A progress report on ultra-high-pressure waterjet cutting underground: the future of narrow reef gold and PGE mining

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Synopsis

High-pressure waterjet technology is proposed as an alternative tool for selective underground mining of high-grade ore sections in stratiform orebodies showing a preferred 'bottom' or 'top' enrichment such as the Witwatersrand reefs and the Bushveld Complex platiniferous reefs. This technique, utilizing known mining technology together with more advanced machinery and additives as used in industrial and cleaning applications, may lead to an increased life-of-mine (LOM) for mining operations. A series of experiments was successfully carried out in a laboratory on Witwatersrand quartzite material, indicating acceptable cutting performance. Mining volumes by selectively cutting of reef portions are considered to be comparable to traditional drilling and blasting. Economic advantages of waterjet mining include energy savings due to the lower quantity of gangue rock to be hoisted to surface, as well as savings by a decrease in the usage of blasting materials. Capital expenditure of waterjet cutting, if applied on a broad scale, could be lower in the long term than that of conventional drilling and blasting methods. Mining by the application of high-pressure waterjet technology could become a competitive 'green technology' improving the economics and safety of labour-intensive mining operations. This paper suggests that waterjet cutting at an industrial scale can become a routine hard-rock mining technique in the future.

Keywords
waterjet cutting, high pressure, mechanized narrow reef mining, abrasive agents, costs, selective mining.

Introduction

New technology is continually being developed and limits are being challenged as a matter of routine. This is also happening in the field of ultra-high-pressure waterjets (Global Rebar; American Society for Metals, 1989; Kalina, 1999), where innovative technologies have evolved in recent years covering a variety of applications. One of these is in the field of cutting of materials, including steel, concrete, and rock, with the addition of abrasive agents to the waterjet (Momber and Kovacevic, 1998; Tazibt Abriak, and Parsy, 1996; Sheet Metal Industries,1990). Due to the uniqueness of waterjet cutting, there are many applications where it is more useful and economical than standard machining processes (Michigan Tech., 2012; KMT Waterjet).

'Hydraulic mining' is a form of mining that uses high-pressure jets of water to dislodge rock material or move sediment; this technique has been applied since historical times (Thrush, 1968). In the placer mining of gold or tin, the resulting water-sediment slurry is directed through sluice boxes to remove the valuable minerals (Fraser, 2010). Previous attempts to cut rocks by drag bits were assisted by waterjets (Hood, 1977), although the rocks were not directly cut by the jet, which operated at lower pressures of 100–500 bar.

The mechanism of waterjet cutting comprises the application of a water jet with an abrasive agent under very high pressure onto the material to be cut, and thereby involves both shattering and cutting of mineral grains and cements (Momber and Kovacevic, (1998). The water jet is generated by a high-pressure pump (Figure 1a) with a diamond-plated orifice through a metal nozzle (Figure 1b). Figure 2 shows a typical abrasive agent. This technique of hard-rock cutting is relatively new, following the development of high-pressure pumps, and is not yet applied as a routine mining method.

The most frequently applied mining method for reef-type orebodies at present is narrow stoping of 0.8 m to 1.5 m high stopes using drilling and explosives (Pickering, 2007). This requires minimum stope heights and often results in dilution by low-grade or barren material. It also produces large amounts of fines and necessitates all material to be hoisted to surface for processing and extraction.

