Reaching into the past for LKAB`s future mine design

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ABSTRACT

LKAB is well recognized for technological advancements and enjoys a particularly high reputation for pushing Sublevel Caving (SLC) to its very physical boundaries. In a company where the use and development of SLC has been its livelihood for decades, increased mining depths with all its implications, varied orebody geometries and challenging ground conditions have put the choice of mining method again in focus. Behavioural changes, well-engineered and re-thought mining methods are key to unlock further reserves. Options include improved SLC, block caving and other existing or new variants in the caving family.

Natural caving methods were applied in LKAB`s Malmberget mine until the seventies at depths of between 200-300 meters below ground surface. Reports indicate that certain caving approaches generally functioned well. Also design elements such as destress slots were used to protect infrastructure. Several old draw points and surrounding drifts are still accessible and provide insights into fundamental aspects. Despite an uninterrupted mining history, it seems challenging to maintain knowledge and experience over time. The mines have become factories based upon SLC, with its pros and cons. The rediscovery of previous methods may be viable steps into the future.

LKAB is planning for continued mining below present main levels to depths of 1500 meters or deeper. Natural caving methods appear to be a viable option in some areas and designated studies are undergoing. This article summarises experiences of caving experiences other than SLC and presents potential scenarios for natural caving at depth.

1 INTRODUCTION

Mining has been conducted in Malmberget Sweden for centuries and the ore was originally transported by horses and reindeer 200 kilometers to processing mills near the coast of the Baltic Sea. In 1888 a railroad was completed and mining in large scale commenced. Surface mining methods were initially used but by the 1920’s all mining was performed underground, starting with different variants of open stop mining with drilling from the muck piles.

The Malmberget mine has adapted its mining methods and capacities over time as mining technology has improved., see example in Figure 1. Marklund (2015) provides an excellent summary of past mining experiences with a focus on Malmberget mine.

Currently, the mine utilizes the SLC method. Above level 1250 m, SLC is designed in a combination of transverse layouts of footwall drifts with crosscuts in wider sections and longitudinal layouts with drifts set out on the strike for narrow orebodies.

Concerning mining at greater depth, below level 1250 m (future mine), alternative mining methods or modifications to the existing one are being investigated. The preliminary results from the University of British Columbia (UBC) selection method indicated for the main orebodies, the suitability of Sub-Level Caving (SLC), Long Hole Open Stoping (LHOS) and Block Caving (BC).

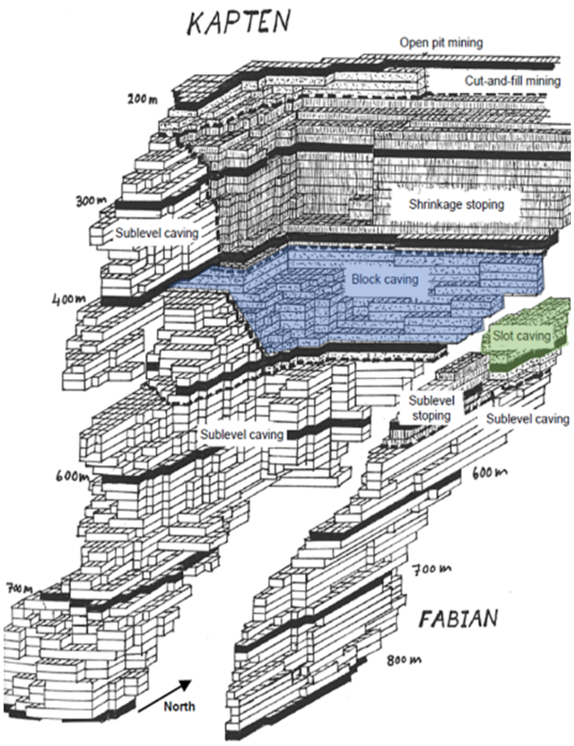

Figure 1 Mining methods used for Kapten/Fabian orebody, Malmberget mine (modified from Rutqvist & Sjöberg (1987)).

On top of that, a new mining method for efficient mining at great depth is under development by LKAB in collaboration with Montanuniversität Leoben, in Austria, the Raise Caving (RC).

2 EVOLUTION OF SLC OVER THE YEARS AND RISING CHALLENGES

LKAB mines are well-known as large-scale, highly technical advanced operations. Despite SLC was not pioneered by LKAB it is still associated as being worldwide most extensively used and developed in the Kiruna and Malmberget mines.

