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Opening sublevel cave slot drifts at Diavik Diamond Mine

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Abstract

Sublevel retreat (SLR) and sublevel cave (SLC) production levels require an initial void for production drifts to begin blasting into. Slot drifts are commonly developed perpendicular to production drifts and used to establish a free face using uphole drilling and blasting. Unlike in open stoping, these openings are filled with caved or blasted material, requiring choke blasting. The overall approach of establishing these slot drifts is relatively straightforward from a high level, operationally there are many options to achieve this. It is important to understand the impact these options have on safety, ore recovery, and production rates.

Diavik Diamond Mine uses SLR/SLC methods to mine two ore bodies. During the last 10 years of production, seven different methods have been used to open and establish slots in SLR/SLC levels. This paper examines the various methods used and their suitability to different situations. The methods used at Diavik are heavily dependent on ground conditions and what the ore quality will allow. The work completed at Diavik may offer a starting point for other mines beginning or changing an SLR or SLC.

Keywords: *sublevel cave, sublevel retreat, slot, blasting*

1 Introduction

Diavik Diamond Mine is located on Lac de Gras in the Northwest Territories, Canada. It is accessible only by air for most of the year and by winter road for two months of the year. Operations began in 2003, initially mining kimberlite pipes using open pit methods, three of which have transitioned to underground mining upon completion of the pits. All kimberlite pipes that have been mined at Diavik were located under the lake; water retention dykes were constructed and the pools that remained inside dyke enclosures dewatered to allow mining of the pipes. The full transition to underground mining occurred in 2012; a fourth pipe subsequently began open pit production in 2018. Mining is planned to complete in 2025 (Yip & Pollock 2017).

Initial studies for underground mining selected blasthole open stoping (BHS) and underhand cut-and-fill (UCAF) to be used as mining methods. During open pit mining and underground construction, the methods were re-evaluated, and BHS was maintained for the A154N orebody while sublevel retreat (SLR) was selected for the A418 and A154S ore bodies (Lewis et al. 2018).

Given the extremely good quality granite host rock, as the SLR front is drawn deeper, the granite has not substantially caved, leaving a crater exposed to surface with unsupported high walls of over 300 m in height. Over time, relatively minor sloughing (compared with the overall opening) of the highwall has caused broken waste to overlay the ore blanket (Jakubec et al. 2004). This has necessitated the use of draw control methods similar to what is used in a sublevel cave (SLC) to regulate grade. For this reason, Diavik could be considered both an SLR and SLC mine.

2 Level slotting in SLR/SLC

Slotting of SLR and SLC levels has drastic impacts on the productivity of the level. Ineffective opening of slots can lead to ore loss, production delays, bridging, back-break, and requirements for re-slotting or recovery drilling. Conversely, slots which are opened quickly and efficiently allow immediate access to ore, additional access to headings, and high production rates (Bull & Page 2000). The general process of opening slot drifts in SLC levels is regularly described in explanations of the method (Bull & Page 2000; Di Giovinazzo & Singh 2010; Kosowan 1999; Power & Just 2008), however detailed information on the process is difficult to find.

2.1 Established slotting methods

Four slotting methods have been described in more detail by Page & Bull (2001):

1. Individual: No slot drift is present at the far end of production drifts; each production drift uses its own raise to be opened.
2. Continuous: A slot drift is developed perpendicular to production drifts at the far side of the contact; a single raise is blasted at one end of the slot drift, and upholes are blasted into the raise along the slot drift.
3. Slashing along axis: No raise is used; each production drift uses fanned holes to break down into the production drift.
4. Slashing perpendicular: Fanned holes are used to break down into the slot drift.

These are illustrated in Figure 1.

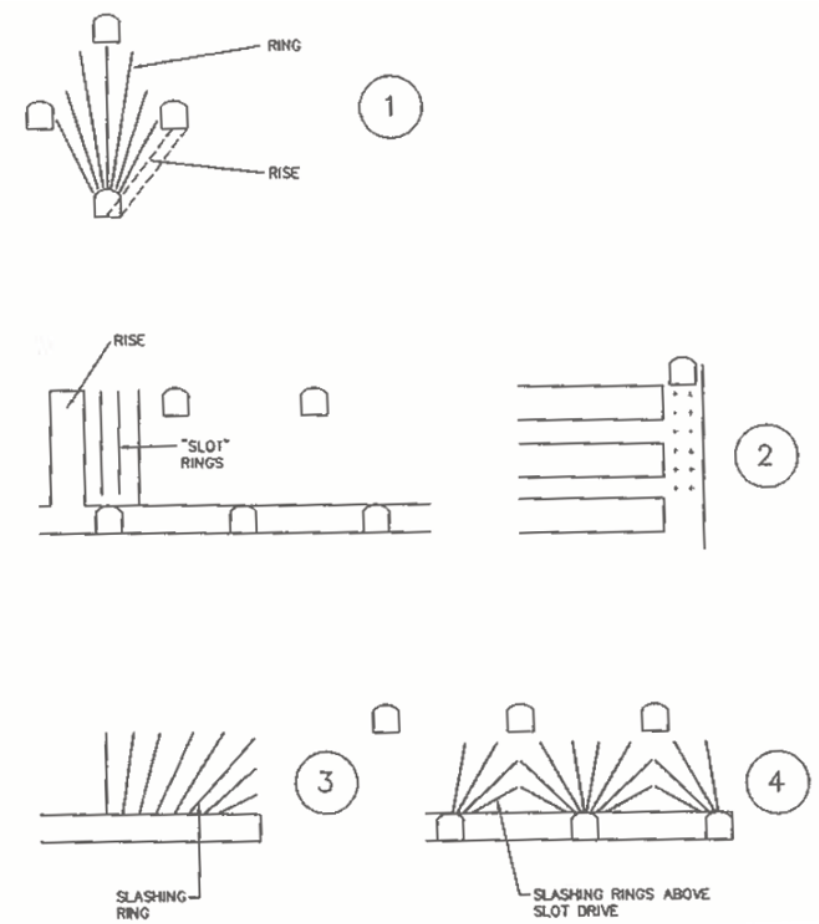

Figure 1 Slot types (Page & Bull 2001)

2.2 Production delays when opening slots

The primary delay involved with opening slot drifts in an SLR/SLC is the failure to open the slot to full height. If the slot is not established, production drifts are unable to be blasted properly as they lack the necessary free face to blast into. Recovery drilling is frequently required in these instances.