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Figure 1a—STREAMLINE™ PRO-I 60 / 125 HP Pro Intensifier, ultra-high-pressure pump with an orifice size of 0.35 mm. Technical features: pressure range 500 to 6.200 bar; threadless Cylinders; 1.6 ℓ accumulator; seal-less end caps; quick-change plunger; HP transducer; integrated dump valve; single hole check valve; ceramic plungers
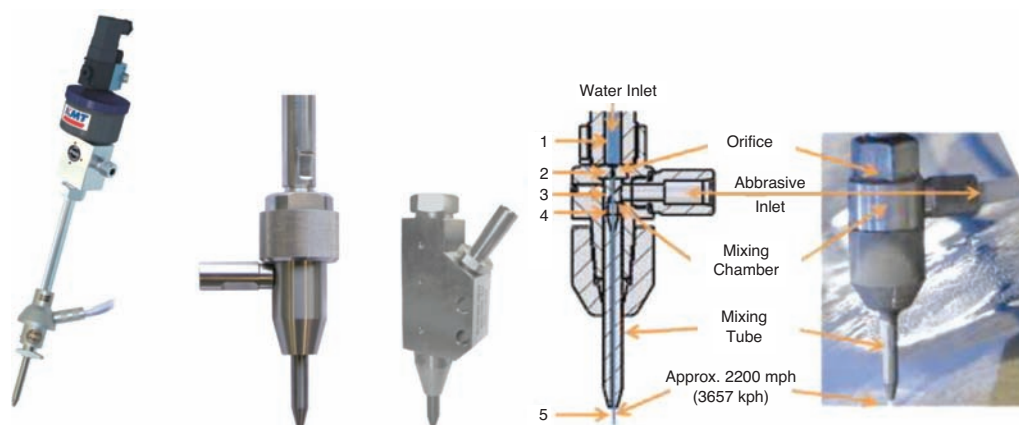

Figure 1b—'Pro cutting' head by KMT Ltd. (for permanent working pressure of 3.5 kbar and max. 6.2 kbar pressure (KTM, 2007), and outline and cross-section of a typical waterjet nozzle (WARDjet)

The possibilities of applying waterjet technology to selective mining have been investigated on Witwatersrand reef material by the department of Geology at the University of the Free State. If the cutting process could be executed successfully, advantages could include the following :

1. Selective removal of high-grade and carbon-containing reef that would have incurred gold losses if blasted
2. A better containment of stope widths
3. A lesser need for support, due to the smaller stopes
4. Less explosives needed
5. Less drilling activities needed
6. An enhanced possibility of continuous mining
7. Better containment of gold losses, resulting in an increased mine call factor
8. Increased stability of hangingwall conditions and increased safety
9. Lower amounts of sweepings
10. Less material to be trammed and hoisted (savings in rolling stock, electricity needed for hoisting, locos and batteries etc.)
11. More capacity in hoisting systems
12. Savings on winches and equipment
13. Savings on labour
14. Quality of ore to the plant can increase recovery due to limited dilution
15. Plant throughput can decrease with less, higher grade material processed, and fewer chemicals such as cyanide are used
16. Opportunity to mine lower grade ore
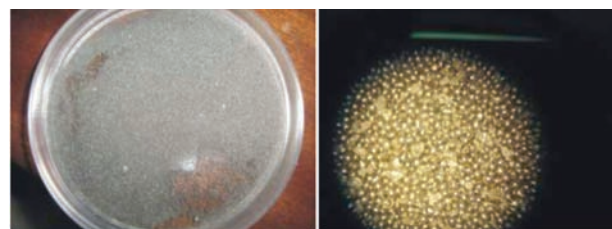17. Increase in life of mine (LOM)

Figure 2—Ferrosilicon spheres (left) abrasives at scale 1:1 and (right) under 20× magnification

18. Less material to slimes facilities, resulting in a marked reduction of acid mining drainage (AMD)
19. Less remediation required.

Stope visit

Two visits to Free State gold mines were conducted in 2007 aimed at investigating working conditions in a stope and to ascertain if waterjet cutting could be executed under the conditions in stope environments. The stopes visited had a smooth footwall and could suit the process of waterjet cutting (Figure 3).

Experimental and results

In order to identify the factors controlling cutting advance of waterjets in hard rocks, a series of cutting experiments of a large quartzite specimen was conducted in December 2007 at KMT Ltd. laboratories in Bad Nauheim, Germany. The dependency of cutting efficiency on waterjet parameters/variables such as water pressure (Figure 5) and flow rate, cutting agent density and shape, and piercing time were investigated. Thereby conditions for the most effective waterjet cut of reef rocks could be identified and optimized.

The sample rock from the Beatrix Mine was installed on the waterjet cutting frame (Figure 4). The technical parameters of the waterjet were as follows:

1. Fixed nozzle aperture with an orifice size 0.35 mm
2. Focus tube size 1.1 mm
3. Pressure 3500 bar (a conservative pressure to start with, as pressures as high as 6200 bar are obtainable)
4. Abrasive agents: 80 grit garnet or ferrosilicon spheres
5. Flow rate 550 g/min, could be varied.

