doi:10.36487/ACG_repo/2435_O-14

Caving method selection and evaluation – Diavik A21 case study

J. Jakubec[a], D. Nakou[a], C. Kottmeier[a], M. Tang[a], P. Lewis[b] and J. Sovka[c]

[a]SRK Consulting, Canada

[b]Rio Tinto, Canada

[c]Rio Tinto, United Kingdom

ABSTRACT

The Diavik Diamond Mine started open pit production in 2003. By 2005, underground development had commenced with plans to mine the A154 and A418 pipes. Several mining methods were evaluated and the sub-level retreat method was chosen for the A154S and A418 pipes, and blasthole stoping with cemented rockfill was chosen for the A154N pipe. In 2020, the A21 kimberlite pipe had advanced its open cast mining to the stage where an underground mining method had to be selected. Both the Sublevel Retreat (SLR) and Incline Caving (IC) mining methods were considered for the A21 pipe. The focus of this paper is to document the experience of underground mining at the Diavik Diamond Mine, the evaluation of the SLR and IC mining methods for the A21 pipe, and the final selection of a mining method for the development of the A21 underground mine.

1 INTRODUCTION

The Diavik Diamond Mine is a diamond mine in the North Slave Region of the Northwest Territories, Canada, about 300 km northeast of Yellowknife (Figure 1). The mine commenced open pit production in 2003 and quickly expanded its operations. In 2005, the mine initiated underground development with the intention of mining the A154 and A418 pipes. Thorough evaluations were conducted to determine the most suitable mining methods for each pipe.

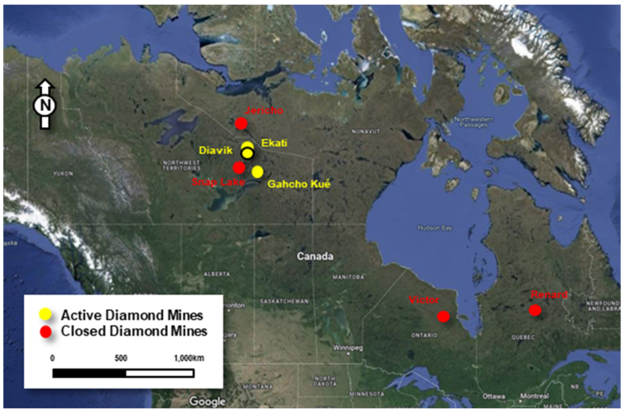

Figure 1 Diavik diamond mine location.

For the A154S and A418 pipes, the sub-level retreat method was chosen. This mining method exploits the orebody in a top-down fashion and uses no backfill. Conversely, the A154N pipe was determined to be best suited for blasthole stoping. This mining method exploits the orebody in a bottom-up fashion and uses backfill comprised of cemented rockfill.

In more recent years, the Diavik Diamond Mine has developed another kimberlite pipe known as A21 (Figure 2).

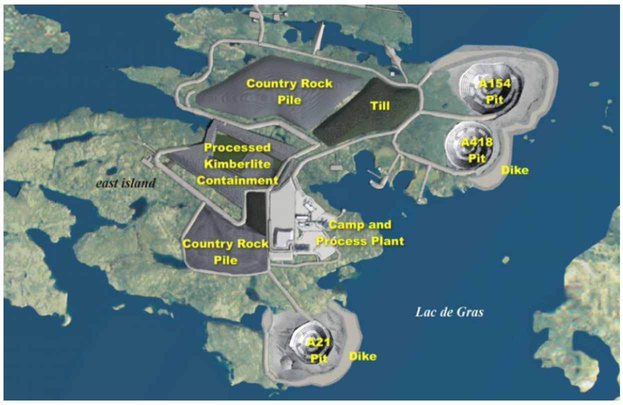

Figure 2 Site layout and location of A21 pipe.

As the open cast mining of A21 advanced, the need for the selection of an appropriate underground mining method arose. Two mining methods were thoroughly evaluated: Sublevel Retreat (SLR) and Incline Caving (IC).

The focus of this paper is to document the experience and lessons learned from the rapid evaluation of both mining methods and the subsequent selection of the most suitable mining method. The objective of the evaluation process was to examine the advantages, challenges, and potential outcomes of each mining method in order to ensure the safe and efficient extraction of diamonds from the A21 kimberlite pipe.

2 A21 PIPE GEOLOGICAL CONTEXT

2.1 Regional Geology

The regional geology surrounding the Diavik Diamond Mine, including the A21 kimberlite pipe, is situated within the Slave Geological Province of the Canadian Shield, a region renowned for its rich endowment of diamondiferous kimberlite pipes (Figure 3). The geological framework of the area is dominated by a complex assembly of ancient granitoid terranes, high-grade metamorphic rocks, and remnants of older sedimentary sequences. These formations have been intricately shaped by prolonged geological histories involving multiple cycles of magmatism, tectonism, and metamorphism, setting the stage for the conditions conducive to kimberlite emplacement.

