total stope closure that has occurred behind the face. The expanse of prior mining around the pillar to be extracted is significant, and a number of discontinuities, trending SW-NE, are located in its northern and southern vicinity. The seismic risk is raised as the pillar width-to-height ratio decreases, weakening its stable load-carrying ability, and promoting the potential for sudden inelastic failure. Experience shows that magnitudes less than about M1.8 are usually within the expected normal range of energy dissipation around the stope with mining. Large-scale shear effects along geological discontinuities or through intact rock, normally at highly stressed abutments, or along bedding planes, tend to generate much larger events. 'Slip' (relative dislocation) of discontinuity surfaces or planar weaknesses is recognised as a common failure mechanism.

The series of plots shown below characterise the seismic behaviour of the rock mass in response to previous mining in the area of interest.

### *2.4.1 Seismic coverage, data quality and history*

Mining of the 18-23 pillar was initiated with some coverage of dynamic movements and deformations afforded by an array of sensors, which now amount to nine tri-axial geophones, laid out in a non-ideal configuration, as shown in Figure. 1. The closest sensors were positioned 1100 m away. The errors in location of seismic events were anticipated to be up to 100 m, compromising the spatial resolution significantly. The installation of an additional geophone station within 150 m of the remaining pillar should improve the location accuracy by some 50%. The network is nevertheless sensitive to micro-seismicity, providing a minimum recordable magnitude (Mmin) of $M_L$ -1.3 (Figure. 2).

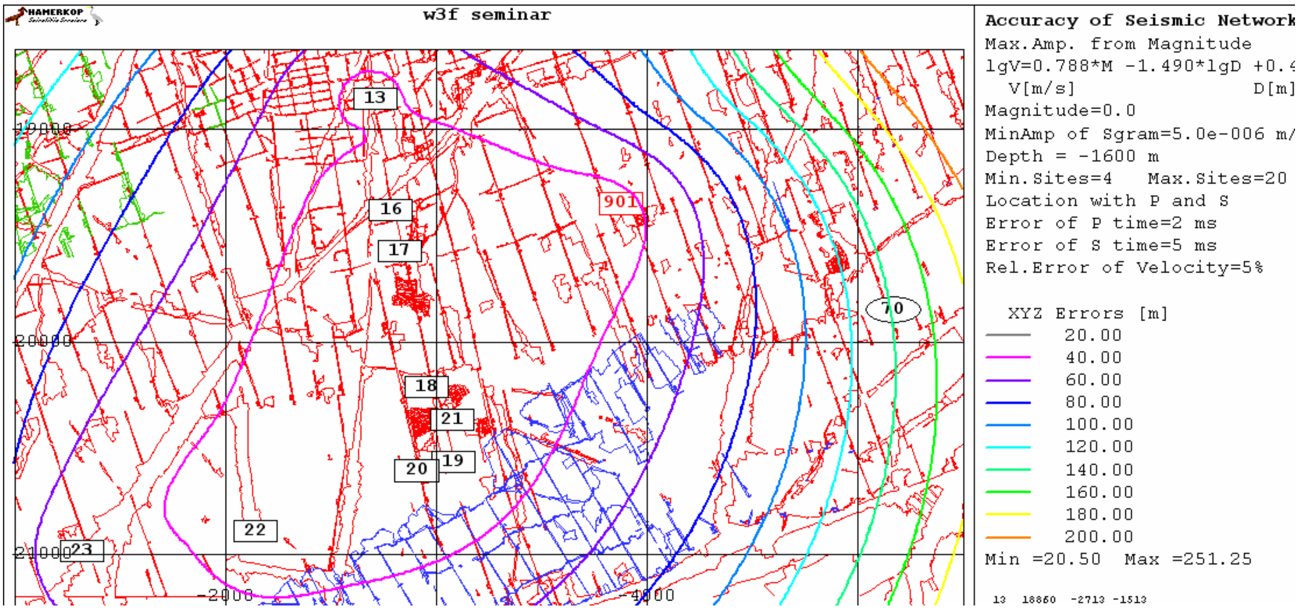


**Figure 1** **Contour plot delineating the accuracy of locations in terms of 3D spatial XYZ errors (m) to M 0.0 at a depth of 1600 m, for a minimum of 4 associated stations, given the configuration afforded by the numbered array of geophones. The arrow points to the 18-23 pillar position. The installation of an additional seismic station close to the pillar improves the location accuracy by some 50%**

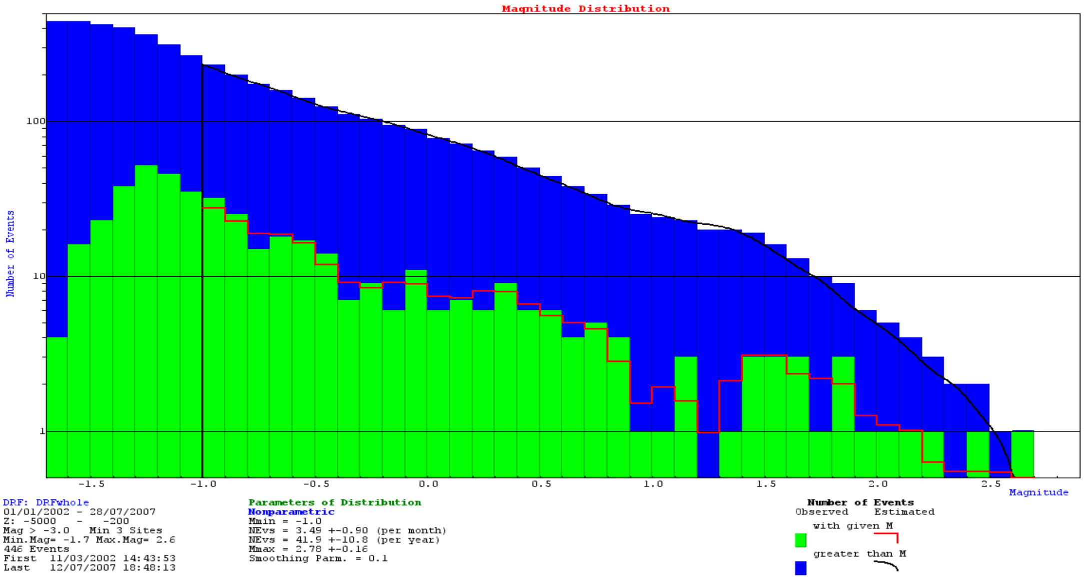


**Figure 2** Frequency-magnitude distribution of the seismicity associated with the pillar extraction, recorded up to July 2007. A non-parametric line-fitting approach was chosen, to cater for lack of completeness in the dataset. The sensitivity of the seismic network allows small events to be detected (i.e. the threshold of completeness is enumerated by Mmin $M_L$ -1.3). A maximum magnitude (Mmax) of 2.8 is expected

The locations of all events recorded in the time period January 1999 to July 2007 are shown in Figure 3. The scatter of locations is expected, although the cluster of seismicity appears biased towards the north of the 18-23 pillar position. The larger events are likely to be associated with the geological features, particularly north of the pillar.

