A review of the sequential grid mining method employed at Elandsrand Gold Mine

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Synopsis

Sequential grid mining has been employed as the primary mining strategy at the AngloGold West Wits Elandsrand Mine since the inception of stoping operations from the sub-vertical shaft system in 1988. Little has been published on sequential grid mining as a mining strategy since, and the purpose of this paper is to describe sequential grid mining, its history, its implementation at Elandsrand, and the outcome to date.

The results obtained using sequential grid mining have been evaluated from seismic data, productivity statistics, and rock related accident statistics. Comparisons with neighbouring mines, namely Western Deep Levels and Deelkraal, have been made to substantiate the improved conditions observed at Elandsrand, and to compare sequential grid mining directly with longwall mining in similar conditions and at similar depths. Sequential grid mMining is shown to be cost-effective, more flexible, and safer than longwall mining in similar conditions, at least on the Ventersdorp Contact Reef in the western part of the Carletonville Goldfield. More work is necessary to establish it as the favoured mining strategy at depths exceeding 3000 metres, and for reefs other than the Ventersdorp Contact Reef.

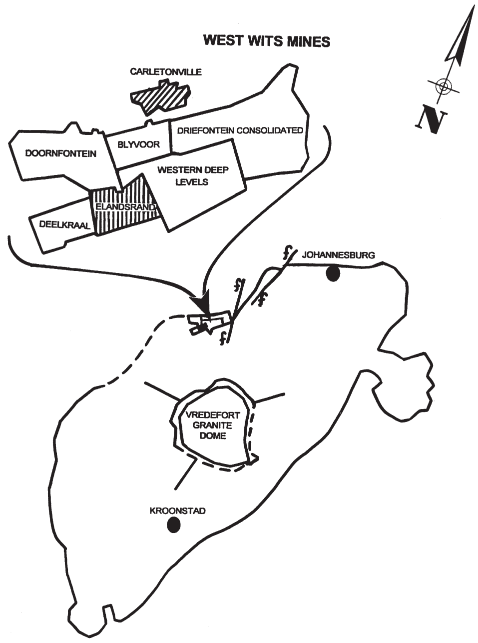

Figure 1—Location of Elandsrand Gold Mining Company Limited

Introduction

Elandsrand Gold Mining Company Limited was incorporated in 1974 to mine the Ventersdorp Contact Reef (VCR) on a mining lease of 2619 hectares straddling the boundary between Northwest Province and Gauteng. The location of the mine is shown in Figure 1. Production commenced in December 1978, and is scheduled to continue well into the 21st century from the current lease. The sub-vertical shafts were completed in June 1984, with final deepening being completed in 1997. The mine is now able to access the VCR over the entire lease area. During 1997, Elandsrand acquired the entire share capital of Deelkraal Gold Mining Company Limited, the neighbouring mine on the western boundary of the mining lease (Figure 1). On 29 June 1998, Elandsrand, Deelkraal and Western Deep Levels were all incorporated into AngloGold, and the three mines now form the AngloGold West Wits Operations.

Deelkraal and Western Deep Levels will not be included in the forthcoming discussion—except for a comparison of the seismic response to longwall mining and sequential grid mining—because neither played a part in the development of sequential grid mining. This paper reviews the sequential grid mining method (SGM) and its application on

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Elandsrand with the objective of describing its merits as a deep level mining strategy. In order to do this, a description of the geological setting of the mine is presented, followed by the development history of sequential grid mining, including some details of the design and rock mechanics modelling results. Finally, an assessment of the success of SGM at Elandsrand is given.

Geological setting of Elandsrand

The surface geology of Elandsrand consists of quartzites and shales belonging to the Timeball Hill Formation, which forms the west-south-westerly trending range of hills known as the Westwitsrante. A diabase sill is present near the base of the quartzites. Andesitic lavas belonging to the Hekpoort Formation cover the southern part of the Elandsrand mining lease area. The Malmani Subgroup Dolomites, the Black Reef Formation, and the lavas of the Ventersdorp Supergroup (Figure 2) underlie the surface rocks. The Ventersdorp Contact Reef is found at the base of the Ventersdorp Supergroup Lavas, about 1700 metres below surface at the northern boundary of the Elandsrand mining lease area, and about 3300 metres below surface at the southern boundary of the lease.

The Ventersdorp Contact Reef is a gold-bearing quartz pebble conglomerate capping the topmost angular unconformity of the Witwatersrand Supergroup (Figure 2). Regionally, it is seen as a separate lithological unit in its own right, and is officially referred to as the Venterspost Conglomerate Formation (Engelbrecht[1]). On Elandsrand it strikes on a bearing of 62° east of north and has an average dip of 24° southwards. It suboutcrops against the base of the Black Reef Formation in a direction parallel to strike along the northern boundary of the lease area.

The VCR exhibits highly erratic morphological and grade characteristics, varying from zero to 3 metres thick. The topography of the VCR depositional area was uneven, and consisted of a series of slopes and horizontal terraces at different elevations. The thickness of the reef is closely related to the nature of the terrain on which it was laid down i.e. slope reef tends to be thin and poor in gold content while terrace reef tends to be thick, containing higher gold concentrations. Terrace reef therefore presents more favourable mining conditions than slope reef.

The VCR unconformably overlies the footwall strata upon which it rests, on average by an angle of 4° to the east. It therefore rests on progressively older Witwatersrand Supergroup strata eastwards, beginning with the Mondeor Conglomerate Formation in the west, and ending with the Elsburg Quartzite Formation in the east. The lavas of the Alberton Formation throughout the lease area conformably overlie the VCR. At present the VCR has been accessed and mined from depths between 1700 and 2700 metres below surface (approximately 3.2 kilometres on dip) within the lease area, and over a distance of 5.5 kilometres on strike.

Faulting on the VCR at Elandsrand is relatively minor when compared with other gold mines elsewhere in the Witwatersrand Basin. The main structural trend lies in a NNE-SSW direction, and a minor trend lies parallel to the strike of the VCR. Dykes and sills ranging from Klipriviersberg to Karoo age also intrude the strata. Many dykes followed pre-existing fault surfaces when they intruded, and now have throws, which previously belonged to the faults. The throw displacements are predominantly normal, seldom exceeding 20 metres, and nearly always 10 metres or less. Fault throws in this size range make it possible to access the reef in a regular grid pattern, which provides a good base for sequential grid mining within a regular stablizing pillar layout.

The deepest stopes on Elandsrand are currently about 2700 metres below surface. The VCR is known to extend down-dip of the current stoping, to about 3300 metres below surface on the southern boundary of the mining lease area. Elandsrand is therefore classified as a deep level gold mine, and needs to employ deep level stoping methods to extract the reef safely. Sequential grid mining with dip stabilizing pillars provides one possible solution in the above-described scenario.

