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Investigation and determination of optimal extraction rates during "skalning" (along hanging wall contact) at LKAB Malmberget mine

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ABSTRACT

Several draw control studies and strategies have been carried out in many sublevel caving operations globally to optimize extraction rates, improve recovery, minimize dilution, and reduce mining costs. In recent years, the draw control studies, strategies, and practices have looked beyond grade control (dilution) and tonnage of ore that may be recovered. The working environment and safety of the loading, charging, blasting crew, and other personnel may also affect and play a significant role in the amount of ore to be loaded from a ring, particularly blasted rings along the hanging wall contact that are not yet in contact with the caved material on a level above (referred as "skalning" in Swedish mining terms). This article describes the investigation and determination of optimal extraction rates when loading in the "skalning" areas at LKAB Malmberget mine as well as for "specific cases of skalning" where some entire drifts are outside previously mined areas (cave contact). The determined and recommended optimal rates include; 35% - 70% for the "skalning" zones with subgroup divisions where applicable, 70%-90% for contact with caved material on one level above, and >90% - free loading for contact with two levels above (towards the footwall for maximum recovery, but general guidelines and loading criteria at the mine still apply). The results have been discussed and specific recommendations to loader operators, implementation of the assessment, and further investigation on the material flow prediction and simulation have been given such that improvements could be made on the optimal rates where needed.

1 INTRODUCTION

Sublevel caving (SLC) is a mass mining method used for the extraction of mineral deposits based upon the utilization of gravity flow of blasted ore and caved waste rock (Kvapil, 1998). The method is highly advantageous because of its high productivity and the room it creates for mechanized operations. However, one of the major disadvantages of the mining method is the dilution of the ore as the waste materials cave to fill the temporary void created from the ore extraction. This has led to several draw control studies and strategies in many sublevel caving operations globally (Shekhar et al., 2016; 2017; & 2018; Sarin, 1981, Gustafsson, 1998; Selldén and Pierce, 2004; Castro et al., 2009; Chitombo, 2010). The goal of these studies and strategies is primarily to optimize the extraction rate of the mine, improve recovery, minimize dilution, and reduce mining costs. The extraction rate can be defined as the ratio of the actual tonnage of ore extracted from the blasted ring to the planned tonnage of the ring. The ratio is sometimes also expressed in percentages. For instance, a ratio of 0.65 can be expressed as 65% actual tonnage extraction to the planned tonnage, although this is in most cases above 100% in LKAB's mines and other SLC operations.

Nevertheless, in recent years, the draw control studies, strategies, and practices have looked beyond grade control (dilution) and tonnage of ore that may be recovered from the blasted rings. The working environment and safety of the loading, charging, blasting crew, and other personnel may also affect and play a significant role in the amount of ore to be loaded from a ring, particularly for blasted rings along the hanging wall contact that are not yet in contact with the caved material on a level above (referred as "skalning" in Swedish mining terms). Figure 1 shows an example of "skalning" for SLC operation in general.

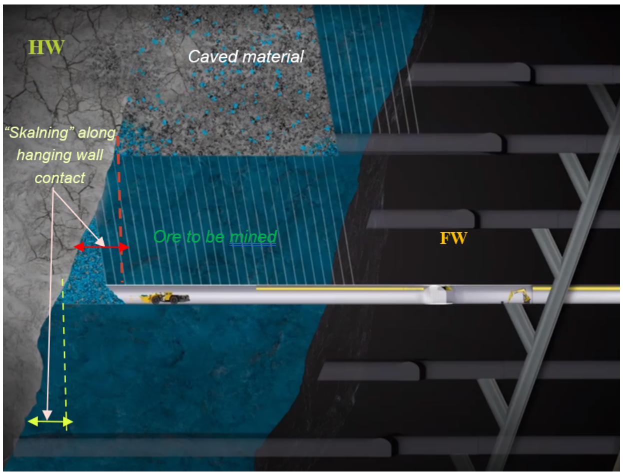

Figure 1 An example of "skalning" in SLC operation (After Epiroc, 2019).

An example of a "skalning" situation in one of the orebodies (ViRi level 930, drift 7890) at LKAB Malmberget mine is also shown in Figure 2. Different "skalning" techniques in the Kiruna mine have also been investigated (Wimmer, 2012; Wimmer et al., 2012).

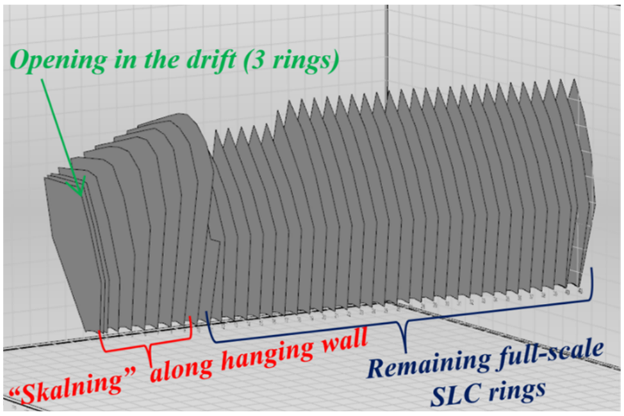

Figure 2 "Skalning" at ViRi level 930 drift 7890 at Malmberget mine.

High extraction rates from these blasted rings may lead to voids or cavities at the draw points which will likely increase the risk of rock fallouts into the void and pose a potential danger to the loading, charging, blasting crew, and other personnel. An investigation therefore is needed to determine an optimal extraction rate in these areas that improve the safety of the workers and maximize recovery, particularly at levels below.

It is important to note that recovery greater than or equal to 100% from rings in the "skalning" areas cannot be reached from a practical point of view. This is because blasting is difficult, and often full heights of the rings cannot be reached. The upper part of these rings in the "skalning" areas might only get some kind of precondition effect since there is simply no free face for the blastholes available (E.g., in a "rapid" scale-up of the rings when the hanging wall contact is steeply inclined). The optimal recovery mentioned here emphasizes the extraction rate in "skalning" areas and situations where drifts are outside the established cave footprint, ensuring that not too much ore is extracted or left behind (due to safety concerns for charging personnel and seismic activities).

1.1 Case study mine

The Malmberget mine (MUJ) consists of about 20 orebodies (see Figure 3) with a surface footprint area of approximately 5km in the E-W direction and 2.5km in the N-S direction (Lund, 2013). Out of the 20 orebodies, about 15 of them are currently being mined at different production rates. The ore is composed of magnetite (95%) and hematite (5%), and the average grade for the different ore bodies varies from 49% to 63% Fe (Lund, 2013). The mine is divided into two parts: Östra Fältet (eastern fields) and Västra Fältet (western field). The ore bodies in the eastern fields are composed of massive magnetite ores with a current known depth of 1600m and provide 80% of the total production. The western fields consist of small magnetite-hematite deposits with a currently known depth of 950m (Lund, 2013).