All experiments were performed at a constant pressure of 3500 bar (Table I). Garnet was used as a cutting agent and a number of cuts were performed. At high water pressure, the garnet would abrade the rock material and would also shatter quartz on impact. Ferrosilicon, with a SG of approx. 7.5 – (double that of garnet - approx. 3.75) (Summers, 1995) – was also used, and this increased both the penetration and the cutting rate.

It was decided to first record the time required to pierce through the rock with a waterjet at 3.5 kbar water pressure (Table I). Subsequently the rock was pierced for a shorter time and cutting started to simulate the actual conditions. For technical reasons, in order to prevent flowback of the water and abrasive agent mixture, the cut has to progress along a line. It took 3 minutes and 39 seconds to pierce through 230 mm of rock. Shorter piercing timespans gave the following results:

➤ Piercing for 3 minutes: pierce depth 205 mm. The cut was started at a cutting rate of 30 mm/min. After about 25 mm the material was pierced and the test was stopped
➤ Piercing time of 2 minutes gave a pierce depth of 188 mm
➤ The cut was started at a rate of 30 mm/min: After about 15 mm the rock was pierced and the test stopped. The rock was then pierced for 1 minute, which resulted in a cutting depth of 230 mm.

The first parameters to be determined are cutting rate and penetration (Table I). Results from this experiment (Figures 6
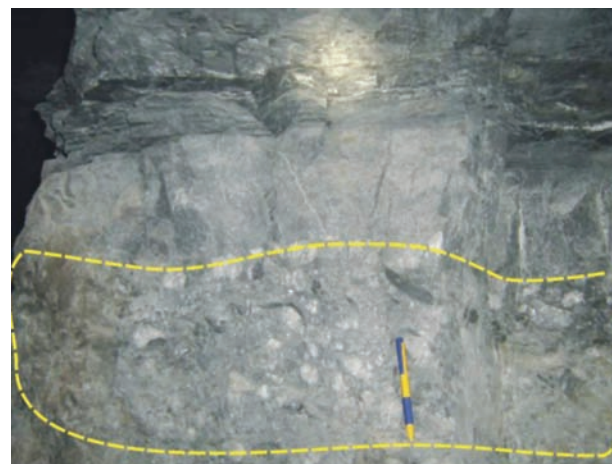

Figure 3—Quartz-pyrite conglomerate-hosted gold-uraninite deposit at one of the Witwatersrand Au-U mines, overlain by shale. Yellow stippled line illustrates the area of selective mining envisaged for waterjetting

Figure 4—Photograph of the experimental set-up of the sample in the cutting frame with various waterjets and nozzles at the Bad Nauheim plant of KMT Ltd in Germany
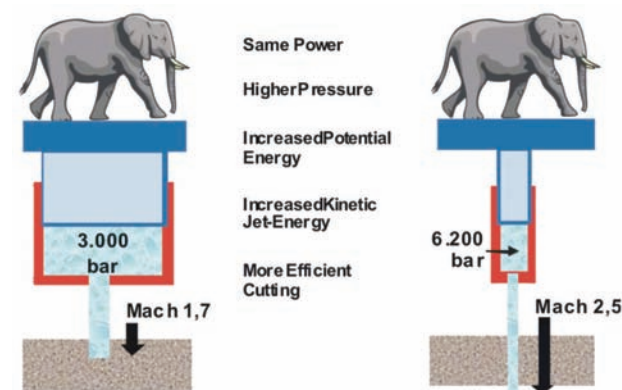

Figure 5—Schematic illustrating advanced cutting efficiency using higher pressures (courtesy KMT Ltd)

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Table I

Summary of piercing experiments at constant pressure, but variable times and with two different abrasive agents

Test no.	Water pressure	Cutting speed	Time of piercing	Abrasive material (SG, dens.)	Cutting depth	Flow rate
1	3.5 kbar	30 mm/min	219 s	garnet, 3.75	160-230 mm	550 g/min
2	3.5 kbar	30 mm/min	219 s	garnet, 3.75 ferro-silicon, 7.50	min.100 mm 150 mm	550 g/min
A	3.5 kbar	30 mm/min	180 s	garnet, 3.75	205 mm	550 g/min
B	3.5 kbar	30 mm/min	120 s	garnet, 3.75	188 mm	550 g/min
C	3.5 kbar	30 mm/min	60 s	garnet, 3.75	42 mm	550 g/min

to 10) on the quartzite sample should enable the cost and specifications of the equipment required to affect the cutting process to be estimated.

