Improving Drive Stability through Efficient Development Blasting Design and Practices

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ABSTRACT

Drive stability is critical in block/panel cave mining. The production levels of these mines are required to remain operational for the entire life-of-mine which can be in excess of 30 years. It is therefore necessary to produce high-quality drives to ensure sustainable mine productivity. In order to improve the quality of drives and pillars, this gold mine instigated a project to optimise their development blasting. The initial aim was to reduce the level of overbreak in development mining, which was averaging approximately 18 per cent. The benefits of controlling overbreak not only included an increase in the integrity of the drives but also a decrease in load and haul and ground support costs. Through focusing on the optimal blasting of the perimeter holes, overbreak was reduced to 4.5 per cent. The project's focus then moved to drill and charge designs for development faces. In optimising these designs, it was anticipated that improvements in the development mining cycle would be achievable.

INTRODUCTION

The mine, a massive low-grade gold/copper deposit, is mined via block/panel caving methods. The mine has a life in excess of 20 years.

Drive stability through efficient blasting practices not only has the benefit of ensuring long life infrastructure; it is an exercise in cost saving, which in today's mining environment – where efficiencies are constantly being sought – is almost a given for the majority of operations, be they underground or open cut.

To achieve optimal outcomes for the project of improving drive stability through efficient development blasting design and practices, it was divided into the following stages:

- quality control/training process
- perimeter control
- drill and charge designs.

Over the entire project in excess of 60 cuts were analysed, providing a comprehensive data set-up on which conclusions regarding perimeter control and design could be drawn.

QUALITY CONTROL/TRAINING PROCESS

A development drill and blast audit was conducted prior to the commencement of the project to highlight any areas where improvement was needed in the drill and blast process. The audit allowed for the identification of key areas of improvement and, most importantly, consistency across all shifts. Only minor issues were noted and rectified. The mine had already entrenched compliance to design as a key performance indicator (KPI) and provided performance feedback to the development drill (jumbo) operators once the heading had been measured for overbreak.

PERIMETER CONTROL

The perimeter control aspect of the project was conducted in three stages:

1. benchmarking of NONEL® LP timing with perimeter holes string loaded
2. continuation of string loading, but introducing the precision timing of electronic detonators
3. baseline measurement of full face electronic initiation.

An integral aspect of the project was the use of string loading technology in perimeter holes. String loading provides a decoupled emulsion charge that is predominantly loaded in perimeter holes to reduce the localised explosive energy, hence reducing damage to the surrounding rock mass and the cause of overbreak. Ensuring string loading functionality on the DynoMiner® emulsion delivery unit was important for the outcome of the project. An example of string loading is shown in Figure 1.

NONEL LP BENCHMARKING

The first step of the benchmarking process was to establish the current levels of overbreak. Site practice was to use pyrotechnic detonators and string loading of perimeter holes (although 100 per cent compliance to string loading was not achieved). Prior to the commencement of the project, overbreak according to survey was on average 18 per cent.

Throughout the project, overbreak measurement was completed via photogrammetry using the ADAM 3D® process and suite of programs. ADAM 3D allows analysis of a series of stereo photographs which are combined to produce a 3D model. This model is dissected to give outputs such as volume and compliance to design (ADAM Technology, 2015).

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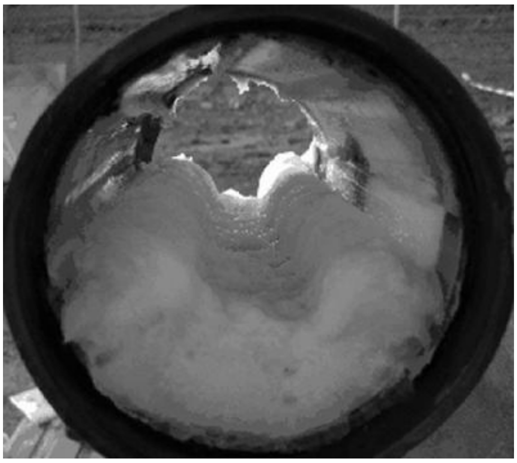

FIG 1 – An example of a string loaded charge.