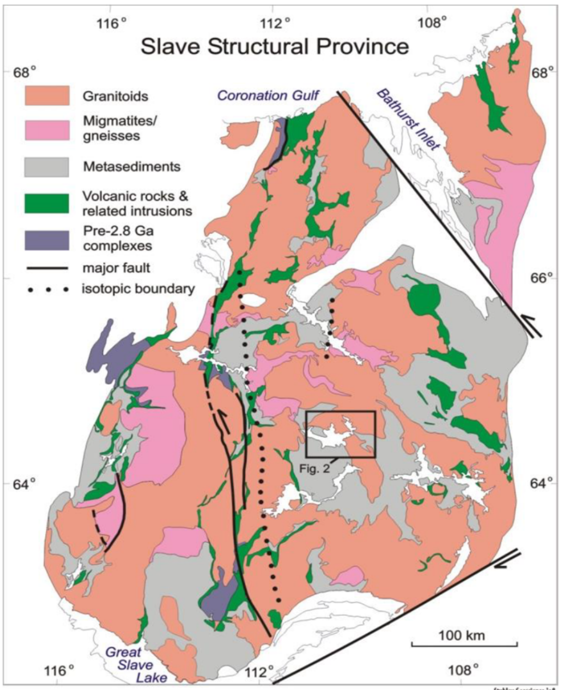

Figure 3 Regional geology – Slave Structural Province.

The Lac de Gras region, specifically, is noted for its tectonic stability which has preserved a significant number of kimberlite pipes, including those being exploited at the Diavik Diamond Mine. The kimberlite pipes in this area, such as A21, are part of the Lac de Gras kimberlite field, which is one of the most significant clusters of diamondiferous kimberlites globally. These pipes are thought to have been emplaced during the Late Cretaceous period, approximately 45 to 60 million years ago, a relatively recent event in the geological timeline of the area. The emplacement of these pipes through the ancient continental lithosphere of the Slave Craton provides a unique opportunity to study both the deep Earth processes responsible for diamond formation and the near-surface geological conditions that have preserved these valuable resources. The regional geological setting, with its deep cratonic roots and stable tectonic history, plays a critical role in the preservation and accessibility of these diamondiferous kimberlites, making the Lac de Gras region a focal point for diamond exploration and mining activities.

2.2 Pipe Geology

The mineral resource and reserve for the Diavik Diamond Mine consists of four diamond bearing kimberlite pipes located under water in Lac de Gras. The pipes are relatively small, each having surface expressions less than 200 m in diameter, but they are high in grade. The kimberlite pipes that underpin the operation are named A154S, A154N, A418 and A21.

Diamonds are generally included as xenocrysts in kimberlite magma as it ascends through the upper mantle and crust. As the earth's surface is approached, the kimberlite magma, which is rich in volatiles such as CO_2, erupts explosively to form a characteristic root-shaped pipe structure. Abundant kimberlite is erupted as pyroclastic ejecta and falls both within and adjacent to the pipe. The pipe is filled with a combination of pyroclastic kimberlite, coherent kimberlite, and country rock that slumped back into the pipe. At Lac de Gras, the tops of the pipes were subsequently removed by continental glaciation. The kimberlites are softer than the surrounding rocks so that depressions were formed after the glaciers retreated and filled with water to become lakes. When the pipes occur under larger lakes, such as Lac de Gras, the pipes typically lie beneath small depressions on the lake bottom.

The Diavik kimberlite pipes are made up of three facies:

- coherent (CK),
- pyroclastic (PK) and
- volcaniclastic (VK).

The CK facies is formed by the crystallization of kimberlite magma, often at depth, and has not been explosively emplaced. The PK facies at Diavik is interpreted as an explosive air-fall deposit which may have been deposited in water. The VK facies is formed by a mixture of pyroclastic deposition and re-sedimentation of pyroclastic kimberlite and host material from a volcanic edifice which flows back into the open crater remaining after eruption. The pipes also contain varying amounts of host rock dilution which was incorporated during the eruption. Figure 4 is a general illustration of the internal geology of the A21pipe.

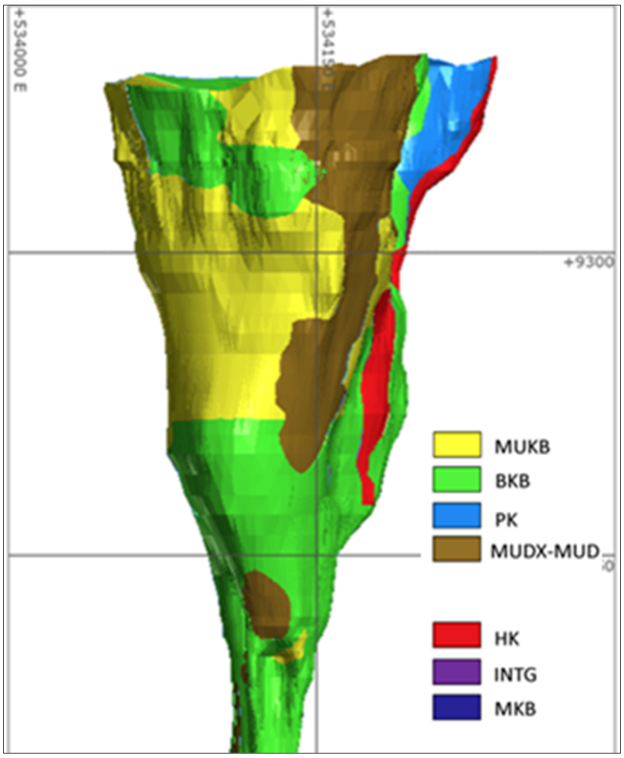

Figure 4 Internal geology of A21 kimberlite types.

The main kimberlite rock types are illustrated in Figure 5.

