Raise Caving—A Hybrid Mining Method Addressing Current Deep Cave Mining Challenges

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Abstract: Cave mining progresses to depths exceeding 1000 m and ore bodies situated in competent and strong rock masses are nowadays extracted by different cave mining methods. Widely applied caving methods in massive deposits are block and panel caving, inclined caving, and sublevel caving. All caving methods have in common that rock mass caves during extraction of an ore body in a controlled way. As a result, regional stress changes occur, considerable abutment stresses form, and large-scale subsidence and significant seismic energy releases occur. Experience shows that these rock mechanics effects become especially critical at great depths, where primary stress magnitudes reach and exceed rock mass strength, as well as in strong competent rock masses, which require large footprints to enable continuous caving. The presented raise caving method addresses previously mentioned rock mechanics issues. Initially, de-stressing slots are developed from raises with a minimum amount of pre-development. Substantial pillars separate neighboring slots in order to control stress magnitudes and seismicity near slots. The slots provide a stress shadow for production infrastructure so that large-scale mineral extraction can take place in de-stressed ground. As mining progresses, pillars are extracted and hanging wall is allowed to cave. Results of a pre-study conducted together with LKAB have highlighted advantages of raise caving from a rock mechanics, safety, and cost point of view.

Keywords: Deep mining, Mining methods, Cave mining, Rock mechanics, Rock pressure management

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Raise-Bruchbau – Ein hybrides Abbauverfahren zur Adressierung von bestehenden Herausforderungen im tiefen Bruchbau

Zusammenfassung: Lagerstätten werden vermehrt in großen Teufen von 1000 m und tiefer sowie bei relativ kompakten Gebirgsverhältnissen mit hoher Gebirgsfestigkeit im Bruchbau gewonnen. Weit verbreitete Bruchbauverfahren sind Blockbruchbau und Teilsohlenbruchbau sowie daraus abgeleitete Variationen. Allen Bruchbaumethoden ist gemein, dass bestimmte Gebirgsteile kontrolliert zu Bruch geworfen werden. Großräumige Spannungsumlagerungen, die Ausbildung von hohen Auflagerspannungen, regionale Oberflächenabrisse und bergbauinduzierte Seismizität sind die Folge. Bestehende Abbauerfahrung zeigt, dass diese gebirgsmechanischen Auswirkungen vor allem in großen Teufen, wo primäre Gebirgsspannungen die Gebirgsfestigkeit überschreiten, sowie kompakten Gebirgsverhältnissen, welche eine flächenmäßig große Unterschneidung für einen kontinuierlich fortschreitenden Bruch des Gebirges benötigen, kritisch sind. Die vorgestellte Raise-Bruchbaumethode adressiert diese gebirgsmechanischen Schwierigkeiten. Zunächst wird die Lagerstätte mittels Schlitzen, welche ausgehend von Raise-Bore-Schächten aufgefahren werden, entspannt. Die dafür benötigte Vorrichtung ist minimal. Zwischen den Schlitzten werden mächtige Festen gewonnen, welche als Schutz für den Abbau dienen. Die Schlitzte stellen in weiterer Folge Spannungsschatten für den eigentlichen Abbau bereit. Der Abbau erfolgt von den Raise-Bore Schächten aus. Im Zuge des Abbaus werden die Festen zwischen den Entspannungsschlitzen gewonnen und das Hangende kontrolliert zu Bruch geworfen. Die Ergebnisse einer Konzeptstudie mit LKAB zeigen das Potenzial und Vorteile von Raise-Bruchbau bezüglich gebirgsmechanischer Aspekte, Sicherheit im Abbau und Abbaukosten auf.
1. Introduction