Based upon the settings of vast orebodies to be mined the choice of sublevel caving (SLC) has gradually established itself as the only underground mining method to be used. At the same time, opportunities for more selective adaptions to the actual conditions were missed out. Great temptation for "copy-paste" approaches of layout and design exists and caused also specific problems being recurrent through the years.

The actual SLC design and work processes were engineered throughout many years. The basis for this was continuous R&D work related to better understand the functionality of large-scale SLC in terms of last function, fragmentation and gravity flow (Larsson 1998, Quinteiro et al. 2001, Wimmer & Nordqvist 2018, Nordqvist et al 2020). This has doubtless also stimulated a broader use of SLC worldwide.

To remain profitable from ever increasing depths in an extremely competitive iron ore market the scale has changed substantially in order to keep specific drift development low, see Figure 2. This scale-up goes hand in hand with the technological progress in drilling and charging techniques.

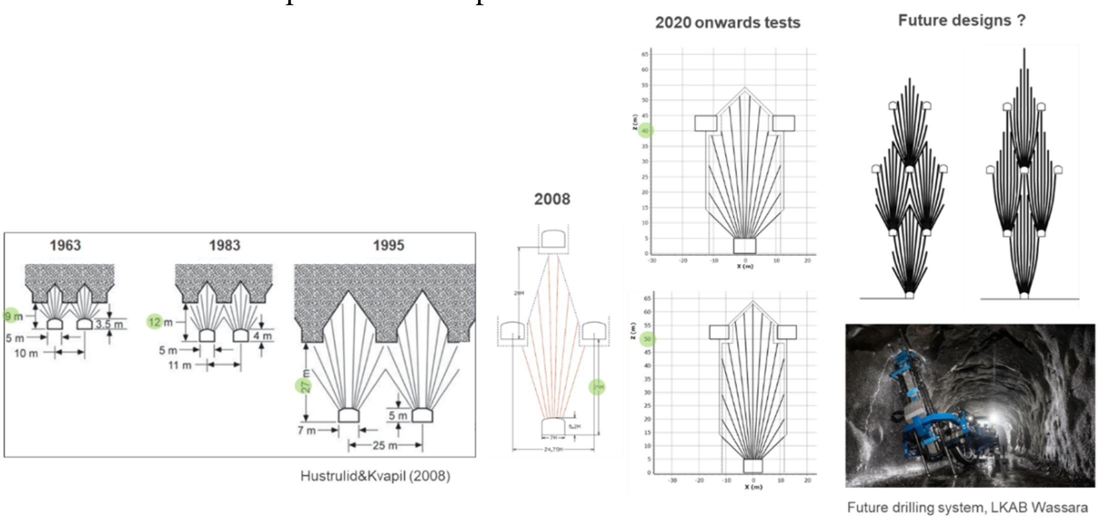

Figure 2 Evolution of scale and design for SLC rings, Kiruna mine.

The sole use of SLC has enabled a streamlining and optimization of processes and equipment to be used. Mines became rock-factory-like. Its application on large-scale and in transverse layout is forgiving in terms of recovery. However, critically compared to other SLC mines (Campbell 2022), also room for improvement exists.

The current trials of further upscale i.e. 40/50 m SLC heights (Quinteiro & Nordqvist 2022) suggest that the method has reached its physical limits. To fully utilize its potential, it requires an application to massive, almost vertical orebodies and in particular completed breakage in the opening phase. Failing to complete breakage implies not only a disruptive production but also a super-imposed high stress situation which is problematic for personnel and assets.

The original inherent advantage of SLC with division of works on several sublevels has meanwhile also turned into a downside. There are numerous active work areas and development needs to be done in hazardous abutment zones. Infrastructure gets potentially damaged several times prior to its actual use. Fragmentation issues often arise from boreholes being damaged and impossible to maintain open. The large buffer of development also prevents changes to be made based upon observations or changed condition.

Over the past 15 years, rock mechanical conditions have become increasingly adverse in both underground mines (Boskovic 2022, Dineva et al 2022, Ylmefors et al 2022, Savilahti 2014).

Overall, the hazards are related to increasing depth (stress), immense strike length (control of mining front, convergence) and its connectedness. Varying geometries and rock mass strength complicate further. It is also important to respect the mining method´s adaptability to fit local conditions in order to maintain cave flow and cave propagation.

Hence, rock mechanics and seismic consideration - based on sound geotechnical models - started to receive the greatest attention for mine design, production control, and operation practices. Its integration into mine plans with long-medium-short term schedules enables highly coveted reliable production prognoses. For example, a barrier pillar in Kiruna is formed, and sequences, layouts, support systems and procedures required for mining at greater depths and within the frame of continued SLC are intensively revised. A similar barrier pillar in Malmberget is currently under investigation with the purpose to address challenging squeezing conditions.