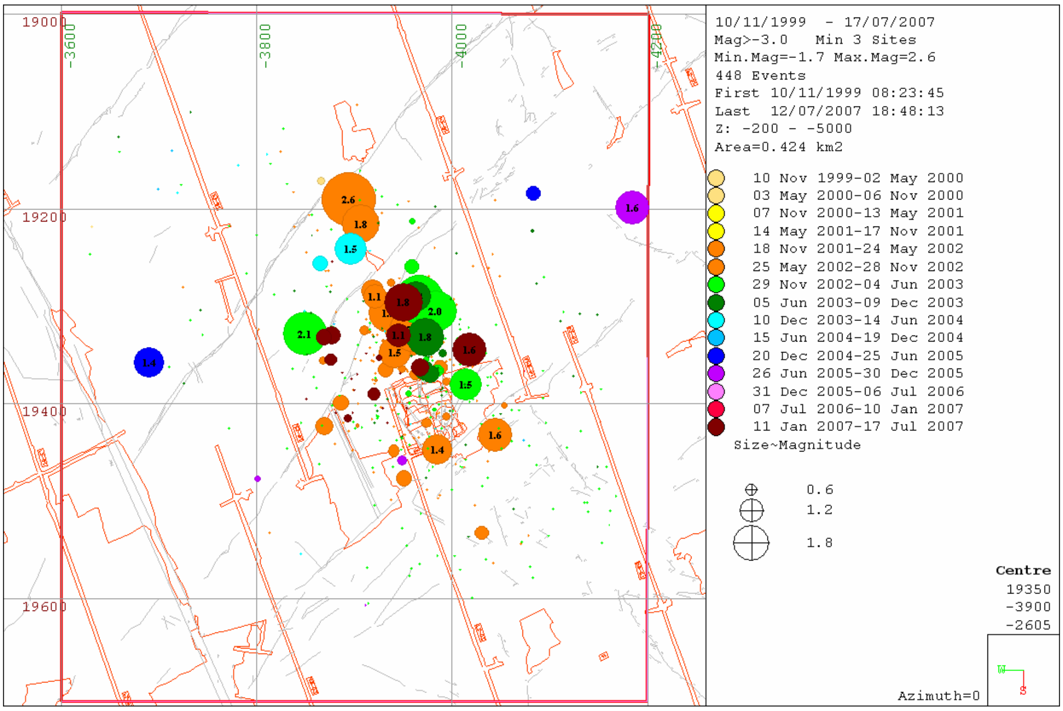
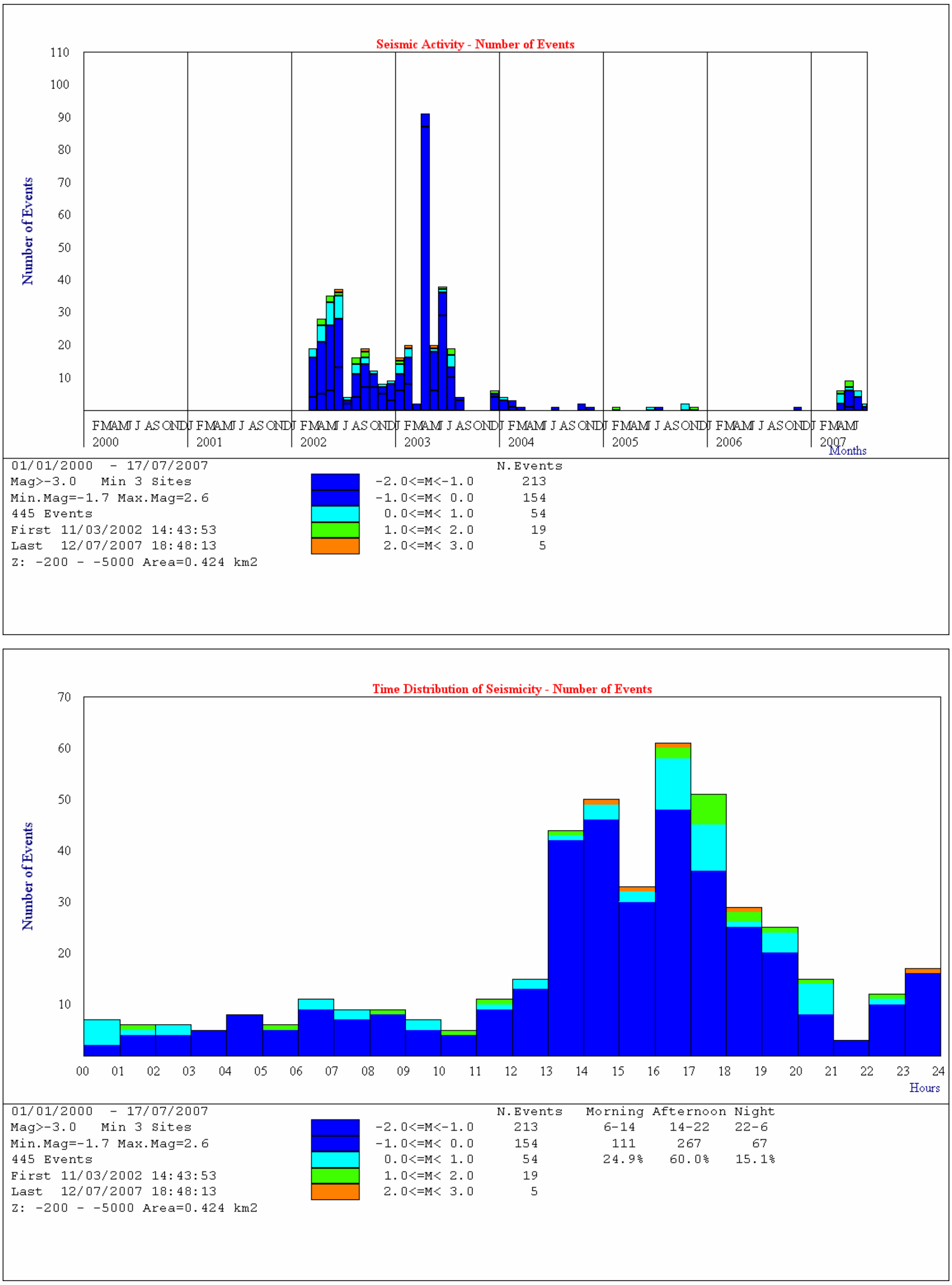


**Figure 3** Plot of the spatial location and magnitude of seismic events, recorded in the vicinity of the 18-23 pillar (encircled), in the time period Nov 1999 to Jul 2007. The scatter of events is due to the poor layout of the local seismic network, lacking nearby sensors

The original mining in this part of the mine took place in 1973, before the monitoring of seismicity began almost a decade later, in July1982. The only seismic data on record is limited to that linked to the extraction of this remnant pillar, initiated in March 2002, suspended in August 2003, resumed for three months in December 2003, and then resumed again in April 2007 (Figure 4). Within this period, in excess of 400 seismic events were recorded, the largest registering M 2.6, with a generalised diurnal distribution showing that blasting typically takes place from around 13h00, immediately followed by the re-balancing of stresses around the excavation, with seismic emissions.



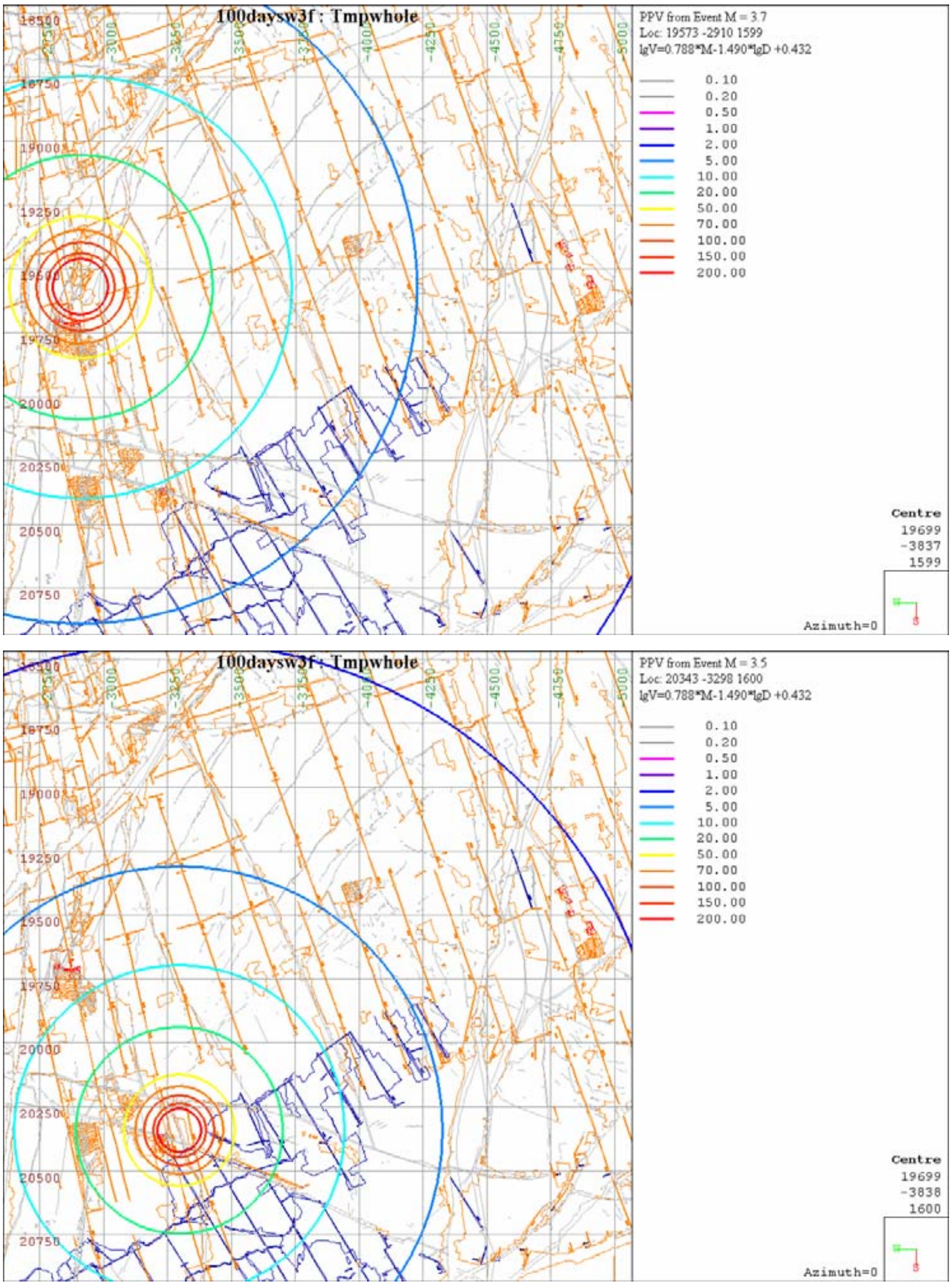
```
01/01/2000   - 17/07/2007                                N.Events
Mag>-3.0   Min 3 Sites              🟦   -2.0<=M<-1.0       213
Min.Mag=-1.7 Max.Mag=2.6            🟦   -1.0<=M< 0.0       154
445 Events                          🟦    0.0<=M< 1.0        54
First 11/03/2002 14:43:53           🟩    1.0<=M< 2.0        19
Last  12/07/2007 18:48:13           🟧    2.0<=M< 3.0         5
Z: -200 - -5000 Area=0.424 km2
```

```
01/01/2000   - 17/07/2007                                N.Events   Morning  Afternoon  Night
Mag>-3.0   Min 3 Sites              🟦   -2.0<=M<-1.0       213       6-14     14-22     22-6
Min.Mag=-1.7 Max.Mag=2.6            🟦   -1.0<=M< 0.0       154        111       267       67
445 Events                          🟦    0.0<=M< 1.0        54       24.9%     60.0%    15.1%
First 11/03/2002 14:43:53           🟩    1.0<=M< 2.0        19
Last  12/07/2007 18:48:13           🟧    2.0<=M< 3.0         5
Z: -200 - -5000 Area=0.424 km2
```

**Figure 4** **Temporal distributions of seismicity, portraying activity rate (top) and diurnal spread (bottom), using the same dataset as shown in Figure 2**

### 2.4.2 *Projected peak particle velocities*

The seismic potential of geological features and pillar failures can be high in this older part of the mine, and needs to be recognised to ensure the design of in-stope support and that employed for the duration of the life of tunnels and access ways can accommodate – in addition to the slow stress-driven deformation – the anticipated dynamic ground motions that the tunnels and pillar may suffer. The projected peak particle velocities (PPVs) that may emanate from those working areas in closest proximity around the pillar of interest were calculated based on the seismic history of each of these areas and the expected Mmax that these can produce. In addition, the potential PPV due to the mining of the 18-23 pillar itself was also calculated. These graphical results are represented in Figure 5, indicating PPVs emanating from the surrounding areas of less than 10 cm/s at the pillar, and a potential PPV at the pillar of less than 1 m/s associated with dislocation on the nearby fault zone.