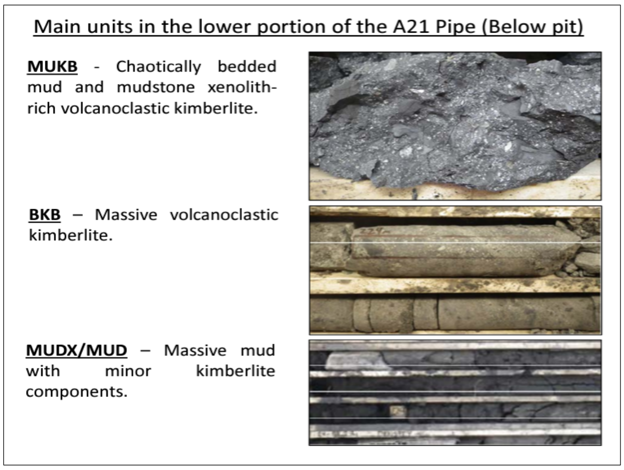

Figure 5 Main kimberlite rock types in A21 pipe.

3 MINING METHODS AT DIAVIK DIAMOND MINE

Diavik Diamond Mine started open pit production in 2003. By 2005, underground development had commenced with initial plans to mine the A154 and A418 pipes using backfill methods. As geotechnical knowledge was gained, the mining methods were re-evaluated and the SLR method was chosen for the A154S and A418 pipes; however, blast-hole stoping (BHS) with cemented rockfill was chosen for the A154N pipe. An aerial view of A418 and A154 pits show SLR stopes at the bottom of the open pits - Figure 6.

Figure 6 Aerial view of A418 and A154 open pits with SLR stopes at the bottom.

Most underground mining methods can be grouped into three basic categories:

- Caving methods
- Open stope methods (unsupported)
- Supported methods

Historically, the underground mining of diamonds worldwide has led to the development and implementation of numerous underground mining techniques; the combinations include 19 different mining methods and variants (Jakubec 2020) from the three mining method categories listed above.

While several underground mining methods had initially been considered for the A21 pipe, the selection process, which evaluated both technical-economic outcomes and potential safety risks, narrowed down the potential mining method options to sub-level retreat (SLR), and incline caving (IC) methods. Selected underground mining method would be continuation of A21 open pit – Figure 7.

Figure 7 A21 open pit.

3.1 Sub-level Retreat Mining Method

Competent country rocks, favorable geometry, relatively competent kimberlite, and the Arctic context of the projects played an important role in the mining method selection process at the Diavik Mine. The schematic section illustrating the SLR method is shown in Figure 8.

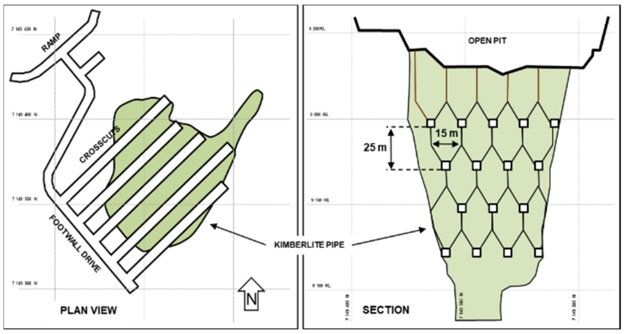

Figure 8 Schematic view of A21 SLR underground mine.

To date, the SLR mining method has been successfully implemented at Diavik on the A154S and A418pipes and some of the operational experiences are described in the next section. The SLR mining method is very suitable for semi-circular pipe-like shaped orebodies which produces stable stope shapes (Figure 9).

Figure 9 Empty SLR stope at the bottom of the A154 Open Pit.

3.2 Incline Caving

Although the incline cave mining method has been used since the 1950s (Brock et al. 1956), it was officially patented and described by Janelid in 1978. Several incline cave mines were in production in Sweden, USA, Canada, Zimbabwe, and South Africa. The last incline cave mine in operation in Canada was at the Ekati Diamond Mine (Jakubec et al 2020).

The term 'Incline Cave Layout' is used for the mining configuration where rows of drawpoints are offset vertically and follow an incline plane. In an incline plane, the individual drawpoints (drawbells) in the row and between individual sub-levels are spaced so that they allow full interaction, more or less the same way as in the horizontal layout.

The incline layout configuration largely depends on the geometry of the orebody and the stability constraints. Therefore, there can be different incline cave layout configurations; for example, for cylindrical vertical kimberlite pipe and for steeply dipping tabular orebody (e.g. see the single-sided footwall layout or double-sided false footwall layout, 360 degrees around the pipe or trough). Schematics of incline cave configuration are illustrated in Figure 10.

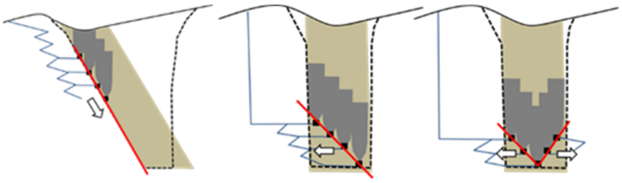

Figure 10 On the left is the design for incline orebody and two incline cave alternatives for vertical orebody are shown in the middle and on the right. Design in the middle uses a "false footwall" layout, and the design on the right uses two "false footwalls."

