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Sublevel retreat mining in the subarctic: a case study of the Diavik Diamond Mine

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Abstract

Diavik Diamond Mine is located on the subarctic tundra of the Northwest Territories, Canada, 300 km northeast of Yellowknife. When its first two open pits were exhausted in 2012, it completed the full transition to underground mining. Three orebodies are currently being mined underground using two mining methods: blasthole open stoping and sublevel retreat (SLR). SLR was not an original method as described in the feasibility study. As the pits were mined, the underground project developed, and additional information became available. Over time, it became apparent that SLR would be the optimal method for two of the orebodies.

A great deal has been learnt throughout development and operation of the SLR method at Diavik. This paper examines considerations for ventilation, production drilling and blasting, geotechnical concerns, and operational constraints for SLR mining in the subarctic. It also describes the process for method selection and the overall lessons learned.

Keywords: *sublevel retreat, SLR, arctic, underground*

1 Introduction to Diavik

The kimberlite orebodies of Diavik Diamond Mine were discovered in the early 1990s below Lac de Gras in the Northwest Territories of Canada. The mine is situated on the tundra of the Canadian subarctic on what is locally known as East Island. It is accessible exclusively by air for 10 months of the year. During the months of February and March, an ice road is constructed to ship in the bulk of supplies required for the year. The mine is self-sufficient and has no hard connection to the outside world.

In order to mine below lake level, water retention dikes were constructed around the kimberlite pipes to contain the eventual pits. The first pit, encompassing the A154S and A154N pipes, began production in 2003. As the A154 pit depleted, a second dike was built for the A418 pipe with production from this pit commencing in 2008.

The underground project commenced in 2005, began ore production in 2010, and became the only source of ore upon closure of the first two pits in 2012. A third dike and pit have been constructed for the A21 pipe. The A21 open pit began contributing to ore production in March of 2018. The A21 open pit and underground operations are scheduled to complete in 2023 and 2025 respectively (Yip & Pollock 2017).

2 Sublevel retreat mining method

The SLR mining method is a top-down unsupported method with no backfill. It is similar to sublevel cave mining in function, except the waste rock hanging wall is strong enough to not cave. Rather than subsidence, it leaves a glory hole exposed to surface. Unlike sublevel open benching, blasts are only mucked until cracked to the surface, leaving a blanket of ore to protect against air blasts and rockfalls from the surface (Jakubec et al. 2004). A drawpoint is considered to be cracked once the muck pile no longer touches the brow, leaving the underground drift open to the pit above. The brow is only cracked slightly to prevent unexpected material from entering the drawpoint.

Initially, parallel transverse drifts are driven across the orebody. The far side is blasted using upholes to the former pit floor/surface. Muck is removed until the brow cracks, then further upholes are blasted. This is continued, progressing back towards the access and across the orebody, blasting one ring at a time. A representative long section of SLR mining is illustrated in Figure 1.

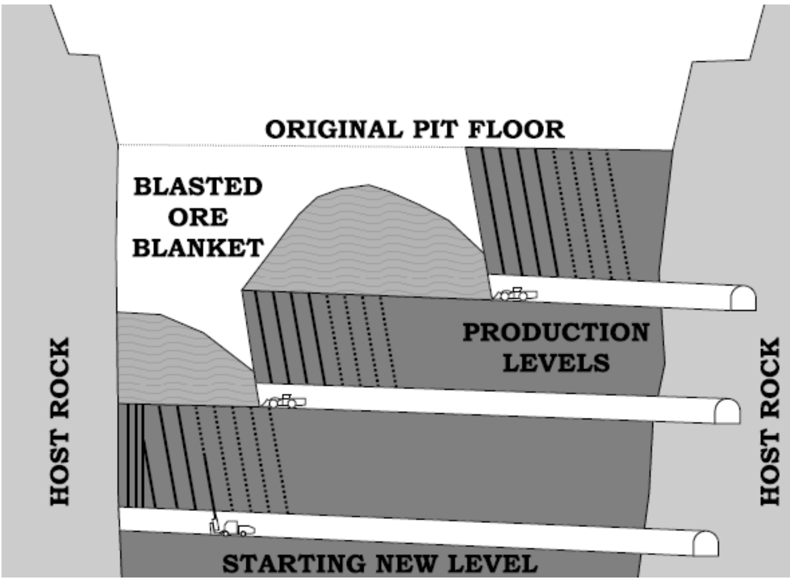

Figure 1 Long section of SLR method

As the level is retreated, the next level below can begin at approximately the same location below where the previous level started. Strong host rock is required to prevent caving. Small-scale host rock failures can occur, requiring that drawpoints are only cracked and not opened to the pit substantially. Figure 2 shows the isometric view of an orebody using the SLR mining method.

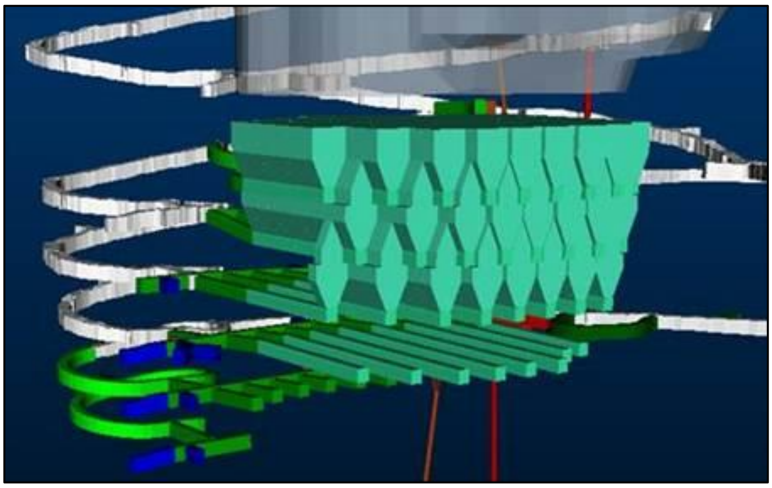

Figure 2 Isometric of pipe (Yip & Pollock 2017)

3 Underground mining method selection process

In the initial feasibility study, blasthole stoping (BHS) and underhand cut-and-fill (UCF) with paste fill were the methods planned for each of the three kimberlite pipes (Figure 3). The details of these plans were outlined in the early stages of the underground project through a feasibility study (McIntosh Engineering 2007) and analysis of whether the fill should be paste or cemented rockfill (CRF) (Golder Associates Ltd. 2009).

