VAN DEN BERG, D.P. 'Rock cutting' – platinum mining of the future? *The 6th International Platinum Conference, 'Platinum–Metal for the Future'*, The Southern African Institute of Mining and Metallurgy, 2014.

'Rock cutting' – platinum mining of the future?

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Introduction

The South African platinum mining industry is currently facing one of the most challenging times in its history. This statement is underpinned by the 2012 Marikana massacre in which 34 people lost their lives and 78 were wounded as a result of unrest and skirmishes between police and striking mineworkers. Industrial action by unionized mineworkers has intensified to such an extent that mines have lost up to six months of production for the year 2014. This fact in itself provides an undeniable case for change in the way platinum producers should conduct their business.

Other indicators that suggest a major overhaul in the way South African platinum mines are operated are:

- The lowest productivity figures to date, compared to historic figures
- Higher operating costs, which persistently beat inflationary costs. In some years the mining industry has experienced double-digit cost increases while inflation has been at a single digit
- An ageing workforce, with little interest from the younger generation workers to join the mining industry. This could be partially ascribed to the image that was traditionally portrayed by conventional drill-and-blast mines (labour-intensive)
- Increased focus on personnel safety and wellbeing has resulted in very rigid standards and procedures, some of which are tedious and require higher work content than was usually the case (affecting productivity)
- Reduced profit margins as a result of all of the above factors.

These signs indicate a strong case for change in the platinum mining industry. Conventional mining methods are not providing compelling business cases for new mines or mine extensions and replacement projects. Figure 1 indicates the productivity levels for stoping and development in a large platinum mine over the past 5 years. The steady decline in productivity re-iterates the need to re-engineer the way these mines are designed, laid out, and operated.

Full mechanization of stoping operations by use of rock-breaking methods other than drilling and blasting has been a target for research for the past two decades, due to the potential substantial benefits. These benefits are said to be increased face advance rates, increased productivity, and lower personnel requirements, reduction in operating costs, increased operational margins, and increased safety and health for employees. Although the prospects for mechanized rock-breaking seem reasonable, factors such as lack of suitable equipment, the specific energy required to cut rock in the hard-rock environment, as well as economic viability due to the cost of rock-breaking tools, have hampered progress towards commercial implementation of the technology.

Engineers and experts in the platinum mining industry express various opinions as to whether rock-cutting technology is sufficiently developed to be implemented in the platinum mining industry, as well as the viability of mechanically excavated mines. This paper seeks to evaluate the suitability of the Bushveld Complex (BC) platinum orebodies for rock-cutting methods, and highlights the information requirements when considering rock cutting. The available rock-cutting technologies are investigated, as well as the ways in which these technologies are most likely to be applied in the BC. A further example of the potential application of the principles associated with rock-cutting technology is given for a typical South African platinum mine. A high-level costing and business case is presented comparing conventional mechanized drill-and-blast and rock-cutting mining methods.

Suitability of platinum orebodies for rock-cutting methods

Overall geological conditions

Rock-cutting methods would largely be focused on on-reef mining layouts with little or no infrastructure located outside the reef envelopes. The major economic reefs in the BC are the UG2 and Merensky reefs, which are narrow and tabular in shape. The general stratigraphy and geology is well understood, and these reefs have been mined for more than half a century. The dip of the UG2 and Merensky reefs

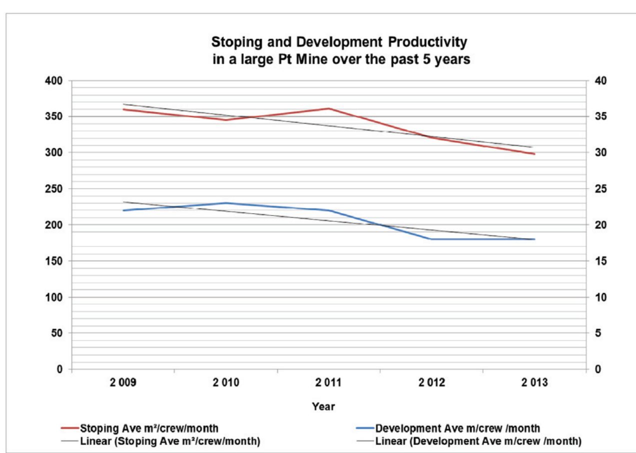

Figure 1. Conventional stoping and development productivity in a large platinum mine over the past 5 years

ranges between 0° and 20°, with the average dip around 12°. The more steeply dipping areas, with dips greater than 10°, would require apparent dip excavations to reduce the dip of the on-reef excavations. The targeted mining width for both these reefs is typically between 1.0 m and 1.5 m, depending on the locality of the orebody within the BC. The orebodies are known to be relatively undisturbed and homogenous. The depth ranges of mining areas vary because some orebodies have been mined out in the shallower areas. Therefore, depth of mining could be from surface to 1500 m below surface. The geothermal gradient would generally require refrigeration from depths of more than 700 m below surface.

Geological losses on the Merensky and UG2 reefs are generally between 20% and 30%. On-reef mining methods have been practised in the BC and have indicated that on-reef mining could be sustained in large parts of the Complex. However, areas with increased geological disturbance would require more detailed studies before any on-reef mining method could be introduced. In general, the BC orebodies do lend themselves to on-reef mining methods, which could include rock-cutting technologies.

Hydrogeological investigation of groundwater and methane

The influence of surface water sources that could result in underground water recharge, such as rivers, slimes dams, and rainwater, should be investigated for the specific target area within the BC. The weathered aquifer system in the BC generally extends to about 40 m depth. Fractures, faults, and dykes that are connected to the weathered aquifer result in controlled, semi-confined deep aquifers. Areas of the BC that have already been mined are generally not expected to contain large quantities of groundwater due to partial de-watering of the aquifer by deeper neighboring mines. In virgin areas where no previous mining has taken place, precautions have to be taken by testing and exploring for groundwater. Primary development in virgin areas should be double-covered by means of advance diamond drilling. It is expected that the risk of groundwater will increase in close proximity to regional faults and dykes. Occasional intersections of pockets of methane associated with iron-rich ultramafic pegmatite replacement bodies (IRUPs) have been reported within the BC. Generally, the risk of intersecting groundwater or methane in the BC can be classified as a low to high, depending on which part of the BC the project or target area is located in, and how well the area is delineated by means of exploration drilling. Both single- and double-cover drilling techniques are employed in the BC to ameliorate the underground water and methane intersection risks. It is expected that double-cover drilling will be implemented in virgin mining areas. Single-cover diamond drilling will be implemented for the low-risk or previously mined areas. Groundwater and methane intersections in a mechanized rock-cutting environment can be dealt with through employing methods similar to those that are already in place in conventional mining areas in the BC.