Recovery drilling involves drilling into ground which has been blasted but has not broken effectively. The causes of bridging, freezing, and incomplete slots are discussed in Bull & Page (2000); unbroken toes and compacted broken ore require intervention to re-establish the area, ensuring ore is recovered and the connection has been made to the overlying blanket or cave.

Drilling into or in proximity to previously blasted ground introduces the risk of drilling into misfired explosives and causing an unintended detonation. To protect underground operators, remote controlled drilling is carried out at Diavik using multiple cameras, allowing the operator to control the drilling from a safe distance in an enclosed, moveable cabin (Lewis et al. 2018). This remote drilling process requires exclusion zones to be established, closing, and barricading of sections of the level.

Drilling through previously blasted ground creates an additional safety risk which must be managed. It requires area closures and additional work to set up remote drilling causing substantial delays in the mining cycle. When recovery drilling is required, production rates are reduced, and ore release may be delayed.

3 Level slotting methods at Diavik

Variations of the individual and continuous slotting methods have been attempted at Diavik to address various deficiencies in preceding methods over time. These designs frequently build on the previous attempt. The priorities at Diavik for selecting the slot opening method are:

1. Safety of operators.
2. Ore recovery.
3. Ease of opening/recovery drilling avoidance.

Slots are established using an initial inverse raise, blasted in a single shot. Initial inverse raises blasted at Diavik use a 762 mm diameter Machines Roger V30 reamer hole drilled with a Cubex Orion drill. Blastholes were historically drilled at 102 mm diameter using Simba M6 production drills, however, more recently blastholes have been drilled at 89 mm diameter using Simba M7 production drills. This has been done to reduce the powder factor and reduce the negative effects of choke blasting.

Blasting in the SLR/SLC is exclusively performed using electronic detonators. During ring blasting, one ring is fired at a time (when not mass or raise blasting). An additional ring is pre-loaded and pre-primed before blasting, always maintaining two pre-loaded/primed rings. Pre-priming is always completed with electronic detonators.

Illustrations in the subsequent sections are based on Diavik's standard 5 m high, 5 m wide, arched profile standard ore development. Level intervals illustrated are based on Diavik's 25 m vertical level spacing.

3.1 Intersection mass blasts

Initially, SLR levels were developed by driving production drifts across the orebody and then developing the slot drift by connecting the end of each drift. In order to develop the slot drift at approximately 90°, jumbo slashing was required resulting in intersections that were frequently in excess of 9 m.

While an 'intersection ring-by-ring' (Section 3.2) was initially considered, it was not used due to geotechnical safety concerns. A brow which is partially through an intersection has areas which are susceptible to localised failure. Once disconnected from the far side of the drift, there is no arching and low stress areas can cause the weak kimberlite to fail where blasting crews, drillers, and loader operators could be exposed.

It was felt that the safest method to advance the slot drift through these intersections was as a mass blast, firing 3–5 rings at once depending on the geometry of the intersection (Figures 2 and 3). While this avoided the geotechnical concern, the method rarely worked as planned. The large amount of blasted material firing against a muckpile usually bridged requiring recovery drilling and blasted ore was rarely recovered, leading to ore loss along the contact.