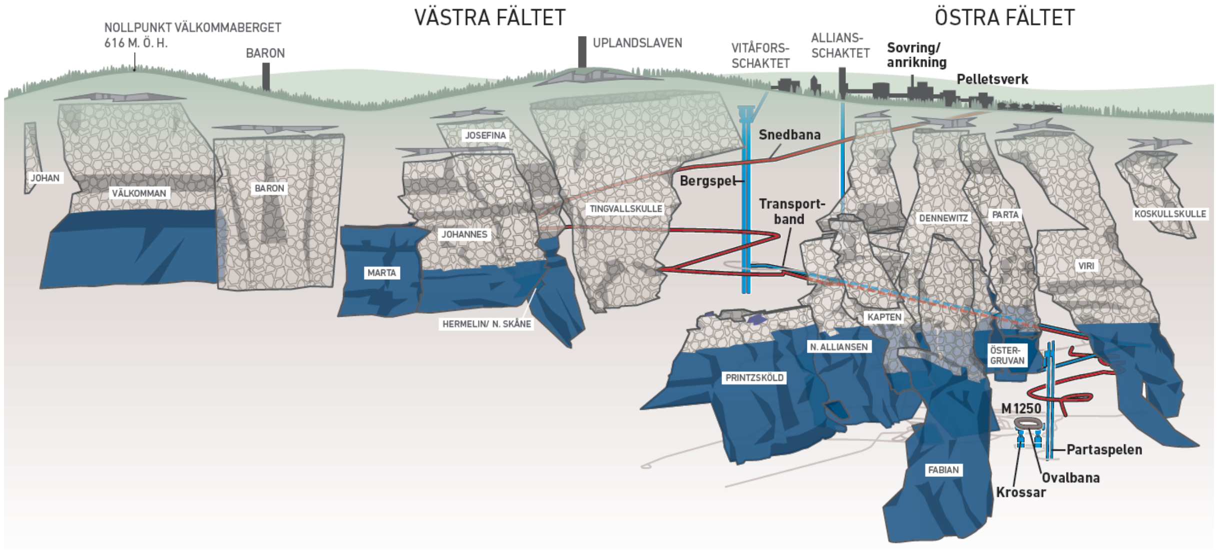

Figure 3 Overview of Malmberget mine with different orebodies.

1.2 Background and motivation

"Skalning" is found in all parts of the Malmberget mine before contact with the caved material on the level(s) above is made. After the opening rings (mainly slot rings with Ø700mm raise borehole opening) are completed in a transverse drift, the blasting in the drifts starts with the rings that are along the hanging wall contact (see Figure 1 and Figure 2) and progresses toward the footwall drive. Currently, at MUJ, there are no specific extraction rate recommendations with regards to limiting the amount of loading or extraction rate when loading in these "skalning" situations, but the same criteria as for other rings are applied, i.e., at least 80% extraction rate. It should also be noted that longitudinal SLC is also used occasionally in MUJ, but this was not covered.

The working environment for charging and loading can deteriorate if there is empty space in front of the next ring, which increases the risk of falling rocks injuring the chargers. This is because charging personnel are required to work close to the brow in general, and in this case, there is little protection against falling rock, as there is a gap at the brow. This may also lead to rapid stress redistribution around the ring and at worst seismically induced rock falls, although this may be difficult to prove unless further investigations are carried out. It could most likely also lead to gravity/subsidence-induced breakouts.

In addition, there are also times when entire drifts should be loaded with loading restrictions because they are outside of already mined areas on a level immediately above (see Figure 4).

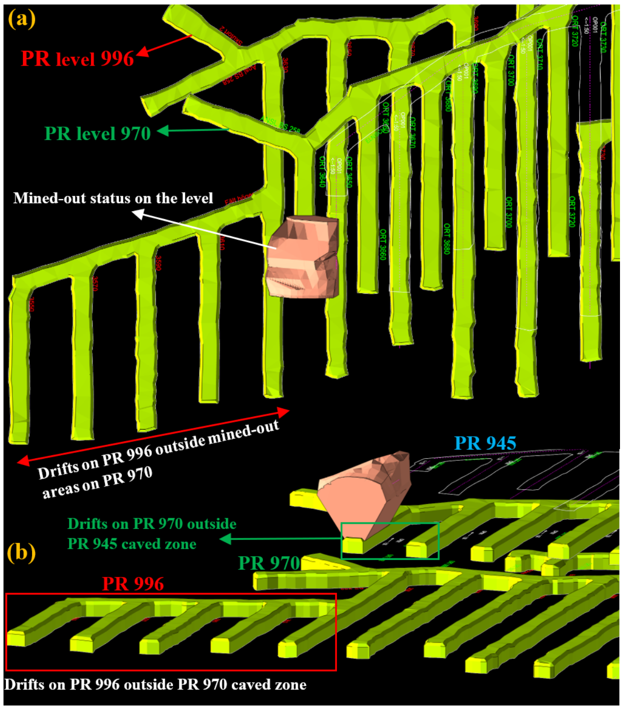

Figure 4 Layout of drifts outside already mined areas at Printzsköld (PR) orebody (a) Top view (b) Isometric front view

This is because a cave is not developed from the level above at all, hence extraction rate limitations must apply for all the drifts outside the caved zone, but also still applicable for several levels below. This might be considered a specific case of “skalning”. It concerns basically the SLC ramp-up in non-daylighting orebodies. In the Kiruna mine, this would e.g., apply to the northern part, where the “Sjömalmen” orebody and its northernmost drifts have no cave developed above.

In MUJ, on Printzsköld (PR) orebody level 970 where two drifts were located outside PR level 945 (see Figure 4), the effect was a significantly increased seismic activity as well as a few major seismic events (ML>1). An investigation of the causes and connection of the events to the loading rates was carried out (Anderson, 2019). A summary of the result for accumulated tonnage in drifts 3640-3880 (including the two drifts outside PR level 945) on the level plotted against the cumulative number of events over the period 2018/11/01 – 2019/12/31 is shown in Figure 5.