The exploration phase of a project should make adequate provision for gathering geotechnical, geohydrological, geothermal, and geological information to guide the study of mechanized rock-cutting operations.

Geotechnical investigation of the target area

A comprehensive geotechnical investigation of the targeted mining area should be undertaken prior to commencement of the rock-cutting feasibility studies. Available exploration drill-holes, areas of previous mining activity, and, wherever possible, underground UG2 and Merensky reef mapping should be used to obtain geotechnical information for both the reefs as well as the stratigraphy above and below the reef horizons. This information should be used to assess the mining strategy, layout, and support requirements suited to the deposit.

The geotechnical environment in which the rock-cutting mining method is planned should be known as accurately as possible. Some mining areas are well known from shallower or nearby mining operations, or from test mining. Geotechnical modelling (elastic and inelastic conditions) should be done for the target area and the expected ground and operating conditions should be accurately inferred from exploration, modelling, and test work. A lot of information already exists from the BC mining operations, and this information could be incorporated in the mechanized rock-cutting studies. The targeted reefs are the UG2 Reef, with a uniaxial compressive strength (UCS) of between 30 and 80 MPa, and the Merensky Reef, which has a UCS of about 130 MPa.

Table I indicates the general rock mass UCS, Young's Modulus, and Poisson's Ratio for BC rock types. This table indicates that rock characteristics within the BC ranges from soft (UCS <80 MPa) to very hard (UCS >180 MPa). The hangingwall and footwall rocks, which comprise pyroxenite and anorthosite respectively, are hard to very hard with a UCS of up to 200 MPa. Apart from the UCS, the abrasiveness of the rocks as well as their drillability needs to be taken into account. Various tests and tools are available to determine the amenability of the rock to excavation by mechanical means. A full evaluation of the rock conditions and stability should be done as part of the feasibility study into rock cutting. The following are examples of the tests that can be done to test the suitability of a rock mass for cutting:

- Modified QTBM for tunnel boring machine (TBM) applications by Barton analysis of some 145 TBM tunnels extending more than 1000 km, which can be used to predict penetration rates and advance rates for TBMs using rock mass classification data
- Bieniawski's rock mass excavability (RME) method for prediction of tunnel boring advance rates
- The linear cutting machine (LCM), which is a full cutting test combined with physical property tests, and is the most reliable available production estimation technique.

In general, the amenability of BC rocks to rock cutting has been proven through the excavation of a large number of raise-bored shafts, most of which have been bored by means of conventional raise-boring methods.

More geotechnical information is required in order to indicate the major joint orientations on a stereo plot (Figure 2). These stereo plots indicate the orientation and dip of major joints in the targeted mining area. Table II shows the typical information derived from these stereo plots. With rock-cutting technologies, the angle between the mining direction and joint orientation should be more than 60º, but closer to 90º in the case of major joint systems.

So far, all the information at hand from a geological, hydrogeological, and geotechnical point of view is similar to the information that would have been used in the design of a conventional, mechanized on-reef mine.

Other information that could be useful when considering a mechanized on-reef rock-cutting operation would be the

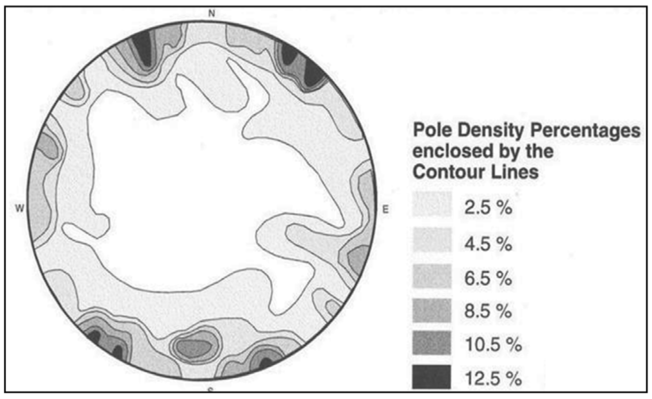

Figure 2 – A typical stereographic plot of major joint orientations in a targeted mining area within the BC

Table I
Typical BC rock mass characteristics

Rock type	UCS (MPa)	Young's modulus (GPa)	Poisson's ratio
Anorthosite	170 – 220	70 – 90	0.3 – 0.35
Pyroxenite	140 – 210	100 – 135	0.2 – 0.25
Norite	170 – 200	80 – 100	0.28 – 0.3
Merensky	130	90 – 130	0.25 – 0.3
UG2	30 – 80	80 – 110	0.25 – 0.35

presence of layers and markers in close proximity to the reefs. Any other reef-parallel features should also be determined.

Hangingwall properties are of particular significance, and features such as joints and partings should be taken into account.

The rock mass ratings are of particular concern, and should be well studied to inform the mine design. In general the BC rocks have Class III (fair rock) or Class IV (poor rock) ratings.

The UG2 Reef, with its laminated hangingwall, poses a particular challenge to the mine and support design. In-stope pillars, on-reef decline barrel pillars, strike drive protection pillars, and dip stabillity pillars are therefore designed to ensure a stable stoping environment. Figure 3 indicates the extraction ratios at various depths typically calculated for an on-reef mining method. These extraction ratios ranges from 56% to 85%, and constitute the worst-case scenario because some pillars could be left in the geological losses area, therefore increasing the extraction rate. Overlaps between geological loss and geotechnical loss could range from 5% in the shallower areas to 12% in the deeper areas. Therefore the extraction rate may vary from 90% in the shallower areas to 68% in the deeper areas, excluding geological losses.

In some mining areas the UG2 and Merensky reefs are very close together, with middlings as narrow as 12 m. In these circumstances, co-extraction of the two reefs from one platform is possible and has high potential. There is, however, the requirement to superimpose pillars in these mining areas. Modelling has shown that the K-ratio, which describes the ratio of the horizontal stress to vertical stress, has a significant impact on the abillity to extract the two reefs in a narrow middling environment. The stabillity of the upper reef is compromised if the lower reef (UG2) is mined first.

The geological, hydrogeological, and geotechnical factors do not pose significant challenges for on-reef mechanized mining methods. The methods and machines that would be employed should be able to handle the physical challenges that the BC orebodies would pose to the equipment.