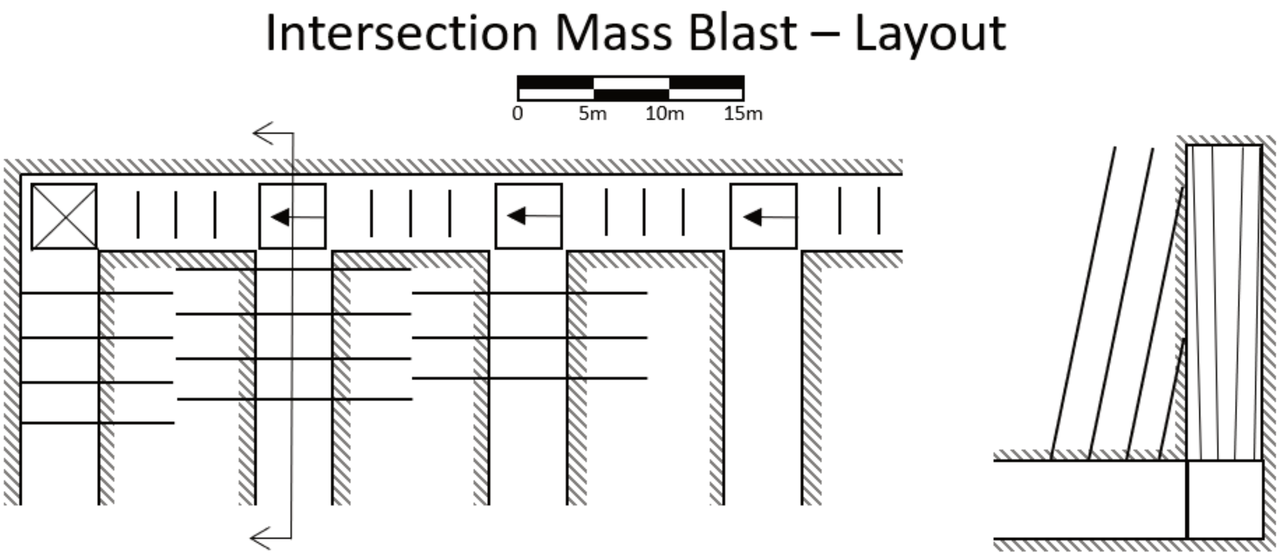

Figure 2 Layout of intersection mass blast plan view and section view

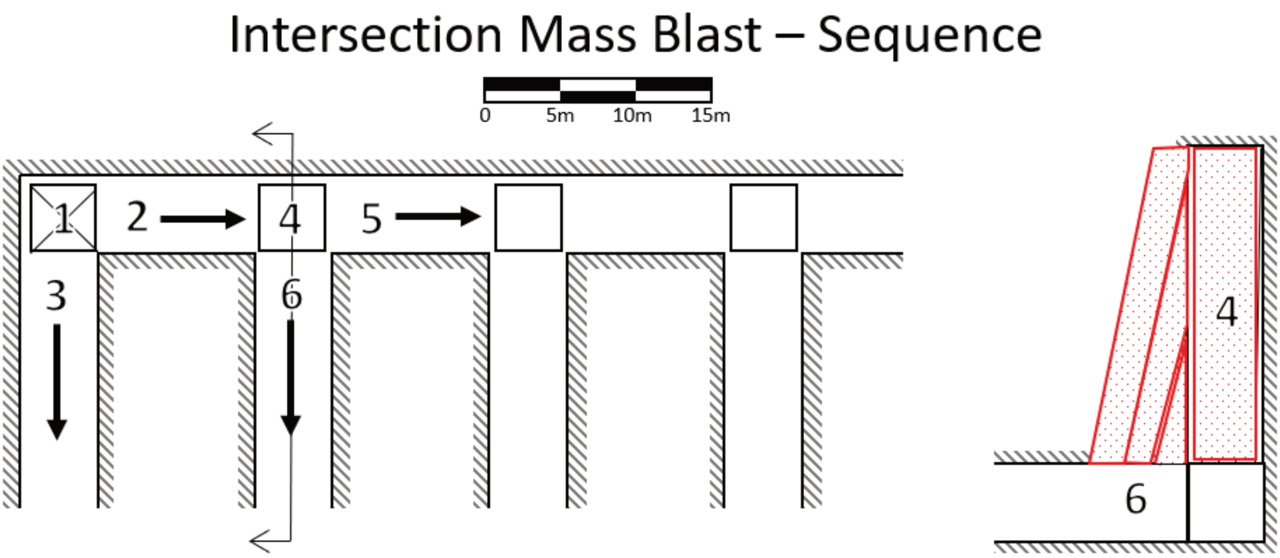

Figure 3 Sequence of intersection mass blast plan view and section view

A slight variation of this method was also used, where the slot drift was developed from the two outer drifts and then production drifts broken through once the slot drift was complete. The resulting smaller intersection from developing the production drifts into an existing slot drift require fewer rings firing in the intersection blast as the intersection was smaller (generally closer to 7 m in diameter). These were slightly more effective; they were less likely to bridge and when they did bridge would require less recovery drilling.

Larger intersections would typically require blasting 4–5 rings at once where the smaller intersections would typically require blasting 2–3 rings at once. The difference in intersection size is illustrated in Figures 4 and 5. While the difference appears minimal, it did allow at least one less ring to be required in the mass blast. The smaller intersections had the added benefit of reduced long support and reduced risk associated with larger intersections in weak ground.