Sequential grid mining method

The shallowest parts of Elandsrand (from 60 to 76 Levels, 1700–2200 metres below surface) were exploited using the standard scattered mining method. At these depths mining induced seismicity and rockbursting were already a worsening problem, especially in the remnant areas between stopes, and on geological features such as faults and dykes

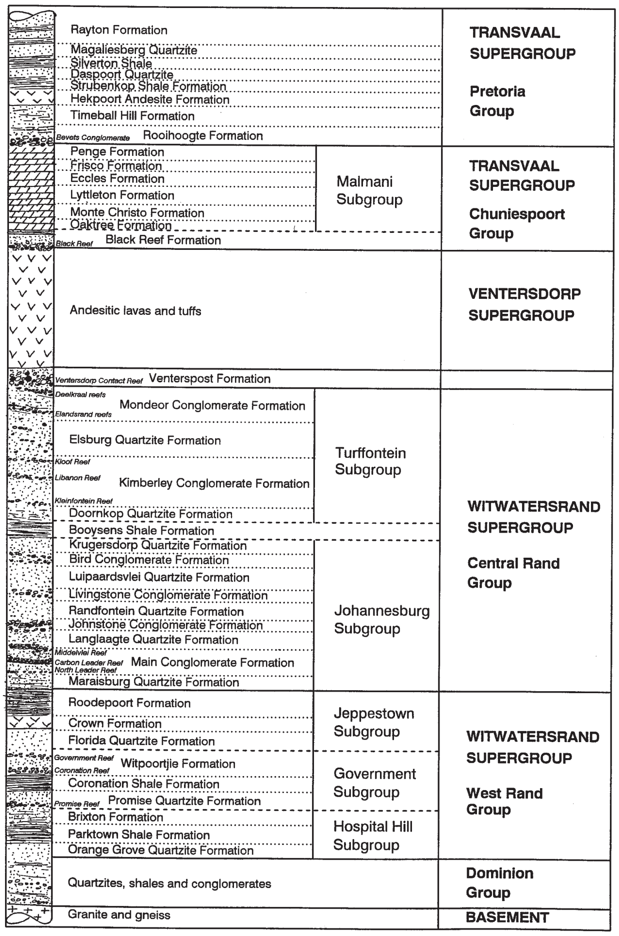

Figure 2—Generalized stratigraphic column for the Carletonville Goldfield

near the stopes. It was therefore apparent that some strategy had to be adopted to reduce the number of remnants being formed, while at the same time minimizing the seismicity generated on faults and dykes.

History of the Idea

Cook *et al.*[2] had shown, with the newly introduced concept of Energy Release Rate (ERR), the value of leaving reef pillars *in situ* as a means of rockburst control. Their diagram to illustrate the point has been converted into *SI* units, and reproduced in Figure 3. In both the cases studied, i.e. mining breast panels on strike and panels up-dip, reef pillars were left on dip. This study showed that ERR was better controlled by mining up-dip, and that a larger percentage of reef could be extracted in this way at lower average ERR, when compared to mining panels on strike. On the other hand, updip mining has the practical disadvantage of relatively small face length per longwall established, whilst breast mining has good face length but soon encounters unacceptably high ERR at relatively low extraction ratios (see Figure 3).

Since good face length and flexibility in a variable orebody would be of prime importance, a breast mining system with panels advancing along strike is preferable. The rising ERR predicted by Figure 3 for breast panels mining on strike could be controlled by limiting stope span, for example by mining on only one side of a raise at a time.

Murie[3] applied these ideas to an area east of the shaft between 70 and 73 Levels. He found that dip rib pillars, in combination with bracket pillars on dykes and faults, would reduce the ERR by 50 per cent when compared with the situation where only bracket pillars were left on the geological features. It was clear that a systematic set of dip pillars would do a lot to control the ERR, with the additional advantage that mining would stop on the planned pillar positions when ERR was approaching an unacceptably high value. The alternative of a longwall mining system with strike stabilizing pillars would be equally good from an ERR point of view, but would be inappropriate because of the variability of grade in the VCR. Also, a significant proportion of seismicity had been observed to be associated with geological structures, which would have to be mined using the longwall system. Thus, a system retaining the flexibility of scattered mining, while at the same time providing regional support in the form of stabilizing pillars, was preferable.

Applegate[4] was the first to recommend 30 metre-wide dip stabilizing pillars on 200 metre centres, resulting in an 85 per cent extraction ratio. Strike stabilizing pillars were also recommended, and pillar layouts for the entire mine were drawn up and analysed. It was recognised that these initial layouts would be modified as new information became available, and that detailed analysis would be carried out on a section by section basis, taking into account mining, geological structure, and grade considerations. Applegate and Arnold[5] concluded that dip stabilizing pillars were more suitable than strike stabilizing pillars at Elandsrand, if flexibility was to be maintained in an erratic orebody. Their reasoning appears in Table I.

By early 1990, a system of 30 metre-wide dip stabilizing pillars on a 200 metre centre to centre spacing had been planned for mining from 76 to 85 Levels (Applegate and Arnold[5]). It was proposed that this spacing be retained for long-term planning purposes, but that the final designs be customized for each area. All major geological features would be bracketed, while the systematic dip stabilizing pillars would be sited in unpayable ground wherever practicable. It was noted that accurate geological and reef grade information would be required early so that the pillar layout design could be finalized timeously.

Despite the choice of dip pillars, Applegate and Arnold[5] realized that there was no single correct solution to the

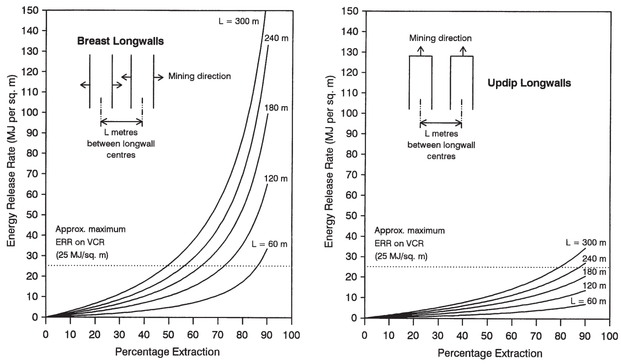

Figure 3—Comparison of energy release rate vs percentage extraction between several adjacent breast and updip mining longwalls (after Cook *et al.*[2])

Table I

Advantages and disadvantages of dip and strike stabilizing pillars in scattered mining (after Applegate and Arnold[5])

Dip pillars: Advantages	Dip pillars: Disadvantages
Holding of panels from adjacent raises avoided—remnant formation therefore prevented	Access haulages must pass under the pillars
No gullies carried next to pillars	In high grade areas there will be a temptation to mine beyond the pillar limit
Pillars only reduced to final size as stoping activity ends	
The major geological trend lies at a 20° angle to the dip direction, therefore some bracket pillars could double as dip stabilizing pillars	
Strike pillars: Advantages	**Strike pillars: Disadvantages**
Access haulages can be sited away from the pillars	Holing required unless adjacent raises are separated by major faults or dykes
Stabilizing effect of strike pillar fairly constant whereas the effect of the dip pillar changes as the final pillar position is approached	Strike gulllies must be maintained next to and parallel to pillars on both sides
	Stope access via strike gullies vulnerable to pillar induced strata control problems
	The pillar must be slotted at regular intervals to allow access crosscuts to pass underneath

problem, and that a systematic pillar system with either dip or strike pillars could be equally effective, each being more advantageous than the other in certain situations. The purpose of the pillar designs, regardless of what they were, was to customize them to the situation at hand, with the goal of making the design practical, easy to implement, and profitable.