A continuous cut from one side to the other at 30 mm/min cutting progress resulted in a cut depth from 160 mm to more than 230 mm (Figure 6). This would allow a cutting depth of 250 to 300 mm at the face.

A reduction of the cutting speed to 180 mm/min over a distance of at least 100 mm resulted in a first pass of a minimum depth of 100 mm (Figure 7).

The second pass over the same cut path resulted in a minimum depth of 150 mm. The previous test was repeated using ferrosilicon as an abrasive agent (Figure 8).

Using garnet abrasive at a cutting rate of 180 mm/min resulted in a first-pass cut depth of 100 mm. The jet with the same parameters but using ferrosilicon cut 125 mm deep in the first pass. Garnet abrasive cut at 180 mm/min in the second pass and achieved 150 mm depth, whereas ferrosilicon abrasive cutting at 180 mm/min achieved 210 mm depth in a second pass (Figure 9).

These runs led to the conclusion that the hardness and density of the rock, as well as the density of the abrasives added, play an important role in waterjet cutting performance. Obviously, the pressure of the water jet leaving the nozzle also influences cutting efficiency.

Advantages and disadvantages of waterjet cutting

Disadvantages

Waterjet cutting is a very useful machining process that can be readily substituted for many other cutting methods.

Figure 7—Cut obtained at a more realistic speed of 180 mm/min for a distance of at least 100 mm. During the first pass a minimum depth of 100 mm was achieved

Figure 6—Test designed not to pierce, but just start cutting from one side to the other at 30 mm/min: A cut depth from 160 mm to more than 230 mm was recorded

Figure 8—The second pass over the same cut path as in Figure 8, resulting in a minimum depth of 150 mm. The previous test was repeated using ferrosilicon as an abrasive

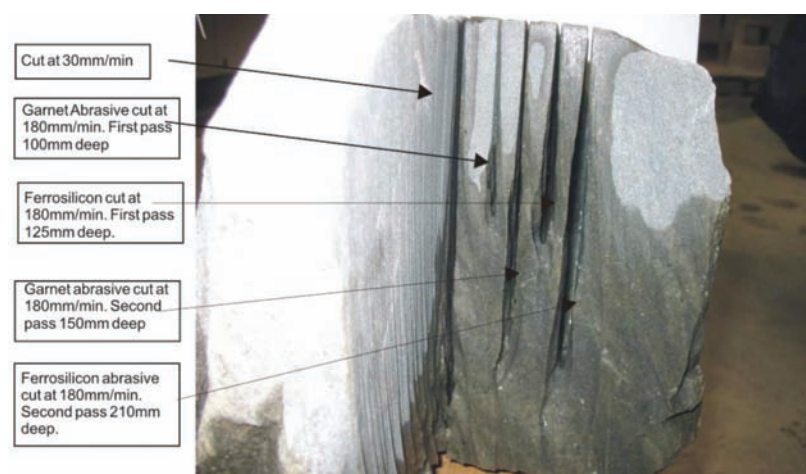# A progress report on ultra-high-pressure waterjet cutting underground

Figure 9—Cuts made at various cutting speeds and using different abrasives

However, there are some limitations to the kind of material it can cut. Listed below are these limitations and a brief description of each (Thrush, 1968; Michigan Tech., waterjet research group).