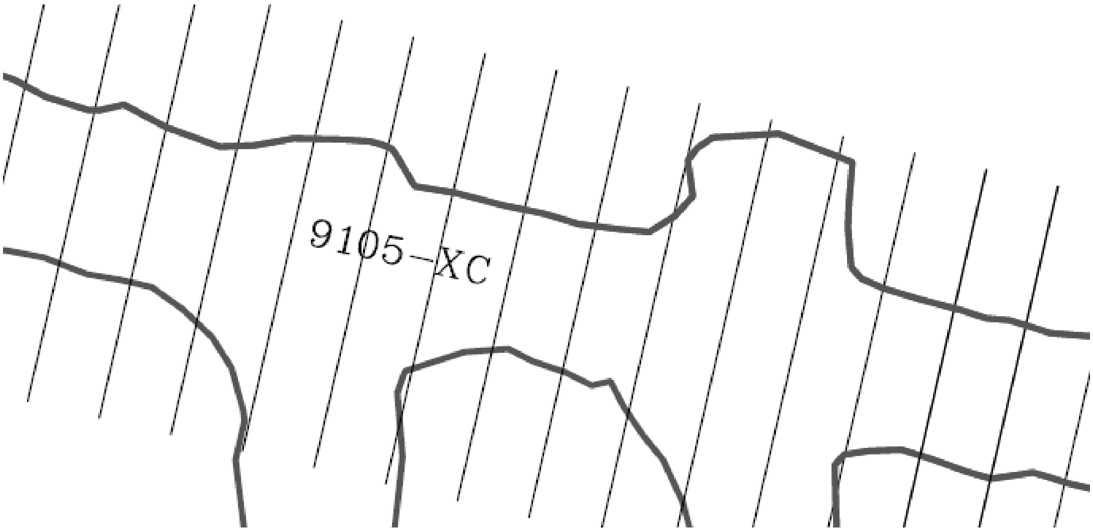

Figure 4 Larger intersection examples in plan view with slot drift rings

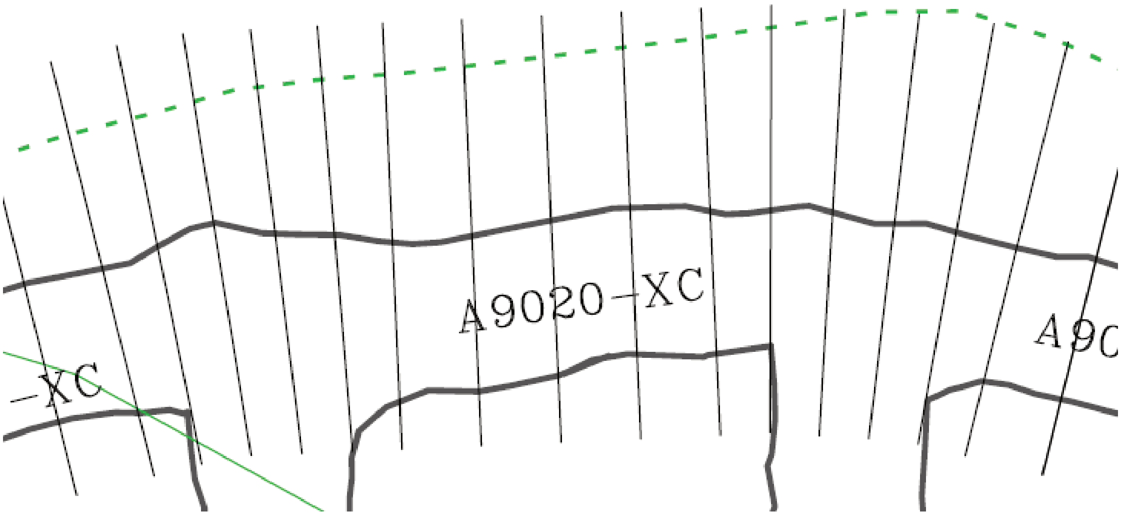

Figure 5 Smaller intersection examples in plan view with slot drift rings

3.2 Intersection ring-by-ring

Intersection mass blasting frequently bridged due to a lack of void. Single ring blasts in the slot drift outside of the intersections were generally successful. If single ring blasts could be undertaken, opening slot drifts would require less recovery blasting and increase ore recovery (Figure 6).

To overcome the risk of localised failures described in Section 3.1, additional ground support was used successfully in the orebody with more competent ground. Initially, 6 m long connectable Pm24 Swellex bolts were used; these were subsequently replaced by 5 m long cement grouted cable bolts. Each ring of secondary support is installed between blast rings at 80° from horizontal to run parallel to the dumped blasthole rings. The change to cable bolts was required after it became apparent that bolts were undergoing shear stress.

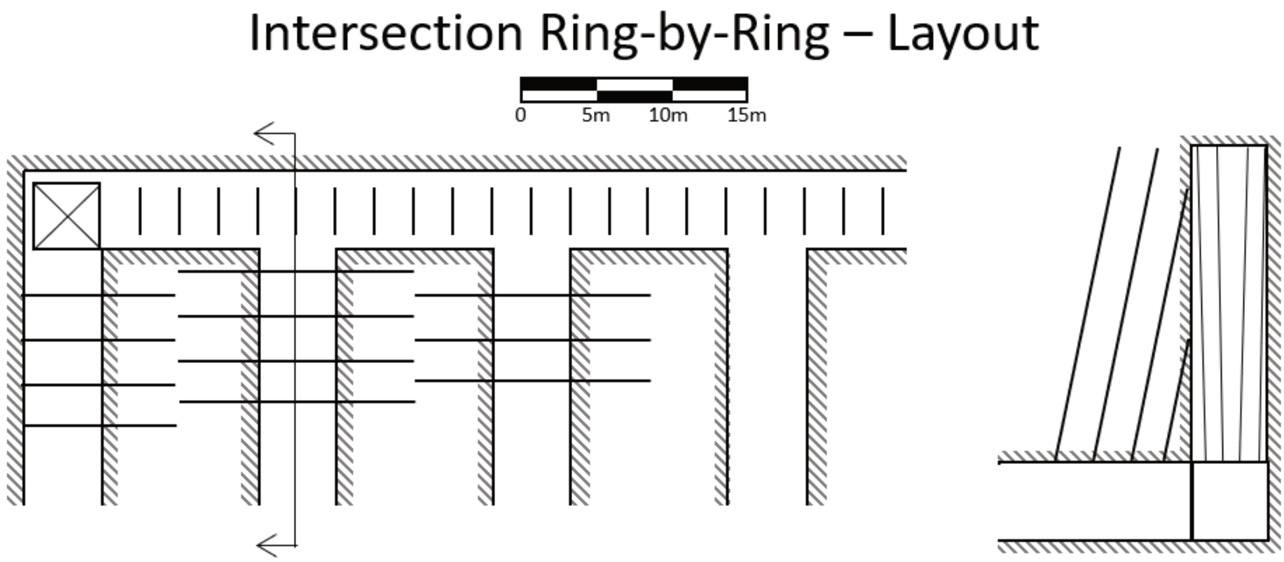

Figure 6 Layout of intersection ring-by-ring plan view and section view

Given the inconsistency in block size and jointing in kimberlite, unconfined compressive strength (UCS) is used at Diavik to differentiate kimberlite strength (Diavik Diamond Mine 2021). The ground in the A418 is poorer quality than in the A154S (Table 1). Low stress conditions in weak kimberlite have been found to cause rock to slough away around rockbolts at Diavik. Due to the low stress conditions near open brows, it was felt that long support would be ineffective in preventing localised failures near brows in the A418 orebody. For this reason, intersection ring-by-ring was never attempted in the A418 orebody but is the preferred method in the A154S orebody.

Table 1 Rock quality of orebodies (Yip & Pollock 2017)

Orebody	Unconfined compressive strength
A418	3–28 MPa
A154S	20–70 MPa

3.3 Slot drift, non-breakthrough

While intersection ring-by-ring blasting proved effective in A154S, the A418 orebody was still using intersection mass blasts. To blast ring-by-ring along the slot drift and avoid blasting through large intersections, slot drifts began blasting without breaking through the production drifts into the slot drift (Figures 7 and 8). Production drifts were developed toward the slot drift and left a pillar. Fanned rings were then drilled toward the slot drift and blasted once the slot drift had progressed past the production drift.