Preliminary design of sequential grid mining method

Cook *et al.*[2] demonstrated that an ERR peak would soon develop with longwall faces mining on strike toward each other, as is shown in Figure 3. Applegate[6] showed that this ERR peak could be kept at acceptable levels by implementing a proper *sequence* of mining where stope spans were kept to a minimum. He outlined the mining strategy as a combination of scattered mining with a system of partial extraction. The *sequence* of mining was important, hence the term *sequential. Grid* refers to a grid of regularly spaced crosscuts and raises, borrowed from the scattered mining system. McCarthy[12] coined the name *sequential grid mining* in 1991.

The overall direction of sequential grid mining is outward from the shaft on strike, moving from raise line to raise line, toward the eastern and western boundaries of the mining lease area, as shown in Figure 4. Because deeper levels would be opened up later than shallower levels, the former would lag causing the overall mining front to be V-shaped down-dip. This is a favourable overall mining configuration. Control of the mining sequence at each raise line is shown in finer detail in Figure 5. The mining from each raise first proceeds towards the shaft, so that final pillar formation takes place at low span (thereby limiting the ERR). At this point the mining ERR reaches a peak, but the hazard is eliminated by the fact that mining stops at this point. Once the pillar formation is complete, mining from the same raise proceeds away from the shaft towards the stopping line for the next pillar. During this phase, stope spans reach their maximum, but this is somewhat negated by the fact that the mining faces are advancing towards solid ground. Overall, the ERR is well controlled, with high stresses (hence ERR) being confined to the pillars, which are left unmined.

Raise spacings are limited by maximum practicable scraping distance. It was clear that if bracket pillars doubled as dip pillars, then they would not necessarily lie in the middle between two raises as shown in Figure 6. This would require a small raise spacing (to limit maximum scraping distance), while pillar widths of at least 30 metres and an extraction ratio of at least 85 per cent would require large raise spacings. A 200 metre raise spacing was chosen as a reasonable compromise (Applegate[6]).

Computer modelling to test the suitability of sequential grid mining

Applegate[6] carried out computer modelling to test the sequential grid mining concept, using MINSIM-D (Chamber of Mines Research Organisation[7]). The modelling analysed the sequential grid mining method, and compared it with an alternative mini-longwall mining method in which strike stabilizing pillars were used. The analysis was repeated in both cases with and without backfill, and with overhand and underhand face configurations.

In all cases, the leads and lags between faces were kept at 10 metres, and face lengths were 35 metres. The dip pillar configuration modelled included 30 metre-wide pillars and 35 metre pillars while maintaining the same extraction ratio of 85 per cent. This was done to investigate the stability of the dip pillars using the Hoek and Brown[8] failure criterion. All layouts were conceptual and kept as simple as possible. The model geometries are shown in Figure 7. The primary variables studied in the models were the ERR on the mining faces, and the average pillar stresses (APS) including the

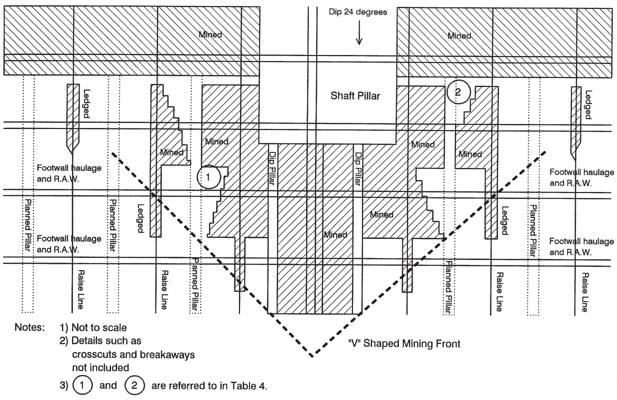

Figure 4—Overall strategy for sequential grid mining

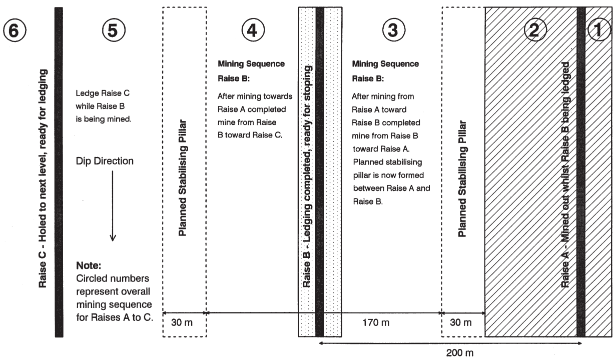

Figure 5—Stoping sequence for sequential grid mining (not to scale, after Applegate[6])

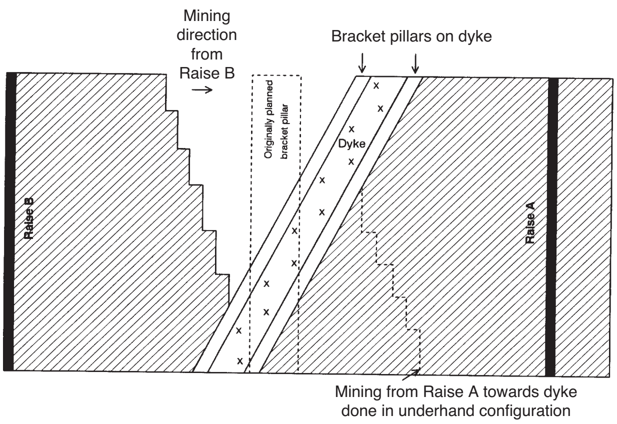

Figure 6—Example of bracket pillar replacing dip stabilizing pillar

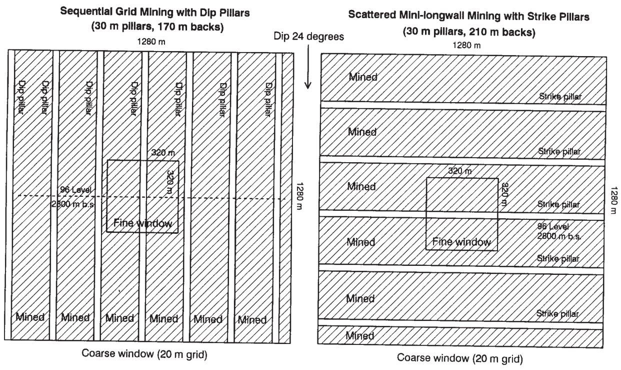

Figure 7—Comparative MINSIM models for pillar stability in mined out case

worst case scenario where everything has been mined except for the stabilizing pillar system. In addition, the effect of pillar induced stresses in the footwall were evaluated and used to establish an optimum depth below reef that the access haulages should be sited.