However, it is still uncertain whether these countermeasures will be sufficient or if further measures are required. These may concern a reduction of extraction ratio and/or further stabilization of the mining front. Given above aspects the question also arises as to whether SLC is the most suitable and only mining method to be further used and developed. BC/natural caving methods address some of the concerns specifically.

3 PREVIOUS BLOCK CAVING AND VARIANTS THEREOF IN LKAB

Kapten is one of the oldest and largest orebodies in Malmberget. Starting as an open pit and proceeding underground using mainly Shrinkage Stoping, worker safety in open stopes became an increasing concern (Blockrasbrytningskommittén, 1964). The host rock was competent while the ore was weakened by three sets of intersecting structural features. A geologist in 1957 predicted that the ore would fracture into 0.2-0.5 m pieces should the Block Caving mining method be used. A prediction that later proved largely correct. Block Caving was applied in the blue area of Figure 1.

3.1 First generation Block Caving, Block 1 and 2

These blocks were developed on Kapten level 460 m equivalent to around 300 m below ground surface. The block height was 50 m and the individual footprint dimensions around 100 × 100 m each although somewhat irregular, see Figure 3. The level was developed for train transport and loading from chutes directly to railway cars.

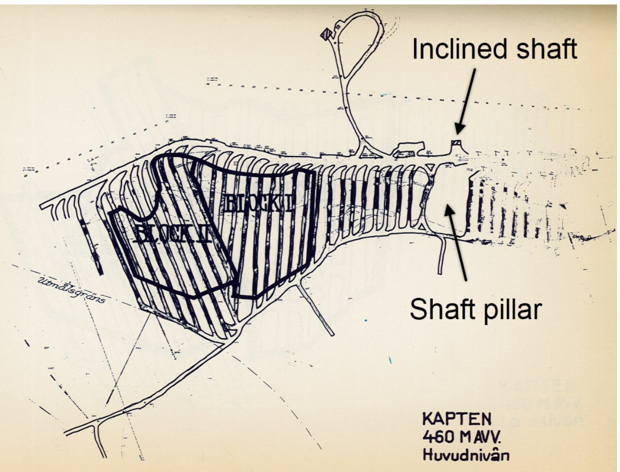

Figure 3 Kapten level 460 m. Inclined shaft and shaft pillar addressed in Section 3.3.

Both blocks were developed in a conventional way with parallel extraction drifts into the orebody every 10 meters. In the extraction drift draw points were constructed every 7 meters by chutes which were expanded upwards to craters. The craters were connected laterally around 7 meters above the floor of the extraction drifts. Undercutting was performed by drilling and basting the pillars between the rows of connected draw point craters, see Figure 4.

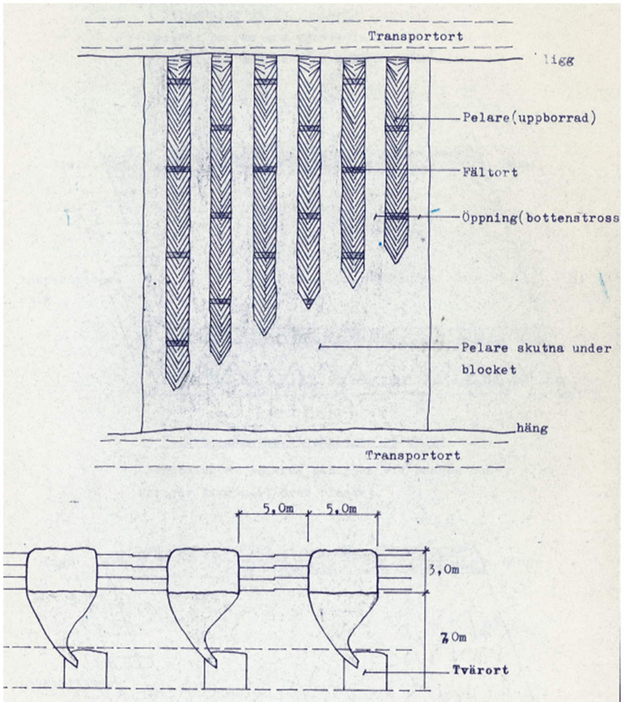

Figure 4 Draw points and undercutting procedure., Blocks 1 & 2.