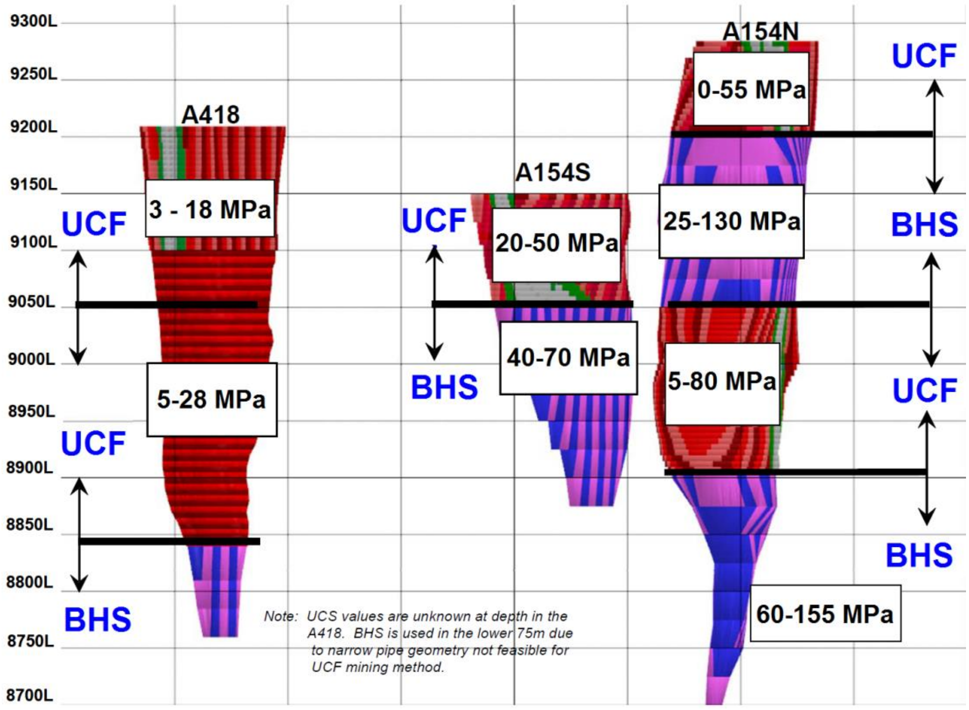

Figure 3 Feasibility study mining methods (adapted from McIntosh Engineering 2007)

The UCF mining method is a top-down method designed to excavate primary, secondary and tertiary panels 5 m high by 5.25 m wide by means of a roadheader and drum miner. Once complete, the panels would be filled in preparation for the subsequent level to be excavated under the fill. This method was chosen due to the poor rock quality in large parts of all three orebodies.

Blasthole stoping was designed to be used where the strength of the intact kimberlite exceeded 50 MPa. It would consist of excavations retreating from the hanging wall to the footwall along primary and then secondary lines. The initial dimensions planned for these stopes were to be 7.5 m wide by 25 m long and 20 m in height. Once a stope was mined out, it would be backfilled with cemented paste fill similar to that used in the UCF method. Excavation of the stope overcut and undercut would be by standard development techniques followed by production mining with a combination of longhole drills and load–haul–dump (LHD) units.

These mining methods were planned and scheduled as the underground continued its development towards the production levels and the open pit continued to work towards the ultimate pit design. In this process, the mine operators became more confident with their understanding of the potential impacts of more cost-effective mining methods such as SLR; in particular, the success of 'open sky mining' at the end of the A154 pit. Open sky mining involved drilling and blasting the bottom part of the open pit ore with surface equipment and mucking and hauling it to surface through the underground mine. This exposed a 40 m high section of the contact wall. To further evaluate the SLR method, the mine enlisted Itasca Consulting Group to conduct 3DEC modelling to evaluate the risks to the pit walls, dikes and existing underground development, should SLR be adopted to replace BHS and UCF as the mining method for the A154S and A418 pipes. This analysis, along with a further study by SRK Consulting and a third party fatal flaw review, gave confidence to proceed with a trial of SLR, given that certain conditions were fulfilled.

Under the new plan, the A154N pipe would remain a BHS mine due to its proximity to the water retention dike, and the A154S and A418 pipes would be redesigned to support SLR mining. The SLR method can be extremely productive when compared to conventional open stoping techniques. This is because no backfill is required, and is also due to the continuous cycling nature of the method.

4 Geotechnical challenges and considerations

At Diavik, there are many geotechnical challenges and considerations associated with SLR mining of kimberlites. As this paper has a focus on issues particular to mining in subarctic conditions, discussion will be limited to ground support, contact wall stability, and inundation of water.

4.1 Ground support at Diavik

A 'horseshoe' development profile was utilised due to its inherent stability. Drift dimensions have been maintained at 5 m wide by 5 m high. This profile, including a typical support pattern for weak kimberlite, is illustrated in Figure 4.

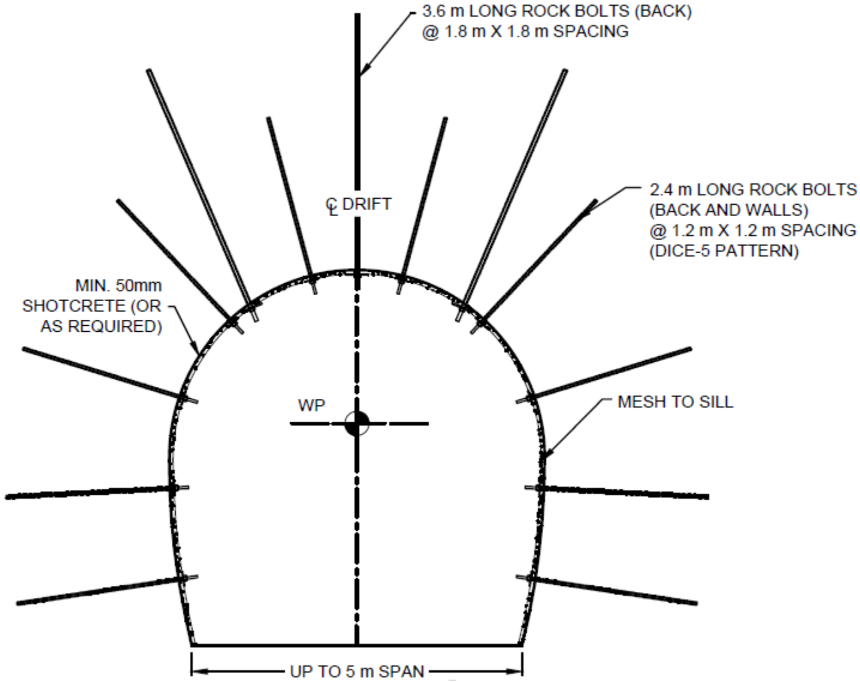

Figure 4 Typical SLR support pattern in weak kimberlite (BGC Engineering Inc. 2017)