➤ Only a limited number of materials can be cut economically. While it is possible to cut tool steels, and other hard materials, the cutting rate has to be greatly reduced, and cutting times become very long and costs increase. However, this does not seem to apply to the quartzite from Beatrix Mine, as shown by the results presented above

➤ Concerns have been expressed regarding the cutting of very thick parts by waterjet and still holding dimensional accuracy. If the part is too thick, the jet may dissipate somewhat, which causes it to cut on a diagonal, or results in a wider cut at the bottom of the part than the top. This can also cause a ruff wave pattern on the cut surface. In selective mining, however, this argument seems not to be relevant because the cuts do not have to be extremely accurate

➤ Taper is also a problem with waterjet cutting in very thick materials. Taper is when the jet exits the part at a different angle to that at which it enters the part, and can cause dimensional inaccuracy. Decreasing the speed of the cutting head may reduce this, although it can still be a problem. Again, the cutting precision may not be as relevant to mining as it is to a tool cutting process.

Advantages

➤ The waterjet cutting process does not generate extra heat to add to that in the stope; however, the high-pressure pump might produce heat

➤ Unlike machining or grinding, waterjet cutting does not produce any dust or particles that are harmful if inhaled, which is very relevant in a mining environment

➤ The kerf width in waterjet cutting is very small, and very little material is wasted

➤ Waterjets are much lighter than equivalent laser cutters, thus several jets mounted on an automated

vehicle on rails could cut at the same time in one stope. This reduces the cutting time, and allows remote operations

➤ Mixing in of various sharp-edged cutting agents can significantly increase cutting rates

➤ Electricity consumption at 6.2 kbar pressure is 7 kWh per metre of reef (at 20 cm height)

➤ At 6.2 kbar pressure, water consumption is 52 ℓ per piece, and abrasive consumption 12 kg per piece. These figures can be reduced by recycling the mixture, which can be successfully done.

Operational factors

Questions that arose from the mine visit included the following:

1. *Where is the cut to be made?* If only the reef has to be removed, two cuts would be necessary, one above and one below the reef. Holes can also be drilled by the waterjet to enable small quantities of explosive to break the reef. This method, however, will create a small space from which to proceed (Figure 10). Will another two cuts be required to enlarge the stope to enable penetration? Another option will be to take a larger cut to remove enough material to proceed. This will determine if two or four cutting nozzles will be required for the operation, and will also impact cutting speed as well as the capacity of the equipment.

2. *The rate at which the face advances is also relevant, i.e. the potential production rates.* One should assume a process in which the face is formed by two parallel horizontal tunnels, with a third tunnel joining these. The face could be 30 m in length. Cutting could start from the parallel tunnels along the face of reef, with the two cutting machines meeting in the centre. It is assumed that cutting from two ends of the stope at the same time, above and below the reef for a 200 mm length at 200 mm depth at a feed of 3 mm/sec would take approximately 2.2 minutes. Assuming such reef geometry it would take about 4.3 hours to cover the entire face length with two waterjets.

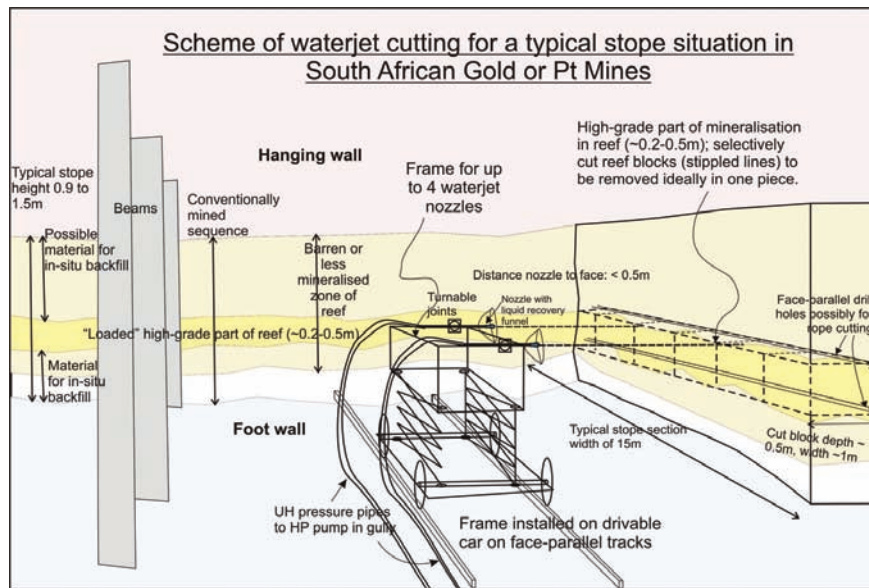# A progress report on ultra-high-pressure waterjet cutting underground