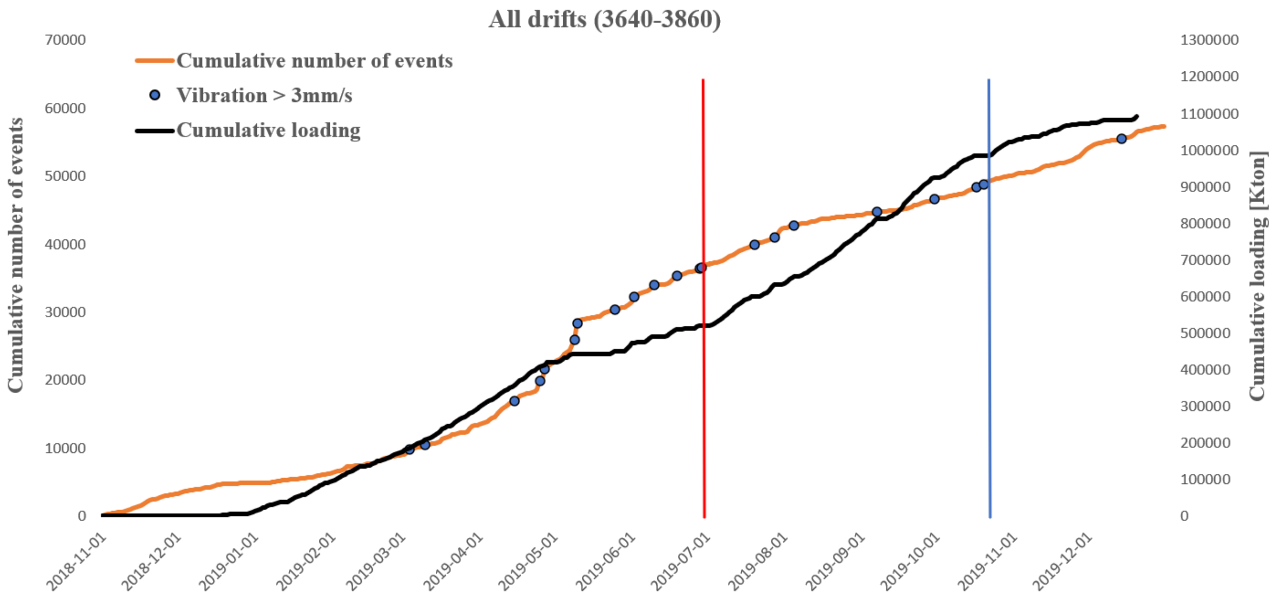

Figure 5 **Accumulated loading against cumulative number of events (2018/11/01 – 2019/12/31). Blue dots indicate significant surface vibrations. The red line indicates the imposition of a 500-ton/drift loading restriction. The blue line indicates the date of the breakthrough of the cave to the ground surface (Andersson 2019).**

The extraction rates in these two locations were 114% and 121%. A limitation in the loading rates in such locations could have resulted in low seismic activities and perhaps even fewer large seismic events. This is evident from Figure 5 where the introduction of a restriction on tonnes per drift (early July) was successful as the number of events causing significant surface vibrations was lower in the second half of 2019. Detailed follow-up report on the effect of the implemented measures and proposals when the entire drifts were loaded have been presented (Jonsson et al., 2020). Västra Printzsköld (PR) orebody will be a special case in the mine where at the current level 996, five whole drifts will be outside the previously mined areas on level 970 (see Figure 4).

Loading in the two drifts on PR level 970 located outside PR level 945 caved zone was investigated to have generated several seismic events with ML>1 in Printzsköld's western hanging wall with subsequent large vibrations (see Figure 6). From Figure 6, the shortest and longest distances of the seismic events with ML>1 above PR level 970 into the HW/caved zone contact were about 194m and 394m, respectively. The mining of the five drifts on PR level 996 will likely give a similar or greater response in the crown pillar since the mining depth has increased and the cave itself has caused the stresses to go under and around the end of the orebody to a greater extent than before (Tallfjärd, 2020).

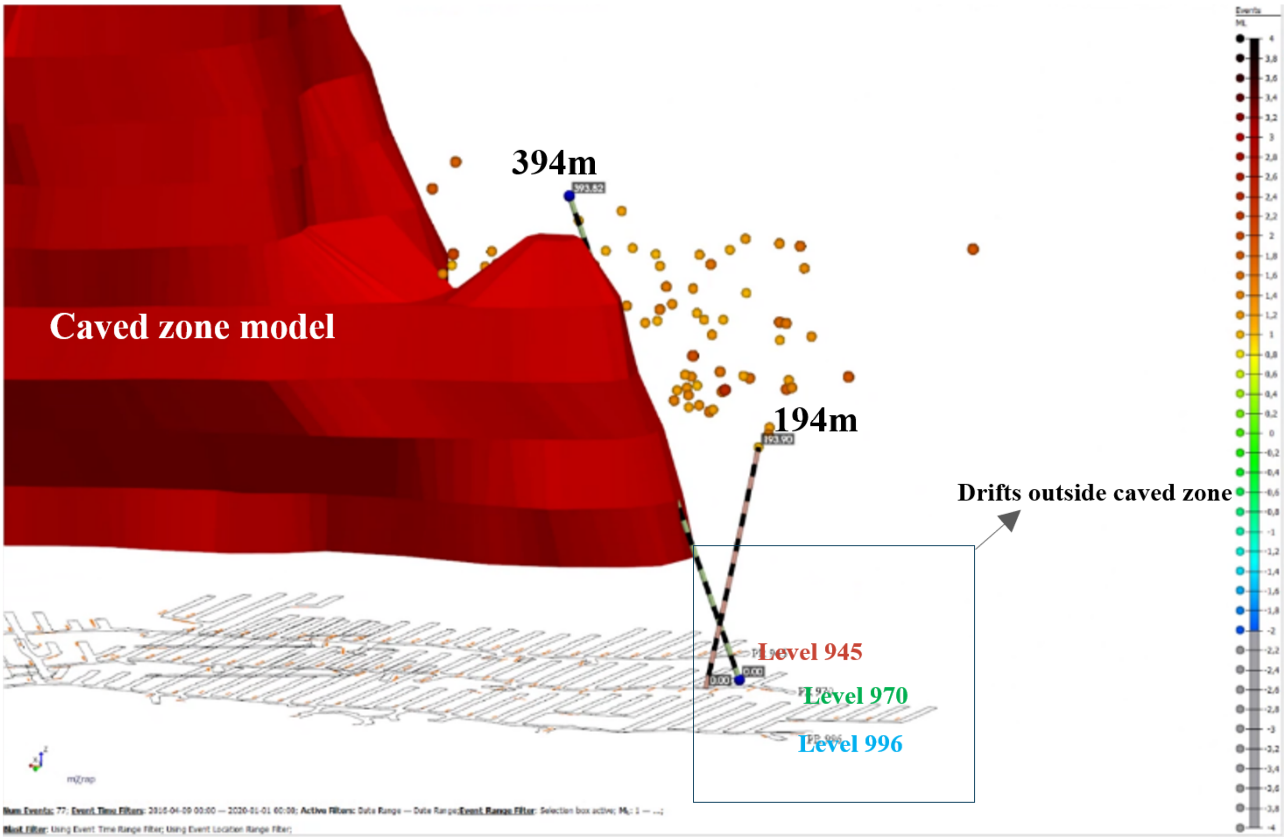

Figure 6 Seismic events with ML>1 between about 200-400m above PR 970 level into the HW/caved zone contact (2018).

A similar situation occurs in Viri satellite ore in the mine, where there has been considerable seismicity. The rings will also not contact the cave at the level above, so all rings in these drifts should be loaded as a "specific case of skalning" with restriction less than the criteria for normal rings i.e., at least 80% extraction rate (Tallfjärd, 2020) but no specific extraction rate recommendations have previously been made regarding this restriction.

2 OBJECTIVES AND AIMS

The purpose of the study was to investigate and determine optimal extraction rates in general in the "skalning" areas at MUJ, as well as for special cases like the Printzsköld areas where some entire drifts will be mined outside previously mined areas (cave contact), so all rings in these areas should be loaded as "specific case of skalning" with restriction. This is because this specific case still exists in the mine today. The aim is to provide a guideline for loading in the "skalning" areas that optimize recovery, temporarily use the remaining blasted but unloaded ore as a cushion (shock absorber) for vibrations from seismic events, and also serve as a "temporary caved fill support material". In SLC mining, a temporary void is created from the loading of the blasted ore while the caved waste material fills the void created by the ore extraction. The "temporary caved fill support material" mentioned here means that the void that is to be filled with caved waste material is temporarily replaced with the remaining blasted but unloaded ore. This is anticipated to lower seismic activities and perhaps even lead to fewer large seismic events at MUJ.