The modelling parameters employed are listed in Table II so that Applegate's[6] work can be repeated. Note that subsequent versions of MINSIM for MICROSOFT WINDOWS and other tabular mining analysers such as BESOL and MAP3D should produce comparable results to those obtained from MINSIM-D.

The modelling results are summarized as follows (after Applegate[6]):

- the average pillar stress, estimated for a depth of 2800 metres below surface at 454 MPa, was less than the currently accepted maximum level of 2.5*UCS = 625 MPa in the case of Elandsrand (Chamber of Mines[9])
- according to the model, the APS would only exceed the 625 MPa criterion at a depth of 3860 metres, thus the current design appears satisfactory for mining to at least the southern boundary of the lease (about 3300 metres below surface)
- dip pillar stability would therefore not be a problem according to the above criterion, although this was contradicted by the Hoek and Brown[8] failure criterion (Applegate[6])
- the modelling results suggested a failed rock mass around the pillars in both cases, when the Hoek and Brown[8] failure criterion was employed, which might point to future pillar instability
- the planned depth of haulages at 80 metres below reef satisfied the design criterion that a haulage should never be subjected to a field stress exceeding 120 MPa
- the ERR for both configurations was kept to acceptable levels (20 MJ/m^2 or less) in all situations
- the sequential grid mining method was able to meet the ERR criterion by proper sequencing of the mining
- the sequential grid mining system was disadvantaged in the case where mining was carried out down-dip of a mined out area—in this case the topmost panel in the overhand configuration gave unacceptably high ERR values, while an underhand configuration went some way to ameliorating this problem
- the average ERR for both the sequential grid mining system and the mini-longwall system were 16 MJ/Ca and 13 MJ/Ca for the case of no backfill and backfill respectively—a result not surprising as both had similar extraction ratios
- backfill reduced the APS in the sequential grid mining system by 7.5 to 20 per cent
- backfill was found to be more effective in sequential grid mining since backfill effectiveness depends on stope closure. Maximum stope closure occurs at the raise line in sequential grid mining, while the highest closure rates are found in the centre panels of the mini-longwall system. In the former, backfill is placed in a low closure environment (when stope spans are small), but must be placed in a high closure environment behind the advancing panels (in the centre of the mini-longwall).

In general both the sequential grid mining system and the mini-longwall system met all the rock engineering requirements for deep level mining, except the potential for stabilizing pillar failure, according to the Hoek and Brown[8] failure criterion. Experience at Western Deep Levels (Hagan[10]) showed that strike stabilizing pillars on the Carbon Leader Reef were prone to failure. Dip pillars were expected to be more stable than strike stabilizing pillars because they are aligned parallel to the overall ride direction, and are more evenly loaded than strike stabilizing pillars (Starfield and Crouch[11]). They were therefore expected to be able to bear higher loads than strike stabilizing pillars before becoming unstable. This suggested that dip stabilizing pillars

Table II

Modelling parameters used to evaluate the sequential grid mining

General elastic constants	Value
Poisson's ratio	0.2
Young's modulus	70.0 GPa
Stoping width	1.5 metres
Cohesion	5.0 MPa
Angle of friction	30 degrees
Backfill variables	**Value**
Cohesion	0 MPa
Angle of friction	30 degrees
Material type	Hyperbolic
Critical stress parameter (a value)	11.1 MPa
Ultimate strain parameter (b value)	0.40
Fill width	1.5 metres
Hoek and Brown failure criterion variables	**Value**
Rockmass quality	Very good
Uniaxial compressive strength of rock	200 MPa
Empirical constant—m value	7.5
Empirical constant–s value	0.1
General computer modelling parameters	**Value**
Coarse window grid size	20 metres
Fine window grid size	5 metres
Panel lead length	10 metres
Model depth assumed (95 level)	2700 metres below surface
Maximum number of solution iterations	15
Successive over-relaxation factor (all iterations)	1.5
Overall stress tolerance	0.2 MPa
Maximum number of iteration cycles	15
Number of lumping shells	3
Iteration start control number	0

may not show the foundation failure characteristics experienced with strike stabilizing pillars given the APS figures calculated in the numerical models.

McCarthy[12] investigated the production potential of sequential grid mining as compared with a mini-longwall layout, with the results listed in Table III. McCarthy's study was based on the mining planned between 76 and 85 Levels, each layout being used to access and exploit the same area of the mine. The sequential grid system allowed a greater amount of reef to be mined while needing less access development. It was expected from this exercise that sequential grid mining would be more profitable because it both increased revenue while at the same time reduced development costs. It was assumed that other mining costs would remain more or less the same. The choice of sequential grid mining for Elandsrand was therefore a calculated risk, with clear production benefits, enhanced pillar stability, reduced access costs, but still unknown pillar behaviour in the long term.

The decision to implement sequential grid mining was eventually based on the following factors:

- less off-reef development: sequential grid mining would produce 28.7 stope centares per off-reef development metre (including boxholes), whereas the mini-longwall system would produce 17 to 24 stope centares per off-reef development metre, depending on the access development layout
- improved selectivity and flexibility in sequential grid mining with respect to planning and mining, which is essential for a variable orebody such as the VCR
- recovered grade in sequential grid mining is better because of the improved selectivity, flexibility, and reduced off-reef mining
- improved available face length in sequential grid mining, which forms a good basis for selectivity and flexibility
- an expected reduction in seismicity in sequential grid mining—no panels would hole into one another, and no panels would need to negotiate major geological features
- strike stabilizing pillars require ventilation slots, which means dangerous mining—sequential grid raise lines are naturally separated into ventilation districts and no pillar slots are required
- strike gullies in sequential grid mining will in general enjoy more stable rock conditions because none are placed next to dip stabilizing pillars whereas the mini-longwall system requires gullies to be placed next to strike stabilizing pillars
- backfill will be relatively more effective in the sequential grid mining system, than in the longwall mining system
- sequential grid mining is dependent on development staying ahead of the mining front, but this enables accurate geological information to be gathered and included in final designs before mining commences—this in itself leads to better planning, safer working conditions and improved profitability.

Elandsrand therefore elected to implement the sequential grid mining system, starting from 76 Level in early 1990.

Table III

A comparison between production from a longwall system and sequential grid mining (after McCarthy[12])

Mining parameter	Mini-longwall	Sequential grid
Square metres mined	3 623 000	3 720 000
Development metres required	219 880	157 550
Gold produced (kg)	202 535	204 297
Square metre/metre development ratio	16.9	28.7

Practical implementation of sequential grid mining

Sequential grid mining was implemented below 76 Level, but its full impact was delayed for several years as increased mining of the deeper reserves slowly replaced depletion of shallower reserves above 76 Level. The practical implementation of the sequential grid mining system has taught some lessons both from the seismic and practical mining points of view.