In comparison to a horizontal cave layout, the incline layout offers:

- Potential for faster cave implementation; uses simple geometry
- Layout flexibility, better secondary drilling options and efficient ore extraction and draw control
- Stronger layout and more effective ground support; the extraction level is backed by solid ground
- Brow wear tends to be less severe than with a horizontal layout
- Complete undercutting is easy to achieve
- The incline layout can handle water and wet muck more efficiently and permits a more uniform draw
- Drawpoint and level drainage is more effective than with a horizontal layout

Compared to a horizontal layout, disadvantages can include:

- Incline layouts incur higher development capital costs in comparison to horizontal cave layouts
- Draw control supervision can be more challenging with multiple levels
- The incline layout may be less favourable for electric LHD.

Incline cave was introduced in 2013 at the Ekati mine as a means to extract remaining ore in the Koala Mine after SLC mining had been completed. This method has number of advantages and disadvantages also manages better potential mudrush risks than with SLC or a front cave.

3.3 Operational Challenges at Diavik - Arctic Context

Operating a mine in the Canadian Arctic during winter can pose several significant challenges (Lewis at al 2018, Jakubec et al 2018). These can include freezing muckpile, country rock contacts, development in permafrost, ventilation, application of shotcrete, and production drilling.

3.3.1 Freezing Muckpile

During the winter months, the broken muck pile in the stope after the production blast can freeze if not removed. The level of muck pile freezing depends on the water content. A key to successful ore recovery is the removal of a freshly blasted muckpile as soon as possible and the prevention of water ingress. Hang-ups of frozen muck have also been encountered. Hang-ups are treated with additional caution as the combination of rock and ice makes the situation less predictable. Any muck left behind, primarily on the apexes between the drawpoints, is recovered on the next level below when it was blasted. Although sometimes experienced, the "carry back" of ore due to freezing in truck dump body has never been a serious problem. Frozen kimberlite has been found to flow very differently than wet kimberlite. Frozen kimberlite tends to flow out of the SLR drawpoints in larger, more angular pieces. The muck piles generally have a steeper angle of repose and mix less with the broken waste above as it is drawn down. Winter storms can also accumulate excess snow and ice in the muckpile (Figure 11).

Figure 11 Snow and ice accumulation in the muckpile of A418 SLR stope.

3.3.2 Wallrock Stability

At Diavik, the large majority of SLR contact wall stability issues occur between May and October, and contact wall failures are variable in size. Large failures have been in excess of 100,000 tonnes (Figure 12). This wallrock granite is then reporting to the drawpoints as dilution, and often as oversize (Figure 13). To manage safety at the SLR drawpoints, the drawpoints are left choked and regular drone surveys are used to characterize the levels of broken muck over the drawpoints. Draw control procedures are also utilized 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.

Figure 12 Wallrock failure at A418 pipe at the Diavik Mine.

Figure 13 Granite wallrock oversize dilution in an A418 drawpoint.

Surface monitoring is done with in-pit radar (Figure 14) and prism monitoring in addition to a suite of other monitoring instruments. Underground uses a range of extensometers, and TDRs. All instruments are tied into a real-time monitoring network and TARPs have been developed to evacuate the SLR levels if significant contact wall instability is detected. Strict control of muckpile thickness is also necessary to protect the underground.

Figure 14 Radar monitoring system at the Diavik Mine.

3.3.3 Fogging - Cold and Heated Air

On production SLR levels, two ventilation setups are utilized. In the A418 pipe, a forced fresh air raise at the back of the level pushes air across the level and onto the ramp. In the A154S pipe, a return air raise draws air from the ramp across the level and into the raise. This design results in the A418 levels being positive pressure and the A154S levels being negative pressure relative to the outside atmosphere. The exhaust raise on the A154S levels was dictated by the ventilation requirements of the blast hole stoping orebody nearby.

When drawpoints are mucked open in the A418, the air exhausts to the pit, where in the A154S outside cold air is drawn underground. When this occurs, the individual drawpoint is sometimes overcome with fog to the point of nearly no visibility, ice begins to form on the sill, and service water pipes can freeze and crack. When this occurs, it is nearly impossible to carry out any work in the heading to rectify the situation. For this reason, ventilation doors are installed at the entrance of each A154S level with secondary fans mounted in the door frame. This increases the relative pressure on the level, ensuring air is exhausted out cracked drawpoints. While this setup has the same end result as the setup on the A418, it requires more infrastructure and management while restricting movement due to the doors.

3.3.4 Shotcrete Mix for Cold Climate

Wet mix shotcrete is utilized. It is produced in a surface batch plant and delivered underground using Normet transmixers and applied using Normet Spraymec shotcrete sprayers. Approximately 25m^3 of shotcrete is sprayed daily. The current mix design for one cubic meter of shotcrete is 585 kg of Type 10 cement; 1,508kg of -10mm aggregate; 215 liters of water, and admixtures. The aggregate is crushed on site and kept heated in the winter months using steam. Batch consistency is maintained by monitoring the mixer power draw. The strength requirement is 5 Mpa in 8 hrs, and 35 Mpa in 28 days.

3.3.5 Development and Production Drilling

Some kimberlite types at Diavik could be weak; however, production drilling is generally carried out using conventional water flushing with few issues. When muddy kimberlite is encountered, the air/water mist feature on the drill is used and successfully prevents hole washout. Due to the softness and poor quality of the kimberlite, bridging and hang-ups are regularly encountered. If drilling is required in the vicinity of drawpoints, or when drilling through previously blasted ground, tele-remote drilling is used to ensure the safety of the operators.