4.1.1 Rockbolt selection

When working in cold climates, some things to consider when selecting ground support include:

1. Effects of permafrost and cold temperatures on performance.
2. Storage implications of ground support consumables (cold storage versus heated storage).
3. Cold weather effects on batch processes such as making shotcrete.
4. Capacity for QA/QC.

At Diavik, when considering the above factors, Atlas Copco Swellex products were chosen as the primary form of rockbolt support. PVC-coated products (for corrosion protection) are used in permanent headings and uncoated products were used in temporary short-life applications. Other forms of ground support were used, such as grouted cable bolts, grouted rebar, resin rebar, lattice girders, etc. However because of cold storage and QA/QC reasons (simplicity of installation and consistency of performance), Swellex products were by far the most widely consumed. Bolting was carried out using Atlas Copco Boltec MC drills.

4.1.2 Manufacture and use of shotcrete

Due to the poor rock quality in the kimberlite pipes, shotcrete is regularly utilised. Diavik sprays approximately 30 m^3/day of wet mix shotcrete product. Diavik has an onsite crushing facility that makes aggregate products for the following uses: general road maintenance, CRF production, airport runway maintenance, construction projects, concrete production, and shotcrete. During the winter months, shotcrete and concrete aggregate is warmed before using steam. The shotcrete is batched in a surface batch plant, delivered underground using Normet transmixers, and applied using Normet Spraymecs. The current mix design per cubic metre is:

- 585 kg Type 10 cement.
- 1,508 kg 10 mm minus aggregate.
- 215 L of water (heated in winter months).
- Plus admixtures (water reducer and retarder).
- Accelerator added at the nozzle when spraying.

All efforts are made to keep the admixtures in heated storage to avoid freezing. This requires heated transportation to the mine site as well as coordination on arrival to ensure that the accelerator does not remain outside before being transported underground. Although manufacturers state that admixtures can be thawed and reconstituted, this requires significant effort, and experience has had mixed results. The additional effort required to prevent the accelerator from freezing is preferable to the effort required and mixed results of the reconstituted product. Batch consistency is maintained by monitoring the mixer power draw. The strength requirements are 5 MPa at 8 hrs, and 35 MPa at 28 days.

4.2 Sublevel retreat contact wall stability and impacts to production mining

In the context of this paper, SLR contact wall stability refers to the general stability of the granite walls that form the perimeter of the SLR opening/hole at the bottom of the original pit. The contact walls are increasingly made larger as the SLR levels progressively deepen. The heights of the walls at the time of writing in the A418 SLR were approximately 190 m, and in the A154S SLR approximately 260 m.

In general, very few contact wall stability issues are experienced between November through April. During May through October, with warmer temperatures, subsequent freeze/thaw impacts, and water ingress due to rain and meltwater, contact wall stability issues become much more prevalent. To date, >350 kt of contact wall material has fallen in the A154S SLR, and >400 kt in the A418 SLR. Rock failures vary in size with the largest having been approximately 100 kt. It is not uncommon to have between 3–5 rockfall events develop per month during the spring to fall seasons.

To manage safety at the SLR drawpoints, the drawpoints are left choked. Regular drone surveys are used to characterise the levels of broken muck over the drawpoints. Draw control procedures are also utilised to help maintain an appropriate level of broken muck over the drawpoints. Monitoring of the contact walls is done through a combination of surface and underground systems. The surface system utilises in-pit radar and robotic prism monitoring in addition to a suite of other instruments (i.e. shape arrays and time domain reflectometry sensors). The underground system uses a suite of multi-point extensometers, crackmeters, and time domain reflectometry sensors, installed from completed and abandoned SLR levels. All instruments are tied into a real-time monitoring network. Trigger action response plans (TARPs) have been developed to evacuate the SLR levels if significant contact wall instability is detected. This system has provided early warning before rockfall events in the pit, allowing the affected areas underground to be evacuated before the event occurred.

The teleremote capability of LHDs on SLR levels has proven invaluable with regard to maintaining production during geotechnical events, and is necessary to manage other geotechnical risks such as mudrush.

4.3 Inundation of water (spring through fall) and mudrush management

Surface water management in the open pits is essential for minimising the entry of spring meltwater and rain water into the SLR openings. To prepare for spring melt, at the start of April, the surface mining team begin a snow removal campaign in both the A154 and A418 open pits. By the end of April, the goal is to have as much snow removed as practical, the ditches re-established, the in-pit sumps dug out, and the pumps ready to deploy. The underground team also undergoes an inundation preparedness campaign and ensures all water ingress points are ready to accept the anticipated inflows of water. An inundation plan and emergency pumping procedure spells out the required pumping capacities. The maintenance of the in-pit water handling system and the underground water handling systems are an ongoing activity throughout spring, summer, and fall. Procedures for decommissioning the surface system in the fall, to minimise the work required to re-activate it the following spring, are also in place.

During spring through summer, a rainfall TARP is also active which outlines specific water management and mudrush management activities that come into effect if certain rainfall thresholds are met.

Despite best efforts, a certain volume of surface water does make it into the SLR openings, in addition to a small volume of water that naturally reports from water-bearing geologic structures. As such, mudrush management is an important aspect of SLR mining.

In general, Diavik experiences one or two small mudpush events during each spring through fall seasons. These pushes are low-volume events – SLRs do not have a large surcharge of material over the drawpoints, as noted by Jakubec (2011) – and typically manifest as a drawpoint muck pile displacing 5–10 m into the oredrive.