Alternative mining methods to conventional platinum mining

An estimated 60% of current world platinum production originates from conventional mines with conventional layouts and labour-intensive mining methods. The remaining 40% of production comes from open pit and mechanized underground operations. This ratio is changing fast as mines mechanize and open pit operations expand.

Conventional platinum mining is labour-intensive and economically marginal due to low productivity levels and current weak metal prices. Alternative mining methods and mine designs are being sought in order to extract more value from the BC platinum mines. Investors are reluctant to invest more money in platinum mines that employ conventional mine designs and practices.

Alternatives to conventional mining methods are:

- Mechanized drill-and-blast mining methods, whereby most of the operations are carried out by means of trackless mechanized mining equipment. These methods include:
  - o Bord and pillar on-reef mechanized mining (mostly the shallower orebodies)
  - o Hybrid mining methods, whereby extra-low profile (<1.7 m) and ultra-low profile (<1.2 m) mining is done with mechanized mobile equipment and supported by low-profile trackless mobile machinery
- Mechanized rock-cutting of the platinum-bearing reefs. Tests have been conducted at Anglo American

Table II
Joint orientation and properties of target area hangingwall

Joint number	Dip/dip direction	Properties
J1	85º/215º	Continuous, clean, rough surfaces.
J2	75-85º/160º	Less continuous than J1 but still significantly long, surfaces often stained or filled with serpentinite.

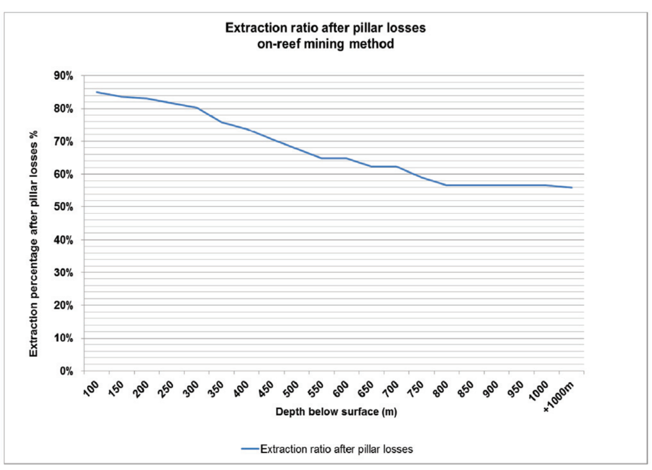

Figure 3. Typical extraction rate after pillar losses for an on-reef mining method

Platinum with oscillating disc cutting, and at Lonmin with a narrow-reef mining machine prototype (disc cutter). These tests yielded variable results, and no full-scale mechanized cutting operation has been put into practice to date. However, rock-cutting test work is continuing.

Low-profile bord and pillar mechanized mining

Some of the mechanized drill-and-blast mining methods, e.g. bord and pillar, are proven. Bord and pillar mines on the eastern limb of the BC are particularly successful, but this method is not feasible at depths of more than 1000 m. This is mainly due to the size of the pillars that are required to keep the excavations stable, which decreases the extraction ratio. The extraction ratio decreases proportionately with the depth of the orebody.

In this mining method, typically 9 to 10 strike bords are assigned to a mining fleet and a strike conveyor system (< 75 m from the face) is used the convey ore on-strike. Mechanized trackless mining equipment is used and the mining height is typically 1.8 m to 2.0 m.

Extra-low profile and ultra-low profile hybrid mechanized mining methods

Some extra-low profile (XLP) hybrid mechanized mining methods are in test phase. Ultra-low profile (ULP) mining equipment is in the developmental stage, and proof-of-concept equipment is currently being tested on-site underground. In these mining methods an on-reef platform is created where mining blocks are pre-developed on a half level. Low-profile (LP) mining equipment similar to the LP bord and pillar equipment is used to pre-develop the half levels. The raises are raised and winzed from the on-reef strike drive and the blocks developed in this fashion. Ledging and stoping operations are conducted from this platform by means of XLP or ULP equipment (the equipment used determines the mining width). XLP is typical 1.2 m to 1.7 m, and ULP 0.8 m to 1.2 m.

Mechanized mining traditionally makes use of drilling and blasting, which necessitates a period during which the mine must be evacuated to accommodate the blast cycle (re-entry period). No production is possible during this period. The establishment of a dedicated return airway system could allow blasting during the shift, but a practical way to implement this has not yet been found.

Mechanized mining by means of rock cutting

Mechanized mining by means of rock cutting makes use of rock-cutting techniques to excavate the tunnels required for accessing the orebody and to slot the stoping operations through cutting the stope excavations. Mechanized rock-cutting eliminates the need for a re-entry period since no blasting is employed. There is therefore potential for continuous operations 24 hours per day, which results in higher utilization of mining infrastructure. Due to the increased time spent on the rock face, less face length is needed compared to drill-and-blast operations, and the operation is less labour-intensive, resulting in higher productivity. The operations become more concentrated and higher production per level is achieved. Theoretically, this should result in higher profit margins.

Rock cutting in the form of raise-boring and tunnel boring has successfully been commercialized in the mining industry, and is a recognized method of establishing shafts, ventilation shafts, orepasses, ventilation holes, ore silos, pipe raises, travelling ways, and even reef raises. Service providers have established a niche market by applying raise-bore technology in creating these types of excavations and the methods are proven. These rock-cutting methods predominantly make use of rotating cutting discs with tungsten carbide button bits.

Cutting of rock in the platinum mining industry by means of raise-boring is proven and a large number of excavations have already been established by this means. Raise-boring techniques can successfully cut through the BC rock strata, and although some rock types are harder and more abrasive than others, generally the button bit discs used are up to the task even in rock harder than 240 MPa.

