Design of a Pillar Support System Combining Stable and Yielding Pillars for use with Mechanised Mining at depth in the Bushveld

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SYNOPSIS

This technical note records the design of a regional support system that combines stable and yielding pillars for use with a mechanised mining operation at depths of between 850 and 1 200 metres below surface.

INTRODUCTION

Although the use of mechanised bord-and-pillar type mining with pillar support is common in the shallow (<500m below surface) bushveld chrome mines, the platinum mines have traditionally employed narrow-width scraper mining as their stoping method, using pillars and elongates for support.

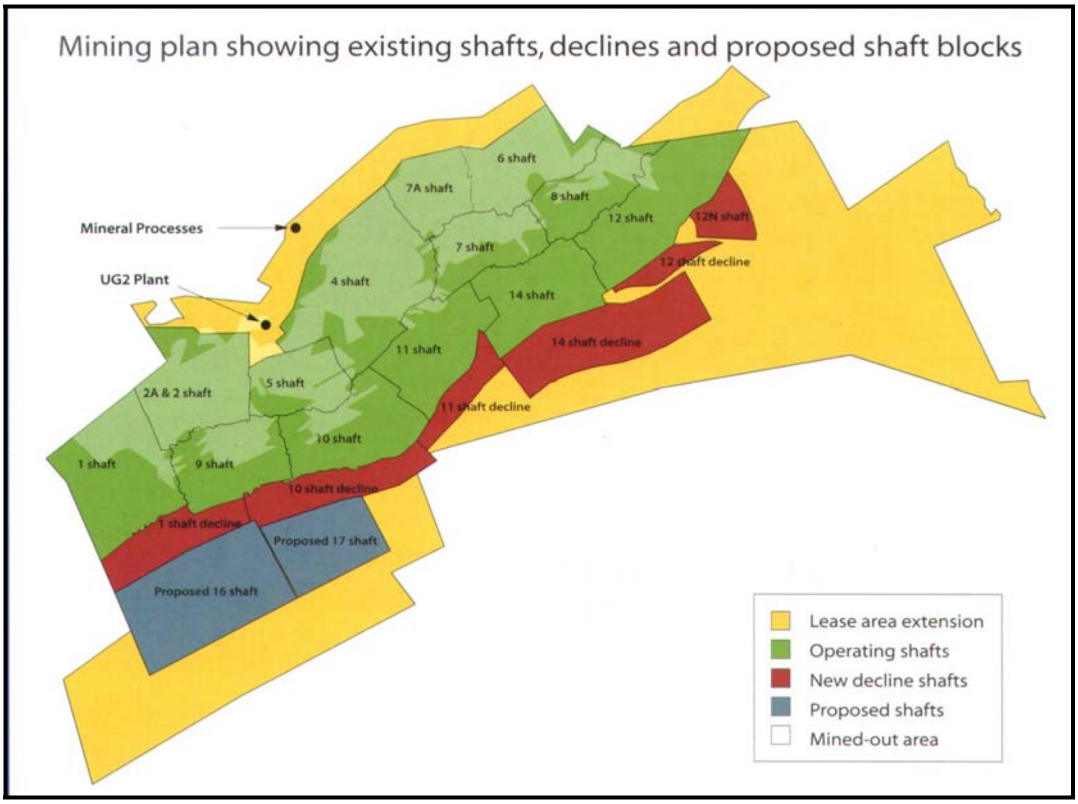
Mechanisation is increasingly being put forward as the answer to rising working costs, increasing mining depths and falling labour productivity. The upside includes greater advance rates, better efficiencies and less exposure of personnel; the downside is increased mining heights, lower grades and dependency on machine utilisation. Also especially relevant of late is that most of the capital equipment, being imported, is exposed to exchange rate fluctuations and continual cost increases.

The major problem with mechanised mining methods that make use of stable pillars to carry the weight of the overburden without failure is that pillar sizes must increase commensurate with increasing depth, reducing extraction percentages until mining becomes uneconomical. The challenge for design teams and especially rock engineers is the optimisation of mining layouts and pillar dimensions that allow for maximum ore body utilisation while maintaining stability.

LOCALITY AND BACKGROUND INFORMATION

Impala Platinum Limited, situated 30km North of Rustenburg in the North West Province, exploits the Western lobe of the Bushveld Igneous Complex for platinum group metals. Thirteen shafts are currently used to access and mine the Merensky reef and UG2 chromitite layer on the lease area, which measures some 12 000 hectares.