Practical Mining Lessons

Figure 8 gives an overall view of how sequential grid mining has been implemented at Elandsrand. The formation of dip and bracket pillars is clear, especially for 1995. It can also be seen that some stopes in the scattered mining areas above 76 Level are separated by dip and bracket pillars. The down-dip V-shaped configuration developed between 1991 and 1995. The development and raises ahead of the mining front are visible in Figure 8, and these all provide advanced access to the orebody and the timeous accumulation of accurate geological and grade information before mining commences.

The design process employed at Elandsrand for the sequential grid mining system is described below (after Applegate[6]).

- *Preliminary design*: lay out dip pillars at the standard spacing, and adjust these where necessary if bracketing of geological structures is planned, or patches of low value reef have been found. At this stage designs are based on practical situations, and 'rules of thumb'. Computer modelling at this stage is inappropriate

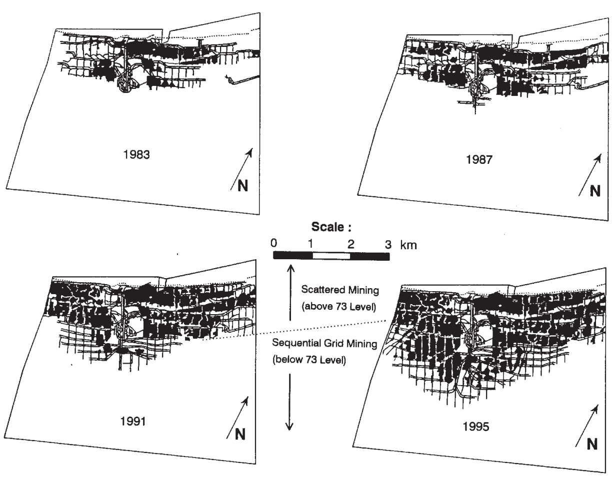

Figure 8— Development of sequential grid mining system on Elandsrand

because of the lack of accurate geological information in the area to mined. The rough design is suitable for the long-term mine plan, where important aspects such as extraction rates and development needs can be determined
- *Final design*: once drilling and raise mapping improve geological information concerning grade and structure, the preliminary designs can be customized to suit the situation. At this stage is is essential that personnel from rock mechanics, geology, survey and mining co-operate to produce the final design. This may involve re-siting dip pillars in unpayable ground, designing bracket pillars for a dyke, etc. Once alternatives are proposed, numerical modelling is carried out to assist in deciding upon the best design for the area. All personnel involved in the above process should agree to any further adjustments to the design made from the modelling results
- *Design changes:* new information may force changes to the final design, which again should be checked by numerical modelling. The procedures listed above should be adhered to when changes are made. Any unauthorized changes, such as mining beyond pillar limits must be strongly discouraged, as this could compromise profitability and safe working conditions.

Mining commences once a reef raise holes on the next level from the level below. When holing is complete, the reef raise is secured by mining it from the top using a down-dip ledging strategy. This is done by advancing a 10 metre-wide face, angled 20° to 45° to the raise line, and scraping broken ore down-dip into the raise. One ledging face leads the other by a distance of not more than 10 metres. The ledged raise is supported by a combination of packs and backfill ribs since it has been found that the central raise line remains much more stable during the stoping operations if it has been supported by backfill ribs. This has been found to be true whether or not backfilling is carried out during the stoping phase.

Typically, a raise takes 8 months to hole from one level to the next, and down-dip ledging takes another 8 months between levels. It takes roughly two years to mine out a raise line between two levels, i.e. replacement of mined-out raises takes roughly two-thirds the time it takes to mine out a raise line between levels. Once stoping of a raise line is completed, sweeping and vamping operations are carried out before the crosscut is closed at the breakaway position. These time constraints dictate that at least three raise lines are in various stages of development ahead of the main mining front on each level. The crosscut nearest the haulage end should be broken away from the haulage, the second developing towards reef, and the third raising on reef. Mining will be in progress on the fourth raise line from the haulage end (i.e. about 600 metres behind the haulage development).

A delicate balance must therefore be struck, where development is kept sufficiently far ahead of mining so that newly ledged raises become available for stoping when required by the sequence. It has been found that if development gets too far ahead, ledged raises stand for too long a period before being mined (in some exceptional cases, two years), and strata control problems develop in the raise and crosscut before mining commences. In terms of selectivity and flexibility, the further the development is ahead of mining, the better. The three raise-line compromise on each level appears to have worked best so far, and is used as a measure to plan future development requirements. Presently, ledging contributes about 25 per cent of the reef centares produced by the mine.

Sequencing of stoping operations exactly as proposed in theory is extremely difficult to achieve in practice. As a result, there have been and will be many instances where the theoretical ideal cannot be followed for various reasons, e.g. the presence of poor grade, unknown geology, or unexpectedly severe seismicity. These conditions could lead to unplanned delays and re-planning. One consequence is that panels from two adjacent raise lines could end up mining toward each other. It was observed that seismicity in the planned pillar area between the two advancing stopes would increase dramatically before the panels had reached the planned stopping positions, thereby increasing the potential for rockburst accidents. This had occurred on several occasions relatively early, and rules to control it were required. A study by Handley[13] revealed that mining-induced stress in the planned pillar area increased suddenly when the panels were 70 metres apart on strike, i.e. when both sets of panels approaching the pillar position were approximately 20 metres from their stopping positions.

The model showed that if one set of panels was stopped, the rate of stress increase in the pillar area was reduced, and by observation, so was the seismicity. The other set of panels could then mine in relative safety to the pillar stopping position. Once this had been achieved, the second set of panels could resume mining, and also reach the pillar stopping position in relative safety. This became known as the 70 metre rule, and is still applied at Elandsrand today.

Essrich[14] has compiled a report covering problems and their remedies in sequential grid mining. These are listed with the appropriate remedy in Table IV.

These problems have all arisen in the past ten years of mining, and have been solved by the remedies given in Table IV. Overall, sequential grid mining can be safely and profitably applied in the VCR environment at depths similar to those at Elandsrand. Furthermore, the rock-related problems encountered using this method can be solved by existing knowledge and experience.

Performance of sequential grid mining at Elandsrand

Performance measures for sequential grid mining considered in this paper are seismicity, productivity, and rock-related injury rates. The discussion below is broken up into these three categories.