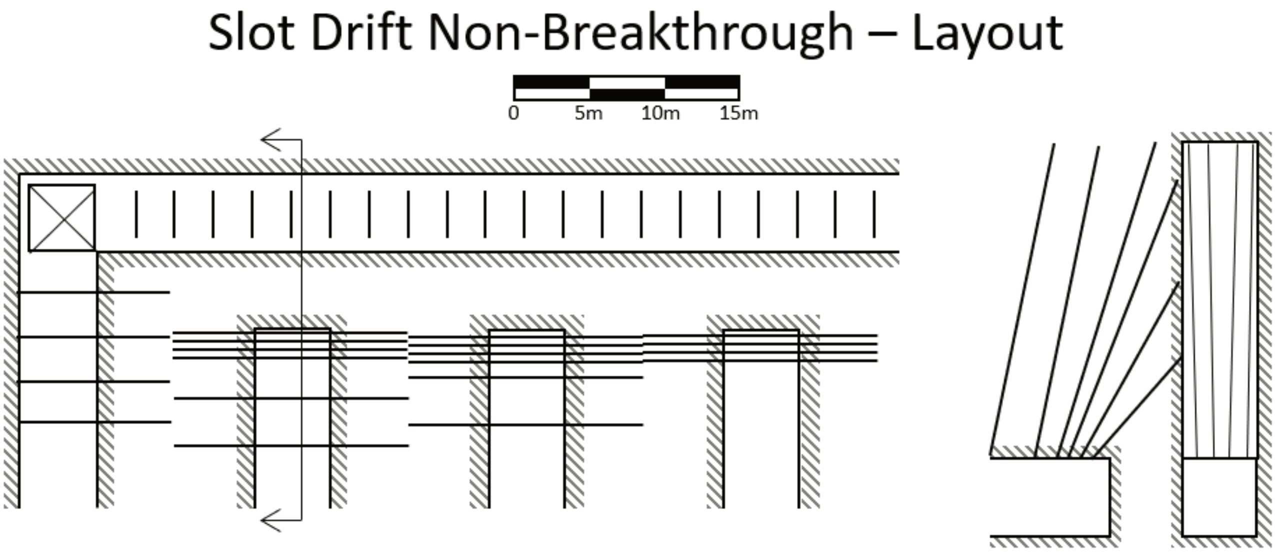

Figure 7 Layout of slot drift, non-breakthrough plan view and section view

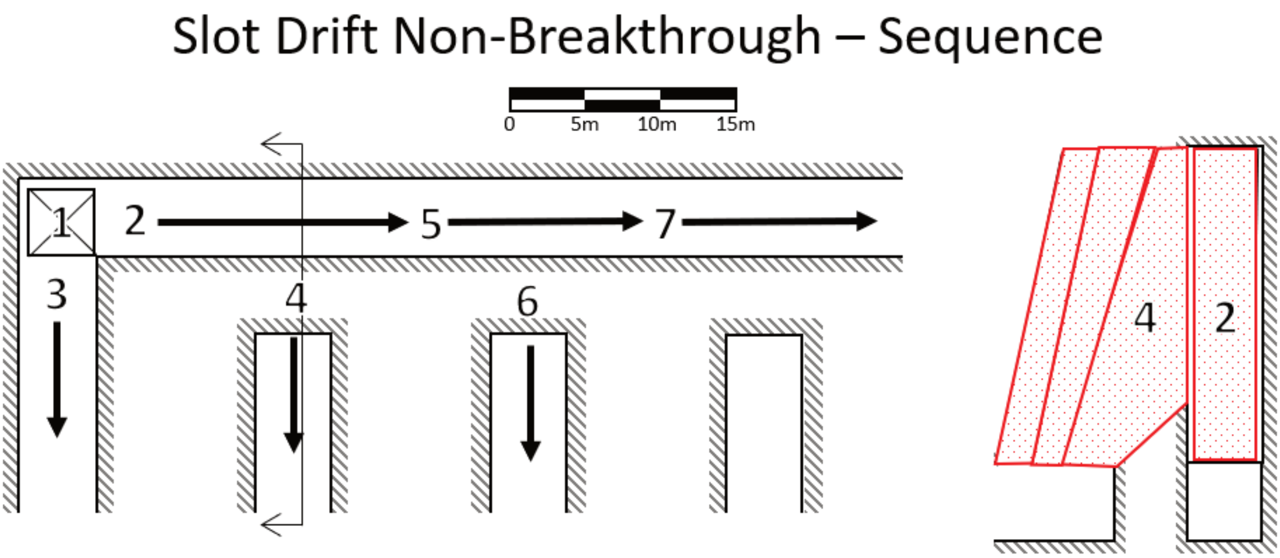

Figure 8 Sequence of slot drift, non-breakthrough plan view and section view

While this method was more successful at establishing the slot drift, it introduced additional recovery blasting at the beginning of the production drift mining. The fan blast was using the slot drift as void; however, the blasting direction of the initial ring was toward the pillar between the drifts. Insufficient void propagated for the entire blast. This method was found to be ineffective and was discontinued.

3.4 Slot drift, post-breakthrough

In order to remedy the problem of insufficient void for the fan blast, a post-breakthrough method was used. Using this method, a slot drift was progressed past the production drift, the fanned longholes were drilled and a long development round was blasted, connecting the production drift and the slot drift. As the fanned holes were pre-drilled and loaded, personnel access was not required in the new drift round, and it was left unsupported. Once the breakthrough round was mucked out, the fanned rings drilled above toward the slot drift were blasted, establishing the production drift (Figures 9 and 10).