Cutting technologies appropriate for platinum reefs and surrounding rock

In the past, the breaking of hard rock in mining has been predominantly by means of drilling and blasting. The electrical energy (power) consumed in this process was to a large degree used only to power compressors to provide

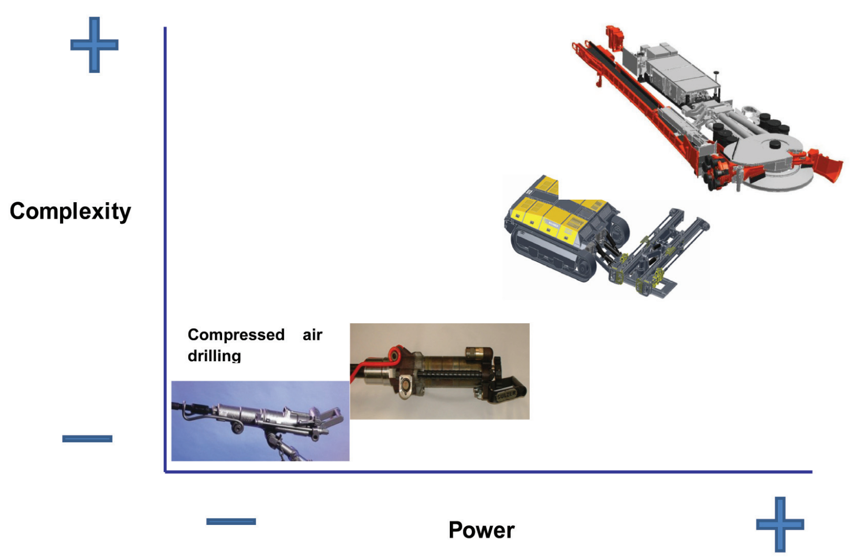

Figure 4. Complexity and rated power relationships in technological advances

Figure 5. A continuous miner for coal cutting, available off–the-shelf

compressed air to drill blast-holes. The energy to physically

Figure 6. An equipped longwall coal shearer

break the rock was supplied by explosives, in the form of a shock wave and resultant energy of expanding gas generated by the chemical reaction of detonating explosives. This was believed to be the most effective way of breaking hard rock (>100 MPa).

In rock cutting, it implies the mechanical energy applied is sufficient to physically break the rock, as opposed to only drilling holes in it. Figure 4 indicates that both the complexity of equipment and the installed power increase if the means of breaking rock moves from drilling and blasting to rock cutting. In the past, the drilling of blast-holes has been predominantly by means of compressed-air driven pneumatic rock drills. These drills are notorious for their inefficiency and wastage of energy. The current movement in the industry is away from pneumatic drills towards higher efficiency drills such hydraulic powered drills or hydropowered drills.

The immediate question is whether the increased power requirement for cutting hard rock and the cost of applying this power makes economic sense compared with the use of explosives. Various rock-cutting technologies will be explored further in order to answer this question.

One of the biggest success stories in the global mining industry is the development and application of coal-cutting technology. Hardly any drill-and-blast coal mines are still in operation, and more than 95% of underground coal mines now utilize coal-cutting methods. The majority of the mines use either continuous miners (CMs) or longwall shearers to produce the coal (Figure 5 and 6). It may be possible to adapt the same mining technology for platinum mining.

Learning from coal cutting

Although coal is not as hard as the BC rock types, coal-cutting technology has evolved significantly over the past decade. The advances and learnings in soft rock cutting, especially coal cutting, have contributed significantly to the advancements in hard rock cutting.

It was established early on that cutting by means of picks and applying similar technology to that used in coal cutting, would not suffice for the UG2 reef, due to its remarkable abrasiveness.

Activated disc cutting

The Bechem activated disc cutting process (Bechem, 1993) involves the superimposition of vibrating forces on the cutting action. The idea of activated cutting is sound and novel, but the actual application through a mechanized means has proved to be difficult.

In the mid-1990s CSIR Miningtek Division, in collaboration with Bechem, conducted some test work on rock cutting. These tests indicated that activated disc cutting requires roughly a third of the energy to break the rock compared to other rock-breaking techniques. It was established that the technology was not mature enough to be applied in norite (UCS 260 MPa), but that it could hold some promise for application in the UG2 reef.

The oscillating disc cutter was subsequently tested in a rock strength environment of less than 120 MPa in a UG2 stope and yielded very promising results. The drawback was the oscillating motion of the cutter disc and the difficulty in designing an oscillating disc system that could withstand the forces and keep a tight hydraulic seal. The prototype oscillating discs were prone to hydraulic oil seal failures, a challenge that still exist today.

Disc cutting

The mechanics of rock failure is a complex process that is influenced by almost all the rock's physical and geological properties. The theory of disc cutting is still imperfectly known and is the subject of much debate, but current understanding of hard rock cutting by means of discs is as follows:

- The dominant mode of failure is through the creation of a zone of highly crushed rock material beneath the cutter tip prior to chipping
- As the cutter penetrates the rock, a crushed zone is formed due to the extremely high compressive stresses generated in the rock under the tip of the cutter
- The pressure in the crushed zone causes tensile cracks to initiate and propagate radially from the point of impact into the rock mass
- If the stresses developed in the crushed zone are sufficiently high, one or more cracks extend far enough

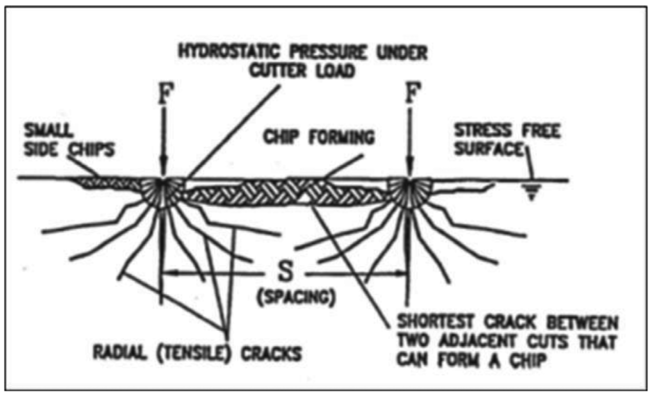

Figure 7. The theory of conventional disc cutting

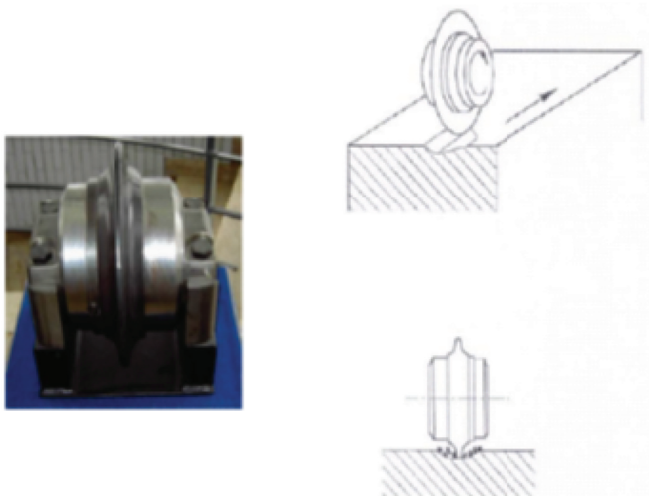

Figure 8. Conventional disc cutting – force perpendicular to the rock

to reach one of the tensile cracks developed from an adjacent cut, or alternatively a free face

- In conventional disc cutting, rock failure is in the form of chipping, similar to raise-boring cutters. Figure 7 shows this process.