The results from the benchmarking of pyrotechnics are presented in Table 1. These figures imply that there is a great deal of variability in results (with overbreak ranging from -9.5 per cent to 32.7 per cent from a sample size of 13 headings). This inconsistency can be attributed to a range of factors including: drilling conformance to design, blasting (including charging perimeter holes with a fully coupled charge), ground conditions and timing (scatter of pyrotechnic detonators). All of these factors can be controlled with good drilling and blasting practices combined with precision timing.

The results from overbreak alone are not entirely conclusive as drilling and ground conditions have a significant influence on the outcome. In this case, the majority of the headings were drilled inside of design, hence giving negative values for overbreak, or underbreak.

Drilled versus blasted overbreak

Fortunately, the Atlas Copco L6 development drills (jumbos) used on site have data recording capabilities. Where available, drill logs were downloaded from the mine's jumbos and 'as drilled' was compared to design and also to the final blasted volume. Table 2 shows this data in the form of drilled versus blasted overbreak. Drilled overbreak refers to the amount of over/underbreak caused by drilling (ie drilling outside/inside of design/profile). Both drilled and blasted overbreak are calculated with reference to the design, with negative values being underbreak (on average) and positive values being overbreak (on average). In the final column, a positive value indicates that blasting created a void larger than was drilled (ie overbreak due to blasting), whilst negative values show that, overall, blasting didn't break to the drill holes (ie underbreak due to blasting).

TABLE 1

Overbreak results from perimeter control with string loading and pyrotechnic detonators.

Heading	Overbreak (%)
1E	8.2
12N	-2.7
12N	-9.5
9N	6.3
16E	26.4
24N	30.3
30N	15.7
26N	32.7
28N	-1.7
26N	-3.2
26N	-4.9
28N	-2.5
28N	-8.1

TABLE 2

Drilled versus blasted overbreak for selected pyrotechnic headings where drill data was available.

Heading	Overbreak (drilled) (%)	Blasted overbreak (%)	Δ (%)
16E	16.0	26.4	10.4
26N	-4.8	-3.2	1.6
26N	2.5	-4.9	-7.4
28N	8.1	-2.5	-10.6
28N	7.9	-8.1	-16.0

Having the ability to accurately analyse 'as drilled' data gave a good insight into the amount of overbreak that relates directly to blasting. Throughout the project, in excess of 60 headings were fired and analysed to varying extents depending on data availability. Unfortunately, this 'as drilled' data was not available for the entire project due to various problems and availability of the aforementioned jumbos in the trial locations.

Whilst benchmarking pyrotechnic detonators, very few half barrels – a good indication of clean blasting and perimeter control – of note were observed.

Figure 2 is a heat map of design (solid surface) and actual results of the same heading from four different angles created in the ADAM 3DM Analyst module. It is evident that there is great variance from design and that the finish is 'rough'. The darker shading indicates a variance of greater than 0.5 m from design.

Extent of scaling and spraying operations

Further aspects of the development cycle that were investigated in the baseline activity included the extent of scaling and the effects of spraying of shotcrete. The mine had concerns that considerable 'over-scaling' was occurring. To determine the extent of this, photogrammetry pick-ups

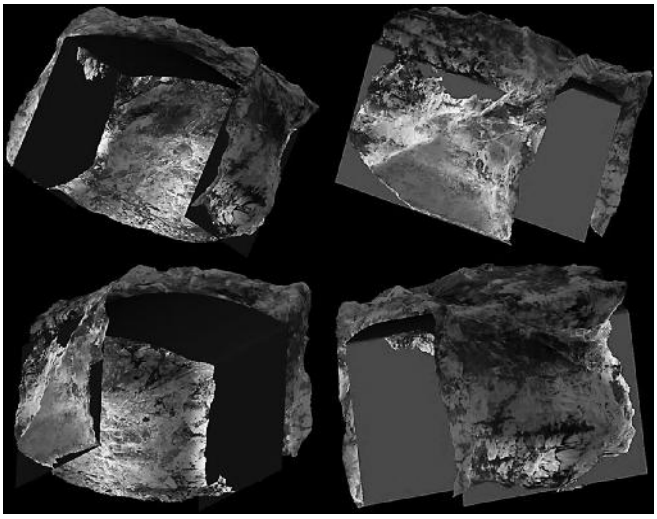

FIG 2 – A series of images showing design versus actual (16 E).

were taken pre- and post-scaling. Unfortunately, accurate volumes or percentages were not able to be determined due to operational scene changes in the drive (extra material was removed from the drives when the scaled material was loaded out). Keeping a sterile scene for measurement purposes such as these is difficult in an underground mining environment; nevertheless, some results were obtained. Heat maps similar to those depicted in Figure 2 were built with pre- and post-scaling images.