Figure 10—Schematic waterjet cutting set-up envisaged for a typical South African gold or platinum mine reef situation (dimensions are approximate) in combination with drilling and blasting development

$$M=(30*0.2*0.2)/4.3 * 2.65 = 0.74 \text{ t/h}$$

$$0.74*27 \text{ g/t} = 20.0 \text{ g Au per hour}$$

3. The voltage available in the current gold mines appears to be sufficient for larger scale waterjet application.
4. The amount of water required for cutting is 3 to 5 ℓ/min, depending on nozzle size. Most of this can be collected by a funnel collector around the nozzle and recycled; thus there is no point in adding too much water to the stope and gullies, which is a problem in conventional mining due to fines losses.

Future development

Waterjet cutting

The first waterjet cutting experiments were very encouraging from a technical point of view. Once an underground prototype solution is set up, and after a better understanding of how selective mining by waterjet can take place at a production level, a new dimension of mining can evolve with *in situ* backfilling of the barren parts of the orebody. Figure 10 displays a possible waterjet cutting set-up envisaged for a typical South African gold or platinum mine situation. An industrial application would involve a number of robust waterjets suitable for industry, in combination with drilling, development blasting, etc. The trend for equipment development applicable to mining points towards the high water pressure 6.2 kbar 125 HP Pro Intensifier waterjet series with the larger 0.35 mm orifice. Since most reef rock in mines has been blasted previously during development, the fact that the rocks used in the experiment had been exposed to some degree of blasting stress it is regarded simulating realistic conditions. At deep mining levels, the microfractures and cracks induced by blasting will facilitate waterjet cutting, an effect which is intended. In the medium term the savings due

to effective cuts will outweigh the expenditure for the sophisticated equipment. A preliminary cost balance is shown in Table II, but these figures should be calculated more precisely.

If waterjet cutting turns out to be feasible, it may make deep mining more economic due to a lower demand for explosives and less hoisting of reef material to surface. Deep Witwatersrand gold mining could under these circumstances also continue longer than envisaged. Increased mechanization of mining would not necessarily result in job losses, but rather the need for more skilled labour handling high-tech mining equipment.

Type of abrasive agent

Since its development, waterjet machining has seen many improvements in its design. Many different types of nozzles, flow rates, jet positions, and types of abrasive have been tested. For the abrasive, garnet with a Mohs hardness of 8 is typically used because it is much harder than most materials and because it breaks in clean, sharp edges. Garnet is inexpensive in relation to abrasive agents such as diamond; however, it still costs around $600 per ton. Working with the Daimler-Chrysler Corporation, Michigan Technicon has found a way to use crushed windshield glass as an acceptable replacement for garnet. Glass, which is made of silica with hardness 6 on the Mohs scale, is not as hard as garnet, but costs only about $50 per ton. Silica glass is nevertheless harder than most materials, and since it is crushed, the particles all have sharp edges and have not been subjected to wear, such as might occur in garnet during mining and handling. A practical application test still has to be done. The other benefit of using silica is that all the glass being used is scrap window glass, which would have otherwise been sent to a landfill where it would be of no use (Michigan Tech, 2012).

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Other improvements

Further improvements and experiments that are being worked on by other companies include:

➤ Using a cryogenic cutting fluid and various abrasives
➤ New uses for waterjet cutting, such as selective mining involving deeper cuts on an inclined carriage along a gently dipping stope
➤ New ways to make waterjet cutting more efficient in already existing mining processes by using sets of cutters.