To manage this risk, a specific mudrush management plan was developed which involves underground operators rating all SLR drawpoints every shift for mudrush potential. Operators use a simple matrix to evaluate the fragmentation and moisture content of each quadrant of the drawpoint to determine the risk rating. A mudrush team, comprised of a geotechnical engineer, geologist, and an operational leader also rates the drawpoints weekly as a check on the ratings performed during the week. This process also extends to the orepass systems. For drawpoints rated moderate or high, specific restrictions are placed on the activities that can occur in those headings. In headings rated high, only teleremote mucking is permitted, and if drilling is required, remote drilling must be used. Most drawpoints rated high do not push; the rating recognises the potential hazard. While events have occurred where material has pushed out of drawpoints, Diavik has yet to experience a large uncontrolled mudrush event. Mudrush management is exercised all year long, not just during spring, summer, and fall. However, the majority of issues that develop occur during May through October.

5 Operational considerations

5.1 Equipment

The primary production equipment at Diavik consists of Atlas Copco drills, trucks, and LHDs. A mixed fleet of auxiliary equipment is also used, including:

- Normet Spraymecs and transmixers.
- Marcotte cassette carriers.
- Komatsu Integrated Tool Carriers and graders.
- Maclean blockholer and boomtruck.
- A Minecat hole cleaning machine.
- A Cubex Orion in-the-hole drill.

M6 Simba longhole drills are used in SLR mining, while M7 Simba longhole drills are used in open stoping. ST1530 LHDs are primarily used in development and SLR areas, while ST14 and a single ST18 LHDs are employed for line-of-sight remote stope mucking, backfill, and orepass loading. The mine currently operates a haulage fleet consisting of MT6020 trucks.

5.2 Production rates

The initial production rates from the open pits were 1.5 Mtpa. Through improvement processes, the process plant eventually was able to process 2.4 Mtpa. Underground production rates are currently 2.3 Mtpa. Of this, 0.7 Mtpa is produced from A154N open stopes, 0.5 Mtpa from A154S SLR, and 1.1 Mtpa from A418 SLR. The underground extents of the A154S orebody are much smaller than the other two pipes. This has constrained production rates in A154S. Production rates in A154S are further restricted by local hydrogeological conditions, making dewatering more difficult in A154S than A418.

Ore recovery from SLR blasting is seasonally dependent. During the colder months, the ore in the ore blanket (Figure 1) will freeze, resulting in poorer material flow and lower recovery. As the ore blanket thaws, the amount of ore that is recovered after each blast increases.

5.3 Heading requirements and sequence

Initially, a single SLR level would be mined as the level below was developed and prepared for production. As the new level commenced, the previous level would be finishing. This would leave only a few active drawpoints at any one time. Whenever problems were encountered, whether from hang-ups, slow mucking due to oversize, or the need to drill or do service work, the limited number of headings would frequently cause drawpoint production to stop. As development and dewatering was able to advance sufficiently ahead of production, levels were initiated earlier. This generated more available headings and greater flexibility when headings were unavailable. Once the practice of having two active production levels at a time was firmly established in A418, production rates increased from approximately 1,000 t per shift to 1,500 t per shift. Multiple active levels and many drawpoints have given the operation the flexibility to achieve higher production. Typically, at least eight active drawpoints are required to achieve production exceeding 3,000 tpd from the A418 pipe.

5.4 Ore handling

Production is concentrated on one or two active levels at a time. Each level produces for approximately nine months, after which all ore has been extracted and the level can be abandoned. With all production from the orebody being concentrated in a small location, certain possibilities exist for ore handling including orepasses, chutes, loading directly onto trucks, or using level stockpiles. Diavik has chosen to use orepasses. Between two and four levels connect to the same orepass and a loadout is constructed for truck loading at the bottom. This increases the haulage distance required, compared to hauling directly off the production level. As a safety requirement, only one LHD is permitted to work in an area at a time. Because there are only one or two levels available for production, if a single LHD was both mucking drawpoints and loading trucks, production rates would fall drastically. The orepasses have added additional equipment and haulage distances but allow for continuous drawpoint production, allowing higher total tonnes hauled.

5.5 Dilution control

As noted in Section 4.2, as subsequent lower levels are mined, the contact wall below the final pit bench becomes taller. Initially, small contact wall failures fell into the ore blanket. As geologic structures have been progressively exposed, larger contact wall failures have occurred. This waste is funnelled into the drawpoints, as ore is removed from below. Immediately following a blast, drawpoint muck consists completely of ore; as the heading is mucked, dilution eventually reports through to the drawpoint. The coarse, angular, white, granite waste is easily distinguished from the weak black kimberlite. Operators have been trained by the geology department personnel in identifying waste from ore and will report on the estimated average dilution at the end of each shift. A draw control and blasting strategy has been developed by the geology and mine planning departments to determine when a heading is to be blasted based on estimated dilution (from operator reporting) and recovery of the previous ring blasted. Whenever possible, waste rock is separated by the LHD on the level. This waste is stored in dedicated re-mucks and loaded on trucks directly on the level. Ore is further sorted with an excavator at the process plant before being fed into the plant. This management system has greatly reduced dilution in the processed kimberlite. Dilution levels from the SLRs were measured to be 16% at the time of writing.

As depth increases, it is being considered whether to begin maintaining an ore blanket to enhance grade predictability. This would reduce granite dilution but may lead to lower recovery as ore in the blanket mixes with the granite above over time and can no longer be recovered.

5.6 Hang-ups and bridging

Blasting does not always go to plan. Several situations cause bridges or hang-ups requiring recovery drilling and blasting. Drilling is carried out by teleremote from a portable sea container at a safe distance. Most situations requiring recovery fall into one of the following scenarios:

1. Weak ground, overloading of collars, and choked brows causing overbreak. This can damage or remove the subsequent ring's hole collars, rendering them impossible to load.
2. Since the rings are collar primed, any discontinuity in the emulsion column will cause misfires at the toe of the hole. This is expected to be the cause of periodic bridging in SLR headings.
3. During the initial phases of SLR mining, no substantial dilution was reporting through the drawpoints. A heading was mucked until cracked to the open pit and the next ring was then blasted. At times, kimberlite would fill in the cracked drawpoints before blasting and cause a choke blast. The soft nature of the kimberlite absorbed the majority of the blast causing the blasted ring to freeze.
4. In later stages of SLR mining, large pieces of granite reporting to the narrow drawpoint caused hang-ups, sometimes accompanied by large voids inside the brow.