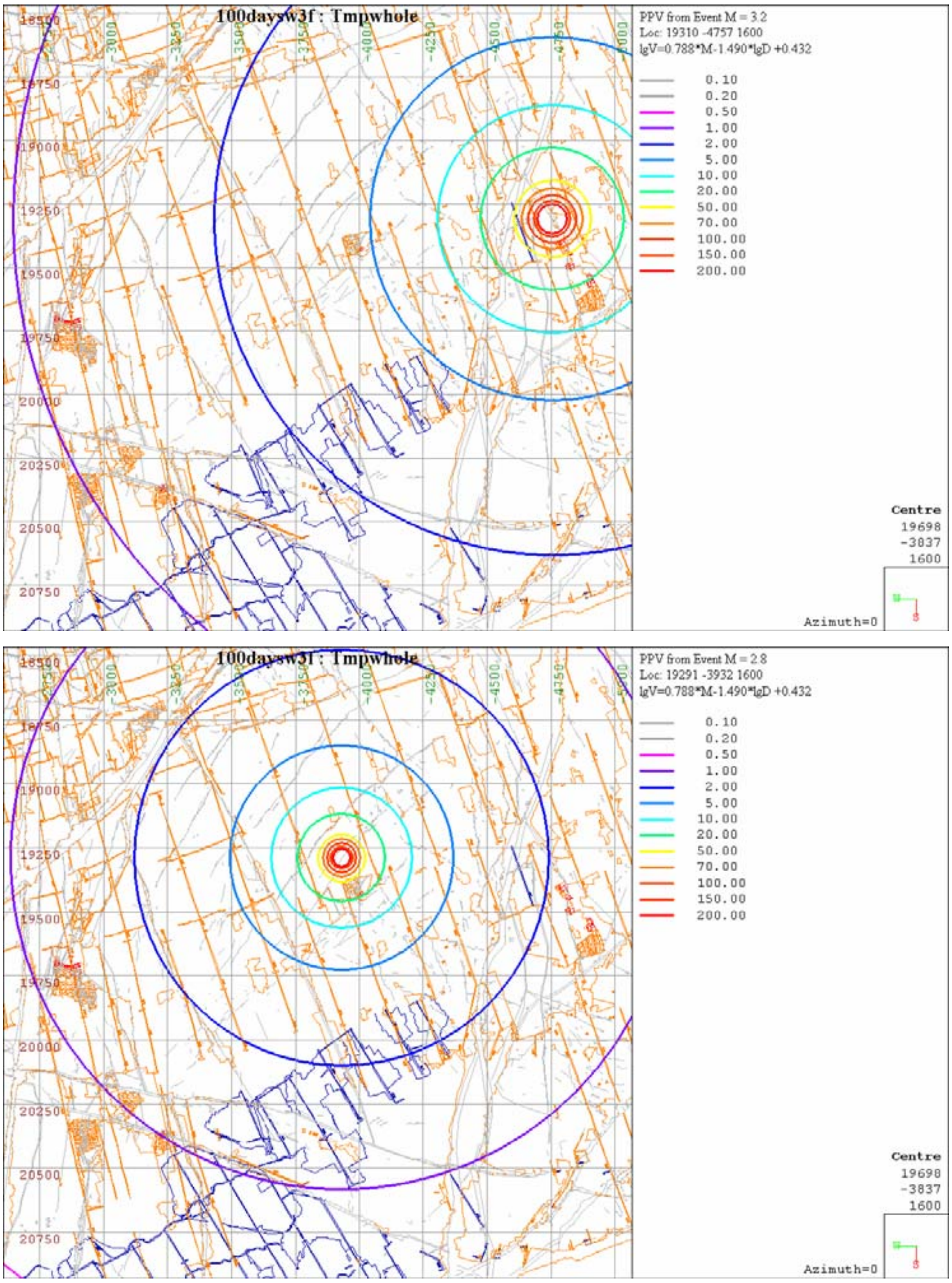
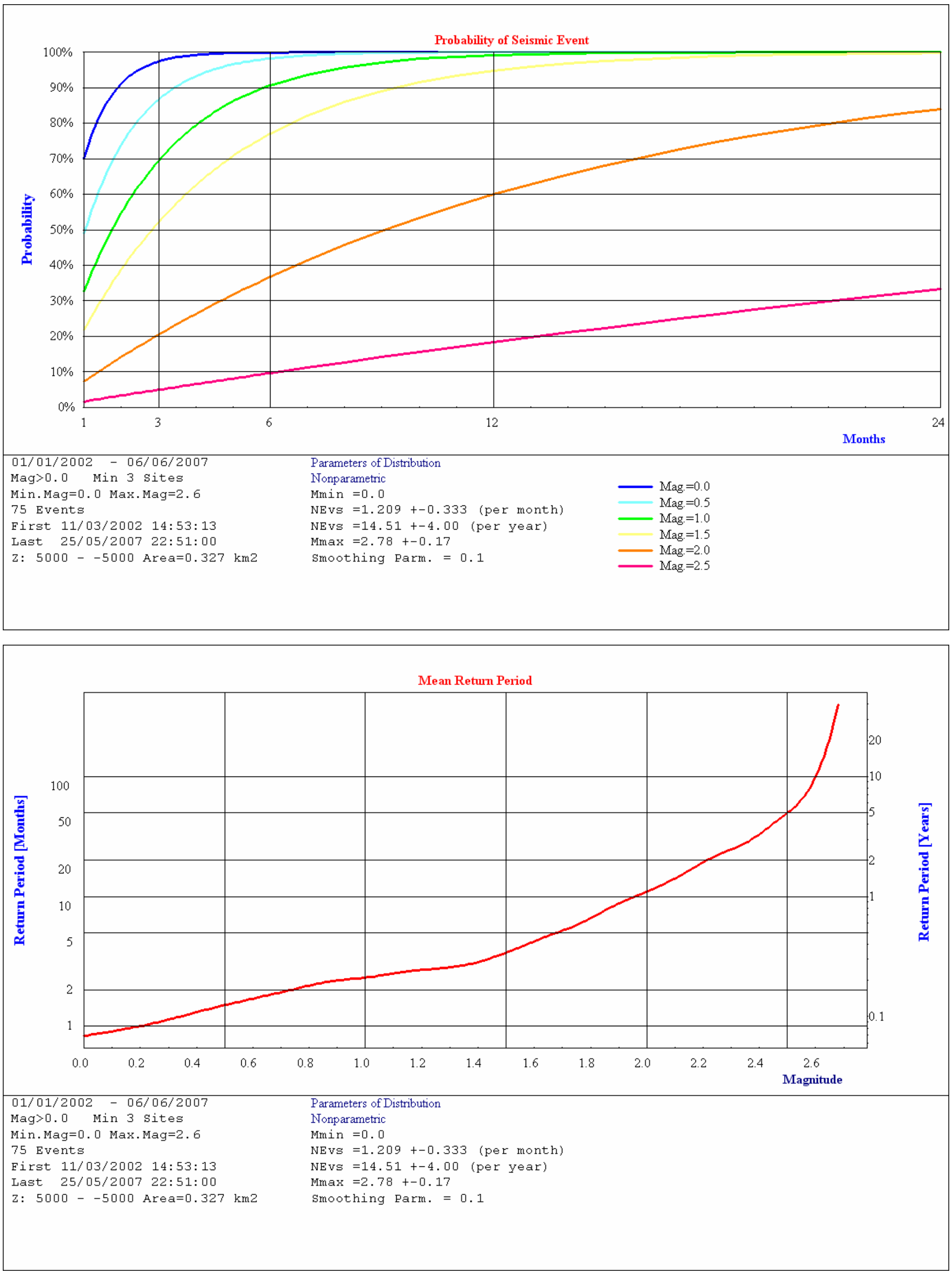


**Figure 5** **Contours of peak particle velocities (using the local ground motion relation logV = 0.788M-logD+0.432 m/s, where V is velocity and D is hypocentral distance; the legends above refer to velocities in cm/s). The arrow points to the position of the 18-23 pillar in relation to other potential sources of large ground motions. From top down: expected Mmax 3.7 near the 20-17 pillar, 1100 m distant; expected Mmax 3.5 near the 24-17 pillar, 1200 m distant expected; Mmax 3.2 near the 22-27 pillar, 1000 m distant. The PPV of the expected Mmax 2.8 near the 18-23 pillar may be within the source region of the event and amplified by near-field effects, which are poorly understood (Jager and Ryder, pp. 25-26)**