2.1 Limitations

The results from this investigation are limited to the assessment of loading and operational challenges at MUJ, data analysis from specific areas (Printzsköld and ViRi), and recommended extraction rates for implementation in the

Malmberget mine. Its applicability outside MUJ may need further re-assessment and possible modification to the recommendations outlined in this paper.

2.2 Background data or information

Literature studies on the loading operations and current draw control strategy at MUJ were carried out. Internal documents, protocols, personal communication, MUJ production data (2012 - 2021), and current internal guidelines and loading criteria at MUJ were also used for the assessment. Findings, comments, and inputs from these activities were then used as the base case to carry out the assessment. The assessment of the optimal extraction rates considered an actual loading condition for ViRi orebody level 930 drift 7890, level 882 drift 7890, and level 906 drift 7900.

3 METHOD OF ASSESSMENT

3.1 Optimal extraction rate

In general, the angle of the ore contact along the hanging wall may determine the number of rings that will not yet be in contact with the cave material on a level above and hence should be blasted and loaded as “skalning” (Falksund, 2015). If the angle of contact is very steep (≈ >60^0), the “skalning” area may be very shallow/short before contact with the level above. On the other hand, a shallow angle will lead to a larger “skalning” area into the drift before contact with one or two levels above (see Figure 7). For such a scenario, the extraction rates in the rings along the hanging wall could be further divided into subgroups 1, 2, and 3. The extraction rates for the groups are selected accordingly as the angle gets steeper into the drift (see example illustration in Figure 12). It is also worth mentioning that at MUJ, it is a common practice that half of the drill rod length, or about 0.5m extra hole length is drilled into the hanging wall contact (see Figure 8). This would be beneficial, in reaching better to full height in “skalning” situations. This has been confirmed from the opening/“skalnings” survey in the Kiruna mine (KUJ) (Wimmer, 2012; Wimmer et al., 2012). Once the contact zone is exposed, further rings have easier “to climb” in height.

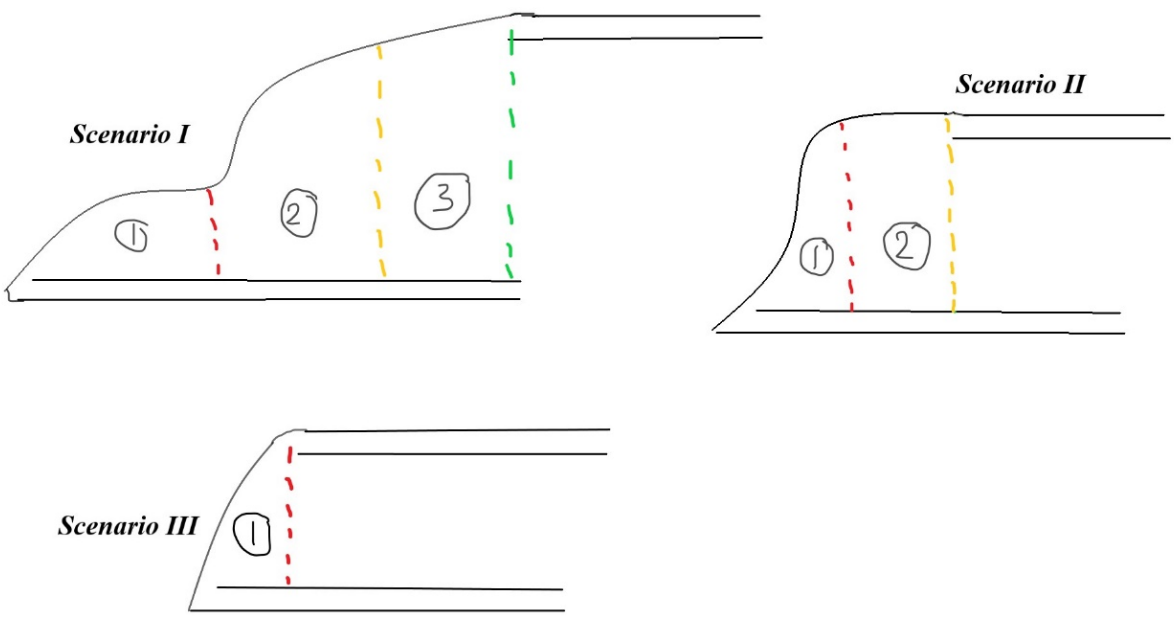

Figure 7 “Skalning” scenarios along hanging wall contact. 1, 2, and 3 represent the further division of the extraction rates for the rings in the “skalning” areas into subgroups.

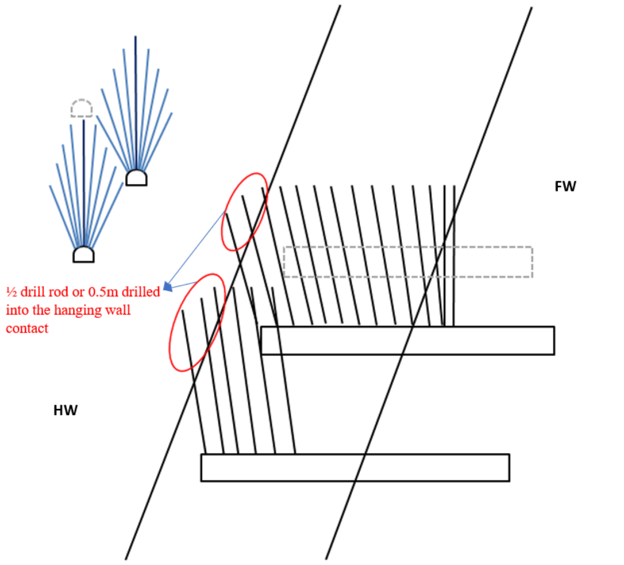

Figure 8 Drilling of a half rod into hanging wall contact in MUJ (Falksund, 2015).

Another factor that takes place in the determination of a steeper or shallower "skalning" area is the standard production ring planning aspect which could be defined as the dip angle from the cave contact from the upper level (see Figure 9). This method has been standardized in MUJ production drill planning and it is defined as -18.5^0 dip (even in steeper orebodies due to observed issues of fragmentation and mucking) starting from the cave contact point on level above in the center axis and stretches down to the planned opening "skalning" start point (Akkan, 2023).

The purpose of using this is to create a smooth vertical curved profile above the opening rings (sometimes referred to as slot rings) and then follow the rings to determine the vertical boundary limit on the "skalning" area up to cave contact. This method also ensures good operational blasting performance and thus beneficial mucking sequences.