Recovery drilling is attempted from the adjacent parallel drift where the mining front was in front of the bridge/freeze/hang-up. This allows drilling parallel to the rings already drilled. At least two parallel rings are drilled in order to blast down into the void/previous drift. If this was unsuccessful or the parallel drilling could not be achieved, multiple rings fanned from a shallow angle were drilled from the same heading. A berm was placed and pushed up to ensure the safety of the workers and drill, which made collaring close to the new brow difficult. There was also a risk of damaging the back during blasting.

5.7 Technology

Teleremote mucking was a prerequisite for SLR mining due to possible mudrush hazard. This system was further expanded to be operated from surface, allowing drawpoint mucking between shifts during blast times. The outgoing shift cleared the level and enabled the teleremote-capable LHD. The information on heading status and level activation was communicated to the oncoming operator in the operations centre on surface. Mucking was then carried out through shift change, allowing true hot changes from one shift to another via the teleremote mucker.

5.8 Safety and equipment interaction

Production from the SLR occurs from two mining levels at a time. The full cycle, including drilling, blasting, mucking, and services occurred within a small area. The possibility of an interaction between the active-mucking LHD and personnel or vehicles was high in such close quarters. To prevent such interactions, segregation and proximity detection controls were put in place.

5.8.1 Segregation

An LHD was confined and segregated to its level within sets of barricades, and no activity or other equipment was allowed. Anyone wishing to enter the segregated and barricaded area was required to make contact via radio to the LHD operator and receive positive radio communication that the LHD's parking brake was applied before any barricade may be removed allowing access to the area. Before releasing the park brake, the LHD operator must have radio confirmation that the requesting person was clear of the area and the barricade had been replaced. Operating procedures also do not allow two LHDs to operate on the same level.

5.8.2 Proximity detection

All pieces of equipment underground and all cap lamps are equipped with RFID tags. When these tags come within approximately 50 m of an LHD or haul truck, the operator is notified in the cab. The tag is assigned to the person or equipment, allowing the operator to know how many pedestrians and what types of equipment are in its immediate vicinity. As a final surety, the LHDs are equipped with cameras highlighting all blind spots to ensure no personnel are in the immediate vicinity after start-up of the LHD.

6 Drill and blast

6.1 Slotting

One of the challenges with SLR mining was with the initial opening of the 20 m slot to start the level. A few iterations were trialled before a reliable design was set. A plan view of the slot design is shown in Figure 5. The relief hole, shown in grey, was drilled with a Machines Roger V30 head mounted on a Cubex Orion drill rig. This is drilled as a blind-bore uphole with 165 mm pilot hole reamed to 254 mm. Initially, due to lack of in-house expertise to drill these holes, a contracted drill operator was brought in to drill the holes with the Diavik-owned rig. After spending time with the contracted operator, enough site experience was developed that in-house training could be offered and the contracted operator was no longer required. After in-house drilling skills were developed, it allowed greater flexibility with the scheduling of the drilling. The placement of the V30 (762 mm) reamer hole along the drift was dictated by the geometry of the drill. Operationally, it was preferable to back the drill into the heading to allow the driller a safe egress in the event such that the drillhole started to collapse. It also provided a larger working area that made the overall process safer for the driller.

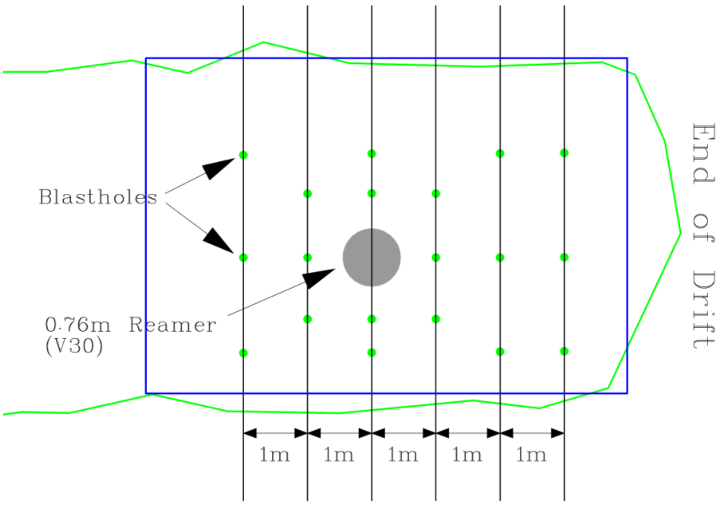

Figure 5 **Plan view of typical slot (n.b. hole diameters are not to scale)**

All of the blastholes in the slot were orientated with a vertical dump and nearly vertical dip. After blasting the slots successfully a number of times, the extent of the blast was pushed out to the full width of the stope, in an attempt to maximise the ore recovered. This proved to be unsuccessful, as the void provided by the undercut was not sufficient and the muck ended up being compacted in the drawpoint, requiring recovery drilling. The current standard is for the slot to be nearly vertical; 6 m long by 5 m wide by 20 m high. This results in a void ratio of ~0.3, providing more favourable results. In general, the slot does not break through to the level above with the first blast, but the blasted tonnage can usually be mined out of the slot.

Initially, the strategy was to gradually add holes to the rings moving away from the slot until the full stope width was reached. The challenge with this was that there can be a significant amount of ore left behind along the kimberlite/waste rock contact. Before there was a significant amount of granite on top of the ore blanket, the ore that was left behind on a level was less of a concern as the ore along these contacts could be recovered from the level below. The high contact walls exposed have resulted in significant introduction of granite on top of the kimberlite. This dilution makes it difficult to recover the ore that is left behind on one level from subsequent levels. Recently, slash holes were added around the slot that are blasted after the slot blast has been mucked, in order to open up the upper level sooner. The areas where this has been done have been successful.