Number 12 shaft is presently the northern-most operating shaft in the lease area. Sunk in the late 1980's, it accesses reef from 560 to 850m below surface. To date mining has been confined to the Merensky reef horizon. Ground conditions experienced on the shaft are among the best on the lease area, and monthly stoping panel advances regularly exceed 20 metres.

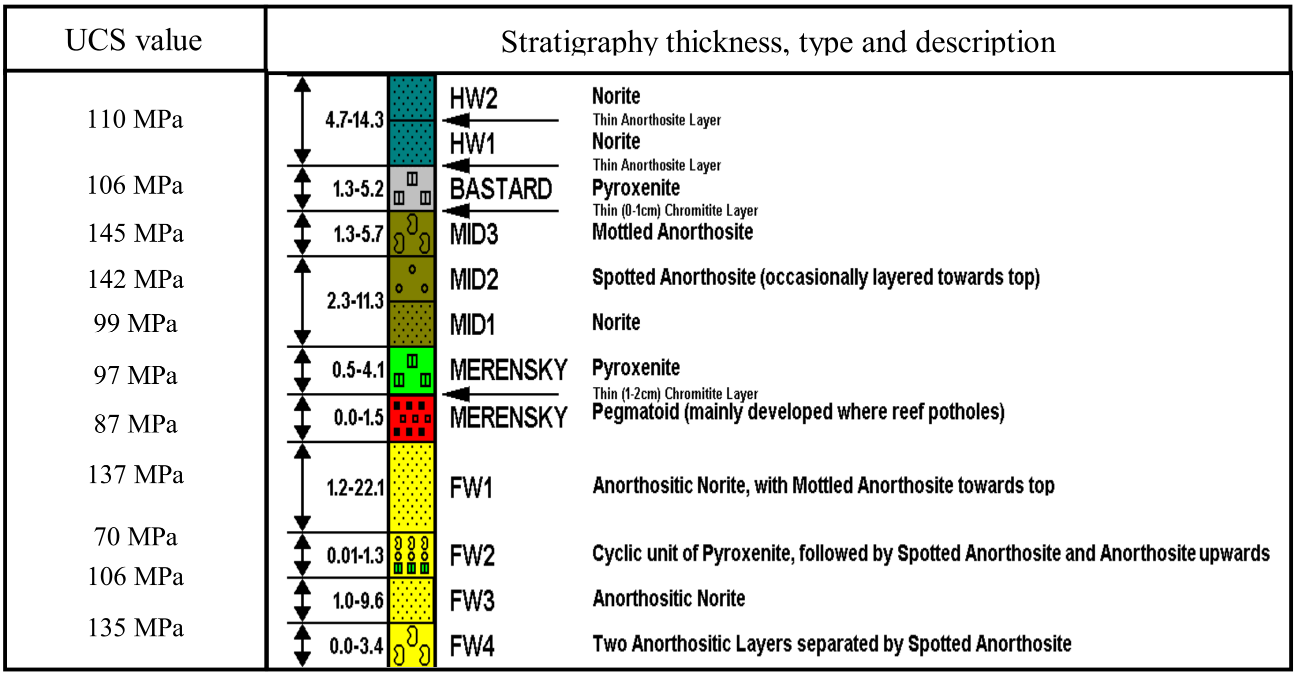

Mining plan showing existing shafts, declines and proposed shaft blocks

When the shaft's reserves began running out in the late 1990's, accessing the Merensky reserves down dip of the shaft became extremely important. As these reserves were effectively split by geological structures, two separate projects were proposed – an off-reef footwall decline with conventional narrow-reef stoping for the Southern block and an on-reef decline with mechanised mining for the Northern block. Later evaluation revealed that because of the grade distribution, the Southern block would also be amenable to mechanised mining, so this project was converted to a mechanised layout as well.

Combined, the two projects represent an area of some 2.75 million mineable square metres, which will produce some 14.7 million tons of ore at an average mining height of 1.8 metres.