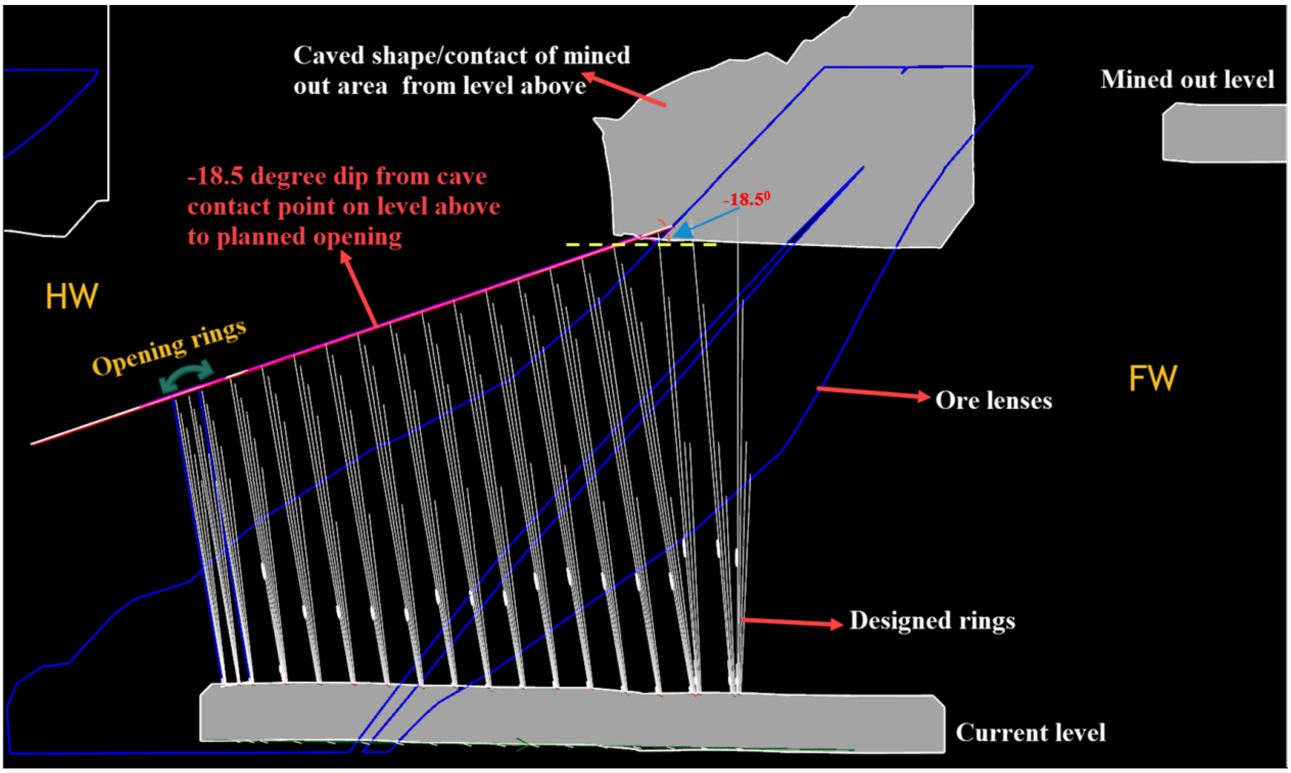

Figure 9 Standard production ring planning in MUJ (courtesy Yunus Akkan)

From the schematic illustration in Figure 7, the 3D model view of the ore contacts for ViRi in MUJ was observed (see Figure 10). From Figure 10, the red dashed lines indicate variations in the "skalning" areas to be loaded out based on the angle of the ore contact along the hanging wall before contact with the caved material on a level directly above. It should be noted that there are multiple cave contacts and "skalning" areas, and not only where the red and green arrows point to in Figure 10.

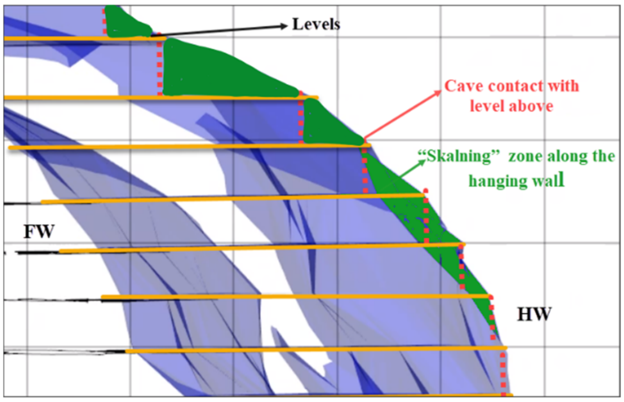

Figure 10 3D model view of the ore contacts for ViRi in MUJ.

An example of an actual loading condition for an area that has been loaded out (with and without "skalning") was presented for ViRi level 930 drift 7890 applying the recommended extraction rates outlined in this report (see Figure 11 and Figure 12) based on the analysis of MUJ production data (2012 - 2021) and current MUJ internal guidelines and loading criteria (see section 6).

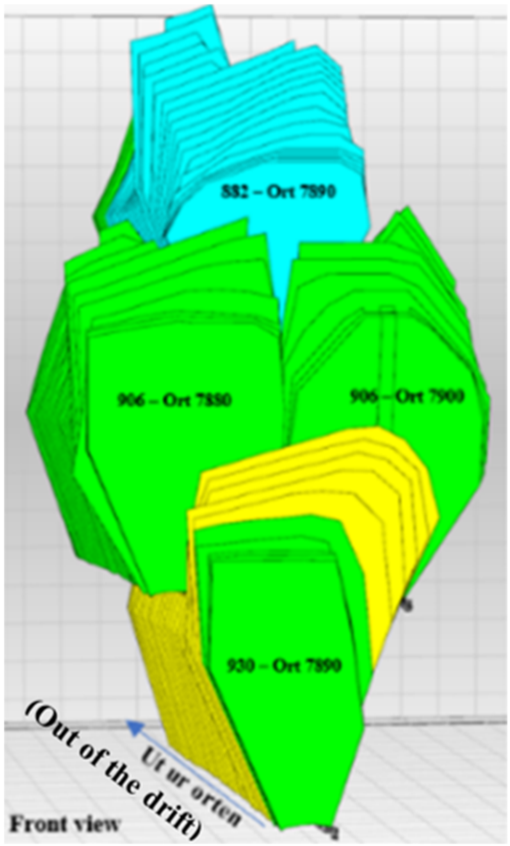

Figure 11 ViRi level 930 drift 7890 (front view).