6.2 Pre-loaded rings

Due to the geometry of the brow and muck pile, it is difficult to use the drill to machine-clean blastholes that are at the brow. In order to mitigate the risk of being unable to successfully clean and load these holes, rings are pre-loaded with emulsion ahead of the blast ring and collar primed for blasting. This is especially advantageous in some of the poorer ground conditions, where loading would be impossible due to plugged holes. A diagram of a typical drawpoint is shown in Figure 6. Two pre-loaded rings are maintained, which allows the drill to set up on the next ring back if cleaning is required. Flexible fibreglass rods are used to manually collar prime the blastholes. ‘Push-rods’ as supplied by blasting supply companies were trialled but were not stiff enough. It was found that 13 mm duct rod worked for collar priming. One of the drawbacks of this method was that the rings were only collar primed, rather than double primed, which would be preferable for the typical 25–30 m emulsion explosives columns. There currently is no mitigation in place for this as it is considered a ‘necessary evil’. Another drawback of this method was that, since the holes were manually primed by the blasters, the maximum unloaded collar length of the holes was 4 m as the priming rod begins to buckle in the hole past this distance. This results in overloading of explosives closer to the collar, but again is preferable to the risks associated with not having pre-loaded rings. Exposure of the pre-loaded emulsion to the extremely cold temperatures has not had a significantly negative effect on blasting results. A variance was obtained from the mines inspector in order to be able to operate an LHD under the pre-loaded rings.

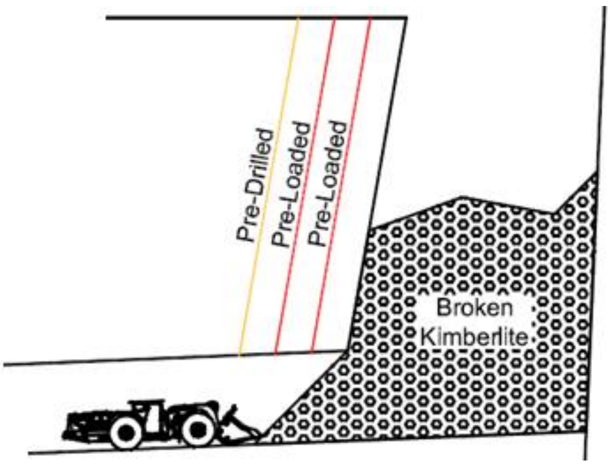

Figure 6 Typical long section

6.3 Blasting sequence

In general, the blasting sequence attempts to reduce stress concentrations in the kimberlite while opening up drawpoints as quickly as possible. In A418, a diagonal profile was maintained with a 2–3 ring offset between adjacent drawpoints. This offset allowed for easier recovery drilling from the adjacent drift.

6.4 Intersection blasting

Large intersections are created due to the configuration of the level entries and the crosscut drift. These intersections have historically been blasted in a single blast in order to avoid creating a large brow across the intersection, especially in poor ground. This created problems in having sufficient void space for blasting since 5–6 rings can be blasted in a single blast. Before the existence of the waste blanket on top of the ore blanket, the drawpoint would be mined beyond what would normally be mined for a single ring in order to generate this void. This would generally provide reasonable results. After the waste blanket became more substantial, mining the drawpoint open to such an extent has become effectively impossible.

Recently, in A154S, additional long ground support and welded wire straps have been installed to allow single rings to be blasted across the intersection. This has had a significant positive impact in the amount of ore that is recovered from these intersections. As the A154S kimberlite pipe is the smallest pipe, and the proportion of intersections versus the proportion of regular rings is larger, this additional recovery will have a measurable impact on the amount of ore recovered. The poor-quality kimberlite in the A418 orebody does not lend itself to this approach.

The next step in the improvement of the level layouts was to stop the development of the level entries one round short of the crosscut. The rings in the crosscut were to be blasted past a level entry and then the round was to be blasted. This removed the intersections and should improve overall recovery. The next level in the A418 pipe will be mined in this fashion as illustrated in Figure 7.

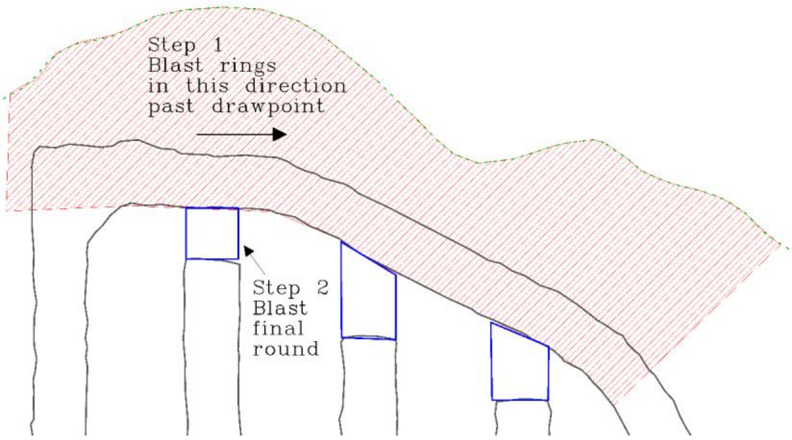

Figure 7 Plan view of elimination of crosscut intersections

6.5 Recovery drilling

While significant gains have been made in blasting practices, recovery drilling is still required. Due to its nature, recovery drilling was conducted into either previously blasted ground or into or near areas that had pre-loaded rings. The Atlas Copco Simba drill rigs are equipped with an automated drilling feature as well as remote pedestals that allow the drilling functions of the rig to be controlled from outside the cab. These features can be used for recovery drilling, but by its nature, recovery drilling is more difficult than normal drilling, and it became apparent that it would be beneficial to have equipment capable of allowing additional control and monitoring of the equipment.

Previously, the mine operations group had worked with a third party supplier to develop a multiple-camera system mounted on the development jumbos and bolters. This system was used for remote drilling operations in areas where development was adjacent to previous mining. The system was installed on the longhole drill rigs to use for recovery drilling. Each Simba drill had a fixed camera on the top of the cab and mounts for two removable pan–tilt–zoom (PTZ) cameras. Three monitors were set up in a small sea container; one for each of the cameras, as well as a control for the PTZ cameras (Figure 8). This allowed the driller to have maximum control of the drill while keeping a safe distance from any potentially unblasted explosives.

Figure 8 Remote drilling cameras circled in orange

7 Ventilation requirements

Due to the nature of SLR mining, close monitoring and controls were required to ensure sufficient ventilation flows were maintained to support safe mining for the underground workforce. During routine mining operations, it was common for drawpoints to be mucked and opened on a daily basis, effectively altering the ventilation circuit due to opening the system to the outside atmosphere. Depending on the outside temperature and which type of ventilation circuit was being examined, the impact of open drawpoints varied significantly. The following section outlines the two types of ventilation systems used at Diavik for SLR, the effects caused by the seasons, and the process of level abandonment.