Figure 8 indicates the more conventional approach to cutting rock with a force applied perpendicular to the rock being cut.

Undercutting of hard rock

Undercutting applies the same principles as disc cutting, but the cutting action is parallel to, rather than perpendicular to, the rock mass. Therefore crack propagation is to an artificially created free face and the rock fragments generated are substantially larger. Theory suggests that the rock is cut in tensile strength and is therefore more easily cut.

Figure 9 indicates the principle of undercutting being applied by cutting more parallel to the rock face and creating a small middling between the cut area and the free-breaking point. Theoretically, less energy is used applying this method and larger chips are created.

Reef boring

AngloGold Ashanti is working on a fundamental shift in deep-level mining technology, away from mechanization towards automation. Current mechanized mining operations rely on drill-and-blast techniques, forcing the operation into a batch process that calls for larger and more robust equipment to deliver ever larger tonnages. In contrast, automation looks to go smaller, focusing on the gold-bearing ore and mining in a continuous operation.

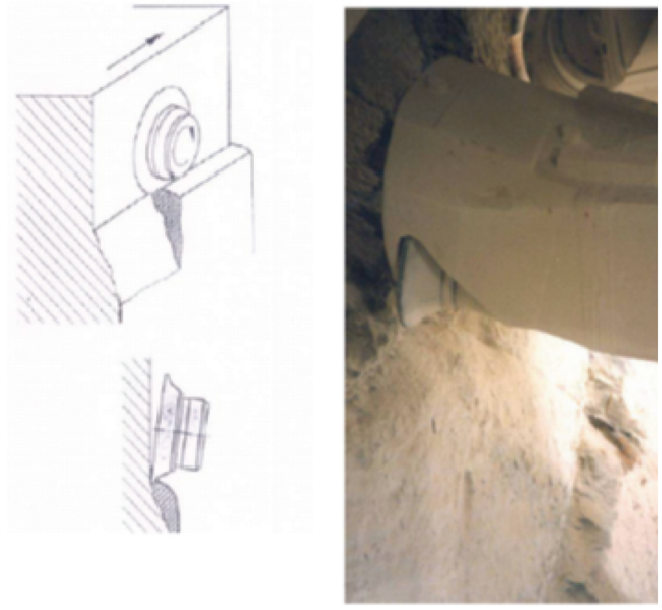

Figure 9. Undercutting principle

Recent programmes within AngloGold Ashanti (ATIC programme) have trialled the boring of gold-bearing reefs as opposed to drilling and blasting. In this application the reef is bored from an on-reef drive with a specially designed 660 mm raise-bore type head. The technology is not new, but the application is.

All the drill chips are collected and pumped to a container which is transported out of the mine for processing, yielding a possible 100% mine call factor.

Mechanised rock-cutting mine design criteria

The following sections investigate whether there are sufficient grounds for taking rock cutting technology further by comparing it with current mining practices in the BC. The design criteria for mechanized rock-cutting technology are assessed and tested for application in various areas of the mine.

It is recommended that a holistic systems-based approach is taken when applying rock-cutting systems in platinum mining. The analogy of a production plant rather than a mine should be drawn. This implies that the mine production system is designed, planned, organized, and maintained to optimize rock-cutting time and that people, equipment, material, and resources are employed to support and maximize the production time of the rock-cutting system.

Mine access and personnel, rock, material, and equipment handling

Shaft and logistical infrastructure requirements

The rock-cutting system could be incorporated into a new surface access system for the target area, or alternatively it could be located adjacent to, within, or below current mining infrastructure. New infrastructure should be specifically designed to accommodate the application of rock cutting and the mechanized equipment and systems to support the technology. Existing shaft systems in the BC have limited ability to lower items of equipment and therefore equipment manufacturers would have to adapt their mechanical equipment to be disassembled, lowered, transported to site, and re-assembled and commissioned on site. New shaft logistical systems and supporting infrastructure should be purposefully designed to accommodate the new machinery.

As well as the shafts, the surface and underground workshops, underground assembly bays, and underground transport systems will be designed so as to accommodate the mechanical equipment. In particular, these systems need to be able to handle large bulky pieces of equipment, weighing tens of tons, easily and safely.

Communication and telemetry systems should be chosen so as to accommodate the information system for future requirements of fully remote-controlled or automated systems.

The main access infrastructure requirements for rock-cutting mines can therefore be summarized as follows:

- Supply 24/7 logistical support to the mechanized rock-cutting machines and system
- Ease of handling of large payloads and bulky equipment from surface to underground and vice versa
- If the existing system is retrofitted it would need to be designed so as to handle batches equipment between surface and underground, with supporting infrastructure to disassemble on surface and re-assemble underground in a purpose-built environment
- State–of-the-art telemetry systems and connectivity to support intelligent mining machines, and even operate them from a remote location
- High system availability to support 24/7 mechanized operations, which could be 3 shifts per day 30 days per month
- Maintenance personnel with customized equipment to easily perform maintenance tasks on-time on schedule
- Critical parts inventory for quick breakdown repairs
- Condition monitoring systems on the rock engagement machines so that preventative maintenance can be carried out timeously Availability of skilled operators with adequate overlap of shifts (hot-seat takeover) so as to allow seamless work around the clock
- Ease of maintenance and system redundancy to accommodate continuous operations
- Sustainable supply and back-up system to provide services to the target area on a 24/7 basis. This includes emergency power and service water basis-up systems.

The above requirements should be adequate to support a mechanized mine that makes use of rock-cutting technology. Existing systems would have limited ability to adapt to the mechanized rock-cutting technology, but retrofitting could assist in this to some extent.