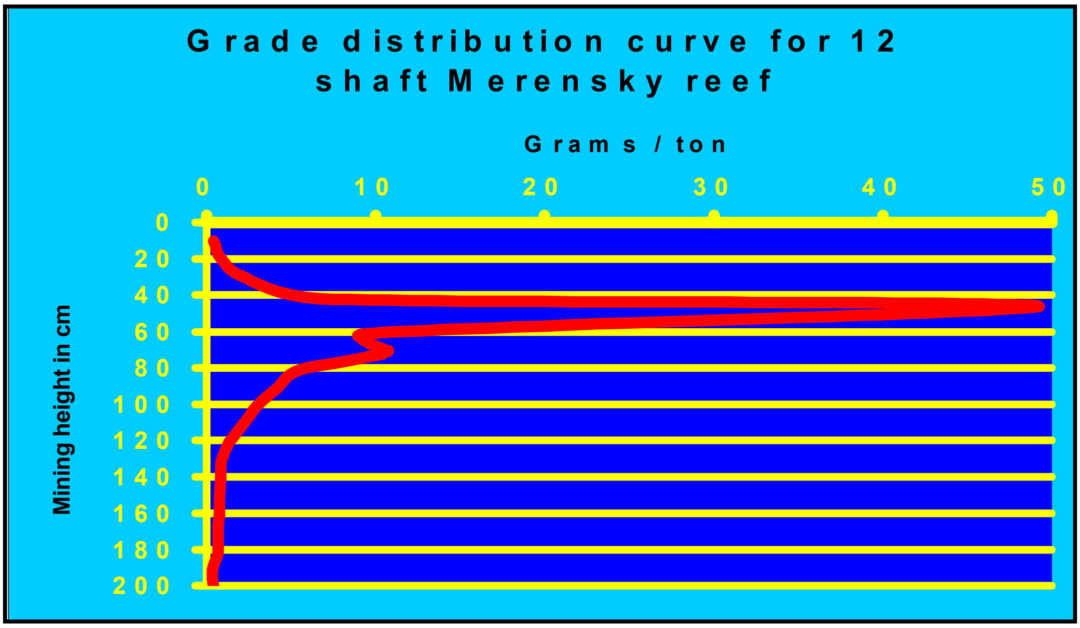
GEOLOGICAL AND GEOTECHNICAL ASPECTS

The geological sequence in the 12 shaft area is typical of that found on the Impala lease area, with near-reef stratigraphy and approximate strengths shown in the figure below. The sequence dips at approximately 9 degrees to the North East.



UCS value	Stratigraphy thickness, type and description		
110 MPa	4.7-14.3	HW2	Norite Thin Anorthosite Layer
106 MPa		HW1	Norite Thin Anorthosite Layer
145 MPa	1.3-5.2	BASTARD	Pyroxenite Thin (0-1cm) Chromitite Layer
142 MPa	1.3-5.7	MID3	Mottled Anorthosite
99 MPa	2.3-11.3	MID2	Spotted Anorthosite (occasionally layered towards top)
97 MPa		MID1	Norite
87 MPa	0.5-4.1	MERENSKY	Pyroxenite Thin (1-2cm) Chromitite Layer
137 MPa	0.0-1.5	MERENSKY	Pegmatoid (mainly developed where reef potholes)
70 MPa	1.2-22.1	FW1	Anorthositic Norite, with Mottled Anorthosite towards top
106 MPa	0.01-1.3	FW2	Cyclic unit of Pyroxenite, followed by Spotted Anorthosite and Anorthosite upwards
135 MPa	1.0-9.6	FW3	Anorthositic Norite
	0.0-3.4	FW4	Two Anorthositic Layers separated by Spotted Anorthosite

Unlike the UG2 chromitite layer, there is no definable economic channel; the highest grade is generally found close to the Merensky chromitite marker and then tapers off – sharply into the hanging wall and gradually into the footwall. Stoping width control limits are thus defined relative to the chromitite marker. A grade distribution curve representative of the area is shown in the figure below.



As the contacts between the different layers are normally gradational rather than clearly defined, there is no "clean" hanging wall plane, thus proper drilling and blasting practice is paramount in creating good hanging wall conditions.