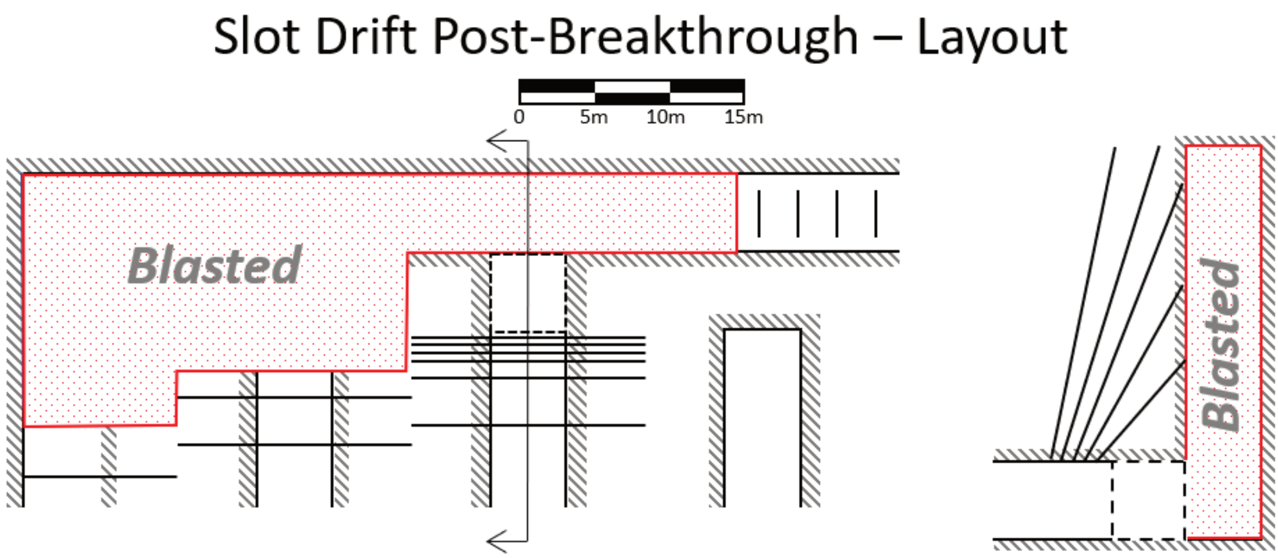

Figure 9 Layout of slot drift, post-breakthrough plan view and section view

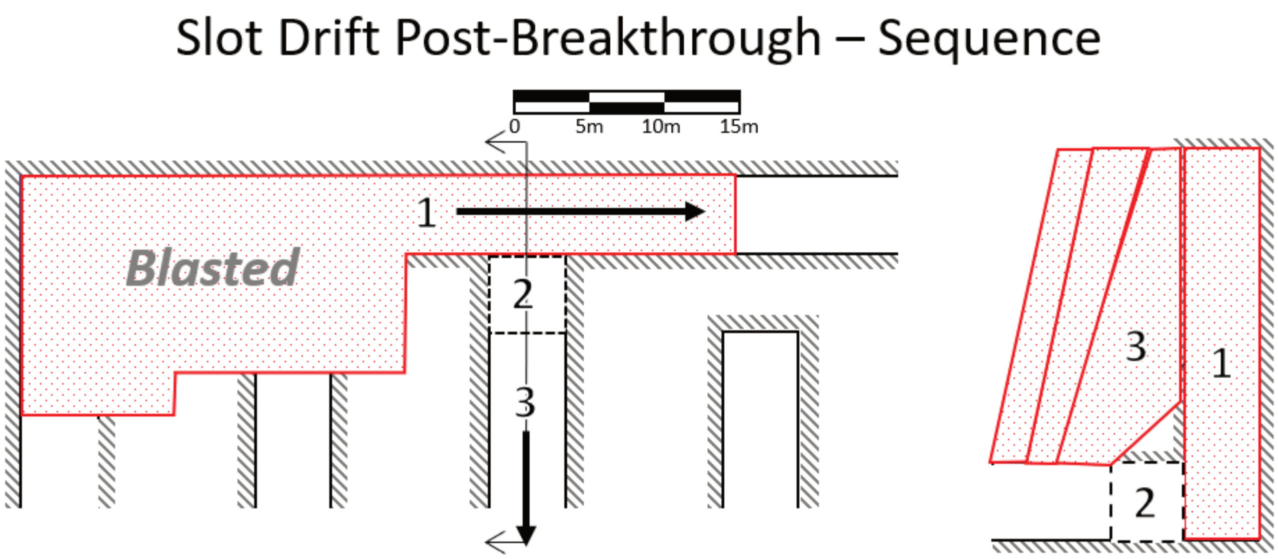

Figure 10 Sequence of slot drift, post-breakthrough plan view and section view

This method has proven effective in opening the slot drift and establishing production drifts and has become the standard method used in the A418 orebody.

3.5 Individual full width

In earlier iterations, individual type slots were tested as well, similar to those described in Page & Bull (2001). This iteration was another attempt to open the slots without requiring blasting through intersections. Individual full width slots when blasted would theoretically establish the slot drift as illustrated in Figure 11. However, in practice, the limited void available in the drift below generally led to bridging in the upper part of the slot, requiring recovery drilling.