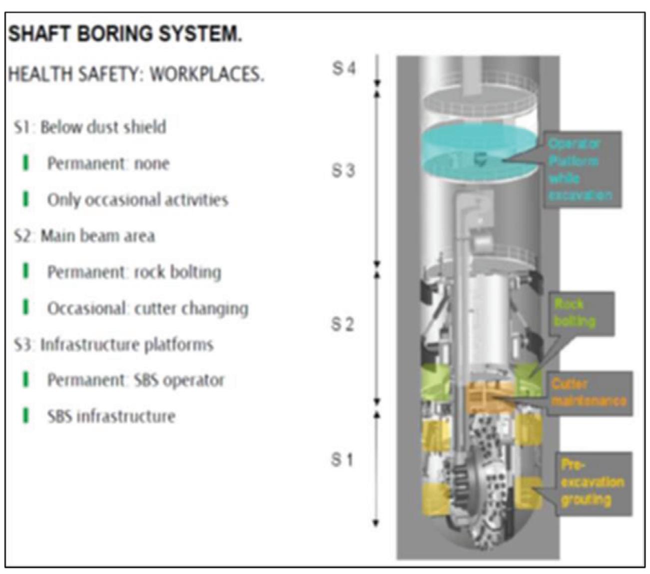

Figure 10. Vertical blind shaft-boring system

Shaft excavation methodology for orebodies shallower than 1000 m below collar

New surface declines will be required to service the mechanized rock-cutting target area. These would typically comprise a pair of large declines up to 6 m wide and 6 m high. Developing a decline of this size would require large conventional mechanized decline-sinking equipment for drilling and blasting. Mechanized decline-cutting machines have been developed for large declines, and equipment that is able to cut the hard BC rock at a reasonable advance rate has been proven in the hard rock cutting environment. A typical example of such equipment is the mechanized tunnel miner or MTM (Figure 11).

MTM 6 suppliers claim daily advances in hard rock of up to 10 m, a turning radius of 30 m (flexible), and the ability to handle tunnelling profiles up to 6 m wide and 6 m high. The machine has full bolting and shotcrete capability should it be required, and can be reversed if necessary. The machine is safe and the operator is well clear of the danger area.

The cutting profiles are smooth and energy exerted on the surrounding rock is negligible compared to drilling and blasting, which makes for little or no overbreak on the tunnel profiles. Figure 12 indicates some profiles which is possible to be cut with the MTM. Muck removal is either by means of truck or by conveyor belt. The muck consists of small fragments due to the mechanized rock-cutting.

This type of mechanized development operation typically requires around six people, compared with around 24 for a typical drill-and-blast set-up. This is in a multi-end application. The cost of excavating a development end in 180 MPa rock is around R19 400 per metre (excluding labour), and advance rates are about 10 m/day, while

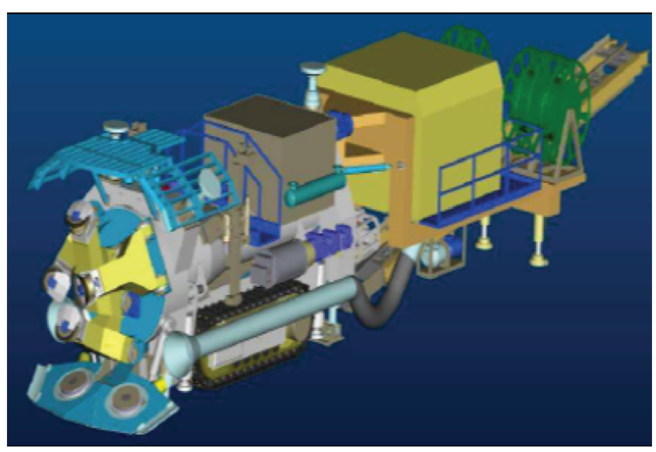

Figure 11. Mechanized tunnel miner

drilling and blasting costs in a multi-front environment would be around R16 700 per metre (excluding labour) with expected advances of around 8 m/day. This comparison indicates that the MTM is around 16% more expensive to operate, but results in 25% higher advance rates.

If the current productivity levels and morale of the South African mineworker is taken into consideration, the investment in technology should provide considerable benefits.

In order for the decline development to progress smoothly, the following critical areas requires attention:

- A ventilation and refrigeration system that is capable of handling the heat loads that will be placed on the development environment
- Special ventilation and cooling systems to cater for higher advance rates and longer distances without through-ventilation or holing
- The muck removal logistics will need to be carefully planned, as a single MTM capable of 10 m/day could generate in excess of 1000 t/day of waste rock. The speed at which the decline development proceeds requires careful logistics planning
- Telemetry and communication systems will require regular updating and installations
- Mining services will require regular updating and installation
- Maintenance for these machines will have to be of high quality, since machine availability is targeted to be more than 90%
- Critical spares and back-up spares should be at the main surface workshop ready to be deployed if needed
- Other vehicles e.g. trucks, graders, and utility vehicles that are required for back-up should be appropriately sized and available to support the development platform
- A water handling system capable of handling up to 20 l/s should be put in place for each MTM
- The mechanized cutting operation should coincide with a system of cover probe drilling. The major primary decline development ends should be double-covered from cubbies excavated close to the development face
- The maintenance back-up system should be capable of servicing the MTM development.

The rock strength in the footwall is a major concern in rock cutting as the BC footwall rocks are very hard, brittle, and in some cases abrasive. Rock types that are expected are norites, anorthosites, and pyroxenites with general UCS values of around 180–220 MPa, but brittle.

Actual tunneling in hard granite rock has proved very successful with the MTM.

Activated disc cutting or disc undercutting methodology would be the most appropriate method to apply.

Where possible, the decline excavations will be placed on-reef so as to generate early revenue.

Shaft excavation methodology for orebodies deeper than 1000 m

The new surface shafts required to service the target area would have to be a large diameter so as to accommodate the bulky rock-cutting equipment. Typically the shaft would be of the order of 10 m in diameter. This would require conventional shaft-sinking techniques. Mechanized shaft-boring machines have been developed for boring of large-diameter shafts, but these are in the prototype stage and still need to be proven (Figure 10).

Conventional blind sinking operations would have an advance rate of typically around 60 m per month, and cost in excess of R300 000 per metre to excavate and support, and an estimated R150 000 per metre to equip. This excludes the shaft headgear, winders, and other surface infrastructure. The capital cost of a large-diameter shaft borer would be in the order of R300–350 million. Development costs using such a machine are estimated at R250 000 per meter, with R150 000 per metre to equip the shaft (excluding surface infrastructure). The advance rate would be a claimed 130 m/month.

Rio Tinto investigated large-diameter shaft-boring systems together with Herrenknecht mining. A large-diameter shaft borer should be able to achieve at least 5 m advance per day – double or three times the rate of conventional sinking. Owing to the substantial capital investment, a partnership should be forged with other companies that need vertical shafts to be sunk. It is expected that the shaft sinking and equipping cost would be similar to the conventional sinking and equipping costs at between R400 000 and R500 000 per metre.

This technology is suitable for application in the platinum target area, although its viability would be determined by commercial and financial considerations. There are no existing operating cost estimates for blind shaft-boring, but these are expected to be on a par with blind sinking.