GENERAL LAYOUT

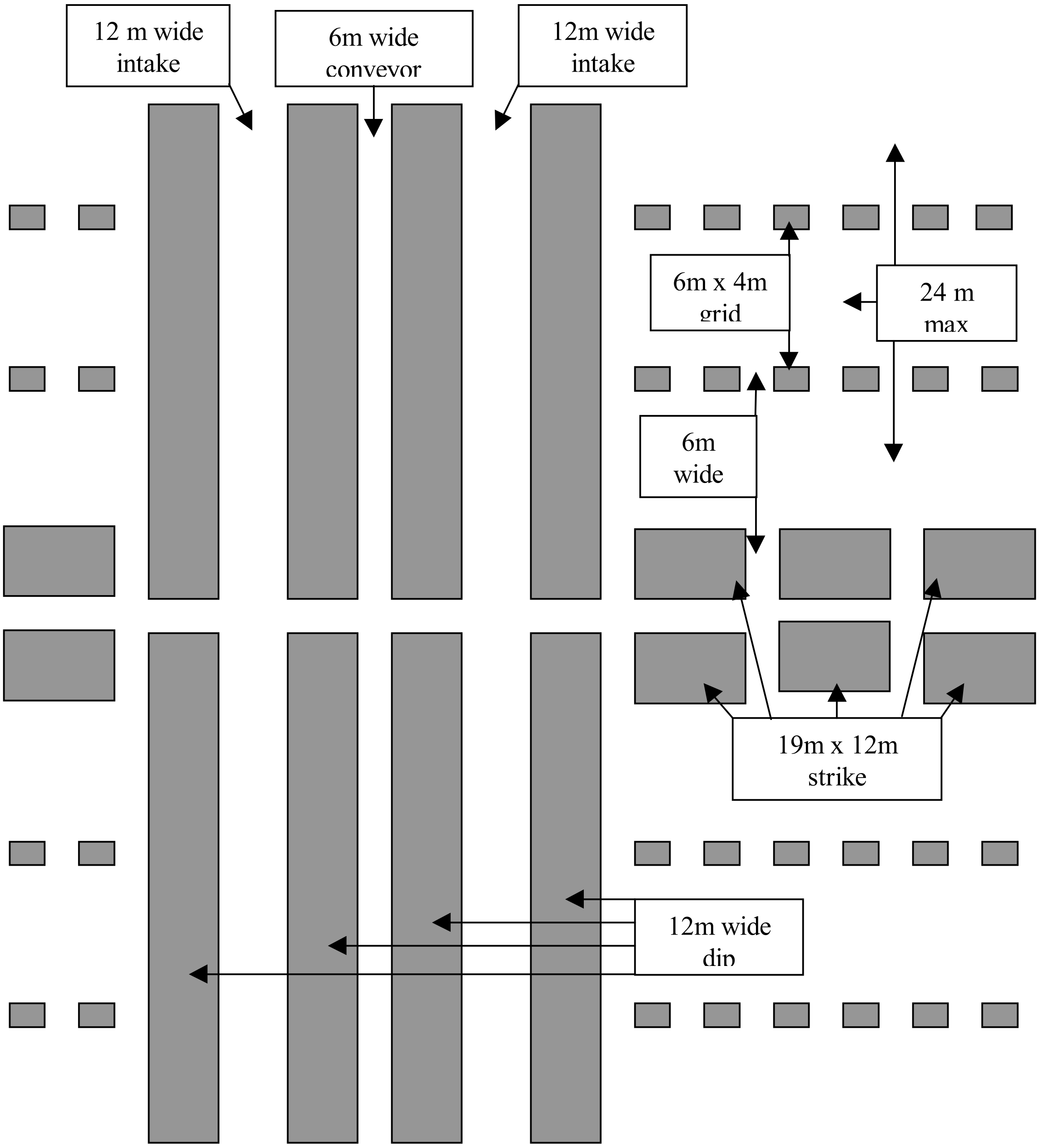
The general layout is an adaptation of the present Impala narrow-reef stoping layout, incorporating safe panel spans based on empirical designs, with in-panel support installed to prevent small-scale falls of ground. The panels are located within a regular system of yielding grid pillars controlling localised rock mass behaviour, protected by barrier pillars designed to ensure regional stability.

The mechanised mining layout depicted below consists of heavily protected dip conveyor and intake airway excavations, together with well protected small-span strike excavations providing access for strike conveyors and mechanised machinery, leading into the stoping panels with their regular grid pillar layout and in-panel tendon support system.

The projects' on-reef workings are presently accessed via conventional rail-equipped footwall drives and crosscuts onto reef, utilising low-angle (10 degree) inclined step overs to limit the overstoping area. It is envisaged that for new shaft layouts, stations will be cut on reef, providing direct access to the ore body.