Development through weak kimberlite had required the creation of a very cautious drilling and blasting method. All ore headings at Diavik for SLR are developed in a ‘horseshoe’ cross-sectional profile; the drift is near round, except for a flat floor. Further to the drift shape, depending on conditions of the specific heading, a combination of the following is used: 2-3m long short rounds were blasted with various forms of perimeter control used depending on conditions, spiling, and additional shotcrete, bolting walls down to the floor (sill), and additional long bolts (3.6m or 5m) were used.

3.3.6 Mudrush

Mudrush is inherent risk with any subsidence mining method. Diamond mines are especially prone to such risks as the kimberlite rocks often contain clays and disintegrate upon exposure to water, and they can generate excess fines.

Although the Arctic does not get excessive snowfall or rainfall, it is typically the spring melting (freshet) that generates potentially large quantities of water that can enter the SLR or SLC stopes.

4 GEOTECHNICAL CONSIDERATIONS

4.1 Rock conditions

4.1.1 Intact Rock strength

Intact rock strength of different kimberlite types is highly variable and could be further impacted by weathering susceptibility and the presence of swelling clays. The available laboratory results are depicted in Table 1.

Table 1 Uniaxial compressive strength data summary by lithology

Unit	Count	Mean (MPa)	Min. (MPa)	P.25 (MPa)	Median (MPa)	P.75 (MPa)	Max. (MPa)
MUKB	68	5	0.4	2	4	6	18
BKB	18	7	1	2	3	7	31
MUDX	8	4	0.5	1	1	3	17
HK	8	51	8.0	28	40	63	124
Granite	97	134	3	113	141	166	241
Pegmatite	18	92	33	60	84	119	172

In order to assess the impact of swelling clays, mainly smectite, Diavik Mine undertook accelerated weathering tests on selected core and lump samples, specifically targeting MUKB kimberlite rock type.

4.1.2 Rock Mass

The main lithological domain is occupied by BKB and MUKB kimberlites, poor to fair quality rock mass.

The MUDX unit is extremely poor quality, but the total volume in the current geological model is very low. Due to the relatively low drilling density, the extent of the MUDX unit is uncertain with depth.

The presence of highly competent and strong hypabyssal kimberlite is also limited and will not impact the mining method selection.

To verify drillhole logging, a photo log of selected drill cores was completed, and three classes of rock mass were recognized and are illustrated in Figure 15

Figure 15 Examples of A21 different kimberlite competency.

The geotechnical domains are based on the kimberlite lithology and the distribution of the main kimberlite types is shown in Figure 16.

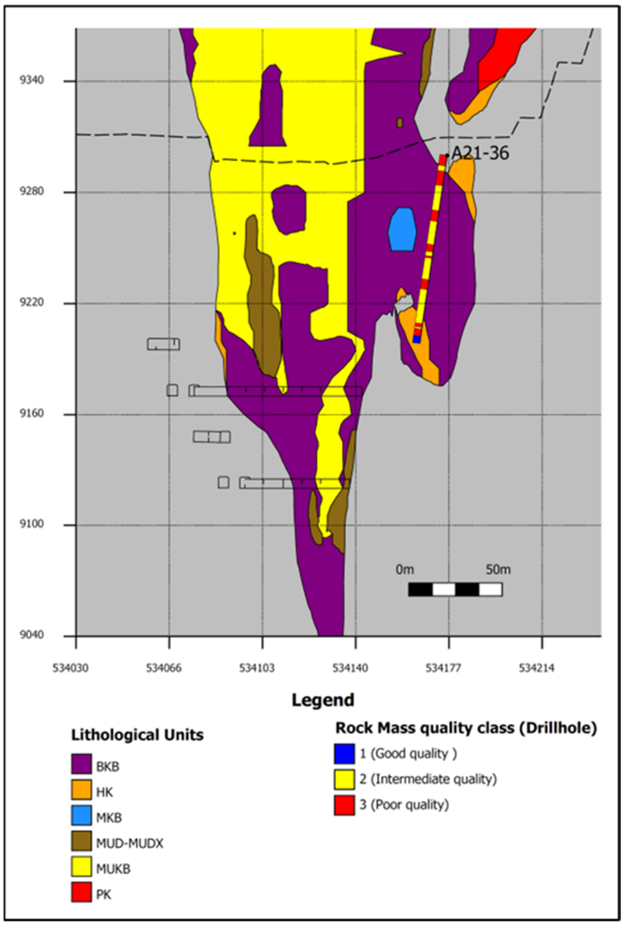

Figure 16 Distribution of A21 different kimberlite competency.

4.1.3 Caveability

Laubscher's stability chart was used to assess caveability for the A21 pipe. Based on logging data and photographic reviews, it was estimated that representative values of IRMR for the poor-quality kimberlite might vary in the range of 10-30, and for good quality kimberlite might vary in the range of 20-40. Due to shallow depth only combined weathering and joint orientation, a mining adjustment of 0.85 was applied. MRMR values of 17-34 for typical kimberlite represents a hydraulic radius (HR) of approximately 10-20.

The results of this analysis suggest that the A21 pipe geometry and rock mass condition is potentially suitable for a caving method. However, there is uncertainty related to the high scatter of the fracturing in the kimberlite and the absence of stress. Therefore, it is possible that the HR necessary to cave the stronger kimberlite is closer to the limit of the available footprint, thus making caveability more marginal and poses risk to caving method.