Costs

There are a number of variables influencing reliable cost estimates. Table II gives an estimate of the cost of conventional drilling and blasting compared to selective blast mining and waterjet cutting methods. The cost is calculated in SA rand per blast / cut, including equipment and consumables, calculated for a stope length of 15 m. Stoping costs are based on 1996 underground cost numbers (Pickering, Smit, and Moxham, 2006; Bock, Jagger, and Robinson, 1998) inflated for 2011, hoisting and milling costs based on an average electricity equivalent of 23 kWh/t for a typical Witwatersrand

reef at an electricity rate of R0.87 per KWh (February 2012). The drilling/cutting cost entries for waterjet include water and electricity, as well as nozzles consumed by the jet and the high-pressure pump. The material cost is for garnet as cutting agent; the use of glass as abrasive agent would be by far cheaper (about 10% that of garnet).

The balance sheet of Table II clearly illustrates that waterjet cutting could have definite cost advantages over conventional drilling and blasting as well as selective blast mining. The main reason for this is lower stoping heights leading to less volume and tonnage extracted. At the same time, higher grades can achieve the same amount of metal extracted. A higher mine call factor of 0.98 is expected due to very little fines material generated during the narrow slit cutting process, improved metal recovery, and lower costs. Lesser cutting, and no charging, explosives, and backfilling costs, concomitant with increased recovery will decrease waterjet cutting costs to approximately half those of conventional mining (Table II). *In situ* underground testing has to be conducted in order to obtain more precise numbers. Once a prototype is tested and the design and process improved, precise capital and operational expenditure for production units can be given.

Table II

Estimated mining cost comparison of conventional drilling and blasting, selective blast mining, and waterjet cutting methods in rands per blast / cut including equipment/consumables calculated for a stope length of 15 m

Parameters/mining technique	Conventional	SBM	Waterjet mining
Advance (m)	1.0	1.0	1.0
Stope width (m)	15.0	15.0	15.0
Stope height (m)	1.5	1.0	0.3
Volume extracted (m³)	22.5	15.0	4.5
Tons extracted (t)	60.8	40.5	12.2
Grade (g/t)	5.5	8.2	27.0
Au mined (kg)	0.33	0.33	0.33
Mine Call factor	0.80	0.90	0.98
Au extracted (kg)	0.27	0.30	0.32
Diff. Au mined/extracted (kg)	0.07	0.03	0.01
R/blast/m stope face	**Conventional**	**SBM**	**Waterjet mining**
Cost			
Drilling/cutting	R75.19	R103.39	R55.00
Initiation/charging	R30.08	R87.72	R-
Explosives	R14.04	R22.56	R-
Backfill	R147.08	R-	R-
Development	R406.03	R380.55	R380.55
Material/other	R324.82	R182.71	R50.00
Total	**R997.23**	**R776.93**	**R485.55**
R/blast, R/cut	**Conventional**	**SBM**	**Waterjet mining**
Stoping cost	**R 14 958.52**	**R11 653.90**	**R7 283.21**
Hoisting, milling costs	R1 215.61	R810.41	R243.12
(23kWh/t, R0.87/kWh)			
Grand total	**R16 174.12**	**R12 464.30**	**R7 526.33**

a Stoping costs are based on 1996 underground cost numbers (Pickering, Smit, and Moxham, 2006; Bock, Jagger, and Robinson, 1998; Bock, 1996) inflated for 2011

b Hoisting and milling costs based on an average electricity equivalent of 23 kWh/t for a typical Witwatersrand reef at an electricity rate of R0.87 per KWh (Feb. 2012).

The drilling/cutting cost entries for waterjet include water and electricity, as well as nozzles consumed by the jet and the high pressure pump, the material entry is for garnet as cutting agent; the use of glass as abrasive agent would be by far cheaper (10% that of garnet)

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Next steps

The results presented clearly indicate the technical viability of the waterjet technology in selective mining. Waterjet cutting companies such as MultiCam RSA should now propose a way to set up an underground prototype solution. A more in-depth knowledge of what is happening at the stope should be obtained. The complete mining process, including mine development, removal of rock to make the area safe, and how the waterjetting process fits into this need to be understood (Figure 10). Once the efficient use of waterjets in stopes has been implemented on a routine basis and at an industrial scale, a new era of narrow-reef mining can begin.

Acknowledgments

We would like to thank staff from Gold Fields Ltd. for enabling a visit to Beatrix mine to learn more about stope conditions, and the Department of Geology at the University of the Free State, Bloemfontein for the use of their facilities.

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