Mine design and layout

Waste handling and infrastructure development

Mine access via tunnels should be rapid and flexible to enable swift footprint development. Importantly the development should not be based on drill-and-blast techniques, but rather on rock-cutting technology. The type of equipment, logistics, and costs are similar to those for shaft excavation for orebodies shallower than 1000 m (see previous section).

On-reef mining layout

The on-reef rock-cutting mechanized mining planned for the target area is derived from mining trials at Lonmin Platinum using a prototype continuous narrow-reef miner the MN220 (Moxham, 2004). The target orebody, however, could be substantially different from the cutting trial area at Lonmin:

- Steeper and narrower reef areas
- Possible dual reef areas suitable for co-extraction of the UG2 and Merensky reefs;
- Areas with specific geotechnical requirements that are required to be designed into the layout
- The mining depth could require specific design elements such as large protection pillars and sidings or slotting of excavations to handle the stress regime.

Tests conducted within the BC have indicated that the cutting of reef is feasible, and prototype machines have successfully cut reefs at competitive excavation rates and costs. Further development is required to get the system to the commercial stage.

Case study of a futuristic mechanized rock-cutting platinum mine

Commercial-scale mechanized rock-cutting has not yet been implemented in the platinum mining industry. The following section provides a view on how such a mine

Figure 12. Excavation profiles of the MTM vary and are flexible

could look and which technologies would be included in such a mine of the future. The block of ground targeted for the concept of rock cutting is less than 1000 m deep, and contains a 1 m wide UG2 Reef dipping 14 degrees. The block is accessible from surface declines.

Half level layout

Current planning practices break the mine down in smaller components. The smallest individual unit, called the half level, embodies all the activities within the mining cycle i.e. development, construction, ledging, equipping, stoping, sweeping, vamping, and reclamation. This terminology is employed by conventional mining, and may be different in rock-cutting mechanized mining.

The 9° on-reef access declines to 1000 m depth

The on-reef mine design would be based on a two-barrelled on-reef decline trucking cluster accessing the UG2 Reef by means of 9º apparent dip on-reef decline excavations. These clusters are developed with protection pillars to ensure stability over the life of mine. The declines are 6 m wide and 6 m high and can accommodate 60 t articulated dump trucks for hauling of reef.

Figure 13 indicates the sinking configuration for the 9º on-reef declines. The 6 × 6 m on-reef declines are developed with the mechanized tunnel miner (MTM 6). The skin–to-skin distance of maximum 30 m between the declines is left *in situ* as a protection pillar. This is required for both sides of a decline. The configuration is therefore a 30 m pillar, the first 6 m decline, another 30 m pillar, and the second 6 m decline with a 30 m pillar. The total perpendicular distance across the sinking decline barrels is therefore is 42 m. Figure 13 also indicates the connecting drives between the declines. These are 50 m in length, 6 m high, and 6 m wide. A connecting drive is placed every 150 m along apparent dip.

On-reef half levels < 1000 m depth

On-reef declines access the respective stations on the UG2 Reef, and the strike drive development for the level is driven from the same on-reef decline platform. On-reef strike drives are driven out on strike to the sections, which will be located adjacent to the decline system. The strike drives are 6 m wide and 6 m high. The strike drive is located in a pillar which is 30 m wide on each side of the on-reef strike drive. Therefore the strike drive system width with the drive and two pillars is 66 m. Consideration was given to having more than one strike drive per half level, but from the pillar design an additional drive would add 36 m in width to the strike drive configuration. Figure 13 indicates the strike drive configuration planned for a UG2 project target area.

The above mine design is based on a trucking model, but it is designed for ease of operation and a high capacity to release half levels with full rock-cutting capacity.

The following aspects are catered for in this design and will underpin the application of cutting technology:

- Ease of clearing muck and reef by means of a high-capacity trucking system
- Ease of access on-reef with apparent dip declines
- Large cross-sections for ventilation capacity on-reef
- Early revenue generation through an on-reef approach
- Large ore system storage capacity (muck bays and storage silos)
- High-capacity water handling system with dams and pump stations
- Quick access (<60 minutes) to underground workings through the decline system
- Large surface-based workshops with service bays underground
- Large material handling facilities
- Ease of maintenance for continuous operations.

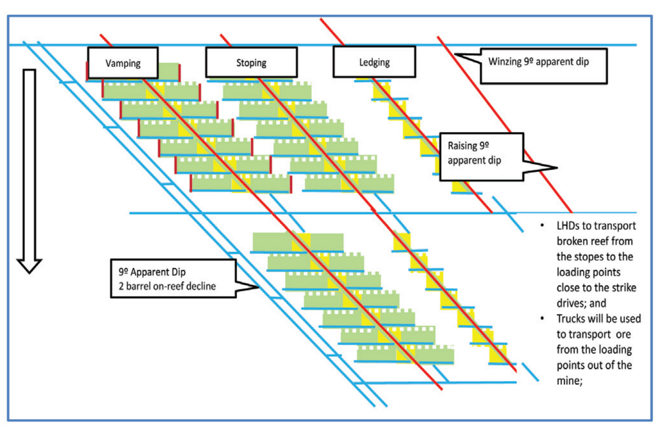

Figure 13. A typical half level layout for UG2 Reef mining

The continuous narrow-reef miner

This machine showed the most promise for on-reef mechanized cutting. It utilizes undercutting technology and can cut as narrow as 1.3 m, weighs 32 t, and cuts a 4 m wide path. Mining trials indicated that 8.5 m^2 production per shift was plausible . This equates to roughly 7000 t per machine per month (Table III). It is expected that four machines per UG2 half level will cut 17 000 t/month per half level. The output per half level is on par with conventional and mechanized mining systems. Expected operating costs are within 8% of conventional stoping costs, with the biggest cost contributor being cutter and machine maintenance. Labour costs should be about one-third of a conventional mining operation.

Design features of the continuous narrow-reef miner

The follow design features are unique to the continuous narrow-reef miner:

- The cutter discs are mounted in the same cutting plane
- The reef would be cut in an undercutting mode, thus minimizing the power and cutting forces and maximizing the chip sizes
- The effective undercutting depth was estimated to be between 50 and 60 mm
- Machine stability and stiffness was essential, thus, the machine must be staked while cutting
- The cutter boom must be as short and stiff as possible
- The machine must be capable of cutting its own entry into the stope
- The machine should excavate the maximum amount of reef from a single set-up
- The machine will not be fitted with crawlers and will 'walk' in the stope using its staking system
- The machine in operation must be flexible enough to follow the major reef undulations
- All rock cuttings must be removed from the immediate cutting area and then transported out of the stope.