Undercutting of Block 1 was completed by the end of 1960 and only one month later caving was detected on the level 50 meters above. Production started directly after undercutting and followed a strict draw control schedule throughout. Some large boulders were formed and detected higher up in the block but by the time they reached the draw points they had been fractured according to plan. The frequency of boulders in need of secondary handling was considered normal and the Block Caving operation in general functioned better than had been expected.

In order to mine the ore closest to the foot wall two vertical raises were constructed from where the remaining un-caved ore could be blasted. The sharp angle on one side of Block 1 created an issue with caving but that was also solved by blasting from the raises.

There were no notable stress related issues on the extraction level during production. However, a two years production stop resulted in significant damage to the extraction drifts which required rehabilitation before production could be resumed. Figure 5 shows current condition of the foot wall drift and two extraction drifts in 2023, around 60 years after production ended.

Figure 5 Footwall drift (right) and extraction drifts (left) on Kapten level 460 m.

Undercutting of Block 2 was completed by the end of April 1964 and also here the caving reached the level 50 m above quickly. In block 2 dedicated measures were taken to monitor the caving process. In the upper part of the block, horizontal boreholes across the orebody were painted internally and pre-tensioned steel wires were installed in them. Stress cells were installed in the hanging wall, below the extraction level and in pillars between draw points on the extraction level.

Also in Block 2 vertical raises were constructed in the footwall from where remaining un-caved ore was blasted, see Figure 6.

Figure 6 Laser scanning of accessible areas in Block 2 including foot wall raise.

3.2 Second generation Block Caving, Block 3

This block was developed on Kapten level 510 m equivalent to around 350 m below ground surface. Block 3 is situated directly below blocks 1 and 2. The block height was 50 m and the footprint dimension around 150 × 100 m, see Figure 7. Originally draw points with chutes were planned but due to poor rock conditions and cost-efficiency reason the plans were changed. The level was finally developed for LHD:s instead of trains and the drifts were bigger than those in previous blocks.

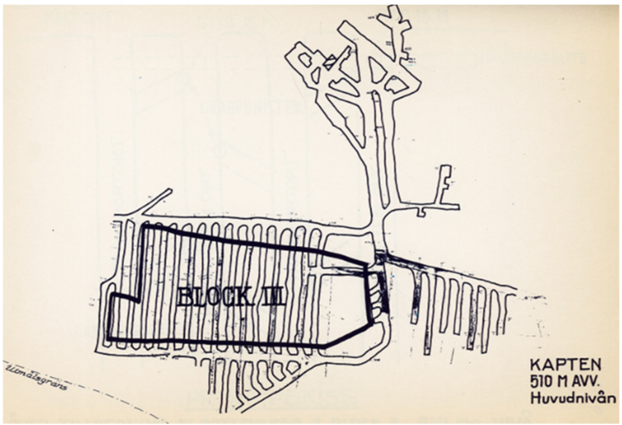

Figure 7 Kapten level 510 m.

Parallel drifts were driven into the orebody every 10 meters. Every second drift functioned as an extraction drift and every other second drift was used for undercutting by first creating an opening slot next to the hanging wall and then blasting the whole drift in a fan-shaped pattern, see Figure 8. This means a dedicated undercut level was not used.

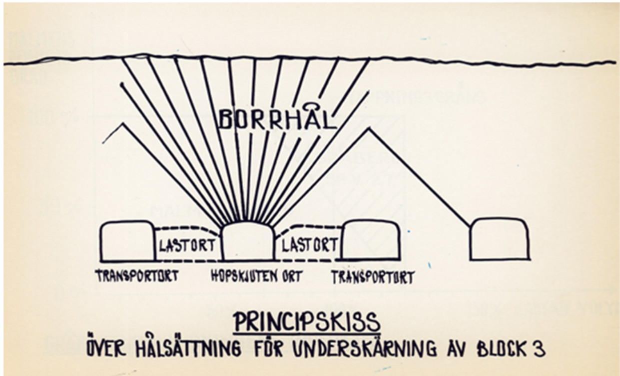

Figure 8 Undercutting procedure Block 3.

Connections between the extraction drifts and blasted drifts were established every 10 meters and were used for loading, see Figure 9 and Figure 10.