What the results did show was that the majority of scaling occurred in the back and shoulders where it is easy for the operator to see and operate. In some headings, areas were scaled more than 700 mm in depth without the presence of significant structure or large, loose material confirming that the mine's concerns were indeed valid.

Similarly, the extent of shotcrete or fibrecrete spraying was compared pre- and post-spraying. Again, changes in scenes did not allow direct volumetric comparisons. Heat maps were employed to analyse the differences. In places, the shotcrete or fibrecrete was over 400 mm thick. Such a thickness is of no benefit to the overall ground support regime, especially where rock bolting is used – bolts will be less effective as they are not as deeply embedded into the surrounding rock mass. These results gave impetus for the mine to further investigate this process.

Electronic initiation in perimeter holes

An inherent problem with pyrotechnic initiation is timing scatter. Scatter is the variability in timing from the preset delay. Not only is scatter unpredictable, it can result in out-of-sequence firing (especially in the longer delays used in underground development mining). The introduction of precision timing through the addition of electronic initiation, which in this instance was SmartShot®, was expected to introduce consistency in the results and provide more predictable outcomes. A similar approach was taken by Kovacs (2014).

Results from the introduction of precision timing were immediate (see Figure 3), with full half barrels visible. Overbreak percentages immediately came down and consistency improved. Average overbreak when electronic initiation was introduced into the perimeter holes dropped to 4.5 per cent. This improvement was generated in a short space of time (only four headings) and gave a high level of confidence in the method and thus enabled buy-in from stakeholders to continue.

FIG 3 – Results of perimeter control using string loading and electronic initiation.

Smooth perimeters and the development mining cycle

Prominent half barrels don't necessarily indicate that the heading has been blasted to design. It only reveals that the ground has broken to where it has been drilled. Control of drilling is a major factor in blasting and conforming to design.

Smooth perimeter profiles with minimal overbreak not only improves drive and pillar stability, they also provide potential to optimise the overall development mining cycle.

A typical development mining cycle could resemble that shown in Figure 4.

Over-scaling is not encouraged when half barrels are clearly visible around the perimeter, furthermore, options to minimise mechanical scaling and utilise hydro scaling are possible. In doing so, the following benefits to the overall development cycle may be derived:

- ability to utilise mechanical scaling equipment elsewhere when scaling is undertaken with a jumbo (eg boring, bolting)
- potential to remove equipment
- load haul dump (LHD) units are not generally required for clean up as less material is scaled
- fewer equipment movements, thus allowing greater productivity.

Hydro-scaling was attempted on a number of headings with good results; however, feedback was provided that the bolting cycle was slightly longer (20 minutes, based on three headings) and was thus suspended. A greater sample size for this would have no doubt provided a better understanding on the value of hydro scaling.

Scaling has a large impact on the development cycle downstream. As mentioned, smooth perimeter profiles will reduce the need for scaling and not encourage over-scaling. Practices such as over-scaling lead to increased spraying of shotcrete or fibrecrete where operators attempt to 'fill in the holes' from the blasting and scaling process in order to deliver a smooth profile. This is a rather costly process that can be avoided when the perimeter profile is presented in a better condition to the downstream processes.

Whether the ground support standards involves bolts and/or cables, presenting the drive to this process in the best possible condition allows this process to be completed in a timely manner with minimal broken or loose ground to bore through. There is also the option to review the overall ground support standards and potentially further optimise it. Ground support is a considerable cost in underground mining and any opportunity to review these standards after the establishment of better drive conditions should be taken.

Hence, achieving good perimeter control has a positive impact on the development mining cycle.

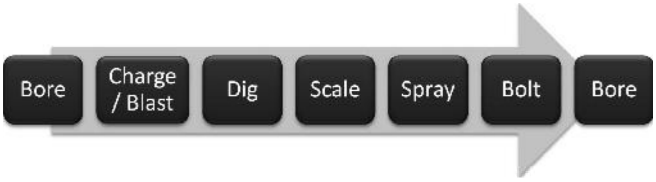

FIG 4 – Typical development mining cycle.