### *2.4.3 Probabilities of occurrence and mean return periods*

Calculated for the 18-23 pillar, as well as a number of other pillars (below), the probability of occurrence and period of reoccurrence of seismic events in various magnitude categories is presented in Figure 6. The results are generalised over the time period of the data set.



```
01/01/2002  - 06/06/2007          Parameters of Distribution
Mag>0.0   Min 3 Sites             Nonparametric
Min.Mag=0.0 Max.Mag=2.6           Mmin =0.0
75 Events                         NEvs =1.209 +-0.333 (per month)
First 11/03/2002 14:53:13         NEvs =14.51 +-4.00 (per year)
Last  25/05/2007 22:51:00         Mmax =2.78 +-0.17
Z: 5000 - -5000 Area=0.327 km2    Smoothing Parm. = 0.1
```

```
01/01/2002  - 06/06/2007          Parameters of Distribution
Mag>0.0   Min 3 Sites             Nonparametric
Min.Mag=0.0 Max.Mag=2.6           Mmin =0.0
75 Events                         NEvs =1.209 +-0.333 (per month)
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Last  25/05/2007 22:51:00         Mmax =2.78 +-0.17
Z: 5000 - -5000 Area=0.327 km2    Smoothing Parm. = 0.1
```

**Figure 6 An M 2.5 event has a 17% probability of occurring in at least 12 months (top), or should re-occur in at least 5 years (bottom)**

### *2.4.4 Seismic risk*

The identification of the seismic hazards is fairly well accomplished. The seismic risk, a further quantification of the seismic hazard, can be achieved in relation to other current mining areas, in terms of actual recorded events and probabilities of occurrence, over the same period of time. The concept of hazard magnitude (Mhaz) (van Aswegen, 2005) is a straightforward measure, which integrates the area under the pertinent frequency-magnitude relation, and, along with maximum magnitudes recorded and expected, ranks the relative risk between different pillar blocks in different geotechnical areas on the same mine.

**Table 1 Classification of seismic hazard**

| Working area | $M_{max}$ recorded | $M_{max}$ expected | $M_{haz}$ | P (M2.5) in 12 months (%) |
|---|---|---|---|---|
| 18-23 pillar | 2.6 | 2.8 | 3.0 | 17% |
| 20-17 pillar | 3.5 | 3.7 | 3.5 | 48% |
| 24-17 pillar | 3.3 | 3.5 | 3.8 | 61% |
| 22-27 pillar | 2.9 | 3.2 | 3.1 | 35% |
| 20-33 pillar | 2.8 | 3.0 | 3.2 | 30% |
| 18-38 pillar | 3.0 | 3.2 | 3.8 | 65% |

The comparative exposure to seismicity and seismic risk of the 18-23 pillar, considering the behaviour of a number of other pillars currently being mined, appears to be considerably less. This observation lends itself to greater confidence in the successful extraction of the old pillar.

## 2.5 Design of extraction sequence

The original mining sequence contemplated developing a reef drive through the pillar on the 18 level reef horizon, and establish breast mining panels in the easterly direction. This sequence was soon changed as the skin of the pillar was found intensely fractured, which did not lend itself to breast mining. The reef drive was continued, but the mining direction was changed to up-dip to cope with the adverse fracturing.

It soon became apparent that the reef drive suffered repeated damage from strong ground movements and ensuing deformations, as the portion of the pillar below 18 level horizon became increasingly isolated. The southern sidewall was particularly badly affected by seismicity. The reef drive was stopped and a strike gully with an advanced heading was implemented. This measure improved the ground conditions as a result of the shorter span and the use of pack support on the shoulders.

The updip mining direction assisted in negotiating the few minor faults that were exposed during the mining operations. The minor faulting trends mostly along dip direction, affording a 90° angle of approach by the mining front to these weaknesses. This mining direction complies with the ‘mining towards the largest solid’ rule-of-thumb, and allows the faults to be gradually exposed and timeously supported.

## 2.6 Numerical modelling

In order to gain an a better understanding of the expected state of stress and energy release rates (ERRs) associated with the extraction of the 18-23 pillar, various boundary element computer codes were employed. The MINSIM and BESOL/MS suite of 3D programs, which are well suited for the analysis of stresses and displacements associated with narrow tabular stopes in linear ground, were used in-house.

Additional simulation of the pillar behaviour with MAP3D software was performed externally. The exercise was outsourced to one of the recognised leaders in this field, as part of due diligence requirements and a quarterly review process of the total mining of the Thabelang Shaft area. The MAP3D program was run with elastic input parameters similar to those quoted below, and the results correlate well.

Numerical modelling is an inherently useful tool to the Rock Engineer, but it is important to note that the results obtained in a numerical simulation of the underground environment are not absolute values, due to the simplification and many assumptions made in the elastic boundary element codes. Numerical modelling as a comparative tool, to evaluate relative risk levels, is likely the best application for these codes. In this instance the results are interpreted and compared to the Code of Practice design criteria, and referred to previous modelling experience.

### *2.6.1 Input parameters and results:*

Young’s Modulus: 55 GPa

Poison’s ratio: 0.2

K ratio: 0.5

Element size: 5 m

Stoping width: 1.2 m

Stress Gradient: Vertical – 27 MPa, and Horizontal – 13.5 MPa per 1000 m.

The BESOL/MS modelling results are summarised in Figure 7 and Table 2.

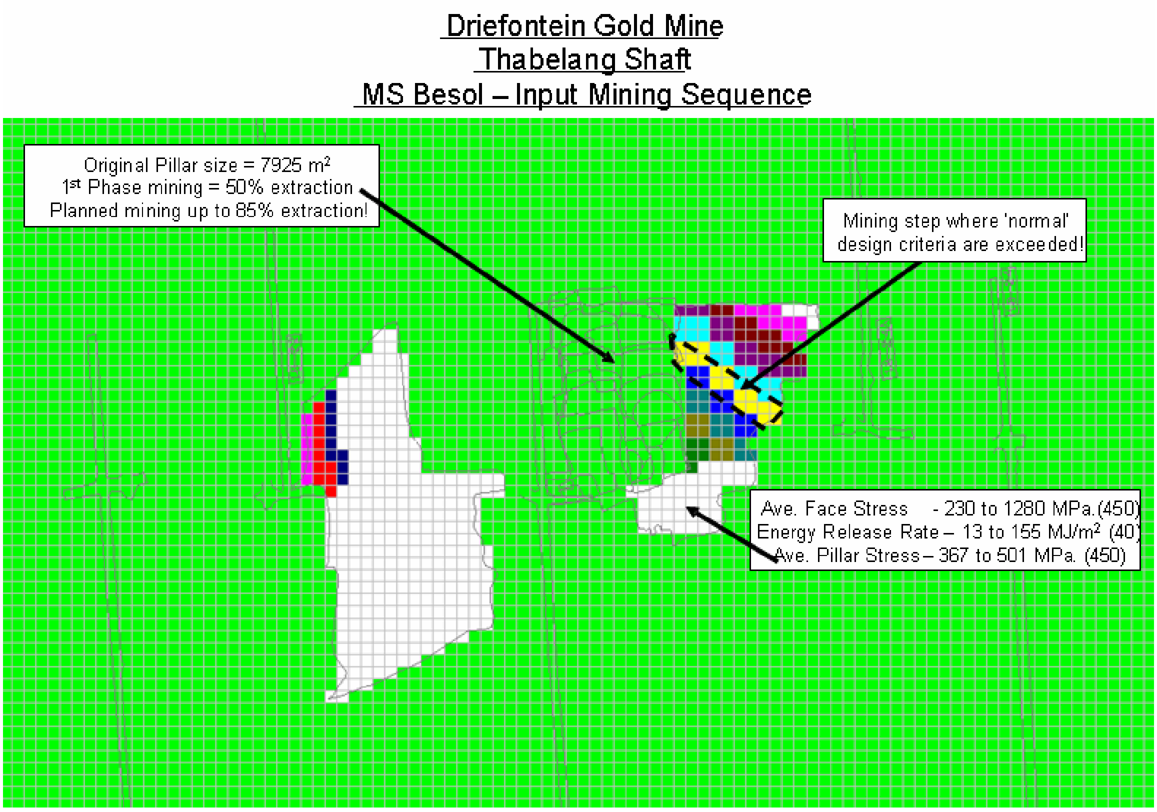


**Figure 7 BESOL/MS calculated stresses and ERRs according to input parameters and mining sequence**

The face stress climb from a moderate 230 MPa to very high 1280 MPa in the final simulated mining step. The virgin stress level at 18 level reef horizon is in the region of 45 MPa, an indication that the face stress regime is likely to approach 5 times the virgin stress levels.

A significant fracture zone is anticipated ahead of the mining faces due to the elevated average face and average pillar stresses. At some point in the extraction of the 18-23 pillar the newly formed fracture zone should encroach and eventually merge with the existing fractures on the opposite side of the pillar, producing a totally fractured core. It is not possible to determine the onset of post failure behaviour of the pillar using elastic simulations alone. Experience has shown that such high stresses do not exist in-situ, as a large amount of the available energy is consumed in the fracturing and deformation of the rock mass.

**Table 2 Numerical modelling results**

**BESOL/MS Results for 18-23 Carbon Leader Pillar**

| Step | Average Face Stress (MPa) | Energy Release Rate (MJ/m$^2$) | Remaining Pillar size (m$^2$) | Average Pillar Stress (MPa) | |
|---|---|---|---|---|---|
| | | | | Southern Pillar | 18-23 Pillar |
| Current | 245 | --- | 2900 | 367 | 301 |
| 1 | 233 | 13.0 | 2775 | 378 | 311 |
| 2 | 305 | 16.0 | 2575 | 384 | 326 |
| 3 | 361 | 23.5 | 2300 | 404 | 320 |
| 4 | 392 | 27.3 | 2000 | 418 | 346 |
| 5 | 429 | 39.3 | 1550 | 437 | 394 |
| 6 | **560*** | **48.0** | 1100 | **453** | **472** |
| 7 | **663** | **73.7** | 675 | **470** | **585** |
| 8 | **775** | **96.4** | 350 | **485** | **783** |
| 9 | **1280** | **155.2** | 100 | **501** | **1280** |

*The updip mining panels begin holing into the worked out area, resulting in the high Average Face Stress and associated Energy Release Rates. Note that steps 4-5 and 5-6 have the highest volumetric extraction in the simulation due to the available face length during those mining steps.