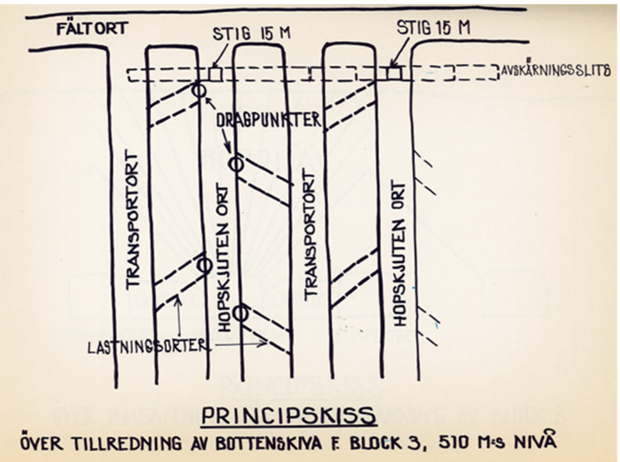

Figure 9 Loading infrastructure in Block 3, Dragpunkter = Draw points.

Figure 10 Laser scanning of accessible areas in Block 3, including one connection between extraction- and blasted drift.

It is noted that a very similar undercut method as in Block 3 was later used in Radenthein mine Austria, see Figure 11. Also, the footwall was undercut with the same purpose as for the Slot Blocking method described in next section. Reportedly this horizontal undercut layout may add stability under high stress conditions and furthermore simplify development and reduce costs (Weiss, 1981). Laubscher et al. (2017) commented on the other hand that optimum orientation of the throughs with respect to stress direction is especially important and that the pillars which extraction drifts run through lack lateral support, making this the weakest option for extraction level design. Experiences from Radenthein mine include that problems with draw often affected production at several drawpoints.

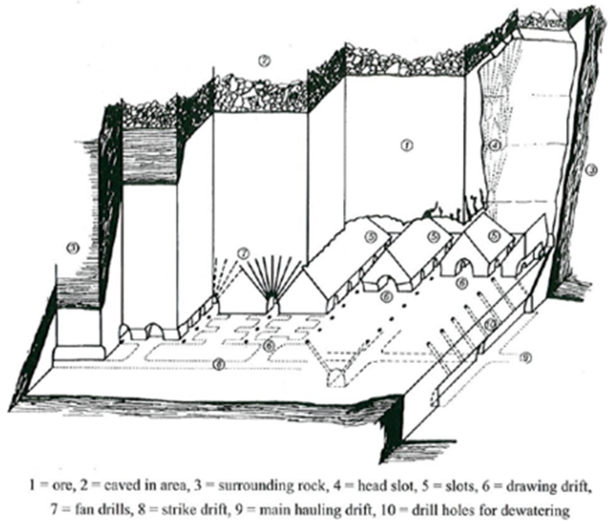

Figure 11 Mining operations layout, Radenthein mine.

3.3 Slot Blocking, Kapten shaft pillar

Following the largely successful Block Caving experiences in Malmberget mine, focus turned to a highly stressed pillar in front of an inclined shaft next to Kapten orebody. The pillar was situated between two previously mined out areas as seen in Figure 3 and Figure 12. The pillar had been left to protect the shaft.

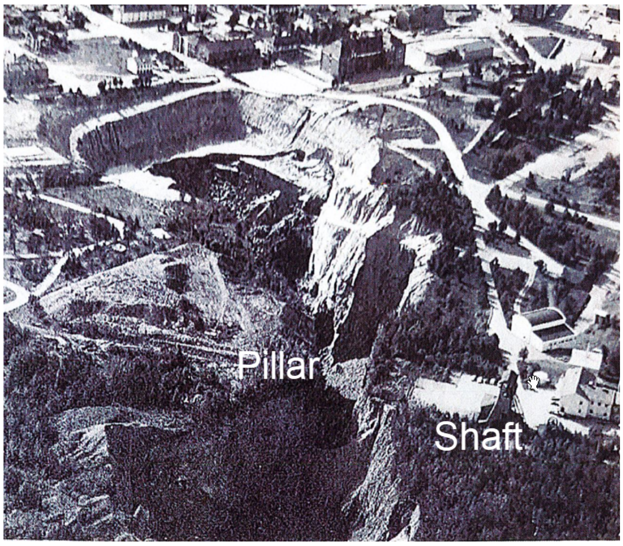

Figure 12 Aerial view of pillar and shaft in Kapten orebody.

Several drifts in the upper part of the pillar had collapsed and the mineralization was not extractable by any known mining method for several reasons, economics and safety being two of them. Instead a new form of Block Caving, called Slot Blocking or Slot Caving, was applied. The pillar was about 160 m high, 50-60 m wide, 30-40 m thick and dipped 65°-70° to the south or left in Figure 12. The idea was to undercut the footwall and to keep the opening free by loading, so that ore could slide down to draw points at the bottom of the pillar. A very fast extraction would be necessary.