FULL FACE ELECTRONIC INITIATION

Concurrent to the perimeter control phase of the project, benchmarking of full face electronics was being conducted. The benchmarking involved analysing the performance of a face design, which closely resembles the current pyrotechnic face design. This benchmarking provided further overbreak data with precision timing in perimeter holes. Overbreak for the benchmark headings averaged approximately six per cent (the figure would have been lower except that a value of 17 per cent was obtained on a heading that showed prominent half barrels signifying that the heading was drilled outside of design).

During this section of the project, average overbreak through the use of electronic detonators in perimeter holes had reduced to less than five per cent.

DRILL AND CHARGE DESIGNS USING ELECTRONIC INITIATION

The project now entered the fine-tuning phase with the optimisation of drill and charge designs. The aim of this phase was to push the limit of the design by removing redundancy. The objective was to remove blastholes whilst maintaining full advance, fragmentation and any gains made in the reduction of overbreak. A summary of the design changes are shown in Table 3.

Between pyrotechnic and electronic benchmark design changes, the difference in blast performance was insignificant indicating there was still some redundancy in the design. The following iterations in designs 1–5 pushed the design to the absolute limit in design 3 where a total of 13 holes were removed (including one reamer) when compared to the current pyrotechnic design.

Design number 5 gave consistent results in relation to fragmentation, advance and perimeter control, showing the conservativeness of the initial electronic design – the removal of seven holes (including one reamer) and a drop in powder factor of over 13 per cent. Should the mine have converted to electronic initiation in development, this design would have been recommended.

In determining the holes to be omitted from previous designs, factors such as explosive energy distribution (EED) were considered.

EED diagrams were of great assistance when analysing designs. There is a fine line between consistently fragmenting the rock to an acceptable standard, pulling the entire round and protecting the surrounding rock mass. The EED in Figure 5 clearly shows there is considerable energy around the cut as well as the floor; however, explosive energy is a little sparser around the shoulders, backs and walls, thus protecting the perimeter of the drive, whilst ensuring adequate fragmentation.

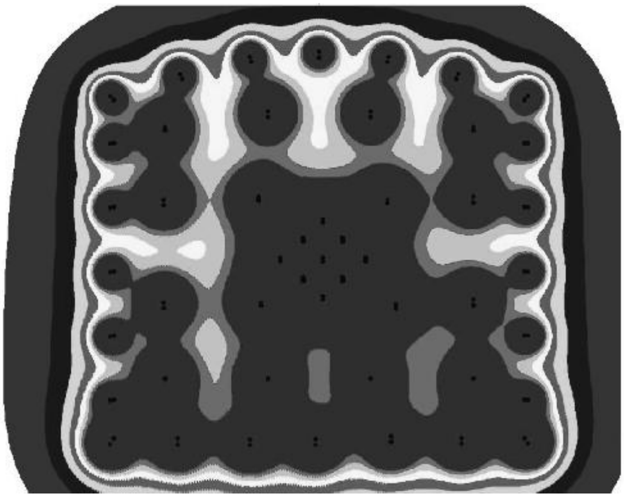

FIG 5 – Explosive energy distribution for the 45 hole design (design 5). Dark shading indicates a higher concentration of explosive energy.

Void ratio, drill accuracy and pushing the limits

The void ratio was lowered considerably with the removal of one reamer hole through the design iterations. A five reamer burn was the standard design for a pyrotechnic firing, having a void ratio of almost 18 per cent.

Not surprisingly, failures in cuts did occur and on occasion faces did freeze. Figure 6 is an example of a face that froze. The figure is an elevation view of the 'as drilled' reamer holes (marked X0-X3 near the design collars) and the design holes (marked Y0-Y3 near the actual toes). There was a 12.5 per cent

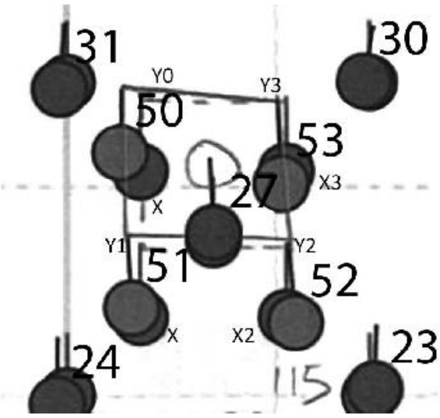

FIG 6 – The 'as drilled' burn of W2. The face was a 43 hole design.