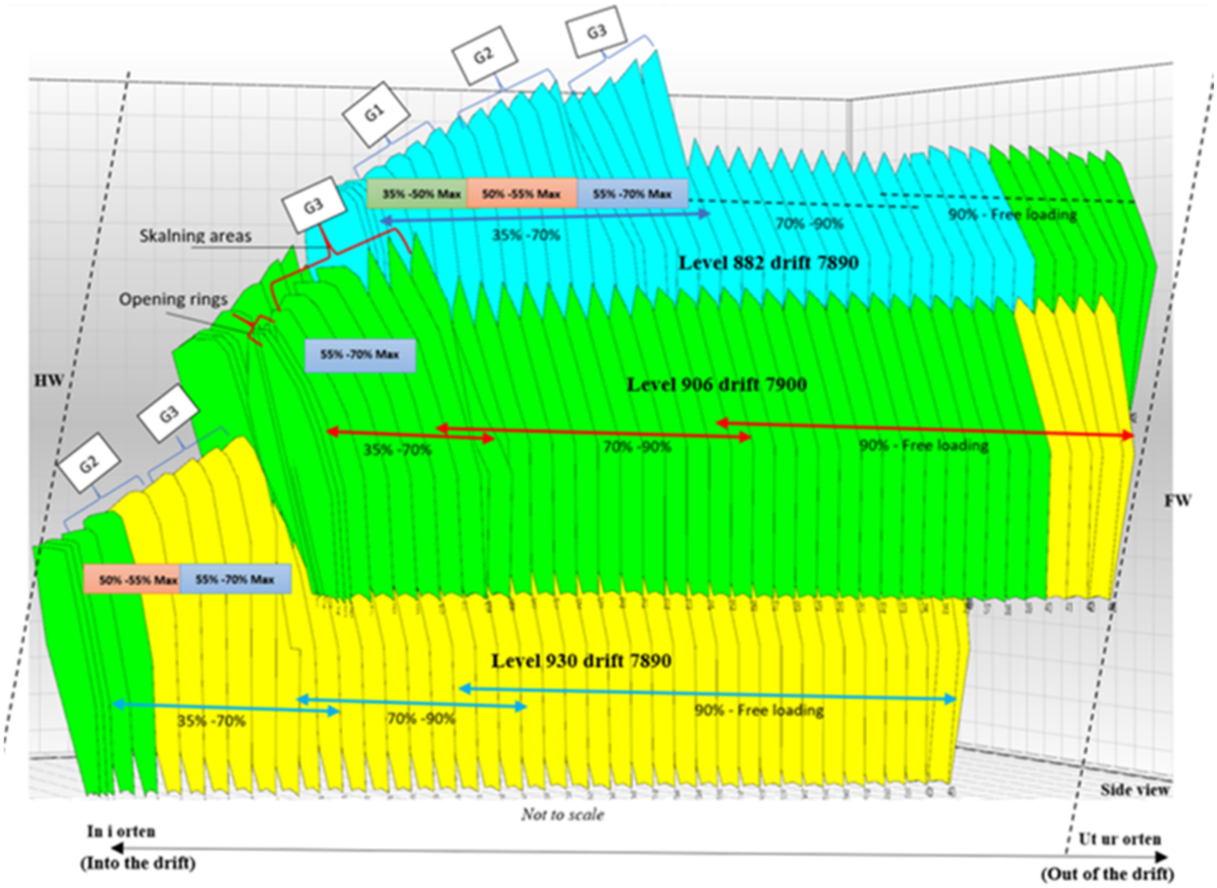

Figure 12 Extraction rates for ViRi level 930 drift 7890 with "skalning" (side view).

From Figure 12, loading was assumed to be carried out on level 930 drift 7890 and the recommended extraction rates were analyzed using extraction data obtained from Giron (LKAB internal program) for the same drift. The actual extracted data from Giron was reassessed or re-calculated using the new recommended extraction rates outlined. Rates between 35% - 70% were applied to rings 3-10 until contact with level 906 drift 7900 where rates between 70% - 90% were used for rings 11-20. Rates >90% were used for rings 21-43 after contact with two levels above. G1, G2, and G3 represent further division of the extraction rates for the rings in the “skalning” areas into subgroups 1, 2, and 3. This subgroup's division and selection depend on the angle of the ore contact along the hanging wall (see Figure 7). The result is presented in section 6. However, a factor, k (see equations 1 and 2) was introduced in relation to the level where loading was carried out to represent the coefficient of loosening of the material and recovery of previously unloaded ore at both one and two levels above during loading. The purpose of the *k* factor is to ensure recovery of the materials from levels above. Nevertheless, this factor is used after the “skalning” areas have been extracted. With this factor, a relationship was established between the theoretical planned volume, the recommended extraction rates with “skalning” outlined in this paper, and the suggested volume of ore to be drawn (SOV). The relationship is given as:

$$SOV = \frac{Theoretical\ planned\ Volume \times extraction\ rate}{k} \tag{1}$$

where k, represents the coefficient of loosening of the material and recovery of previously unloaded ore relative to the level where loading is carried out (E.g., one and two levels above). It is defined as:

$$\mathrm{k} = \frac{\text{Contact level with caved material (one or two level numbers above)}}{\text{Level number for the drift where loading is carried out}} \tag{2}$$

The level numbers are used when the ring(s) on a level being loaded are in contact with the cave material and the respective levels (one and two levels above). The idea is to provide a *k* value <1 that increases the suggested volume of the draw to ensure that not too much ore is left behind due to “skalning”. For example, with the scenario for ViRi, if the assumed loading level is 930 drift 7890, the *k* values for levels 882 drift 7890 and 906 drift 7900 will be 0.95 and 0.97 respectively. These *k* values are of interest for the loading on level 930 to ensure successive recovery of the materials from levels 882 and 906 above.

3.2 Use and limitation of the factor, k.

It must however be noted that the *k* value does not apply to loading along the hanging wall contact (during “skalning”). The use of the factor *k* (see equations 1 and 2) may be limiting in some extent, but the idea here is to guide material recovery by providing an optimal and ideal threshold limit for ore extraction (suggested volume of draw) after the “skalning” areas. It is also to ensure that not too much ore is left behind due to “skalning” when compared to the suggested extraction rate without the *k* factor. This means that the extraction rates in these areas should be on or above the ideal threshold limit (suggested mucking rate with factor, *k*, see Figure 14) for ore extraction to be considered as optimum.

4 RESULTS AND DISCUSSIONS

4.1 Results

With reference to the angle of the ore contact in the drift along the hanging and the opening sequence on the level, the optimal extraction rates were determined and recommended. The

estimated and recommended extraction rates were based on an analysis of MUJ production data from Giron (2012-2021), which included box and whisker plots to give a visual summary of the data and quickly identify mean values, data dispersion, and signs of skewness. The three loading criteria at the Malmberget mine as well as the current internal guidelines were determined. The final extraction rate for MUJ production data from Giron (2012-2021) was set to three times the theoretical tonnage (0% <data set ≤ 300%) for a total of 12414 rings. The recommendations were based on the analysis of two sets of data: 9897 rings from other orebodies in the mine, and 2517 rings from the Fabian (FA)/Kaptain (KA) orebodies only (separated due to high production from these areas).