Figure 14 indicates the design features of the narrow-reef miner.

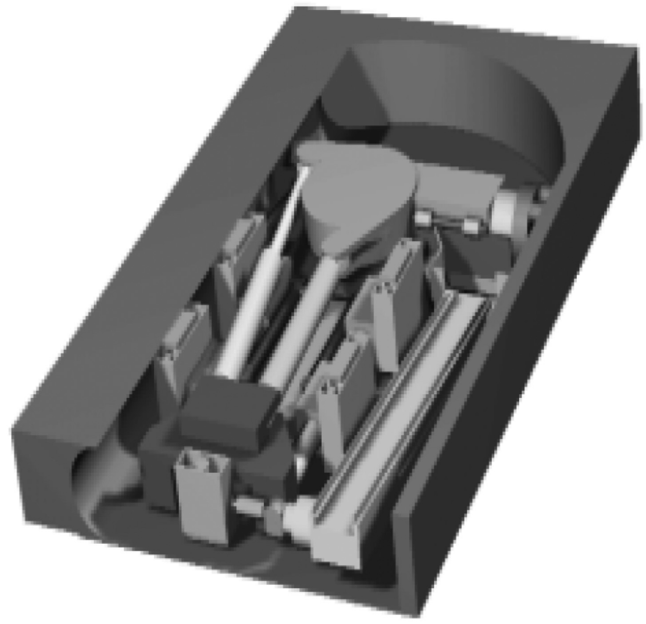

Figure 14. Isometric view of a continuous reef miner

Comparitive efficiencies of a narrow-reef miner

It is expected that the productivity of rock-cutting systems will be high compared to conventional and mechanized drill-and-blast operations. Rock-cutting machines resemble an industrial factory approach, and the machine availability and utilization are the keys to achieving the highest production possible.

Half level outputs, as indicated in Table IV, would be on par with, and even slightly higher than conventional mining, and outputs of around 3000 to 4000 m^2/month could be achieved.

Labour efficiency would be six times greater than conventional operations.

Table III
Continuous reef miner – expected production outcomes

	Original	Modified	Expected
Cutter cutting diameter (metres)	0,85	1,0	1,0
Cutter cycle (min/cycle)	3,5	3,5	2
Production rate (tons/cycle)	0,8	0,95	0,95
Nett mining rate (tons/hour)	12,8	15,2	26
Available time (% of total time)			65
Available time (hours)			15,6
Operating cycle time (% of available time)			70
Utilization (% of total time)	38	38	45
Other cutting and maintenance time (hours)			4,7
Daily production (tons/day)	116	137	280
Monthly production (tons/machine/month)	3 500	4 100	8 500
Monthly production (square metres/month)	1030	1 025	2125
Production operators (three shifts + one shift)	8	8	8
Labour productivity (square metres/man/month)	129	128	265

All tonnage calculations are based on an assumed specific gravity of 4.

Table IV Continuous reef miner – benchmarking production outcomes					
	Unit	Rock cutting	LP (bord and Pillar)	ULP	Conventional
Half level stoping/ ledging output	m^2/month	3000 - 4000	1800 - 2200	4000 - 6000	2000 - 3000
Stoping labour efficiencies	m^2/stoping labourer	120 - 130	40 - 50	50 - 60	15 - 20

Table V Continuous reef miner – inferred production costs				
	Shaft head cost comparison (rands per ton)			
	Rock cutting	LP (bord and pillar)	ULP	Conventional
Dev. cost	100	20	50	40
Stoping	300	140	115	330
Other direct mining	70	100	70	90
Mining engineering	70	75	90	120
Dev. maintenance	10	10	40	20
Stope maintenance	20	90	80	20
Shaft services	30	30	30	30
Total (R/t)	**600**	**465**	**475**	**650**
Total (R/4E oz)	**4321**	**4325**	**3421**	**4681**

Table VI Continuous reef miner estimated IRR					
		Indicative unconstrained IRR comparison			
	Unit	Rock cutting	LP (bord and pillar)	ULP	Conventional
IRR (12.5% discounted rate)	%	21% - 25%	10% -15%	18% - 25%	15% -20%

Comparitive cash operating costs of a narrow-reef miner

The cutting of reef is much less labour-intensive and therefore lower labour costs are expected. The major cost component for the mechanized rock-cutting system will be cutter costs and engineering maintenance. Table V indicates the estimated shaft-head costs for the narrow-reef mining system to be around R600 per ton. This makes the narrow-reef miner cheaper than conventional options.

Comparitive financial runs results of a narrow-reef miner

High-level financial runs yielded positive results for a rock-cutting mine. High development rates generally offset the high capital costs. It is expected that a mechanized rock-cutting mine will be between 25% and 30% more capital-intensive due to the cost of rock-cutting technology, but quicker build-up and more control over mining profiles support the business case and Table VI indicates that a return of between 21% and 25% should be possible if mechanized rock cutting is implemented successfully. These returns are on par with ULP mining.

Advantages of the narrow-reef miner

The cutting trials of both the Merensky Reef and the UG2 Reef at Lonmin yielded the following advantages of the continuous narrow-reef miner:

- The machine is a simple design
- The machine is operated remotely and could easily be automated
- The functionality of the machine is hydraulic-based and easily maintainable
- The machine could handle inclinations of 14º, and with adjusted gripper systems could easily cut up to 30º
- The machine is suited for continuous operations.

The mining trials have yielded cost comparisons that are on a par with current stoping costs.

Conclusion

A high-level business case for the mechanized rock-cutting platinum mine shows positive results. Rock-cutting technology has advanced to a point where there could be considerable benefits in applying the technology to platinum mining. The rock types encountered in the Bushveld Complex are hard and difficult to cut. Although some rock-cutting machines have demonstrated that it is possible to excavate stoping areas in these rock types, the business case depends on a successful proof of concept and implementation of mechanized rock-cutting technology.

The main drawback of such a system will be the multiple new technologies and machines that would be required for a new mining system and environment. From a practical mining point of view there are no 'show-stoppers' for rock cutting as the technology has been proven for raise boring and in-stope rock cutting.

The most logical step would be to implement the technology in trial mining areas while investing in further development towards operationally readiness.

As indicated in this paper, it seems that machinery already exists for the all of the facets of platinum mining –shaft sinking, access development, on-reef development, ledging, and stoping.

Collaboration between major equipment manufacturers and mining houses should be actively pursued to achieve the breakthroughs that are needed.

Is the need for change urgent enough?

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