TABLE 3

A summary of the design changes carried out in this phase of the project.

Face design	Total holes	Including reamers	Perimeter holes	Perimeter holes removed	Face holes	Face holes removed	Explosive kg/face	Powder factor (kg/t)	Powder factor reduction (%)
Pyrotechnics	53	58	25		28		514	1.43	
Benchmark elect.	51	56	25	0	26	2	481	1.34	-6.5
1	48	52	22	3	26	2	4623	1.29	-10.0
2	46	50	21	4	25	3	446	1.24	-13.3
3	41	45	20	5	21	7	389	1.08	-24.3
4	43	46	23	2	19	9	384	1.07	-25.2
5	45	49	23	2	20	6	418	1.16	-18.6

increase in cut area due to drilling. This coupled with the shot hole also not being drilled to design (indicated by the pencilled circle) resulted in the cut freezing.

The lowering of the void ratio removed redundancy in the design and placed a larger emphasis on drill accuracy.

With respect to the perimeter hole designs, there is not a lot of redundancy overall. To achieve a smooth perimeter, it is not possible to remove many holes without increasing the powder factor (eg fully coupled charges). Furthermore, when perimeter holes are removed and drill accuracy is not maintained, holes diverge and/or converge resulting in large perimeter areas without any charge, thus resulting in rough profiles. The removal of perimeter holes does have the positive of time saving during boring; however, any adverse results from the blast far outweigh the positives.

It is recommended to use caution when removing perimeter holes in design optimisation processes. Any inaccuracies in drilling or sloppy charging practices will inevitably result in poor profiles.

Pushing design boundaries with pyrotechnic initiation is possible but often the results are inconsistent as the detonation sequence and subsequent availability of the required void cannot be guaranteed.

Drilled versus blasted overbreak

A comparison of drilled and blasted overbreak was completed for full face electronics headings where sufficient data allowed, with the analysis conducted being similar to that for pyrotechnic benchmarking in Table 2. The results of the comparison are in Table 4.

The sample sizes for pyrotechnic and electronic initiation are similar, although the difference between drill and blasted overbreak is smaller for electronics and has a narrower spread – indicating more consistent blast results.

Consistent with the pyrotechnic benchmarking phase, heat maps were created and an example is shown in Figure 7. It is evident that the results are more consistent – repeatable – when electronic initiation is used in perimeter holes, even in poor ground conditions.

Optimisation and the development mining cycle

Face design optimisation plays a part in the development mining cycle. Timing optimisation through the introduction of precision timing can enhance muck pile profile and fragmentation for LHD units. For example, fast timing can throw the blasted rock a long way down the drive, resulting in a loose, flat muck pile. However, this may require more pushing up by the LHD and lead to tyre damage (which was witnessed in some cases). Does an optimal shape actually exist? There are factors such as the following which may influence what an optimal shape may be:

TABLE 4
Drilled versus blasted overbreak for selected electronic headings where sufficient data was available.

Heading	Overbreak (drilled) (%)	Blasted overbreak (%)	Δ (%)
216 W 2	11.6	12.4	0.8
216 W 4	10.8	5.5	-5.3
226 N	-11.4	-5.9	5.5
226 N	-8.2	-2.2	6.0
226 N	-3.4	0.0	3.4
228 N	1.6	1.6	0.0
228 N	-0.7	5.7	6.4

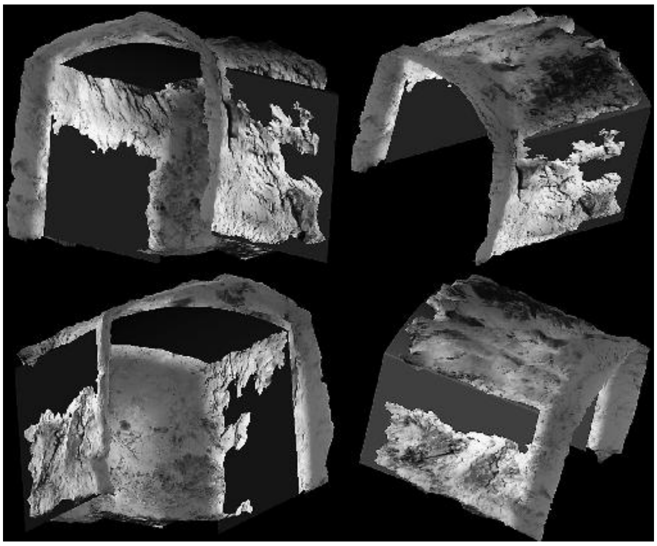

FIG 7 – A series of images showing design versus actual (16 E). Blasts were conducted utilising electronic initiation.