Undercutting was planned by using two vertical 150 m long raises along the footwall contact. Horizontal drifts were to be established intersecting these raises at 20 m vertical intervals parallel to the orebody strike. From these drifts, holes would be drilled parallel to the raises and subsequently blasted, see Figure 13.

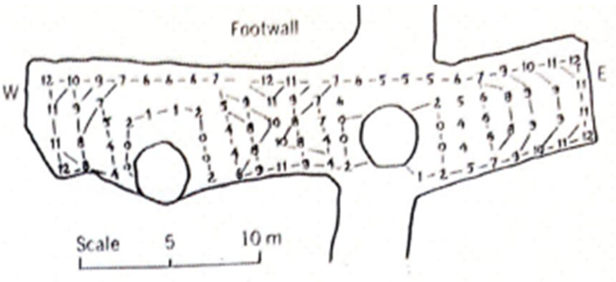

Figure 13 Drill hole plan for slot blasting.

Draw points were to be established on levels 460 m and 450 m on the foot wall side, four on each level in a staggered design. It was anticipated that these two loading levels would achieve a very high output and facilitate boulder handling as well as secondary blasting. The complete layout and sequence are shown in Figure 14.

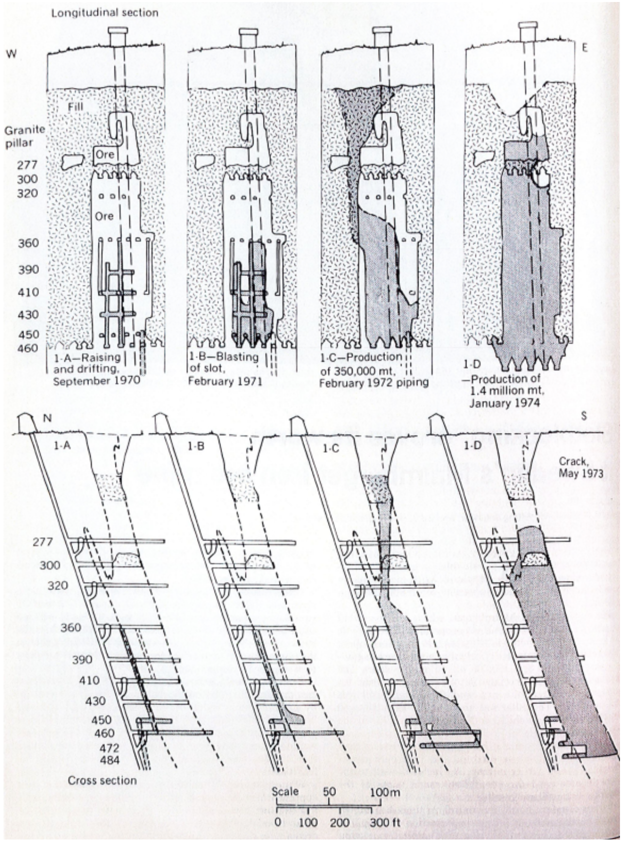

Figure 14 Slot Blocking sequence and principle in Kapten shaft pillar.

Due to poor rock conditions, development for undercutting was problematic. The raises were only possible to extend to 80 and 100 m respectively, compared to the planned 150 m. One of the horizontal drifts also collapsed. The slot was finally blasted by April 1971. Some caving began immediately but general caving was delayed for about six months since the slot had not been opened to its full planned height.

Development results for extraction of the pillar were not favorable and the cost was high due to poor rock condition. Production results and production cost on the other hand were very favorable. The ore characteristics generally promoted caving while the rock pressure and the open slot reduced the number of boulders. Furthermore, the staggered draw point design facilitated boulder handling as expected. This led to the assumption that Slot Blocking would be useable in Malmberget for 40-50 m wide orebodies dipping more than 70°. "Because of the splendid economy that resulted during slot blocking of the pillar at Malmberget, LKAB is subjecting the method to thorough analysis.

Among the advantages of the method are all those of block caving-in addition to highly mechanized development and good ventilation possibilities” (Haglund and Hedberg 1975).

3.4 Slot Blocking, Fabian orebody

The Slot Blocking method was then applied in the Fabian orebody which is situated directly east of Kapten, see green area in Figure 1. The orebody was 400 m long, 40 m wide and the block height 170 m. A vertical undercut slot was constructed by longitudinal stoping of 8 drifts along the footwall, see Figure 15. Horizontal undercutting was done by two Sublevel Caving crosscut levels at the bottom on 548-560 m and drawpoints were created by retreating the upper level crosscuts a little more than the lower. Loading was performed with access from the hanging wall due to lack of infrastructure on the foot wall side. Furthermore, it should be noted that loading was not planned nor performed vertically along the whole footwall contact, which would have been the case with the Inclined Caving mining method (Laubscher et al., 2017).