The energy release rates correlate with the average face stresses, and increase considerably towards the end of the planned mining sequence. The ERR parameter, through experience, has proven to be an effective indicator of expected ground conditions. The higher the ERR, the more pronounced the fracturing observed in the stope face. Mining step 6 reveals that the design criteria under 'normal' mining conditions, as specified in the mine's Code of Practice, are likely to be exceeded. Intense fracturing can be expected at this stage, with increased likelihood of adverse seismicity, but cognisance of modelling limitations precludes a decision to cease operations at this stage. Such finality depends on the behaviour and stability of the 18-23 pillar with the progress of mining. The pillar is, from the outset, mined as a 'Special Area – Restricted' (within a framework of due diligence, acceptable risk and individual accountability, supported by sound geotechnical considerations and warranted precautions).

The simulations indicated that total closure could be expected within 30 m of the pillar edges. This was verified when the first phase updip sequences holed into the mined out area north of the pillar. It was possible to access the 'old abutment' gully through the holing, but the old stope panel had closed and it was only possible to crawl into the panel for about 10 m.

## 2.7 Overall risk assessment

The overall Rock Engineering risk rating is performed on a monthly basis. Five parameters are taken into account and weighted, resulting in a risk rating for each individual panel. These parameters include a seismic rating (described below), geological features and/or geological rating, the stress regime, the mining sequence and physical conditions.

In a data capture sheet, the 'Rock Mechanics Control Sheet', consideration is given to seven parameters, namely, geology, seismic rating, lead/lags, support, face shape index, panel risk rating, and ERR. It also notes the applicable support standard and whether or not the working place has been declared a special area. This sheet is used as a planning tool and is discussed at all pre-planning meetings.

Continuous seismic monitoring is used interactively, in order to assist with mine planning and risk assessment techniques, and encompasses short, medium and long-term assessments of recorded seismic data. Apart from the localisation of events in space and time, seismic instability analysis (short-term, i.e. incorporating time periods of the order of hours and days) is undertaken daily in all working areas of the mine. It analyses trends through visual inspection of five seismic parameters, and aims to raise the awareness of the likelihood of instability.

Monthly seismic ratings (numerically ranging between zero and a maximum of 20, described below) and statistical hazard maps form part of the medium- to long-term (i.e. encompassing time frames of months and years) seismic monitoring programme. The rock engineering department and production personnel use this information during pre-planning meetings in order to identify areas with higher than average seismic potential. The seriousness of the rating and the reaction thereto increases with a rating above 15. Additional precautions are required when the seismic rating exceeds 15 (apart from the mine standards and other requirements which are normally applicable). The ratings for the 18-23 pillar, calculated over the last 12 months of production, are tabulated elsewhere in this paper.

## 3 Specifications of mining

The minimum obligatory precautions for a 'Restricted Special Area' or 'Special Area' are listed in Appendix B. Other strategies or site-specific instructions are added at the discretion of management, according to the conditions encountered, and, if so, these need to be documented.

Additional measures in place at the 18-23 pillar involve:

- The practice of face-perpendicular precondition blasting, to reduce the potential for stress lock up in the fracture zone ahead of the stope face. The longer precondition blast holes are timed to initiate just prior to normal production blast holes. These precondition holes introduce high pressure gasses into the existing fractures, not intended to 'break' the rock, but rather to 'open' up and extend the existing fractures.
- The practice of single-shift mining using a two-day cycle, comprising a support and blast shift, followed by a cleaning and support shift. This allows approximately 15 hours for stress redistributions and rebalancing after the onset of the blast, before the production personnel re-enter the working place.
- The use of rapid-yielding hydraulic props (RYHPs) as immediate face area support. The RYHPs give a very high support resistance and possess the ability to yield under dynamic loading. Large headboards are used in conjunction with these props to increase the areal coverage and provide better support to the highly fractured hangingwall.
- The limitation of production blast holes to a length of 0.9 m, to control the rate of face advance, thereby reducing the amount of stress redistribution resulting from the decreased volumes of extraction. This measure also reduces the amount of broken rock that needs to be handled in the cleaning shift, and reduces the accumulation of broken rock in the access ways. This is important in the 18-23 pillar, as the broken rock is cleaned into a strike gully, then loaded into hoppers in the reef drive with a rocker shovel.
- Remedial actions to rectify the outcomes of poor mining discipline or deviations from specified standards, following from regular site visits and in-situ inspections.

A typical decision rights framework for a number of mineral resources (pillars, remnants, incomplete reef extractions, sweepings and reclamations) is exemplified by the appended flowchart (Appendix C).

A copy of an updip support standard is appended in Appendix D.

# 4 Observed rock mass behaviour with mining

Regular in-situ observation of the pillar has revealed a large amount of co-seismic stope closure, which seems to be predominantly in the form of footwall heave. Continuous seismic monitoring not only completes the feedback loop of information, but plays a crucial role in identifying the potential post-failure behaviour in the pillar and justifying deviations from the planned strategy of extraction. A useful tool in helping to determine the behaviour of the remaining pillar consists of logging and correlating the rate of production with the rate of seismicity.

## 4.1 Rates of production and energy dissipation

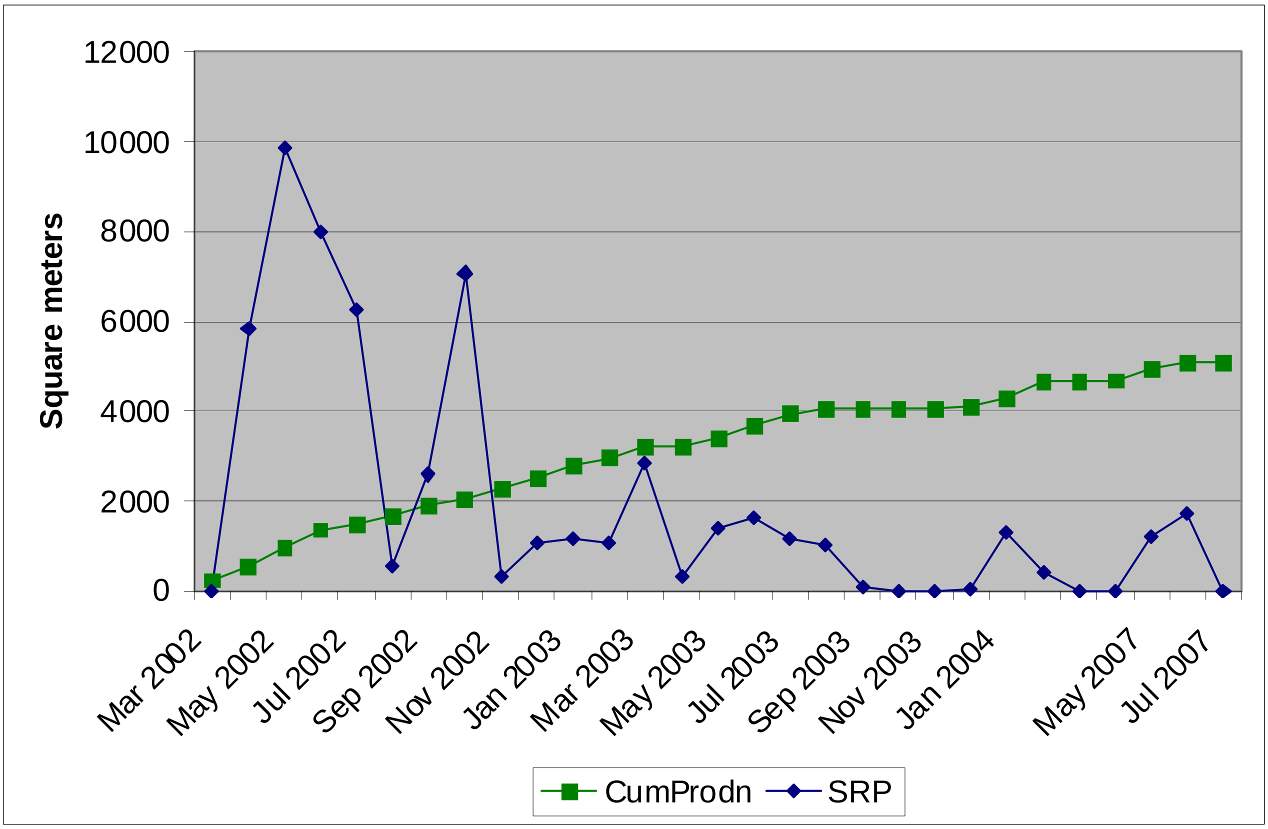
The so-called Seismic Response to Production (SRP index) relates the seismic response of the rock to the rate of extraction. It is calculated as a simple ratio of cumulative seismic apparent volume (i.e. a measure of rock strain, in cubic metres) to the actual volume of extraction (i.e. production, in cubic metres). A plot of SRP over time (days and/or months) describes the seismic deformation to the amount of mining done in a particular area; a constant value of SRP (i.e. a flat graph) over a given period of time indicates a consistent release of strain energy. A decrease from a constant value indicates that more energy is being stored than normal, which could suddenly be released in the form of a large seismic event or rockburst. The opposite also applies: an increase in SRP is indicative of a faster rate of energy dissipation than normal, analogous to the stress-strain curve of a rock sample just before it fails. Generally, a change from a constant value of SRP is regarded as an undesirable situation, reflecting the change in the stiffness of a system.