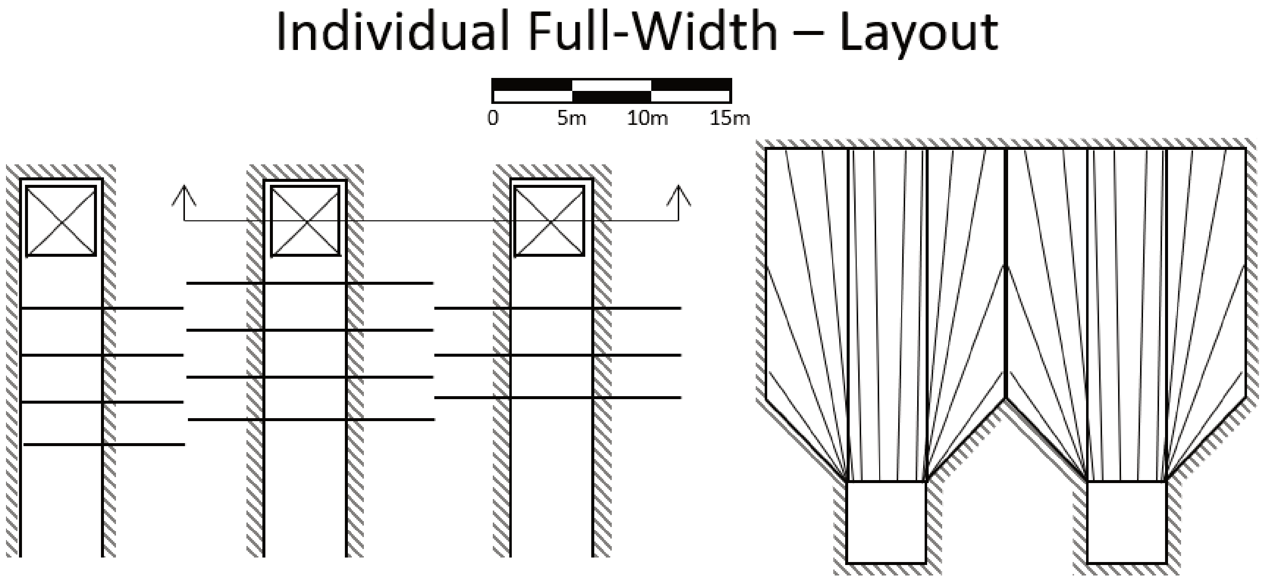

Figure 11 Layout of individual full width plan view and section view

3.6 Individual

In an attempt to reduce bridging and recovery drilling, vertical individual slots were used (Figure 12). This type blasted with 25–30% void ratios and would generally pull to full length. However, they did not open the slot to full width. In order to open production drifts to full width, production rings were designed to gradually widen from 5 to 15 m over multiple rings. This method reduced recovery drilling, however there was poor ore recovery on the far side of the orebody. In the SLR method, this ore could potentially be draw on the next level, however there was a delay in draw, uncertainty, and potential for increased dilution to recover this ore.

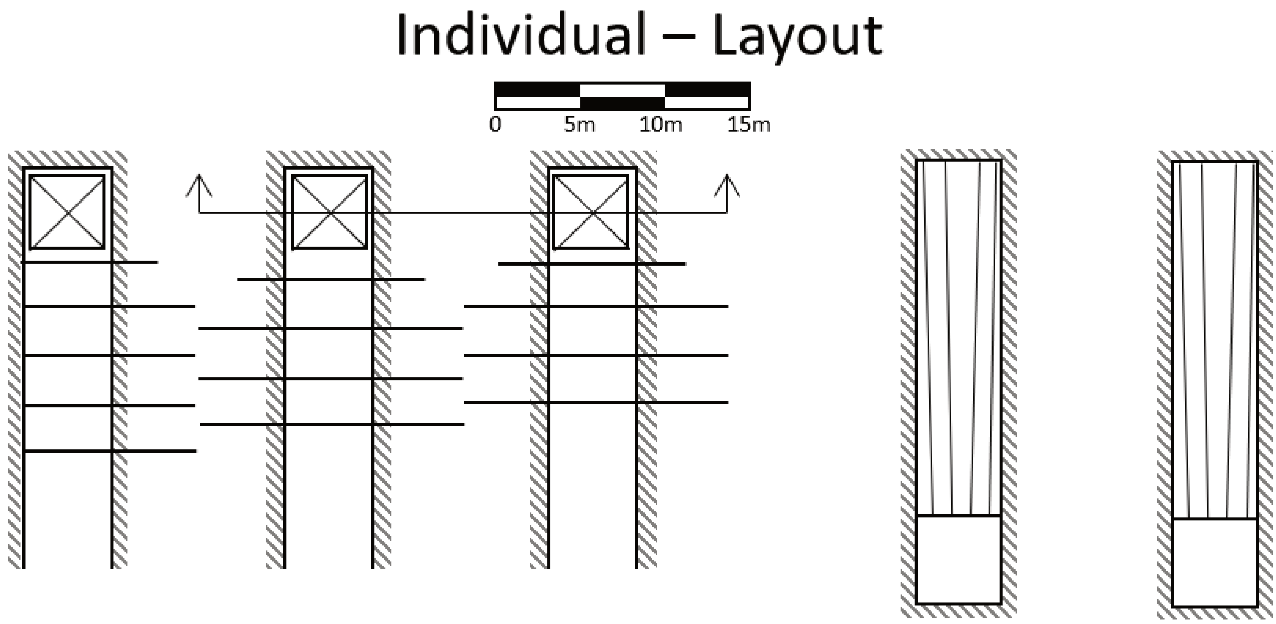

Figure 12 Layout of individual plan view and section view

3.7 Hammerhead

To reduce the requirement for recovery drilling and recover as much ore as possible, the hammerhead method has been proposed. Production drifts are slashed and developed either side. An uphole raise is drilled with vertical rings; the entire hammerhead is then blasted in a single shot (Figures 13 and 14). This method produces adequate void for the individual full width using additional development. It has similarities with the intersection mass blast method, however it slowly opens using the initial void from reamers rather than blasting choked into a muckpile.