4.1.4 Pipe Contact Zones and Structures

It is often observed that poor quality rock mass is found at the contact with a kimberlite body. This condition can create mining difficulties when crossing the contact. From a geotechnical perspective, two types of contact zone are usually recognized: the internal contact zone within the kimberlite body and the external contact zone developed in the country rocks. Visual classification from photo-logging shows that in the case of the A21 pipe, the external contact zones are variable both in their geometry and competency, and they are not very strongly developed. Typically, as the development in the country rock approaches the kimberlite pipe contact, there will be a zone of granite approximately 1 m to 10 m in width that is more fractured and weaker than the undisturbed country rock. This external pipe contact zone thickness determined safe stand-off distance for footwall development.

Several faults were intersected in A21 open pit. The most important are Joe's and Stubley's faults – Figure 17. These faults were taken into design consideration from underground stability and potential water inflow point of view. Just like large faults mentioned above, it is expected that external pipe contact zone will likely have higher hydraulic transmissivity thus higher water inflow.

Figure 17 Stubley's fault exposed in A21 pit.

4.2 Ground Support

4.2.1 Incline Cave Ground Support

The following ground support was recommended for the Incline Cave option:

- Granite Good – grouted bolting, 2.4 m/22 mm @ 1.5 m spacing from spring line and mesh on the back.
- Granite Poor – 50 mm fibrecrete, grouted bolts @ 1.5 m spacing from floor to floor and mesh on the back.
- Kimberlite Good – 50 mm fibrecrete, grouted bolts @ 1.2 m spacing from floor to floor and mesh on the back.
- Kimberlite Poor – sealant, 50 mm fibrecrete, grouted bolts @ 1.0 m spacing from floor to floor, mesh floor to floor and a second layer of 50 mm fibrecrete. Spiles and limited round length may need to be introduced as well as 4.8 m long anchors.
- Contact Zones – as poor kimberlite plus OSRO straps one round before and after contact and 6 m long anchors – cablebolts.
- Drawpoints in granite – as for Granite Poor, plus steel arches, fully anchored with long cablebolts – as per detailed design.
- Drawpoints in kimberlite – as contact zone plus steel arches, fully anchored with long cablebolts – as per detailed design.

4.2.2 SLR Ground Support

The following ground support was recommended for the Incline Cave option:

- Granite Good – grouted bolting, 2.4 m/22 mm @ 1.5 m spacing from shoulder to shoulder and mesh on the back.
- Granite Poor – 50 mm fibrecrete, grouted bolts @ 1.5 m spacing from floor to floor and mesh on the back.
- Kimberlite Good – 50 mm fibrecrete, grouted bolts @ 1.2 m spacing from floor to floor and mesh on the back.
- Kimberlite Poor – sealant, 50 mm fibrecrete, grouted bolts @ 1.0 m spacing from floor to floor, mesh floor to floor and a second layer of 50 mm fibrecrete. Spiles and limited

round length may need to be introduced as well as 4.8 m long anchors.

- Contact zones – as per Kimberlite Poor plus OSRO straps one round before and after contact and 6m long anchors – cablebolts.

5 INCLINED CAVING AND SLR TRADE-OFF STUDIES

5.1 Incline Cave design

In the first stage of the analysis, conceptual cylindrical drawpoints of 15 m diameter were located according to the orebody footprint. The different coloring of the drawpoints reflects their extraction level in Figure 18.

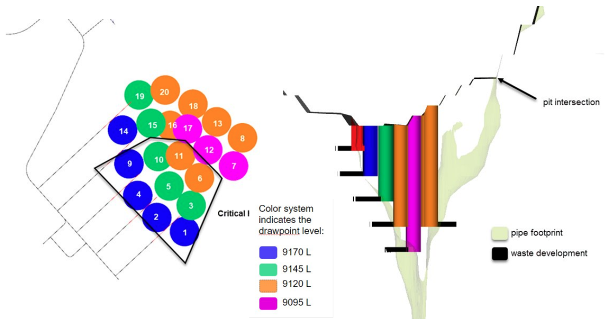

Figure 18 Plan view and section of initial Incline Cave evaluation.

GEOVIA's GEMS™ application Footprint Finder was used to help locate the extraction level which maximizes the value for each drawpoint. After receiving the Footprint Finder analysis results, the locations of the drawpoints were updated as it is shown in Figure 19.

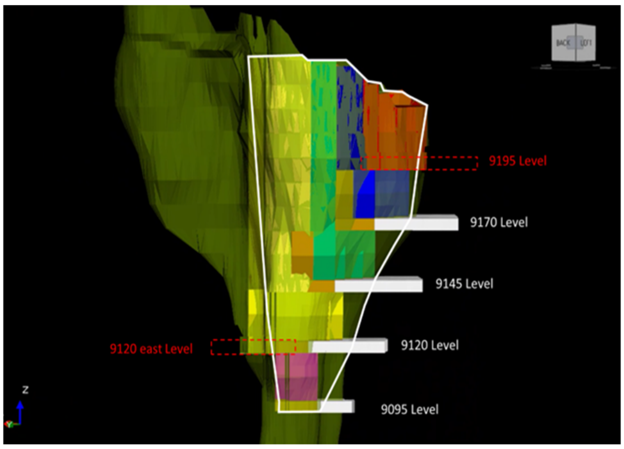

Figure 19 Cross-sectional view of Incline Cave layout.