To provide an optimal extraction rate (suggested volume of draw) for material recovery after the "skalning" areas, a k factor was used to establish a relationship between the theoretical planned volume and the determined extraction rates (see equations 1 and 2). The purpose of the k factor is to ensure recovery of the materials from levels above. The limits of the extraction rates and loading criteria selection from the box and whisker plot were determined and outlined (Gyamfi, 2023). From the box and whisker plot in Figure 13;

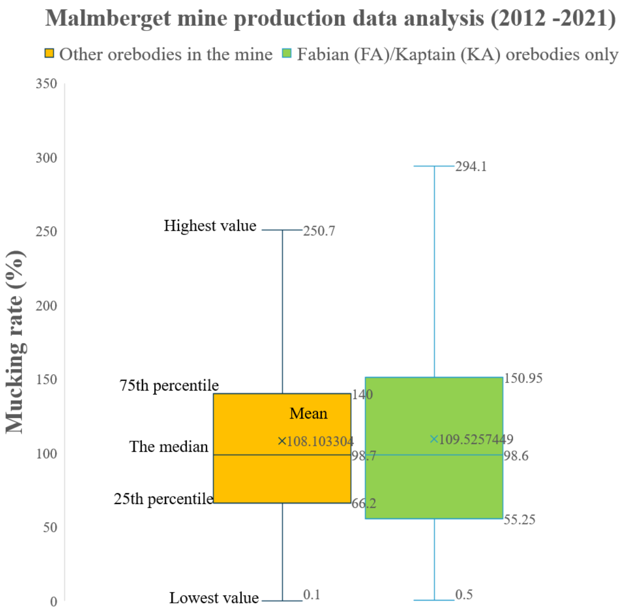

Figure 13 Box and whisker plot of MUJ production data from Giron (2012-2021)

- The 25th percentile for the other orebodies in the mine for MUJ production data (2012 - 2021) (to the nearest tens) was set as the limit (35% - 70%) for loading in the “skalning” areas. The minimum extraction rate of 35% for the “skalning” areas was also set based on analysis of the two sets of data for MUJ production data (2012-2021) for the first 10 rings and similar findings from the Kiruna mine (Shekhar et al., 2017).
- The average for the difference in interquartile range (IQR) (to the nearest tens) for a combination of both sets of data for MUJ production data (2012-2021) was set as the limit (90%) for contact with caved material and one level above (70% – 90%).
- Any rate greater than the average interquartile range (IQR) (to the nearest tens) for a combination of both sets of data for MUJ production data (2012-2021) was set for contact with two levels above (>90% - free loading).

The determined and recommended extraction rates are:

1. **“Skalning” areas** – 35% - 70%. Where the “skalning” area in the drift is gently dipping (shallow angle rather than steep) before rising steeply to contact the level above, it may be necessary to further divide the rings into three different subgroups of extraction rates. This is to increase safety near the hanging wall while maximizing extraction along the rings toward the footwall. The division should be based on the stretch and angle along the hanging wall (see Figure 7).
   - *Group 1, 35 % - 50% ≈ 35^0 – 50^0 angle (ore contact to the hanging wall).*
   - *Group 2, 50 % - 55% ≈ 50^0 – 55^0 angle (ore contact to the hanging wall).*
   - *Group 3, 55 % - 70% ≈ 55^0 – 70^0 angle (ore contact to the hanging wall).*
2. **Contact with caved material and one level above** – (70% -90%).
3. **Contact with two levels above** - >90% - free-loading (towards the footwall for maximum recovery, but general loading criteria at the Malmberget mine still apply (E.g., ore grade trend shown in the wireless online loading information system (WOLIS)).

From the recommended rates, Figure 14 presents the results for the example extraction rate for ViRi level 930 drift 7890 with "skalning" as well as consideration of the *k* factor with the actual mucking rate (Giron data) for analysis. Rings 7,9 and 12 had no data entry and hence were excluded from the analysis. Also rings 40 and 42 were double rings with no tonnage allocated, hence were considered with rings 41 and 43 respectively. The corresponding actual and suggested (with and without factor, *k*) mucking tonnage analysis of the rates is presented in Figure 15. Note that the *k* factor is only applied outside the "skalning" areas.

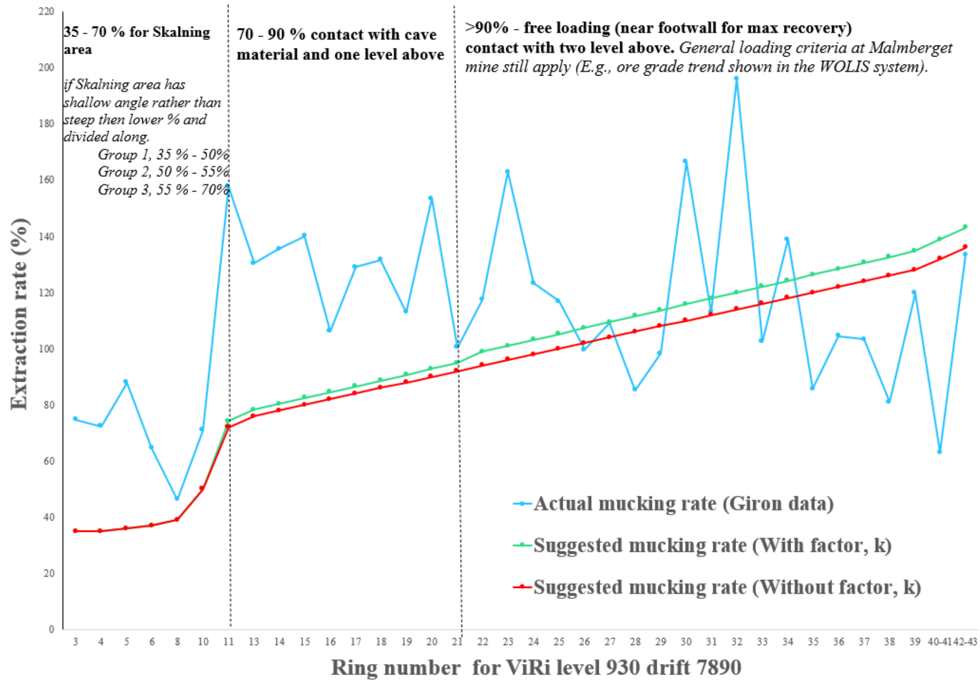

Figure 14 Mucking rate for ViRi level 930 drift 7890 with "skalning".