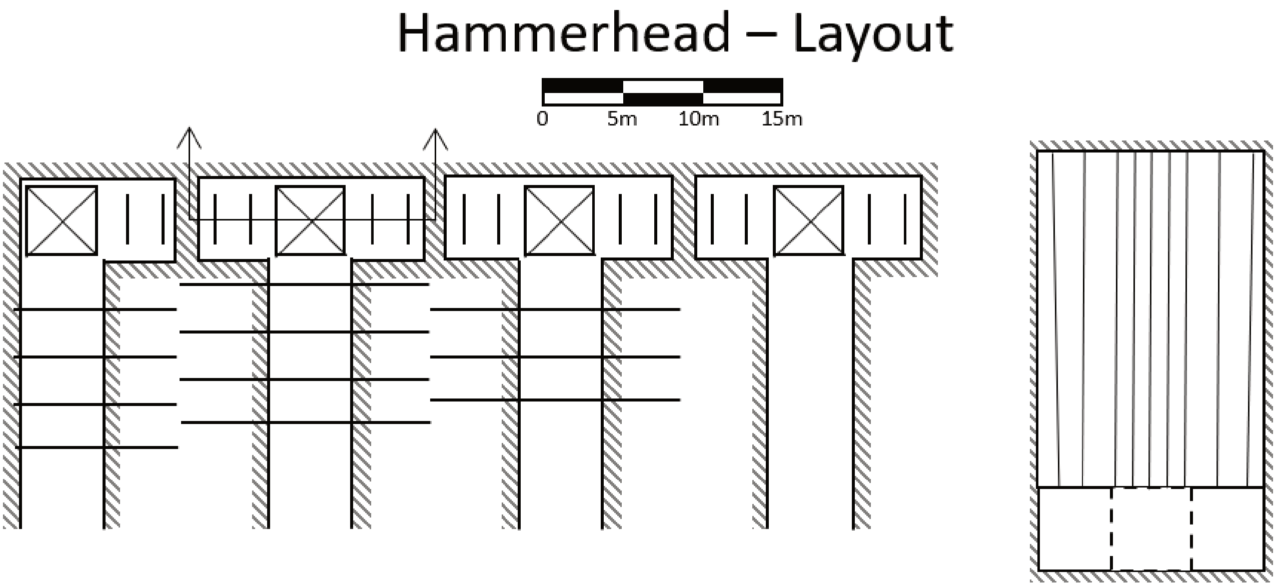

Figure 13 Layout of hammerhead plan view and section view

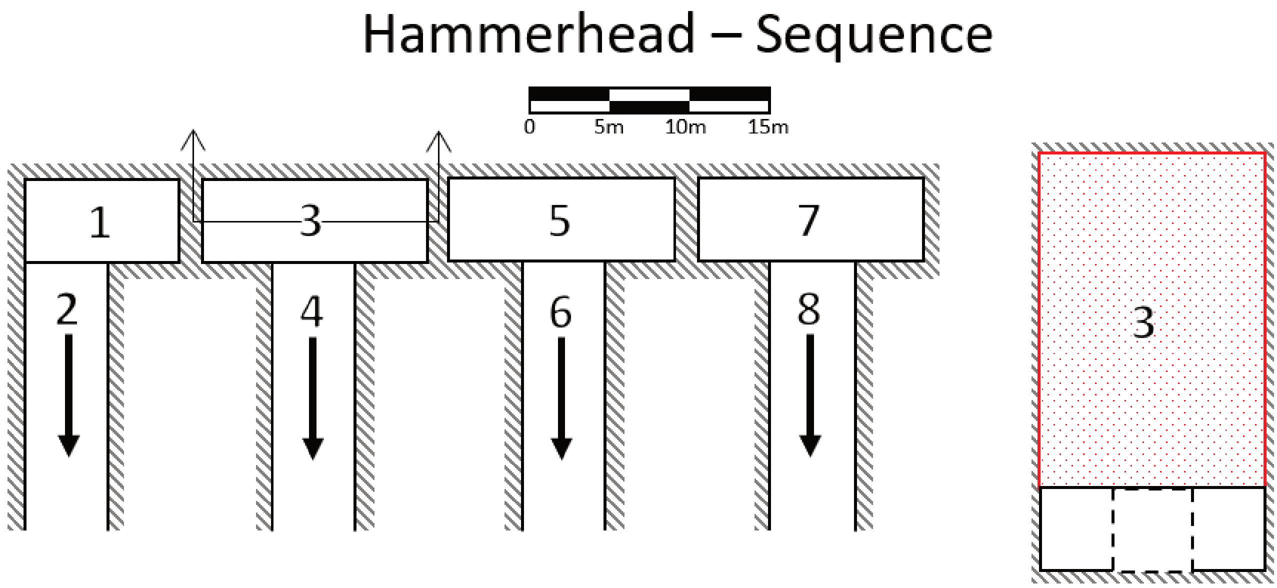

Figure 14 Sequence of hammerhead plan view and section view

At the time of writing, the hammerhead method was planned for a level in the A418 as well as for a single heading in the A154S. These locations had not been drilled or blasted so no results are available yet.

4 Discussion

Slot drift methods are used to establish levels efficiently, allowing for maximum ore recovery. Safety of operators is paramount, and methods are not considered if undue risk to personnel is anticipated. A summary of the methods used at Diavik is illustrated in Table 2.

Intersection ring-by-ring proved to satisfy safety concerns, ore recovery, and ease of opening, only where ground conditions allowed adequate support to protect workers. Compared against the slot drift, post-breakthrough method, was also generally easier from an operational perspective as development could be completed ahead of time, and remote development drilling not required for the post-breakthrough round.

Where ground conditions do not allow an intersection ring-by-ring method, Hammerhead may offer a simple alternative, however it was unproven at Diavik at the time of writing. While the slot drift, post-breakthrough method required additional operational delays and effort, it still produced a safe and predictable method.

Table 2 Summary of slot methods at Diavik

	Safety	Ore recovery	Ease of opening
Intersection mass blasts	Green	Red	Red
Intersection ring-by-ring	Yellow	Green	Green
Slot drift, non-breakthrough	Green	Green	Red
Slot drift, post-breakthrough	Green	Green	Green
Individual full width	Green	Yellow	Red
Individual	Green	Red	Green
Hammerhead	Green	Green	Green

Notes regarding Table 2:

- Colour ranking:
  - Red: Unacceptable/completely ineffective.
  - Yellow: Partially effective.
  - Green: Effective/successful.
- Intersection ring-by-ring was determined to have excessive risk in weaker ground; it was never attempted in A418 which is why safety is marked yellow.
- Individual full width opens the slot drift at the far side of the orebody, however with the recovery blasting that is required, there is still poorer ore recovery which is why ore recovery is marked yellow.
- The Hammerhead method has been planned, however it had not been attempted at the time of writing; the ratings are estimates only.

5 Conclusion

Diavik's path to optimising its slot drift opening kept safety as the principal value. An iterative approach was then taken trialling and refining various methods. Multiple methods are available depending on local conditions to maximise ore recovery and reduce production disruptions. The most successful methods used were intersection ring-by-ring and slot drift, post-breakthrough; results of the hammerhead method were pending at time of writing.

The purpose of this paper has been to share the lessons learned at Diavik to provide options, ideas, and a starting point for other SLR and SLC mines. When beginning a new SLR or SLC, other mines may use experience gained at Diavik as a starting point for slot drift opening methods. Every orebody and mine will encounter unique situations and challenges, however the experience gained at Diavik may allow other operations the ability to skip unsuccessful methods and focus on those which have shown more successful.

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