Ore handling begins with low profile LHDs loading ore blasted in the stoping faces, dumping onto strike conveyor belts located a maximum of 180 m apart to keep LHD travelling within limits. The strike conveyors discharge onto the dip conveyor belt, dumped from the dip conveyor belt/s into storage ore passes before being trammed across to the shaft via the footwall haulages. In the case of mechanised mining from a new shaft, the conveyors could be laid out to tip straight into the shaft ore passes.

Faces are drilled by low profile single boom drill rigs, with support holes being drilled using small, remotely-controlled portable trolley-mounted rockdrill / airleg combinations. Support tendons are inserted by hand and tensioned by impact wrench. Charging up of blast holes is also done by hand, using ANFO-type explosives.



BARRIER PILLAR DESIGN

The purpose of barrier pillars is to compartmentalise the mine, restricting the amount of volumetric closure, reducing the height of potential tensile zones, enhancing ventilation and water-ingress control and providing a cut-off barrier in cases of large-scale instability. Present conventional Impala practice employs dip-orientated pillars spaced at intervals of less than half the depth below surface.

In order to provide long-term strength, barrier pillars should be squat pillars, with a width: height ratio of greater than 10 for single, isolated pillars, or for multiple pillars spaced close together a width: height ratio greater than 6 for the individual pillars. Possible modes of failure for these heavily loaded pillars include failure of the pillar material itself as well as failure of the foundation material.

For the mechanised mining scenario, 12m wide pillars were placed on either side of critical excavations to provide a barrier pillar function. At the proposed maximum mining height of 1.8 m, these pillars have a width: height ratio of 6.7. The use of barrier pillars alongside the strike conveyor access ways, although changing the pillar orientation from dip to strike, reduces the inter-pillar spans to 180 m, well below the maximum interval of half the depth below surface.

For deep-level gold mining, the generally accepted criterion for barrier pillar stability is that the average pillar stress should not exceed 2.5 times the Uniaxial Compressive Strength of the pillar material and the surrounding rock types. An alternative method of evaluation, commonly used in shallower bord-and-pillar situations on coal and chrome mines, compares the pillar strength to the average pillar stress, giving a factor of safety that should be greater than 1.5.

In addition to the above criteria, rock engineering monitoring conducted by Spencer on the upper levels of 12 shaft in 1993 revealed that when average pillar stress levels exceed some 135 MPa, the footwall 2 layer yields plastically, causing footwall heave, as shown in the photographs below.

It was thus also important that stress levels on the barrier pillars were kept to below 130 MPa. To cover all bases, the barrier pillar stability was evaluated in terms of all the above criteria.

In order to conduct this evaluation, a computer model was set up using the MINSIM elastic modelling code. The model encompassed an area of 768 m on strike x 576 m on dip, giving a totalled mined area of 442 368 square metres. The scenario resembled the envisaged layout as closely as possible and incorporated in-situ stress values recorded in the area during a recent stress measurement programme.

To simplify matters, no geological losses were incorporated (actual losses are approximately 23 %), so this represented a worst possible case. Two runs were conducted, one at a depth of 850 m below surface, the other at 1200 m below surface.

The results of the criteria evaluation are shown on the table below. The average pillar stress on different pillars was evaluated from the models' results, with only the greatest values being shown.