The attached SRP graph for the 18-23 pillar (Figure 8) shows a general flat trend since late-2002. This seems to indicate stable conditions. Should it be perceived that unstable conditions and increased risk develop, and in order to reduce the worker exposure as much as possible to a damaging event, the daily mining rate would be capped, the blasting would be spread evenly in space and time, and the monthly production would be strictly controlled so as not to deviate from the imposed limitation. This should allow the rock mass to better accommodate the stress changes taking place in the un-mined blocks of ground, thereby regaining equilibrium. In the event that stability is not achieved, mining will cease.

## 4.2 Monthly seismic ratings

Aimed at the medium- to long-term assessment of seismic risk, the ratings are produced on a monthly basis, and attempt to highlight the development of an abnormal rock mass response to mining, relative to all other mining areas. The seismic rating takes into account the frequency of seismicity (i.e. numbers of seismic events above M 0.0, or some other predetermined magnitude floor), the damage to the rock mass or consequences of that seismicity (as measured by some seismic parameter which describes deformation, e.g. seismic apparent volume), and the change in recorded seismic activity over the average of the last three months. Ratings of 1-10 are considered low risk, ratings 11-14 are considered moderate risk, and ratings of 15 and above are considered abnormally high (the maximum value is 20).

On a monthly basis, the ratings related to the last 12 months of production are reproduced in Table 3. The total risk ranking for the 18-23 pillar has ranged from low to moderate, generally supporting other favourable analytical results:



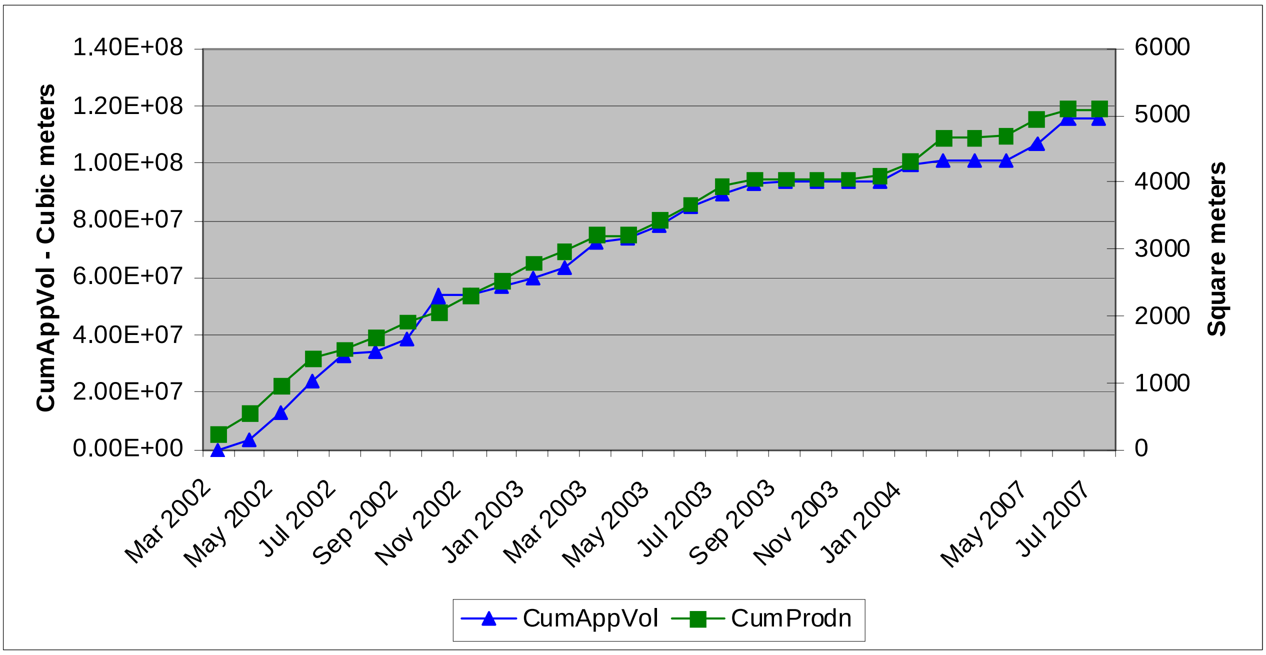


**Figure 8 Cumulative production in relation to SRP trends (top) and the seismic parameter of cumulative apparent volume (bottom). The general long-term SRP trend line shows an 'even' rate of energy dissipation, while the rate of deformation accompanies the rate mining, and indicates stability in the extraction process, without the need for intervention, at this stage**

**Table 3 Monthly seismic rating for the 18-23 pillar**

| | Jun 2003 | Jul 2003 | Aug 2003 | Sep 2003 | Oct 2003 | Nov 2003 | Dec 2003 | Jan 2004 | Feb 2004 | Apr 2007 | May 2007 | Jun 2007 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 18-23 pillar | 11 | 11 | 8 | 8 | 8 | 9 | 13 | 11 | 9 | 13 | 13 | 11 |

## 5 Conclusions

A multi-disciplinary approach, from initial feasibility investigation, to mining proposal, to actual initiation and progress of extraction of a remnant pillar in an older part of the mine was presented. This tried and tested pragmatic approach has proved robust, successfully marrying the science to practice.

Work in progress aims to measure the rock quality (RQD) of the pillar through diamond drilling core analysis, and determine the size of the solid inner-pillar core relative to stoping width, to provide a more reliable measure of average pillar stress. The intention is to verify (or modify) design parameters and assumptions (e.g. the planning of mining strategies, to help determine support requirements and assist in the calibration of input parameters used in numerical models), to guide progressive extraction.

Continuous monitoring of the seismic sensitiveness to mining ensures the information feedback loop is closed, and highlights remedial actions, if or when needed. The monthly planning review process draws on the multi-disciplinary inputs and dictates whether mining of this and other remnant pillars should continue, or be terminated.

## Acknowledgements

The authors wish to thank Gold Fields, and the Management of Driefontein Gold Mine in particular, for the opportunity to put this paper together, and permission to submit and participate in the 4th International Seminar on Deep and High Stress Mining. The work collated in Driefontein's guidelines (Driefontein Gold Mine Standard, 2003) for pillar mining is gratefully acknowledged to F. Castelyn and J. Klokow. Smit, N.J., Shaft Manger, Thabelang Shaft, Driefontein Gold Mine, Personal Communication.

Someone else cut the trail we currently follow; we strive to widen and deepen it a little further, and sometimes, just maybe, we make lasting inroads of our own.

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Jager, A.J. and Ryder J.A. (1999) (eds) A Handbook on Rock Engineering Practice for Tabular Hard Rock Mines. The Safety in Mines Research Advisory Committee (SIMRAC), Johannesburg, pp. 25-26, p. 30, pp. 33-34.

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# Appendix A - Glossary of Terms and Definitions

| | |
|---|---|
| **Abutment:** | The areas of un-mined rock at the edges of mining excavations that may carry elevated loads resulting from re-distributions of stress. |
| **Advanced heading:** | An excavation cut in the immediate footwall of the reef for the purpose of enabling the removal of rock from the stope face and providing access to the face for men and material. |
| **Apparent volume:** | A measure of the volume of rock in which inelastic seismic deformation has occurred. |
| **Back:** | This is the ore-body between a level and the surface, or between two levels. |
| **Bedding planes:** | Planes of weakness in the rock that usually occur at the interface of parallel beds or lamina of material within the rock mass. |
| **Brittle fracture:** | Sudden failure associated with the complete loss of cohesion across a plane. |
| **Closure:** | Reduction in dimensions of an opening. |
| **Convergence:** | Reduction of the distance between 2 basically parallel surfaces (usually hangingwall and footwall). |
| **Cribbing:** | Steel or wooden units used to form part of the structure on installing sets in an underground excavation, providing passive areal support between the set legs and the rock face. |
| **Cross-cut:** | A horizontal opening, like a tunnel, that cuts the rock formation at an angle to the strike in order to reach an orebody. |
| **Deformation:** | A change in shape or size of a solid body. |
| **Dip:** | Angle at which a stratum or other planar feature is inclined from the horizontal. |
| **Discontinuity surface:** | Any surface across which some property of a rock mass is discontinuous (e.g. bedding planes, fractures). |
| **Drive:** | A horizontal opening, like a tunnel lying in or near the orebody, parallel to the strike. |
| **Earthquake:** | Groups of elastic waves propagating within the earth that cause local shaking/ trembling of ground. The seismic energy radiated during earthquakes is most commonly caused by sudden fault slip, volcanic activity or other sudden stress changes in the earth's crust. |
| **Energy Release Rate (ERR):** | A theoretically calculated quantity related to the amount of elastic closure and stress change associated with mining, which relates to the expected severity of the seismicity that may be expected. |
| **Face:** | The ‘face’ is the immediate area where mining operations take place, and is typically between the solid rock to be blasted and the ‘old area’ demarcation. |
| **Failure:** | Condition in which the maximum strength of a material is exceeded by an applied load. |
| **Footwall:** | Mass of rock beneath a discontinuity surface (in tabular mining, the rock below the reef plane). |
| **Footwall heave:** | The occurrence of heaving or doming of the footwall behind and between the first or second rows of support, also caused by increased stress at the face, indicating that lateral movement is being restricted on either the footwall, the hangingwall, or both. |