Seismicity

Before 1992, an analogue seismic location system was functioning, but the data it produced was both inadequate and unreliable. In 1992, a digital seismic system produced by Integrated Seismic Systems International of Welkom, South Africa (ISSI) was installed underground. This system is a fully digital real-time seismic and non-seismic geotechnical monitoring system. It provides facilities for on-line quantitative data processing, data interpretation and data visualization. The seismic system consists of the following equipment:

Table IV

Problems and remedies associated with sequential grid mining (after Essrich[14])

Problem	Remedy
Minor pillar seismicity encountered—up to two raise lines behind current mining	Wider pillars and smaller stope spans at greater depths
Seismicity on geological structures	Appropriate bracket pillar planning and designs for all active geological structures
Geological structure intersecting haulage under pillar	Avoid placing haulage in geological feature directly under pillar
Difficult to mine top panel in overhand configuration in abutment (see points 1 and 2 in Figure 4)	Apply underhand configuration in abutments below mined out areas
One-sided loading of abutment while mining first side of ledge	Start up one or two panels, mining slowly to allow rockmass to release stress
Starting panels from ledge, or re-starting stopped panels	Ensure stiff last line of face support, increase support density during start-up phase
Lack of flexibility	Correct long-term planning
Large seismic events in mining final stages of raise line section	Reduce number of active panels and mined panel length towards end of raise life
Remnant pillar mining	Avoid totally unless alternative regional support system is in place (e.g. backfill)

- geophones installed underground and on surface
- underground data acquisition and communications equipment including intelligent, processing and multi-seismometers
- electrical cable linking underground equipment with surface computers
- a central control site with computers
- processing, interpretation and visualisation software.

All the seismic hardware is modular in design, making it easy to add and remove components. This is particularly useful when extending the system as the mine expands to exploit new areas. Deelkraal possesses the same type of system, which became functional in 1995.

A count of mine seismic frequency for all seismic events greater than or equal to magnitude 1.0 on the local Magnitude Scale have been plotted in Figure 9 against the build-up of sequential grid mining at Elandsrand. This graph clearly shows a major drop-off in seismic activity induced by mining during 1993 and 1994, after which it has remained at 20 to 30 per cent of former levels. This cannot be ascribed to sequential grid mining alone, but the introduction of the new mining method must have played a part. Other factors which played a role are discussed in Section 4 above. Although Figure 9 is compelling evidence of the success of sequential grid mining, a more rigorous analysis of seismic activity was still considered necessary to establish it as a viable deep level mining strategy. Comparative analyses carried out by SIMRAC[15] and Essrich[16] have been done, and are described below.

SIMRAC[15] have compared the seismic response to longwall mining with that of sequential grid mining by considering Elandsrand and Deelkraal, both of which are mining VCR in a similar geotechnical environment at similar depth. Variables such as geology, rock type, stoping width, and depth can be ignored for the seismic comparison, and differences can thus be ascribed to the mining method. The seismic data from both mines was recorded in 1996, when both operated similar seismic location systems (the type of seismic system could have an effect on the seismic statistics obtained).

The results quoted by SIMRAC[15] have been reworked slightly and presented in Table V. The number of seismic events has been normalized to the area mined on each mine, to illustrate the relative seismic frequencies encountered at each mine. It can be seen that for magnitude 0.8 events and larger, approximately 45 per cent more can be mined using the sequential mining system than is the case for the longwall system. For events with magnitude exceeding 2.0 (which have a good chance of damaging underground excavations), approximately 153 per cent more can be mined with the sequential grid system than with the longwall system. This means that the seismic hazard due to potentially damaging events is far lower in a sequential grid mine than in an equivalent longwall mine.

SIMRAC[15] quantified the seismic hazard for each mining method using the variables V_{eff} and VGM (see Table V). V_{eff} is the volume of rock in which all the seismic events occurred—i.e. a measure of clustering. For example, a large number of seismic events clustering into a small volume would pose a threat to any mining excavation in that volume, because their potential to damage it would be high. If the seismicity is more *diffuse* (i.e. has a larger V_{eff}) then the damage potential to an excavation in the volume would be less. VGM, the volume of ground motion, integrates standard seismic hazard parameters (*b*-value, seismic activity rate, and maximum magnitude) into one parameter that combines the statistical and physical attributes of seismicity with its damaging potential (Mendecki[17]). A smaller VGM means that a relatively smaller volume of rock has been affected by damaging seismic events i.e. the damaging potential of all the seismicity recorded is likely to be less.

Normalizing for the two mining methods given in Table V, VGM/V_{eff} for the sequential grid mining system is 0.85/1.80 = 0.47, and for the longwall system 1.10/0.50 = 2.20. Finding the ratio between these numbers i.e. 2.20/0.47 = 4.68, means that the longwall system can be considered to be 4 to 5 times more 'dangerous' than sequential grid mining, based on the seismic statistics analysed (SIMRAC[15]).

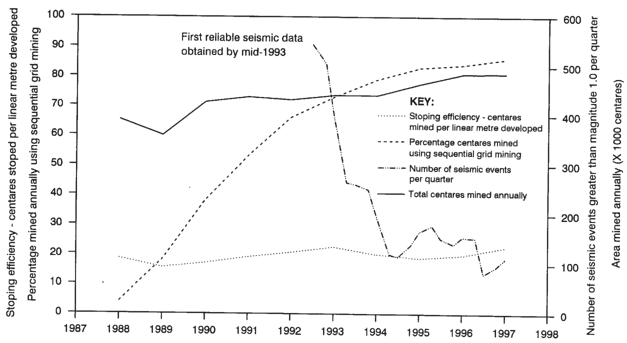

Figure 9—Production statistics for Elandsrand from 1988 to 1997

One can also look at the relative seismic hazard between the two mining systems by again considering VGM in Table V above and the area mined (assuming that the stoping widths are the same). Normalizing the VGM per unit area mined (in this case choose the unit area mined as 100 000 ca) for sequential grid mining gives 0.85/3.18 = 0.27, and for longwall mining 1.10/1.97 = 0.56. This means that in terms of area mined, longwalling is more than twice as 'dangerous' (0.56/0.27 = 2.07) from a seismic hazard point of view as sequential grid mining (SIMRAC[15]). It must be noted that the data presented here was gathered over one year only, and conclusions may change for larger data sets. In summary, it appears that sequential grid mining is the safer method for the VCR in the western part of the Carletonville Goldfield, but that larger data sets are necessary to define the relative seismic hazard more precisely.

Essrich[16] carried out a similar comparison between the 76-36 Longwall West at Western Deep Levels and the 80-32 W2 to W5 Panels at Elandsrand (Table VI). The latter panels formed part of the sequential grid system at Elandsrand. In both cases, the stopes were bounded by dykes to the west; at Elandsrand a bracket pillar was left on the Footwall Dyke when the panels reached their planned mining limit, and at Western Deep Levels the toe of the longwall was stopped on the Georgette Dyke. The different methods used to approach the geological structures at the two sites are likely to be responsible for some of the differences in the measured seismic responses. While the intersection of the South Georgette and Tarentaal Dykes in the case of the longwall was a centre of high seismic energy release during mining, no such concentration of failures was observed on the Footwall Dyke at Elandsrand. Instead, the seismic energy release in the sequential grid stope showed a positive correlation with area mined, and showed a peak in the 4th quarter of mining, and a decline afterwards. When the mining approached closest to the Footwall Dyke, seismic energy release had already dropped to pre-peak levels. This study shows that the integration of major geological features into bracket pillars in the sequential grid mining environment plays an important role in reducing the seismic hazard, because mining is not required to intersect the dyke, as in the case of the longwall.