7.1 Positive versus negative ventilation systems

A418 was ventilated using a positive pressure system which is created using two 183 cm, 186 kw fans pushing air down a fresh air raise and onto the active mining levels. Figure 9(a) contains a simplified schematic showing the ventilation configuration in the A418 SLR.

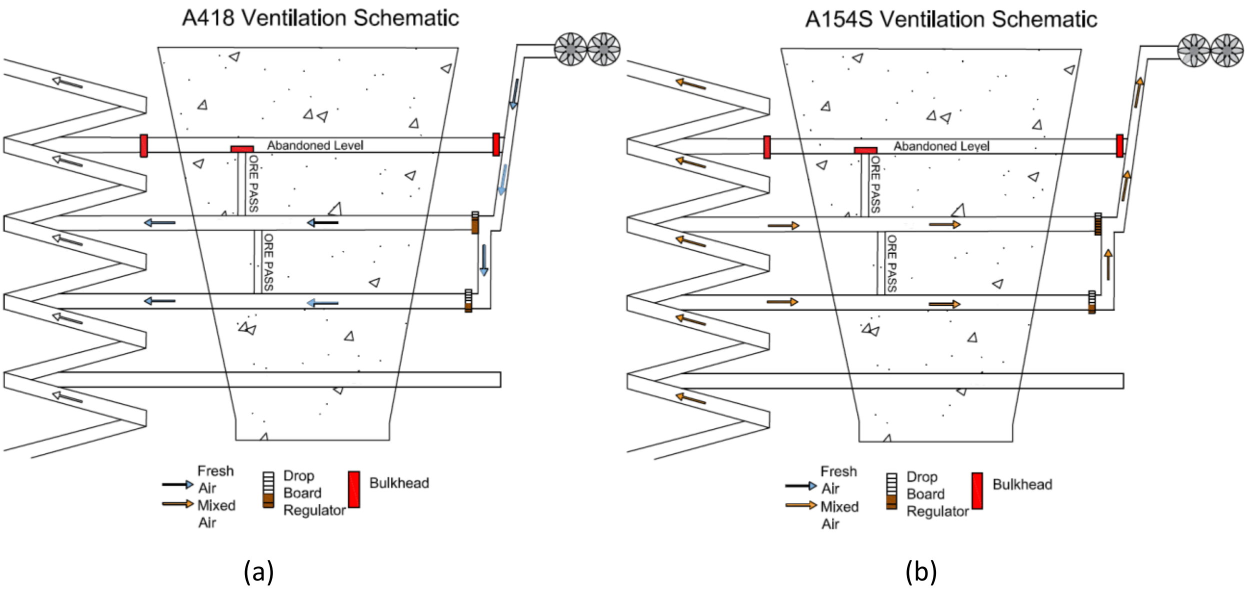

Figure 9 Ventilation schematics of (a) A418; and, (b) A154S

Ventilation flows were distributed among the active mining levels using simple drop board regulators. Generally, the minimum ventilation requirement for an SLR level was 12 m^3/s, which was the requirement to run one Atlas Copco ST14 LHD. The maximum ventilation requirement for an SLR level was 30 m^3/s, which was required to run one Atlas Copco ST14 LHD and one Atlas Copco MT6020 60 t haul truck. These ventilation requirements were maintained for both the A418 and A154S SLR. A separate ventilation raise system was in place which supplied the bottom A418 ramp with fresh air. One disadvantage to this system was related to emergency response. In case of a fire on an active level, an emergency response team may be advancing through smoke.

A154S was ventilated using a negative pressure ventilation system which was configured in much the same way as the A418 system. However, instead of fans pushing air into a fresh air raise, there were two 152 cm, 75 kw fans pulling air up a return air raise. Figure 9(b) contains a simplified schematic showing the ventilation configuration in the A154S. Relative positive pressure was maintained on the level using Zacon ventilation doors with inset fans.

Ventilation flows were distributed among the active A154S SLR levels just as they were in A418 by using simple drop board regulators. The main difference between the A418 and A154S SLR levels was that in A154S, the fresh air for the level is drawn from the ramp access. A separate ventilation raise system was in place which supplied the bottom of the A154 ramp with fresh air.

7.2 Effect on ventilation: summer versus winter

The seasons have a profound impact on the performance of Diavik's ventilation system. Summer temperatures exceed 20°C with winter temperatures regularly below -40°C. Depending on the season, there can be advantages and disadvantages to both positive pressure systems and negative pressure systems.

During the summer months, air will escape through open drawpoints in both the A418 and A154S SLR. Due to the positive pressure system in A418, this was a greater concern. Controls were in place to ensure drawpoints were not left wide open, as substantial amounts of airflow could be lost to the outside. This resulted in lower than optimal airflow on the A418 ramp. The negative pressure system in place in the A154S made airflow loss to the outside atmosphere less significant.

During the winter months, when Diavik faces extreme weather conditions, caution was exercised to maintain efficient mining, specifically in A154S. Due to the negative pressure system established in A154S, dense cold air had the tendency to enter any A154S drawpoint which has been mucked enough to allow airflow. Freezing conditions were further exacerbated by visibility issues caused by fog from the cold air mixing with warm, humid, underground air. In order to ensure cold air inflows did not impede mining operations in A154S, a Zacon ventilation door was installed at the entrance of the level. The Zacon door was equipped with two 137 cm, 75 kw fans; one of which was connected directly to vent ducting to provide auxiliary ventilation to the level entries with the other fan installed strictly as a blower fan. These fans effectively positively pressurised the level relative to the outside atmosphere and prevented cold air from entering the level, allowing efficient mining. Although this negative pressure system established in A154S was not optimal, it was implemented due to air volume constraints created by the need to ventilate both the A154S and A154N orebodies, which were mined separately.

Despite the addition of doors and fans, it was still possible for water lines and equipment left on the level to freeze. The mine operations team ensured that drills were not left on the level between shifts during the winter and that the water lines were blown out with compressed air when not in use to mitigate the risk of freezing. The positive pressure system in A418 was sufficient for preventing cold air inflows during winter, making it the optimal ventilation configuration for SLR mining in winter. Figure 10 shows a simplified plan view of an A154S mining level which illustrates the ventilation infrastructure in place to control cold air inflows during winter.