Based on possible extent of pipe external contact zones minimum stan-off distance of 15-20 m distance from the pipe boundary was kept for all sublevel footwalls. Sublevel vertical spacing was kept at 25 m and the crosscuts were staggered between the sublevels. No changes were applied to the main ramp, ventilation raises, and dewatering system in order to fairly compare alternate mining methods.

5.2 SLR Design

The new lateral development was proposed to extend off of the lower part of the existing exploration decline. The profile sizes planned were 5.0 m H by 5.0 m W for the extraction drives and infrastructure drifts, and 6.0 m H by 6.5 m W for all development drifts where haul trucks will be used (decline and sublevels footwall drives). The larger profile size was selected based on the NWT Mine Health and Safety Regulations which, for worker safety, require an additional 1.5 metres of drift width on top of the width of the largest piece of equipment in use.

From the access ramp, production levels would be driven from the footwall drives. Levels are used to provide ventilation access and haul truck loading areas. The loading areas were designed in a form of a loop to provide flexibility in cases of high traffic load on the level.

Same as for Incline Cave design, stan-off distance of 15-20 m distance from the pipe boundary was kept for all sublevel footwalls. Sublevel vertical spacing was kept at 25 m and the crosscuts were designed on a staggered layout between the sublevels. The basic layout of the rings is shown in Figure 20.

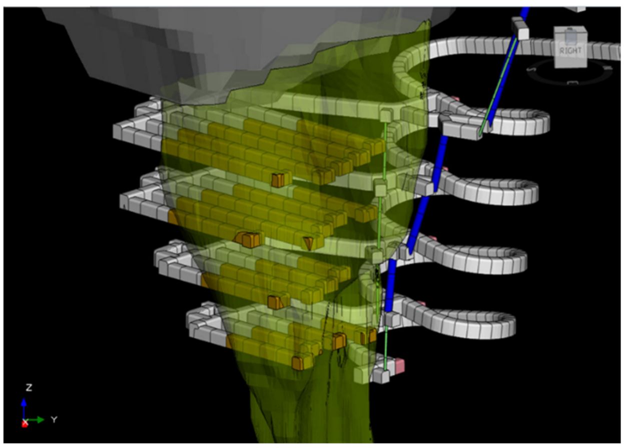

Figure 20 Isometric view of SLR layout.

A set of productions rings with 5m increments was generated to create the simulated material extracted throughout the extraction drift and at the pipe margin the rings were cut against the external pipe contacts. The new shapes were then interrogated for their in-situ tonnes and grades using Deswik software.

To capture all the remaining resource on the sides of the pipe, the basic layout was slightly transformed by extending the width of the upper parts of the production ring while at the same time, maintaining the same angle of the pillar between the surrounding rings.

6 DEVELOPMENT AND PRODUCTION PROFILE

Although waste development for Incline cave is higher, more costly, and possibly riskier development in ore is significantly less. A comparison of development meters for both methods is illustrated in Table 2.

Table 2 Summary of the Incline Cave and SLR development

Development Type	SLR Method (meters)	Incline Caving (meters)
Development in waste	3,200	4,150
Development in ore	1,045	450
Total	**4,245**	**4,600**

As can be seen from Figure 21, higher tonnage sooner from the SLR was important advantage.

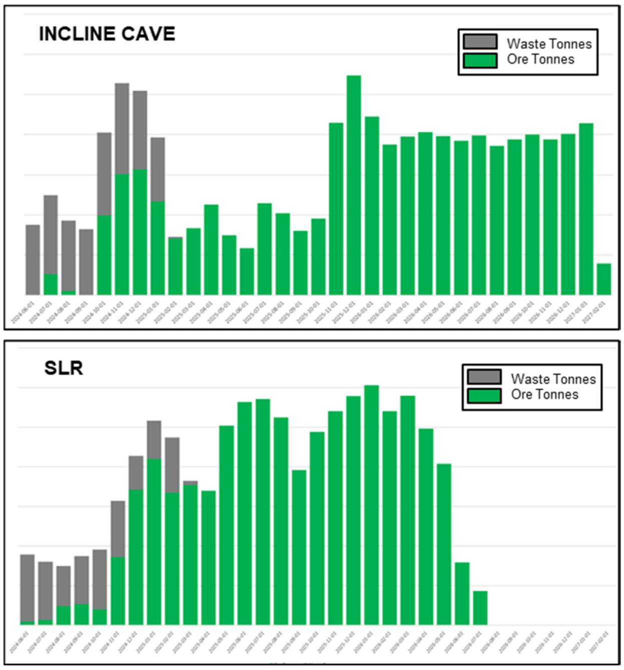

Figure 21 Comparison of Incline cave and SLR production profile.

7 RISK EVALUATION OF INCLINED CAVING AND SLR

A high-level risk assessment was completed for both mining methods. The technical risk analysis included the following key areas:

- Geotechnical orebody knowledge
- Implementation and QA/QC
- Fit for purpose mine design for geology context
- Optimistic and unrealistic expectations
- Cost cutting measures and project implementation
- Deviation from mine plan and not following cave mining principles
- Unexpected mine stoppage

Both methods have advantages and disadvantages, and major technical risks are listed in Table 4.