Table V

Comparison of seismicity generated by a longwall system and sequential grid mining at Elandsrand (after SIMRAC[15])

Parameter	Sequential Grid (SG)	Longwall (LW)	Ratio (SG/LW)
Area mined (centares)	318357	197402	1.61
Ave. sq. m mined per event with mag. ≥ 0.8 (total no. events)	428 (743)	296 (667)	1.45
Ave. sq. m mined per event with mag. ≥ 2.0 (total no. events)	22740 (14)	8973 (22)	2.53
Magnitude of largest event	3.0	2.9	1.03
Magnitude of second largest event	2.6	2.8	0.93
V_{eff}—effective volume covered by seismic activity (km^3)	1.8	0.5	3.60
VGM—cumulative volume of rock affected by ground motion ≥ 55 mm/s (km^3)	0.85	1.1	0.77

The measurements listed in Table VI were not the same as those of SIMRAC[15], but some of the results are very similar. It can be seen that the mining in the longwall was much more intensive, with much higher production rates, from essentially the same volume of rock. This is the most important driving force behind mining-induced seismicity, and probably accounts for the differences in seismic rates (expressed as an average number of centares mined per seismic event) presented in Table VI. For example, the longwall experienced much higher seismic rates than the sequential grid stopes, all compressed into a period of five months for the former, compared with the 18 months for the latter. The impact this may have had on safety is not known since Essrich[16] confines his discussion to mining-induced seismicity.

Comparing the seismic rates in Tables V and VI it is clear that the results are similar. It would appear that both studies typify the differences between longwall and sequential grid mining, since both were carried out at different times, and compared different mining areas. It is concluded, from the findings of SIMRAC[15] and Essrich[16], that sequential grid mining is safer than longwall mining on the VCR in the western part of the Carletonville Goldfield.

Productivity

Sequential grid mining should result in productivity improvements; these are not necessarily a direct consequence of the mining method, and could also arise from good management practice. Therefore only two measures are considered, namely area mined annually and average area mined per linear metre of development. Both measures are plotted in Figure 9 with the mining-induced seismicity.

Table VI

Comparison of seismicity generated by a longwall and a sequential grid stope (after Essrich[16])

Parameter	Sequential Grid (SG)	Longwall (LW)	Ratio (SG/LW)
Reef type	VCR	VCR	-
Period over which mining took place	Sep. 1994 to Mar. 1996 (18 months)	May 1996 to Sep. 1996 (5 months)	3.60
No. of panels mined	4	9	0.44
Block dimensions in which mining took place (metres)	140 × 120	360 × 40	-
Average face advance rate (metres per month)	6	7	0.86
Average depth of mining (metres below surface)	2200	2100	1.05
Total area mined (square metres)	12500	11800	1.06
Average area mined per month (square metres)	700	2360	3.37
Average sq. m mined per event with mag. ≥ 1.0 (total no. events)	431 (29)	223 (53)	1.93
Average sq. m mined per event with mag. ≥ 2.0 (total no. events)	12500 (1)	2360 (5)	5.30
Cumulative seismic energy measured (MJ)	304	473	0.64
Area backfilled expressed as a percentage of area mined	0	20	-
Rockburst related accidents	2 reportable	2disabling 5 reportable	-

There has been a steady increase in the area mined on the VCR annually, from 392 000 square metres in 1988 to 486 000 square metres in 1997, a 24 per cent increase over the period (Figure 9). This is not remarkable in itself until the seismic statistics are considered: in the same period there was an approximate 80 per cent drop in mining-induced seismicity (Figure 9). When considering the comparisons in the previous section between longwall mining and sequential grid mining, it would appear that sequential grid mining meets expectations for the control of mining-induced seismicity. The curves in Figure 9 therefore show that it is possible to manage mining-induced seismicity effectively using the sequential grid mining system.

During the same period sequential grid mining has allowed the stoping to development ratio to improve by 22 per cent from 18.50 square metres per linear metre developed to 22.55 square metres per linear metre (Figure 9). This improvement falls short of McCarthy's projected figure of 28.7 square metres per linear metre (Table III) by 21 per cent, but is still a 33 per cent improvement on the comparative figures expected for the mini-longwall layout. The reason why sequential grid mining has not reached projected expectations is that the mine needed a far greater development rate below 76 Level to open the orebody sufficiently for the expected mining flexibility. Therefore annual development rates have equalled or exceeded the minimum required to regenerate mined out reserves using the sequential grid method. This rate should flatten in future while stoping rates will continue to increase slightly, which should result in further improved stoping to development ratios.

Rock related injury statistics

Rock related injury statistics (including both rockbursts and rockfalls) can be used to reflect the anticipated improvements offered by sequential grid mining. For this purpose, the work by Moalahi[18] has been summarized in this section and presented in Figure 10. The statistics cover a period of 10 years (January 1988 to December 1997), spanning the time that sequential grid mining was introduced and implemented on Elandsrand. The rockfall and rockburst injury rates were calculated by counting the total number of persons injured (both fatally and non-fatally) each year and expressing the result as a rate per 100 000 centares mined.

Plots 1 and 3 in Figure 10 compare rockfall injury rates for the scattered mining and sequential grid mining methods at Elandsrand. Application of the sequential grid mining method is not expected to influence rockfalls, which should be controlled by other factors. The recent downward trends for both scattered mining and sequential grid mining are similar, showing that an amalgam of mine-wide factors contributed to the reduction in rockfall injury rates e.g.:

- improved support methods (Hamman[19])
- improved safety management including for example training, barring down, and compliance with support recommendations
- recognition of the influence of 'slope reef' conditions on the stability of the hangingwall in stopes (Hamman and Close[20]).

The curves in plots 1 and 3 help to confirm that the introduction of sequential grid mining ought not to influence rockfall injury rates.