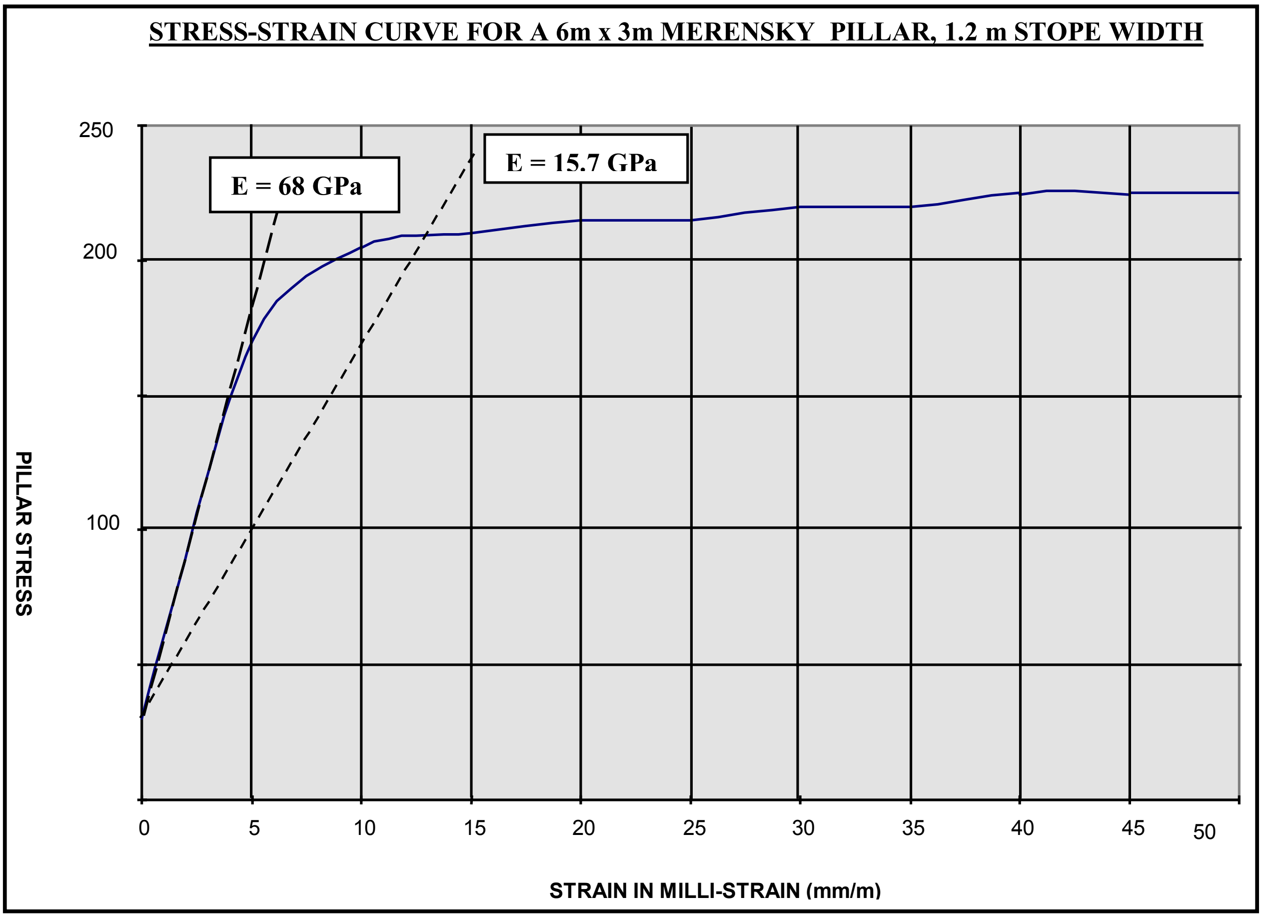
Depth below surface	**Maximum APS – dip pillars**	**Maximum APS – strike pillars**	**2.5 x UCS Merensky hanging wall**	**2.5 x UCS Merensky reef**	**2.5 x UCS Merensky footwall**	**Factor of Safety – 2.5 x UCS criterion**
850 m	58 MPa	66 MPa	337 MPa	337 MPa	232.5 MPa	Safe
1200 m	83 MPa	94 MPa	337 MPa	337 MPa	232.5 MPa	Safe

Depth below surface	Maximum APS – dip pillars	Maximum APS - strike pillars	Minimum width: height ratio (12 m x 19 m)	Pillar strength – squat pillar formula	Factor of safety – strength vs stress criterion
850 m	58 MPa	66 MPa	8.2	162.7 MPa	2.8(dip), 2.45(strike)
1200 m	83 MPa	94 MPa	8.2	162.7 MPa	1.96(dip), 1.73(strike)

The above results show that the barrier pillars will not be overloaded and will remain stable, ensuring regional stability in the area. Also, as the average pillar stress levels peak at 94 MPa, footwall heave is unlikely in the long-term conveyor and transport excavations.

IN-PANEL PILLAR DESIGN

The design of the in-panel pillars is based on that of the yielding grid pillars presently in use on Impala. The original design has been extensively researched and instrumented by both Spencer and Lougher and has proven extremely successful, with millions of square metres extracted safely since its implementation. The postulated stress-strain curve for these pillars, derived from the instrumentation work, is shown in the figure below.