Table 4 Summary of Diavik's major technical risks

Source	Issue/Risk	Description	Impact on Project	SLR Risk Level	ICM Risk Level	Suggested Mitigation Program
Geotech/ Mining	Excavation stability for both SLR & ICM	Drawpoint and pillar collapses and loss of brow in drawpoints located in poor quality kimberlite	• Project delays • Revenue reduction • Increased costs	High in poor quality kimberlite	High in poor quality kimberlite	• Ore body knowledge • Robust ground support design • Blasting practices • Possible application of sealant to prevent kimberlite weathering
Geotech/ Mining	Blasthole drillability & stability	Ability to drill and keep blastholes open due to swelling clays in poor quality kimberlite	• Project delays • Increased costs • Fatal flaw for SLR	Very High for poor quality kimberlite	Moderate	• Ore body knowledge • PVC inserts in moderately weathered kimberlite • Dry drilling
Geotech/ Mining	Fragmentation	Coarse fragmentation, oversize and hang-ups	• Project delays • Increased costs • Increased safety risk	Low - engineered fragmentation	High	• Ore body knowledge • Draw control (rate of caving) • Secondary blasting • High undercut/overcut
Geotech/ Mining	Pipe wall rock stability higher than expected	Potential for wall rock sloughing and structurally controlled wedge failure	• Increased dilution • Undercutting levels above • Increased safety risk • Increased costs	Moderate	Moderate	• Blasting practices for SLR • Structural mapping of the contact zones (possible ground support wedges) • Maintain minimum muckpile thickness • Schedule mining in coldest weather
Geotech/ Mining	Dilution	Unplanned wall rock dilution	• Revenue reduction • Increased operating costs	Initially Low, later Moderate	Low	• Develop draw control plan • Compliance with draw control plan • Blasting control for SLR
Geotech/ Mining	Inclined Cave Undercutting	Inability to properly undercut in very poor kimberlite (cohesive soil-like behaviour) Inability to properly undercut to required HR if kimberlite much stronger than expected	• Ramp-up delay • Cost overrun • Fatal flaw for ICM unless assisted caving implemented • Potential void and airblast risk	N/A	High	• Ore body knowledge • Sufficient length of undercutting to be established • Strict QA/QC on drillholes and blasting • Increased undercutting/overcut
Geotech/ Mining	Airblast	Void formation and sudden collapse	• Loss of life • Loss of productivity • Project delays	Low	Moderate	• Monitoring cave propagation and muck pile height for ICM • Removing only swell until the HR is reached and confirmed for ICM
Geotech/ Mining	Cave propagation	Irregular cave propagation	• Revenue reduction • Production rate reduction • Resource loss in wedges above drawpoints	N/A	Moderate to High	• Ore body/geology knowledge • Draw control adherence • Monitoring cave propagation • Assisted blasting • Increased undercutting/overcut

8 CONCLUSIONS

Underground mining of the A21 pipe is technically feasible using both SLR and ICM mining with similar production rates expected from each.

The main operational risks are the kimberlite ground conditions, chiefly rapid weathering of kimberlite, and the presence of swelling clays. The initial bulk sampling tunnel excavated during the evaluation stage in 2007 experienced some stability challenges, primarily due to high hydraulic head pressures from the lake above. However, a recent test drive into the kimberlite confirmed that Diavik's ground support plan was more than adequate for dealing with low-quality Kimberlite, especially once the area is effectively dewatered.

A rapid technical-economic evaluation of both the ICM and SLR mining methods confirmed that both are applicable for the exploitation of the A21 kimberlite pipe. Due to the relatively close ranking of both methods on technical-economic and risk basis, the final selection was influenced by the familiarity of the Diavik Diamond Mine with the SLR mining method, lower up front capital development and higher production tonnes early on. Both the A418 and A154S pipes were successfully extracted by using the SLR mining method, and Diavik's management and operational teams' experience with SLR mining method carried a significant weight in making SLR the final choice for the A21 pipe. Additionally, a final advantage of selecting the SLR method is that in case of severe kimberlite stability issues, the mine can be converted to incline cave.

ACKNOWLEDGEMENT

The authors of this paper gratefully acknowledge the comments, and input provided by the staff at the Diavik Diamond Mine and SRK Consulting geologists and engineers.

REFERENCES

Lewis P. A., Clark, L. M., Rowles, S. J., Auld, C. P., Petryshen, C. M. & Elderkin, A. P. (2018). Sublevel Retreat Mining in Subarctic: A Case Study of the Diavik Diamond Mine. In Y Potvin & J Jakubec (eds), Caving 2018: Proceedings of the Fourth International Symposium on Block and Sublevel Caving, ACG, Perth Australia, pp. 57-72.

Jakubec, J., Lagace, D., Boggis, B., Clark, L. M. & Lewis, P. (2018). Underground mining at Ekati and Diavik diamond mines. In Y Potvin & J Jakubec (eds), Caving 2018: Proceedings of the Fourth International Symposium on Block and Sublevel Caving, ACG, Perth Australia, pp. 73-88.

Jakubec J. & Woodward R. (2020). Incline Caving at Ekati Diamond Mine. Proceedings of the Eighth International Conference & Exhibition on Mass Mining Massmin 2020, Santiago Chile, pp 195-207.

Jakubec J. (2020) Mining for Diamonds – History and Present. Proceedings of the Eighth International Conference & Exhibition on Mass Mining Massmin 2020, Santiago Chile, pp 73-86.