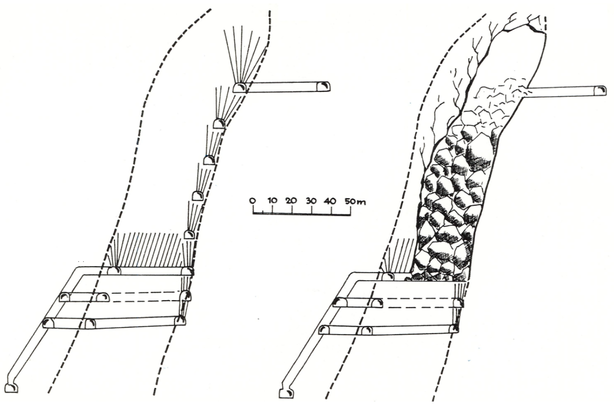

Figure 15 Slot Blocking undercuts (left) and resulting effect (right).

Unfortunately, the hanging wall or the back did not cave. Fragmentation was poor, requiring extensive secondary blasting and eventually an open stope was formed supported by a natural arch (Holmberg et al. 1982, Rustan 1995). It is obvious that the horizontal stresses across the orebody were cut off, which would not have promoted fracturing. The hydraulic radius of the horizontal undercut was limited (below 20) and in addition, the orebody was probably not highly stressed and pre-fractured as was likely the case with Kapten shaft pillar. To avoid a sudden collapse and potential air blast, a pillar was left in the middle of the orebody to isolate the void. The other side of the pillar was then mined using Sublevel Stoping.

It is the authors of this article’s belief that this failure may be part of the reason for not continuing with natural caving mining methods in Malmberget mine, although the original Block Caving concept was not to blame.

4 RESUMED BLOCK CAVING STUDIES

More than half a century after the first implementation of Block Caving in LKAB mines, the method has become appealing again.

4.1 BC Assumptions, design parameters and input data

In 2014, SRK Consulting (UK) conducted a study to investigate the potential of Block Caving Fabian ore body at depths between levels 1250 and 1500 m, see Figure 16.

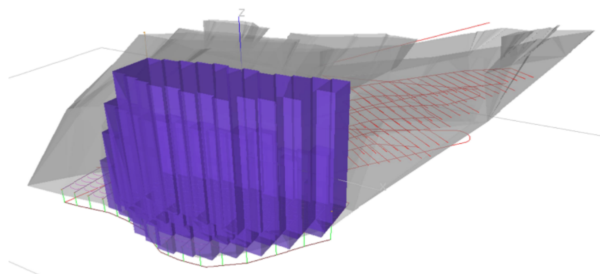

Figure 16 Isometric view of the block cave (SRK 2014).

Before 2017, only 4 km of total geotechnical drilling was conducted below 1250 m level at Fabian orebody. However, after the year 2017, more than 86 km of drilling were processed, leading to a significant improvement in the geotechnical knowledge of the orebody.

Geotechnical logging systematically captures the elements of the drill core that enable a full geotechnical model to be constructed. When logging the geotechnical features, rock strength data, fracture attributes, major structures, and orientation data are all collected. Alongside recent and historic drill core data, additional data sources are drift mapping data from the operational areas. These data sources allow for the calculation of rock mass classification systems of RQD, GSI, Q Prime, RMR89, and IRMR.

Eight years after the first one, in the 2022 scoping study, based on the updated geological and geotechnical information, a conceptual mining plan was developed with a three-lift scenario internally by LKAB to estimate possible productivity rates and costs, see Figure 17 and Figure 18.

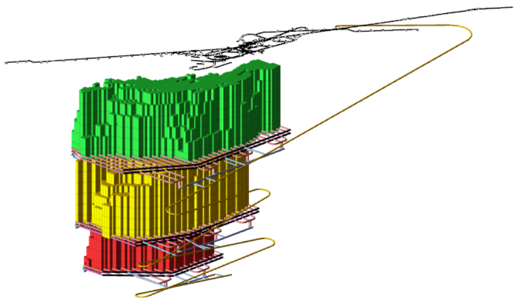

Figure 17 Conceptual design of BC (Bergström & Papagianni 2022).