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| **Geological structure:** | A general term that describes the arrangement of rock formations. Also refers to the folds, joints, faults, foliation, and schistosity, bedding planes and other planes of weakness in rock. |
| **Geophone:** | A seismometer that measures ground velocity. A ‘tri-axial geophone’ boat contains three ground motion sensors, oriented orthogonally to each other, to measure ground motions in three dimensions. |
| **Gully:** | An excavation cut in the immediate footwall or hanging wall of the reef for the purpose of enabling the removal of rock from the face or providing access to the face for men or material. |
| **Hangingwall:** | Mass of rock above a discontinuity surface (in tabular mining, the rock above the reef plane). |
| **Hazard:** | A source of, or exposure to, danger. |
| **Hypocentre:** | Location in 3 dimensions of the source of a seismic event. Also known as the focus (or source location). |
| **Inelastic deformation:** | The portion of deformation under stress that is not annulled by the removal of the stress. |
| **Induced stress:** | This is the stress that is due to the presence of an excavation. The magnitude of the induced stress developed depends on the magnitude and orientation of the in-situ stress and the shape and size of the excavation. |
| **Joint:** | A naturally occurring plane of weakness or break in the rock (generally aligned sub vertical or transverse to bedding), along which there has been no visible movement parallel to the plane. |
| **Ledging:** | Is the process whereby stoping operations are established from a raise. |
| **Level:** | All openings at a horizon from which the orebody is opened up and mining is started. |
| **Magnitude (seismic):** | Measure of the size of a seismic event. May encompass energy, moment, or both in its calculation. $Ml = 0{,}324 \log E + 0{,}464 \log M - 6{,}039$; where<br>E = Seismic Energy and M = Seismic Moment. |
| **Mining induced seismicity:** | The occurrence of seismic events in close proximity to mining operations. During and following blast times, there is a significant increase in the amount of seismic activity in a mine. Mining induced seismicity is commonly associated with volumes of highly stressed rock, sudden movement on faults or intact failure of the rock mass. |
| **Overstoping:** | An extension of mining over some other excavation; an effective method of protecting off-reef excavations from the effects of large mining-induced stress changes. |
| **Peak Particle Velocity:** | Maximum velocity of the rock mass measured directly at a geophone or calculated from ground motion relations. |
| **Permanent support:** | Support that, once installed, is not removed. |
| **Pillar:** | Rock left in situ during the mining process to support the local hanging wall, roof or to provide stability to the mine or portion thereof. |
| **Plane of weakness:** | A naturally occurring crack or break in the rock mass along which movement can occur. |
| **Raise:** | Any tunnel having an inclination (above horizontal in the direction of the working of more than 5 degrees but not included under the definition of a shaft). |
| **Ravelling:** | This is the gradual failure of the rock mass by rock blocks falling / sliding from pit or tunnel walls - usually under the action of gravity, blast vibrations or |

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| | deterioration of rock mass strength. A gradual failure process that may go unnoticed. The term unraveling is also used to mean the same thing. |
| **Reef:** | A vein, bed or deposit (other than a surface alluvial deposit) that contains minerals, except in the case of coal or diamondiferous formations. |
| **Regular review:** | Assessment of the conditions of an area through discussions, plan critique, planning meetings and/or underground visits. |
| **Risk:** | The likelihood that occupational injury or harm to persons will occur. |
| **Rockburst:** | Seismic event that causes damage to underground workings. |
| **Rock Engineering:** | Is the engineering application of rock mechanics. |
| **Rock fall (fall of ground):** | Fall of a rock fragment or a portion of fractured rock mass without the simultaneous occurrence of a seismic event. |
| **Rock fracture:** | Rock fracture is the failure of the rock as a result of the in-situ stress which exceeds the strength of the rock. |
| **Rock mass:** | The sum total of the rock as it exists in place, taking into account the intact rock material, groundwater, as well as joints, faults and other natural planes of weakness that can divide the rock into interlocking blocks of varying sizes and shapes. |
| **Rock mass instability:** | A softening within a critical volume of rock indicated by accelerating deformation and a drop in stress. |
| **Rock mechanics:** | The scientific study of the mechanical behaviour of rock and rock masses under the influence of stress. |
| **RQD:** | Referring to ‘rock quality designation’, the ratio of the length of core recovered from drilling, counting those pieces of 100 mm or larger, to the total length of the core. |
| **Scattered mining layout:** | A layout where dip-pillars are left behind as ‘planned remnants’, acting as load-carrying stability pillars, and permitting significant advance exploration to be carried out. |
| **Seismically active mine:** | A seismically active mine is a mine that sustains losses to persons and/or property, underground or on surface, caused by the dynamic response to a seismic event induced when creating or enlarging an excavation. |
| **Seismic event:** | Transient earth motion caused by a sudden release of the strain energy stored in the rock. |
| **Seismicity:** | The geographic and historical distribution of earthquakes. |
| **Seismology:** | The scientific study of earthquakes by the analysis of vibrations transmitted through rock and soil materials. The study includes the dynamic analysis of forces, energy, stress, duration, location, orientation, periodicity and other characteristics. |
| **Seismometer:** | A device (transducer) that converts ground motion into an electric signal. |
| **Seismic moment (scalar):** | Measure of the strength of an earthquake or of a seismic event and an indication of the amount of deformation (displacement) at a seismic source. |
| **Sets:** | A structure or structural feature erected into an underground excavation to maintain its stability. |
| **Shaft:** | Means any tunnel having a cross-sectional dimension of 3.7 m or over and: (i) Having an inclination to the horizontal of 15 degrees or over, or (ii) Having an inclination to the horizontal of less than 15 degrees but more than 10 degrees where the speed of traction exceeds 2 m/s. |

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| **Snook:** | A snook is an unmined portion of a pillar that is left behind during the process of pillar extraction. Snooks of predetermined size may be left intentionally to crush once pillar extraction has progressed a certain distance, or they may be left unintentionally due to adverse geology, etc. |
| **Spalling:** | This the longitudinal splitting in uniaxial compression, or the breaking-off of plate-like pieces from a free rock surface. |
| **Special areas:** | During the course of routine mining an increased risk of rock falls or rock bursts may develop. Such areas requiring additional attention and precautions must be designated special areas. |
| **Stope:** | An underground excavation made in removal of any ground or mineral, other than coal, but does not apply to excavations made for engine rooms and pump chambers or for development purposes such as shafts, drives, winzes and raises. |
| **Stope width:** | Width of the tabular excavation made during stoping operations. |
| **Strain:** | The change in length per unit length of a body resulting from an applied force. Within the elastic limit, strain is proportional to stress. |
| **Strain burst:** | Rock burst at the lower end of the spectrum of violent events occurring essentially at the surface of an excavation. |
| **Strength:** | The maximum stress that a material can resist without failing for any given loading regime. |
| **Stress:** | Force acting across a surface element divided by the area of the element. Stress=force/area |
| **Stress field:** | A descriptive term to indicate the pattern of the rock stress (magnitude and orientation) in a particular area. |
| **Stress shadow:** | An area of low stress levels due to the flow of stress around a nearby excavation, e.g. a large stope. This may result in joints opening up, thereby causing rock falls. |
| **Strike:** | Direction of the azimuth of a horizontal line in the plane of an inclined stratum (or other planar feature) within a rock mass. |
| **Support:** | A structure or a structural feature built into or around an underground excavation to maintain its stability. |
| **Thickness:** | Perpendicular distance between bounding surfaces (e.g. bedding planes). |
| **Triaxial compression:** | Compression caused by the application of normal stress in 3 perpendicular (orthogonal) directions. |
| **Uniaxial (unconfined) compression:** | Compression caused by the application of normal stress in a single direction. UCS refers to uniaxial compressive stress, a measure of rock strength. |
| **Updip:** | Name given to a ‘wide raise’, where mining progresses in the up-dip direction. |
| **Vamping:** | The removal of all redundant equipment, and remaining broken ore from a depleted or abandoned working place, prior to sealing it off. |
| **Vector:** | A quantity having magnitude and direction but no fixed position |
| **Virgin stress:** | Are natural stresses which exist in the rock mass prior to any excavation. |
| **Width-to-height ratio:** | An indicator of pillar stability; the strength of a pillar, assuming competent foundations, increases significantly as a function of its w:h ratio. |
| **Working place:** | This is the place where mine workers normally work or travel to. |
| **Yield:** | Occurs in a sample when there is a departure from the elastic behaviour in the material and some permanent deformation occurs |

# Appendix B – Obligatory Strategies

The obligatory strategies state that: -

1 A notice displaying the words **“RESTRICTED SPECIAL AREA”** must be posted at the waiting places or stope entrances.

2 Two separate access ways, independent of each other, shall be maintained, be clearly marked and kept clean and free of obstructions, as far as is practicably possible.

3 The number of person in the crew assigned to a special area working place shall be kept minimum, which shall be controlled by the responsible miner on each shift. All other person entering a special area must sign on entry and exit from that special area in a book provided at each entrance and shall report to the miner in charge. If a person exits on a different level then he should sign out in the book at the exit, and should have indicated his intention to do so in the entry book.

4 Waiting places, explosives boxes, miners’ boxes and refuge chambers must, as far as practically possible, be situated away from areas where they may be affected by ground movements.

5 Telephone communication to surface must be available at all waiting places. The waiting places and stope entrance travelling ways must be adequately illuminated. A first aid bag and stretcher per 10 persons working in a restricted special area must by readily available at the closest refuge bay to the working place or at the waiting place.

6 Support of all access ways, gullies, faces and headings in a special area should adhere to the recommended and documented standard at all times. Special attention must be given to the support and headboards/additional support units must be installed wherever necessary.

7 Where there is risk of damaging seismic activity, then all support types used should have the capacity for stable yield under rockburst conditions.

8 Face advance should be continuous and regular, ideal face shapes should be maintained and lead/lags controlled, as far as is practically possible.

9 The stoping width shall be kept to the agreed and documented minimum, which shall not be less than 1.2 m. Where the stoping width has to be increased, to comply, the footwall waste must be opened up.