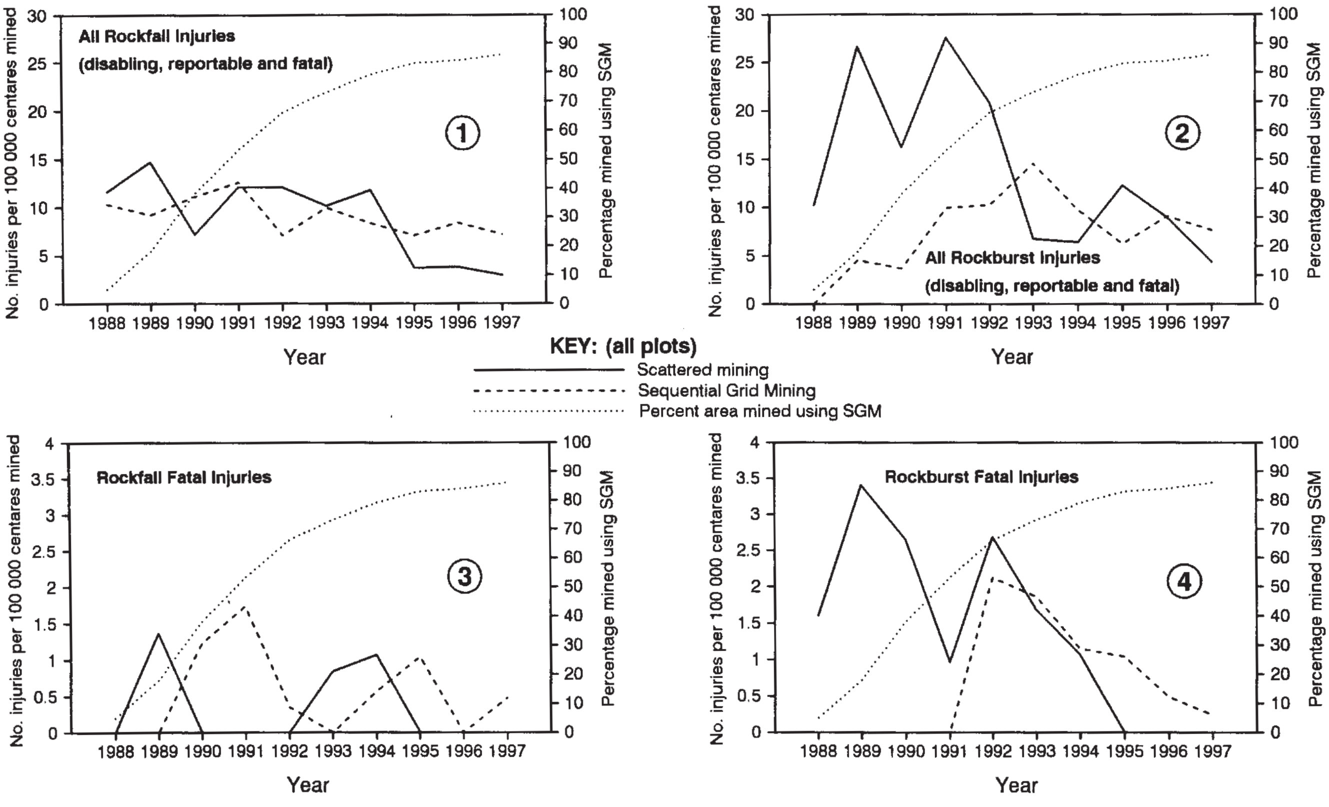

Figure 10—Rockfall and rockburst injury statistics for Elandsrand from 1988 to 1997 (after Moalahi[18])

The rockburst injury rates compare the benefits of scattered mining and sequential grid mining in plots 2 and 4 in Figure 10. In plot 2 reductions in overall rockburst injury rates have been larger in the scattered mining area than in the sequential grid mining area. It appears that support improvements, insights, safety management, the application of the remedies listed in Table IV, and other factors mentioned above brought about reductions in rockburst injury rates during the past five years. The results for the scattered mining area could have been helped by a reduction in mining rate during the same period, and the fact that the average mining depth is 500 metres (18 per cent) less than the sequential grid mining area.

Strong downward trends in the rockburst fatality rate are present for both scattered and sequential grid mining between the beginning of 1993 and the end of 1997 (Figure 10, plot 4). Here, improved support and the recognition of unstable hangingwall (Hamman[19] and Hamman and Close[20]) would have played particularly important roles. As a result, there has been a 100 per cent reduction in rockburst fatalities from 1992 to 1995 in the scattered mining area, and no fatalities since. From 1992 to 1997, there has been an approximately 80 per cent reduction in the rockburst fatality rate in sequential grid mining, which coincides with the reduction in mining induced seismicity shown in Figure 9. Improved support, recognition of unstable hangingwall conditions, and the application of remedies listed in Table IV would have contributed to this reduction, but it is expected that reduced seismicity could have played a leading role. The linear correlation coefficient between mining-induced seismicity and the rockburst fatality rate was calculated to be 0.69. It is proposed that a detailed study into the causes of rockburst injury statistics be undertaken for sequential grid mining in order to identify the relative benefits that different factors such as support, etc. have contributed to safety and productivity.

In summary, Elandsrand has reduced all rock-related injury rates significantly in the past five years. This has been the result of several improvements, and cannot be ascribed to sequential grid mining alone. The flexibility inherent in sequential grid mining may have contributed to the reduction in mining-induced seismicity, which in turn is likely to have reduced rockburst injury rates. Again, other factors would also have contributed to this reduction. A more detailed study of rock related injury rates is necessary to identify the contributions made by the different factors.

Conclusions

It is concluded that, although the evidence presented is not complete, sequential grid mining is a simple methodical way of exploiting the deep level Ventersdorp Contact Reef reserves at Elandsrand which:

- ➤ results in a regional dip pillar support system
- ➤ keeps energy release rates to an acceptable minimum by sequencing mining in an optimal manner on a regular grid system
- ➤ allows pillar location on geological features and low grade areas, thereby maximizing gold recovery
- ➤ provides good geological and reef grade information for short- and long-term mine planning and design purposes
- ➤ offers the opportunity of revising mining plans before mining commences when new geological information comes to light
- ➤ requires less linear development per square metre stoped than an equivalent mini-longwall system
- ➤ through its flexibility of application enables effective management of mining-induced seismicity and associated losses
- ➤ has to date not presented the miner with any insoluble mining or ground control problems
- ➤ by comparison with longwall mining methods applied at similar depths in the western part of the Carletonville Goldfield, has been shown to be the safer method both in terms of mining-induced seismicity and rockburst injuries.

There are four negative aspects to sequential grid mining, namely:

- ➤ the regular mining layout can result in lack of flexibility in planning and mining
- ➤ sequencing the mining limits the amount of face available for exploitation
- ➤ sequential grid mining requires a higher up-front capital input to establish mining faces than does longwall mining, which in turn can have a negative impact on the internal rate of return on a mining project
- ➤ the long-term potential for instability in the pillars is still unknown.

There are, as yet, no viable solutions for the first three problems. In terms of the fourth problem, no disruptive pillar failures have occurred to date, but the potential remains, and will increase as more pillars are formed. The above-named problems need to be solved by further research before sequential grid mining can be unequivocally claimed to be the preferred method of extracting deep level tabular orebodies. Sequential grid mining has been shown not to influence rockfalls, but it ought to influence rockbursts, and more work needs to be done to establish the magnitude of this effect.

To date, experiences with sequential grid mining at Elandsrand have shown that it is possible to turn a deep, medium grade orebody with erratically distributed gold values to profitable account.

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