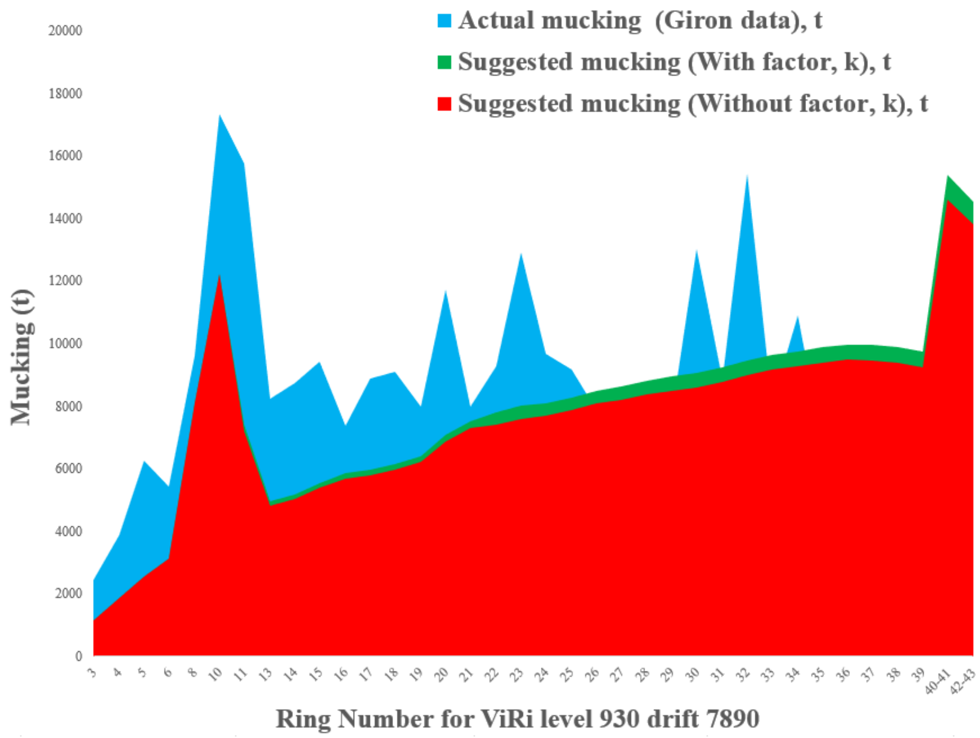

Figure 15 Mucking tonnage analysis of the rates presented for ViRi level 930 drift 7890 with "skalning"

It is apparent from Figure 15 that the analysis with the suggested mucked tonnage shows significant ore loss, especially in the 70-90 % area compared to the actual mucking. This is because the actual mucked tonnage was without "skalning" taken into consideration hence seismic and safety concerns. However, its applicability is expected to show otherwise with improved recovery of remaining ore at two levels below while the loading limitation results in lower seismic activity and perhaps even fewer large seismic events.

It can be observed from Figure 14 and Figure 15 that "skalning" of the drift 7890 along the hanging wall limits the extraction of ore (Ring 3 – 11) to account for the safety of chargers and other personnel at the draw point and also in some situations serve as a cushion or shock absorber for vibrations from seismic events, and also serve as a "temporary caved fill support material". This means that the void that is to be filled with caved waste material is temporarily replaced with this remaining blasted but unloaded ore. It must however be noted that this limited ore extraction may be recovered from levels below (specifically two levels below) which is accounted for by the factor, *k* in the later rings in a given drift. The amount of ore left unloaded along the hanging wall ("skalning") may vary depending on the dip angle of the ore contact along the hanging wall, anisotropy of the ore seam, and the selected extraction rate subgroup in the "skalning" area for safety and other related reasons.

It can also be seen from Figure 14 and Figure 15 that the *k* factor provides an optimal suggested mucking rate (compared to the suggested mucking rate without factor, *k*) for material recovery after the "skalning" areas to ensure that not too much ore is left behind due to "skalning". The *k* factor makes some difference in the mucking rate which can be significantly higher in the long run. The difference in the mucking rate for all the rings considered in the analysis is presented in Table 1. Nevertheless, in situations where dilution is very high and other operational challenges such as hang-ups and poor brow conditions are encountered, the rates without the factor, *k* can be used instead as the optimal suggested mucking rate threshold.

Table 1 Total tonnage analysis with and without factor, *k* for ViRi level 930 drift 7890.

Theoretical Planned tonnage	303575	303575	303575
Actual mucked tonnage	326306.1		
Suggested mucking tonnage with factor, k		284573.3	
Suggested mucking tonnage without factor, k			273034.8
Difference (Mucked tonnage – theoretical planned tonnage)	22731.1	-19001.7	-30540.2

4.2 Discussion

This work contributes to the existing knowledge of draw control studies and strategies by highlighting the need to look beyond grade control (dilution) and tonnage of ore that may be recovered from blasted rings along hanging wall contact in SLC operations.

The "skalning" areas however need to be identified and where applicable divided into the subgroups presented. The identification and subdivision may also be supported with a 3D view of the area under consideration. The transition from one zone to another (especially from the "skalning" areas) should be in the form of overlap such that it is a gentle transition and not a sharp one. This will help to optimize the recovery and increase the safety of the operators. It must also be noted that the minimum extraction rate for the "skalning" areas should be at least 35% based on MUJ production data analysis (2012-2021) for the first 10 rings and findings from the Kiruna mine (Shekhar et al., 2017). However, operational issues and poor blasting of rings near the hanging wall can result in extraction rates less than these recommended rates. A practical recommendation for such a situation is for LHD operators to always keep the brow closed.

It may also be worth mentioning that these recommended extraction rates may change in the event of challenges at the draw point (hang-ups, brow failure, pillar failure, poor fragmentation, or ring freeze) hence it is important that visual monitoring of the draw point by the loaders when loading is carried out. These recommendations should also be supported with the available grade control system in WOLIS for optimum recovery. In a hang-up situation, it is important that the loader operator does not load the ring empty, and also should ensure to keep some pile close to the brow, to limit a possible collapse and flow of material into the drift.

5 CONCLUSIONS, RECOMMENDATIONS, AND FUTURE WORK

5.1 Conclusions

This paper outlines the investigation and determination of optimal extraction rates in general in the “skalning” areas at MUJ. The determined rates are also applicable for special cases where some entire drifts will be mined outside previously mined areas (cave contact), so all rings in these areas should be loaded as a “specific case of skalning” with restrictions.

Despite its limitations to MUJ, this study certainly adds and offers valuable insights into our understanding of draw control strategies along the hanging wall contact in SLC operations. The findings suggest that the working environment and safety of the loading, charging, blasting crew, and other personnel should play a significant role in the amount of ore that must be loaded from blasted rings along the hanging wall contact that are not yet in contact with the caved material on a level above in SLC mining.

An optimal extraction rate has been defined based on the analysis of MUJ production data (2012 - 2021) and current general loading criteria at the mine. It is expected that the recommended extraction rates would provide a guideline for loading in the “skalning” areas to optimize recovery, temporarily use the remaining blasted but unloaded ore as a cushion (shock absorber) for vibrations from seismic events, and also serve as a “temporary caved fill support material”.

This is anticipated to lower seismic activities and perhaps even lead to fewer large seismic events and provide a safe work environment for the loading, charging, and blasting crew, and other personnel in MUJ.

5.2 Recommendation and future work

It is recommended to investigate the material flow prediction and simulation based on the above assessment and the scenario outlined in this paper. For future studies, Rebop gravity flow modeling software can be used for further evaluation of the assessment outlined. This would provide a better understanding of the mechanics of the cave flow behaviour and propagation along the hanging wall contact.

This should be followed up with a close monitoring of seismic events in the mine. A comparison with previous seismic data should also be carried out. This can probably be used to establish the relationship between “skalning” and caving seismicity such that improvement can be made on the optimal rates where needed. If the comparison of seismic events and data is not representative due to many factors that could bias it, the work safety and visual inspections could also be used as a KPI to contribute to this evaluation. It is crucial that loader operators are aware of these recommended extraction rates so that they do not load the ring empty, and also should ensure to keep some pile close to the brow, to limit a possible collapse and flow of material into the drift.

From a stope stability point of view, the “skalning” section can be considered as an irregular stope with an asymmetric stope surface and the Matthews stability graph could be used to assess and predict the onset of continuous caving. In this way, the rock mass parameters such as RMR, stress factor, joints, and stope face angle are considered in the assessment (which was not considered in this study).

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