The in-panel pillars are intended to provide support resistance sufficient to prevent "backbreak" type in-panel failures, while yielding in a stable manner. As such, they are designed with a width: height ratio of approximately 2, meaning that for the mechanised mining height of 1.8 m they are 4.0 m wide x at least 6.0 m long. This ensures slabbing of the pillar material under load and failure of the pillar in classic "hourglass" fashion.

Given that these pillars can absorb a maximum stress level of more than 200 MPa, well above the 135 MPa at which footwall heave is expected, it is anticipated that some footwall heave will occur. The computer modelling however indicates that the 135 MPa average pillar stress is only attained some 50 m back from the face.

A significant reduction in mining height is anticipated in the back areas, due mainly to the footwall heave, but also because of elastic closure of the hanging wall and footwall. For this reason vehicles are expected to use the protected conveyor roadways for access to and from the stoping faces, only entering the stoping panels close to the working face areas.

PANEL SPANS

The panel span for any mechanised mining operation is primarily a function of a drill rig's boom spread or set-up. The present low profile drill rigs can drill a maximum of a 6 m spread of parallel holes in a single set up, so a 24 m panel span was proposed (4 x drill rig set ups). As panel spans on the Merensky reef normally exceed 30 metres, a 24 m span was not thought to pose serious stability problems.

Impala's rock engineering department regularly conduct rock mass ratings using Barton's Q-system to quantify ground conditions and identify problem areas. Ground conditions are known to deteriorate at Q-ratings of less than 3, with serious strata control problems experienced when values fall below 1.

An evaluation of rock mass ratings obtained from on-reef development ends situated in the project area provided the following information:

Total no of RMRs	RMR values 0 – 1	RMR values 1 - 5	RMR values 6 - 10	RMR values 10+	Average RMR value
25	0	4	2	19	21.52

As Rock Mass Rating values increase logarithmically, these results indicate that the general ground conditions are likely to be very competent, with few areas having ground control problems. This correlates with present experience on 12 shaft as a whole.

In areas where deterioration in ground conditions is experienced, panel spans can be reduced by cutting in-panel pillars, normally with an immediate improvement in conditions and amelioration of the problem. This is significantly easier in a mechanised mining environment than in conventional stoping and is viewed as standard practice on nearby mechanised chrome mines.

Despite the above evidence and the blessing of senior Bushveld rock engineering consultants, an external review team expressed serious concerns regarding the panel span issue, believing the 24 m span to be excessive. A cautious strategy has thus been adopted – 12 m panel spans will initially be implemented and intensively monitored. Should these prove successful, the panel span will be increased incrementally.

IN-PANEL SUPPORT

In-panel support in mechanised mining typically comprises some form of tendon support. Ideally this should be easy to transport and install, protrude minimally into the mining excavation and provide active support immediately after installation. The system must also satisfy Impala's support resistance requirements of 33 kN / m^2, as determined from a fall of ground analysis.

The present system comprises mechanically anchored forged head bolt tendons, complete with washer, spherical seat and load indicator device. The preferred product has a 14.5 mm diameter with 550 MPa yield steel strength and can be installed spaced as shown below, depending on face advance per blast:

Face advance	Tendon length	Tendon load capacity	Installation angle	Downrated load capacity	Strike spacing	Dip spacing	Support resistance
1.5 m	1.5 m	91 kN	70 deg +	85 kN	1.50 m	1.50 m	37.7 kN/m^2
2.0 m	1.5 m	91 kN	70 deg +	85 kN	2.00 m	1.25 m	34.0 kN/m^2
2.5 m	1.5 m	91 kN	70 deg +	85 kN	1.25 m	2.00 m	34.0 kN/m^2
3.0 m	1.5 m	91 kN	70 deg +	85 kN	1.50 m	1.50 m	37.7 kN/m^2

To ensure proper tensioning and achievement of the correct pre-load tension, tendons are pre-tensioned using an impact wrench rather than a T spanner or tensioning adaptor attached to the jackhammer. Damaged tendons are replaced and additional tendons are installed in the vicinity of geological discontinuities.

Although the implementation of resin-grouted tendons was considered, the use thereof has been excluded until a suitable mechanised roof bolting system is commercially available. Trials at other locations on the property have shown inconsistent installation quality when installing resin-grouted tendons by hand.