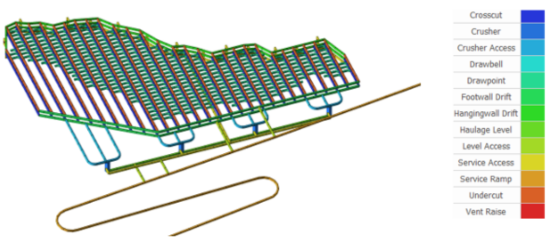

Figure 18 Extraction level 1550 (Bergström & Papagianni 2022).

Following the scoping study, extensive technical assessment was needed. In collaboration with SRK Consulting Inc (Canada), a new scoping level study was conducted for the Fabian deposit. SRK used Footprint Finder (FF) analysis to establish the most economical footprint for a base case two-lift scenario as shown in Figure 19 and Figure 20.

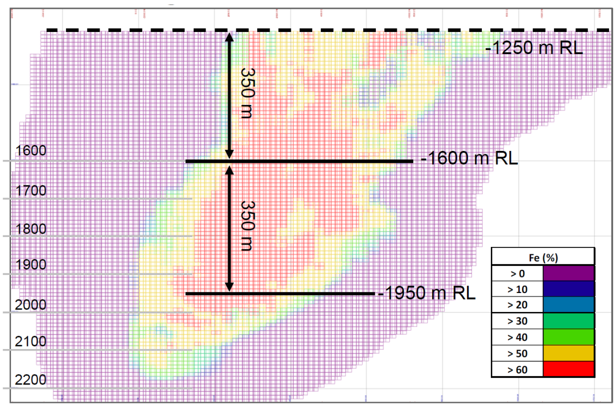

Figure 19 Footprint elevations (SRK 2024).

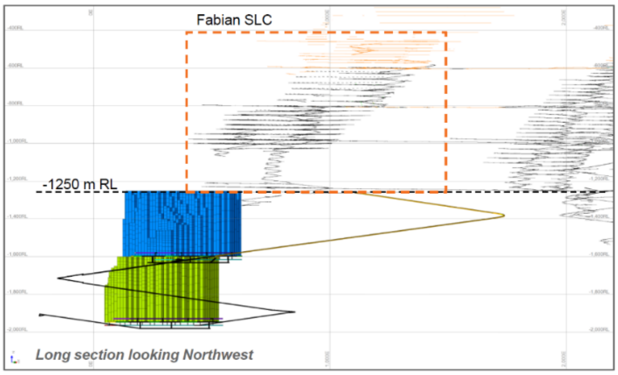

Figure 20 Block Cave Lifts - Access From -1250 m RL (SRK 2024).

Several geotechnical design criteria were analysed and investigated:

- Caveability - hydraulic radius
- Caving rate - recommended production rate curve (PRC) values
- Fragmentation, secondary breakage, and preconditioning
- Subsidence angles
- Undercutting strategy and design
- Extraction layout and recommended dimensions
- Cave initiation location and advance rate

4.2 Recommendations for next steps

- Optimized BC mine design
- Mine design for Fabian ore outside of BC footprint, possibility of hybrid model with sub-level shrinkage (SLS) and sub-level caving (SLC), see Figure 21.
- Materials handling and Ventilation trade-off studies should be performed to determine the most cost-effective options

- Assessment of preconditioning requirements
- Evaluation of Fabian as a stand-alone mining operation with independent access and infrastructure

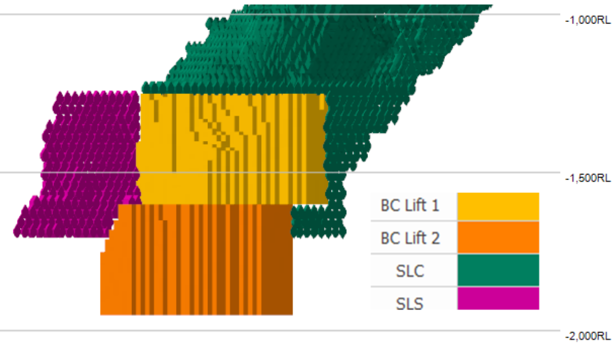

Figure 21 Potential hybrid model.

5 SUMMARY

Block Caving may once again become a viable option for underground mining in LKAB, more than half a century after last time the method was applied. There are inherent advantages with BC compared to SLC, and indications that upscaling of SLC may have reached its physical limits emphasize the need to investigate other options. However, mining depth still poses challenges. There are very few block caves currently operating at depths equivalent to the first potential lift in Fabian and none at all equivalent to the second lift. Also SLC is untested for those depths. It is therefore likely that LKAB will continue pioneering the field of underground mass mining for many years to come.

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