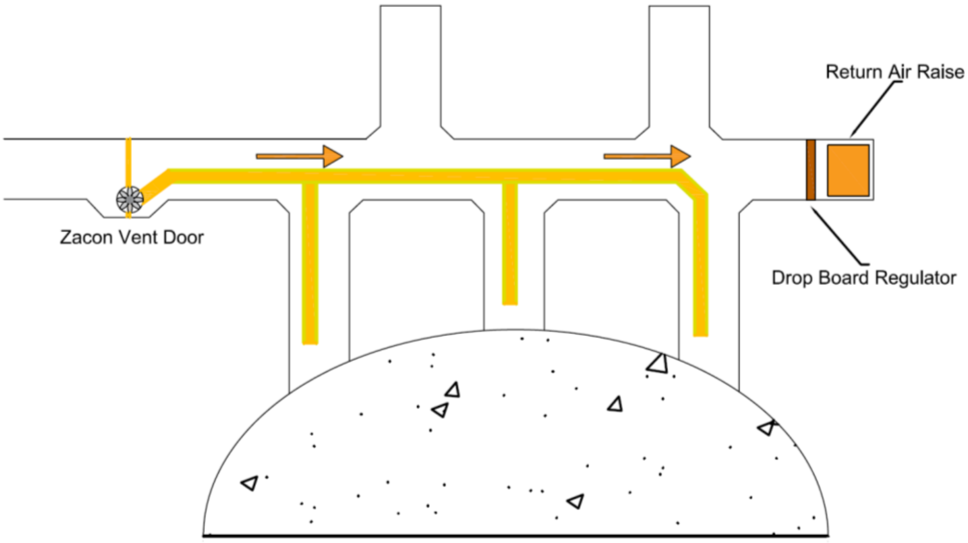

Figure 10 A154S level configuration established during winter

7.3 Level abandonment

Level abandonment in both the A154S and A418 SLR was a necessary process once a level was completely mined out and no longer active. This process was simple and was accomplished using shotcrete bulkheads. Figure 9 illustrates the configuration of shotcrete bulkheads to complete level abandonment. The levels were isolated from the ventilation raise system at the far end of the level, the orepass system which connected to levels below, and from the ramp at the entrance of the level. In some cases, it can be cost-effective to fill an orepass with waste or CRF, rather than constructing a shotcrete bulkhead.

8 Conclusion

8.1 Geotechnical

Geotechnical instrumentation for high wall stability is important and should be installed at the earliest opportunity to get the baseline performance of the high wall. Geotechnical understanding of the rock mass will evolve over the life of the SLR mine, and early characterisation using a suite of modern instrumentation will accelerate that evolution.

In the case of the weak kimberlites at Diavik, just-in-time development would prevent many instances of rehabilitation of ground support. Early instrumentation, along with just-in-time development and flexible ramp geometry could lead to the ability to optimise the level spacing. Early monitoring will also support robust, appropriate TARPs for geotechnical and inrush events.

8.2 Equipment

One of the most important equipment selection options at Diavik was the decision to operate a teleremote LHD system that can either be operated from stations underground or from an operator's station on surface in the operations centre. With assistance from Atlas Copco, Diavik developed a multi-level, multi-LHD system with autonomous tramming capability. This system enabled production to continue during seasonal geotechnical events that have caused the exclusion of personnel from the production levels. This system also provided the opportunity for a true hot-seat change, allowing for maximum production.

8.3 Ore handling

SLR mining is a high-production method, and as such, ore handling needs to be considered in detail during the design phase. The design needs to be able to adapt to production increases that will be achieved as the mining method matures in an orebody. At Diavik, the A418 pipe, producing approximately 100 kt per month, was primarily serviced by orepasses and an efficient loadout station approximately every four levels. The A154S pipe, producing 30 to 40 kt per month, used a combination of loading directly on the mining level and a short raise between levels where the trucks were loaded on the level directly below the active production level. Load factors on the A154S pipe are notably lower than those where trucks are loaded at a purpose-built loadout. The heading size of the waste access on the A154S levels needed to be adjusted to optimise the on-level loading of trucks. Production rates increased incrementally at Diavik from an initial design of 1.2 Mtpa to the current 2.3 Mtpa. At the current rate of production, it may have been more efficient to invest in a vertical haulage system early in the mine life, such as a shaft or conveyor.

8.4 Drilling and blasting

It is important to keep optimising and challenging the drilling and blasting designs. Slotting a blind uphole raise can have varying degrees of success, so it is important to arrange the level entries and crosscut that affords drill and blast engineers some options for slashing holes to expand the initial slot. If the SLR is operating under a diluted blanket of broken material, multi-ring blasts prevented operators from being able to muck all of the ore from the blast before dilution became excessive. Not developing the intersections between the crosscut and the level entries allowed for multiple angles that blastholes can be orientated for creating the initial free face and a more controlled retreat from the blind slot raise. Not developing intersections also enabled engineers to plan single ring blasts for the entire level, rather than multi-ring blasts across an intersection. Like any mining operation, SLR mining needs a detailed QA/QC program. This program should be designed and implemented early in the mine life to be able to track and assess changes, challenges and optimisations.

8.5 Ventilation

Ventilation was difficult to control when drawpoints were constantly changing between open and closed. This was made more complex at Diavik due to the seasonal changes in natural ventilation flow. The positively pressurised system used in the A418 SLR, where the levels were pressurised separately from the pressurised ramp, has proven to be the best method. Care still needs to be taken with open drawpoints to minimise ventilation losses. However, there was little to no chance that a piece of equipment could be damaged by freezing inflows of air. Dilution from high wall failures was generally thought of as a suboptimal condition. However, in the case where external temperatures vary to the point of affecting ventilation flow directions, dilution from the high wall, if left in the drawpoint to keep the level mostly sealed, can be considered an advantage for the ventilation engineer.

8.6 Summary

The decision to change from combined open stoping and cut-and-fill methods to SLR in the A418 and A154S kimberlite pipes at Diavik has changed the path of the operation. This method has introduced further complexity due to the underground interaction with the open pit and additional geotechnical considerations caused by relatively tall high-walls. The elimination of backfill requirements for this method has greatly reduced operating costs and the high productivity levels have increased the underground mine's output substantially.

The use of SLR mining at Diavik has, in retrospect, had an extremely positive impact on the business. It has enabled it to remain competitive in a challenging market, and less dependent on high-cost methods.

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