OFF-REEF MINING

While the pyroxenite rock type surrounding the Merensky reef horizon is generally competent and fairly strong, the hanging wall strata grades into the anorthositic norite Middling 2 horizon. Previous experience shows that at these depths this anorthositic rock is likely to spall and fracture on exposure, significantly increasing support levels and costs, as well as slowing advance rates.

For this reason, excavations requiring increased height, such as tipping points onto the conveyors, are constructed by increasing depth into the footwall rather than blasting into the hanging wall.

It is inevitable that geological anomalies such as reef rolls and potholes will be encountered. The mechanised mining system allows mining up to the very edges of such features. In some cases vital excavations, such as conveyor access ways, will have to traverse these features, usually mining through the anorthositic hanging wall strata.

In such cases the following strategy has been adopted:

- Minimise the number of excavations traversing the anomaly;
- Reduce the size of the excavation as far as possible;
- Pay special attention to drilling and blasting practice, ensure minimum blast damage;
- Reduce the spacing of tendon support and consider installing support into sidewalls;
- Should spalling and fracturing occur, a membrane-type support such as shotcrete should be installed as soon after the blast as possible (prior to tendon installation) to provide a sealing layer and generate support resistance;
- Secondary support such as meshing and lacing is installed where needed to ensure longer-term stability.

MONITORING AND INSTRUMENTATION

This project will provide valuable insight into rock mass behaviour using mechanised mining methods at depth. To ensure safe extraction and maximum ore reserve exploitation, together with providing answers regarding rock mass behaviour, the following measures have already been implemented or are proposed:

- As with other departments, experienced rock engineering staff members have been allocated to the project section, with a dedicated junior staff member to provide daily input regarding data gathering, observations, geotechnical condition reviews and on-the-job training;

- The Senior Rock Engineering Officer, together with the project's production personnel and explosives supplier, is specifically addressing the issue of drilling and blasting design to ensure minimum hanging wall and support damage;

- In-situ stress level measurements have recently been conducted in the project area as part of a mine-wide programme;

- To quantify the level of micro-seismicity associated with mechanised mining and to ameliorate seismic risk, it is intended to extend the shaft's present single station system into a six-station seismic network, which will tie into the greater mine-wide network. The expansion will result in greater event location accuracy, enhanced seismic detection capability of micro-seismicity associated with pillar fracturing and event focal mechanism analysis;

- A specialist consulting firm has been contracted to conduct a detailed investigation into aspects such as hanging- and footwall deformation levels, in-panel closure levels and rates, pillar sidewall fracturing and pillar behaviour under load;

- Pillar cutting control, critical to the success of the project, is assisted by the following measures:
    - The provision of survey lines located close to pillar lines;
    - The issuing of laser marking devices to responsible production personnel;
    - Continuous on-the-job training and assessment of production personnel regarding the importance of pillar cutting control;

- The monthly measurement, analysis and discussion of pillar cutting and pillar robbing, with disciplinary action being taken against guilty parties where necessary.

INITIAL RESULTS

Although still in its infancy, the project has to date been reasonably problem-free. Teething troubles worth mentioning include:

- Pillar cutting control – solved by providing sets of survey lines at the top and bottom of each panel, close to the pillar edges, rather than a single set of lines in the middle of the panel;

- Accuracy of blast hole drilling was initially hampered the lack of parallel-holding booms on the drill rigs – these have subsequently been changed;

- Skills training for the various members of the production crew took longer than initially anticipated, significantly increasing cycle times, resulting in lost blasts. As the crews have become more adept at their jobs this problem has been eliminated.

Shown below are some photographs taken during the initial stages of the project:

Drill rig drilling face blast holes

General view showing mining height and hanging wall conditions

Small, portable roofbolt-drilling rig in action – note remote control operation

Pillar edge showing hourglass fracturing

LHD cleaning blasted face

Forged-head support tendon showing load indicator that disappears when tensioned

CONCLUSION

While the successful implementation of mechanised mining has the potential to dramatically alter the platinum mining industry, possibly it's greatest risk lies in overcoming the rock engineering challenges.

In this regard the design team have worked from a safe base - the rock engineering designs for mechanisation have been developed as extensions of existing practice; and any changes or modifications have been simulated using numerical modelling techniques, with results being carefully assessed against industry-recognized criteria.

In addition, the designs have been scrutinised and assessed by three separate external review agencies. Their comments have been considered and where necessary built into the design. The design team is sure that there cannot be a better base from which to begin.

ACKNOWLEDGEMENT

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