- operator preference and mood
- LHD and drive size
- power of LHD units (new versus old)
- tramming distance to dump point
- floor conditions
- fragmentation considerations.

A reduction in the number of face holes drilled delivers the benefit of boring out the face in a shorter time frame. Through the implementation of face designs 3 and 4 (Table 3), boring time was reduced by approximately 45 minutes per face.

Fewer holes also mean that charging operations are completed quicker and with less explosives. Significant savings to operations are possible through development optimisation with the potential existing for equipment to be removed from service.

VALUE

Good perimeter control and development design optimisation can deliver long-life pillars and drives, thus ensuring safety and longevity which enables consistent production. It also carries a financial benefit, not only in the present, but also in the future where rehabilitation costs may be avoided.

Overbreak can be a very costly problem where excess material is required to be moved out of the mine via LHDs/trucks/conveyors or shafts. Thus, production is affected as critical machinery and infrastructure is being utilised to remove this excess material. In the case of trucking, where decline truck traffic is also taken into account, overbreak begins to affect *all* other aspects of the mining process.

Prior to the commencement of the project, the mine indicated that their baseline overbreak was approximately 18 per cent. Through the efforts in implementing and maintaining good perimeter control practices via string loading and precision timing, overbreak was able to be sustainably reduced to 4.5 per cent. Furthermore:

- A reduction in baseline overbreak of 13.6 per cent meant that the mine was not required to remove 113 000 excess t of material per month (based on development rates of just over 1000 m/month).

- Maintaining overbreak at 4.4 per cent led to a reduction of load and haul costs of almost $172 per development metre. On an annualised basis, this is a saving in load and haulage costs in excess of $2 M.
- Reducing the average shotcrete or fibrecrete thickness through smoother profiles led to a cost saving in the sprayed material of almost $3 M/a.
- When analysing the financial benefits of optimising full face designs with electronic initiation, cost savings from hole reduction are in excess of $1 M/a (based on drill and explosive cost savings).

Overall, potential savings could be in the region of $6.5 M/a (Table 5).

TABLE 5

Value derived from development optimisation practices.

Aspect	Saving ($M)
Load and haul	2.1
Spray	3.0
Charge and fire	1.2
Advance	0.2
TOTAL	6.5

Unfortunately, advance benefits could not be quantified when full face electronic initiation was implemented. The potential for a hefty financial benefit from increased advance still exists if the necessary work can be completed and validated. For example, just a 0.1 m increase in average advance has benefits of $160 000/a.

Whilst the upfront costs do increase, the quantum of cost saving is several times larger.

SUMMARY, CONCLUSIONS AND FURTHER WORK

Drive and pillar stability is crucial to ensure mine infrastructure has the required longevity. With safety being paramount, stability of mine infrastructure ensures safety and a comfortable work environment for personnel.

Perimeter control is relatively quick and easy to implement, it also delivers the most value in a short time frame. Quality assurance and control is critical in maintaining the gains made in delivering overbreak reduction. Regular audits and compliance KPIs are encouraged. As witnessed, when there is control over charging and timing, blasted overbreak can essentially be eliminated and the heading will break in close proximity to the 'as drilled' location of the holes. Unfortunately, pyrotechnic initiation provides inconsistent results due to the delay scatter and perimeter control performance cannot always be guaranteed in the ground conditions encountered.

Further work is recommended to prove the potential of full face electronic initiation in terms of advance, with trials being conducted over a longer term to enable the filtering of inconsistent data.

Along, with advance, value drivers such as those listed as follows could be further pursued:

- hydro-scaling
- ground support review
- optimal muck pile profile/fragmentation
- development cycle/equipment optimisation
- ventilation.

Optimising this has considerable potential in producing further value and efficiencies in the development mining cycle.

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