10 Broken rock must not be allowed to accumulate on the faces and in the gullies and access ways.

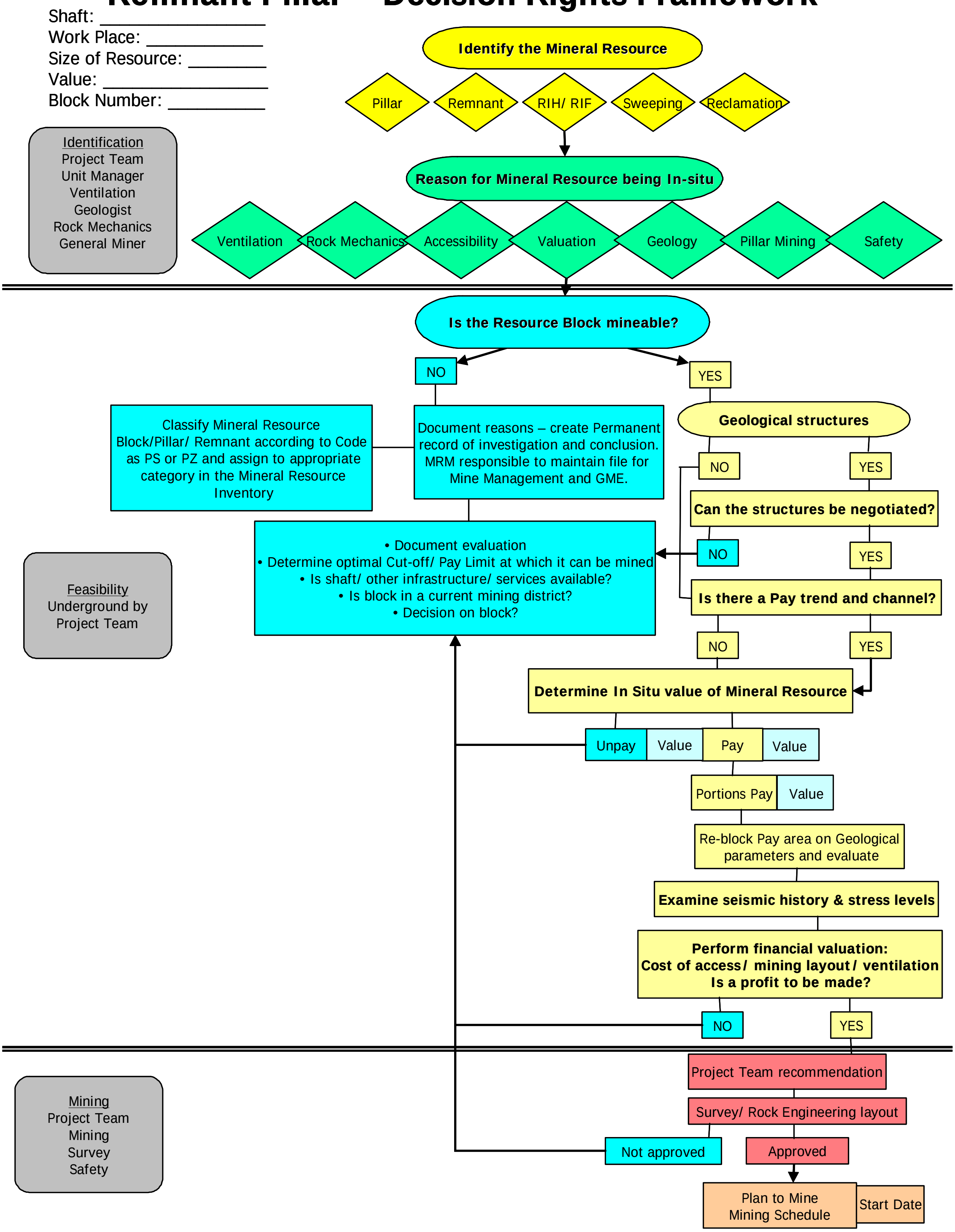
11 No development into a special area shall be allowed unless authorised by the responsible Operations Manager and under the conditions laid down in writing and in consultation with the suitably qualified rock engineering practitioner.

12 Any other development that passes over or under a special area, and whose continued use is required, shall be adequately supported.

13 The latest Special Area Sheet shall be posted on the notice board at the waiting place. The above precautions shall be implemented from the first day that is restricted special area declaration is made and shall be enforced until the area has been vamped and stropped, unless written instruction to the contrary has been issued and signed for by the responsible Operations Manager.

# Appendix C

## Remnant Pillar – Decision Rights Framework



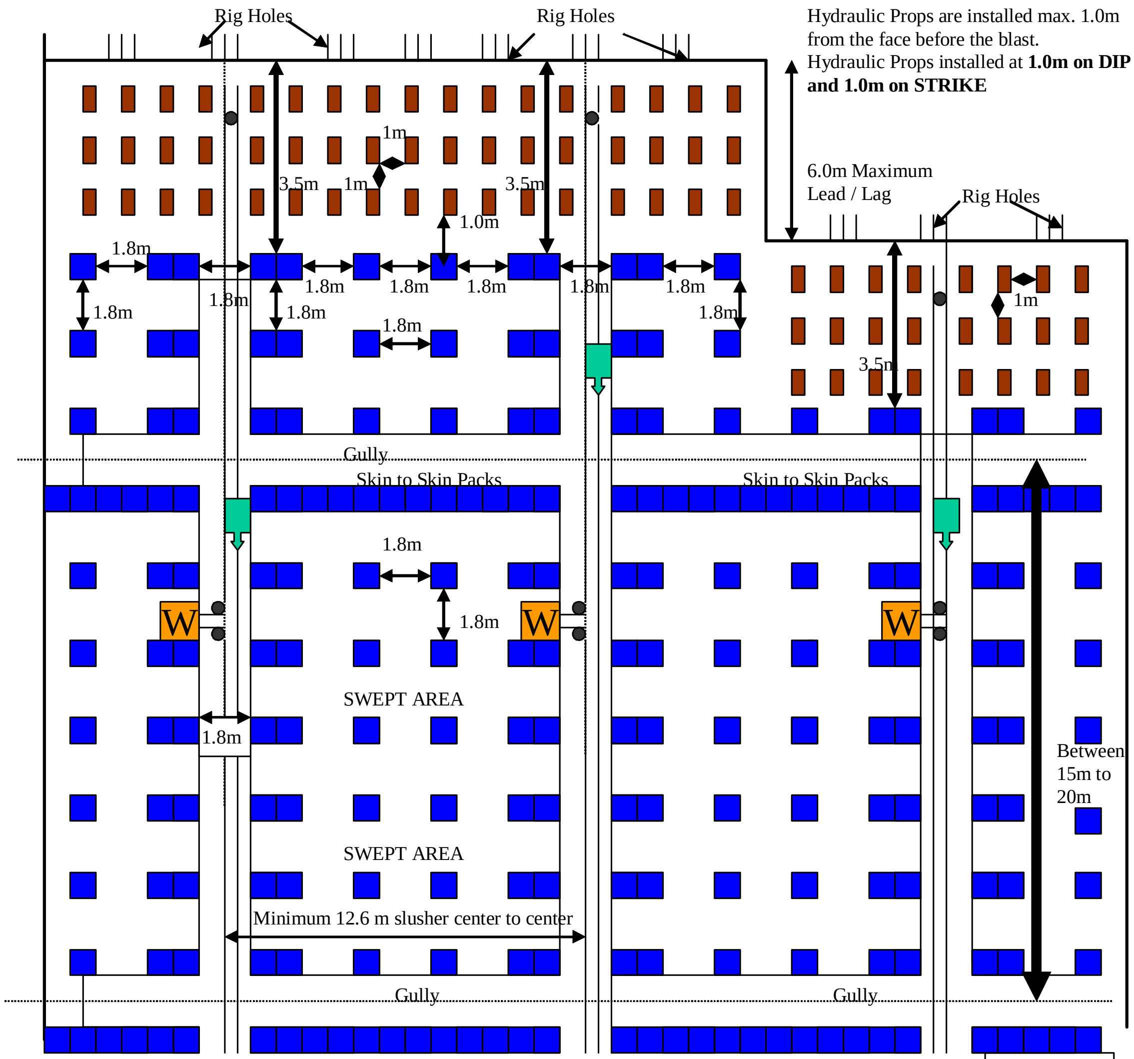
# Appendix D

Managerial support instruction for double wide raise updip mining:

## Driefontein Consolidated

## <u>Thabaleng Shaft MSI 03-2007</u>

## <u>Carbon Leader Reef – Updip Mining (Double Wide Raise)</u>


Hydraulic Props are installed max. 1.0m from the face before the blast. Hydraulic Props installed at **1.0m on DIP and 1.0m on STRIKE**

Not to Scale

**NOTES:** <u>.Special Instructions</u>

**•Any dislodged support 7m from the face needs to be replaced.**

**•No person to work further than 1m from installed support.**

**•Gullies to be blasted to within 3.5m from the face. All gullies, dip and Abutment gullies to be supported with 1.2m tendons on diamond pattern 1:2 and 1m apart up to last line of packs.**

**•<u>Maximum Support Distances to Face</u>**

**Maximum distance, RYHP to face 1.0m before the blast.**

**Pack to face 3.5m after the blast. Pack size in stope 90 x 90( CLC) at a Stope width of min 1.2m**

**Maximum blasted gully width 1.6m**

**Maximum span across gully 1.8m Gully Pack Size 1.80 x 90( CLC)**

**<u>Temporary Support-(when necessary ) Camlok Props</u>**

**Maximum 1.0 m from the face and 1.5m on strike**

Snr Rock Eng.

Mine Overseer.

Shaft Manager 10#.

Rock Eng Manager.

Manager Operations.