Caving methods in massive deposits rely on naturally induced rock mass failure either by means of gravity, prevailing stresses, or a combination of both. In block, panel, and inclined caving, the ore body is undercut and caving of the ore body is initiated, whereas in sublevel caving, ore bodies too competent for caving have to be mined by means of drilling and blasting. In all caving methods, hanging wall rock mass is allowed to cave as mining advances. Cave initiation and continuous propagation are easier to achieve in weak rock masses. The caveability chart of Laubscher [1] highlights that the majority of investigated cave mines had a MRMR lower than 60, whereas investigated stable excavations had a MRMR higher than 50. Moreover, cave mines at that time operated at relatively shallow depths, where stress magnitudes could be handled, i.e., Shabani asbestos mine in Zimbabwe or Premiere diamond mine in South Africa. However, starting in the late 1990s, cave mining progressed to greater depths and more competent rock masses, for example Northparkes mine, Cadia mine, or Kiruna mine. With increasing primary stress magnitudes and increasing rock mass strength, caving is more difficult to realize and more rock pressure related issues are faced. Problems experienced comprise amongst others production level instability during undercutting and production (e.g. [2–4]), mining induced seismicity and associated rock burst damage (e.g. [5–7]), or difficulties in cave initiation and in ensuring continuous cave advance (e.g. [8–10]). In a worst-case scenario, these issues could end up in major economic losses or in a termination of the operation. As a consequence of these difficulties, major international research projects (International Caving Study, Mass Mining Technology Projects) were initiated in Australia and were sponsored by international mining finance houses. Results of these studies are summarized in [11–18].

A simple rock mechanical model illustrating critical points in currently applied caving methods in massive ore bodies is a tabular slot. Such a tabular slot provides an overview of the stress distribution around an undercut in block and panel caving before continuous caving is initiated and around active sublevels in sublevel caving. Fig. 1 shows the characteristics of the stress distribution around a tabular slot. Extreme abutment stresses develop at the sides of the slot, whereas de-stressed zones develop above and below the extracted area. Fig. 1 shows only the stress situation below the slot. The high abutment stress magnitudes are critical and can damage the undercut and production infrastructure, adversely affect rock mass properties in the future production level, or trigger damaging seismic events. Applied approaches against abutment stresses are for example certain undercutting strategies minimizing pre-developed infrastructure in abutments (e.g. [19, 20]) or pre-conditioning methods for reducing abutment stress magnitudes (e.g. [21–23]). However, the main approach against high stresses and seismicity seems still to be the installation of heavy support and reinforcement systems (e.g. [3, 24, 25]). Moreover, the trend to more competent rock masses calls for larger undercut areas. In the slot model, this circumstance is equivalent to increasing the span, which results in higher abutment stress magnitudes and higher seismic energy release. Although the slot model loses its validity in block and panel caving in areas where caving has been initiated and has propagated, the abutment stress issue during undercutting is inherent. In sublevel caving, the slot model is even valid after hanging wall caving started. Accordingly, abutment stress issues are present throughout (Fig. 1).

2. Deep Mining Approach

In order to address critical rock mechanical issues in currently applied caving methods, the raise caving method relies on a proven and successfully applied deep mining approach: namely, de-stressing of rock mass with minimum amount of infrastructure, placing of critical infrastructure and production infrastructure in de-stressed zones, extracting of the ore body inside a de-stressed zone, and controlling release of seismic energy by means of the mine layout and mining sequence. Wagner and Salamon [27] describe the application of this approach. Especially deep South African gold mines have been using this concept for several decades [28]. Gold reefs up to a depth of 4000 m have been extracted successfully. Reefs are extracted in narrow tabular stopes (slots), which extend over several square kilometers. A development of infrastructure ahead of stope faces, which could result in considerable damage due to high stresses, is avoided as far as practically possible. Infrastructure is rather developed in de-stressed zones, which are provided by mined-out stopes. The release of seismic energy is controlled by massive stabilizing pillars, which are left behind between neighboring stopes. Occasionally gold reefs form thick, massive reef packages. In the latter case, those massive ore body portions are de-stressed by initially mining a narrow stope (slot) or a room and pillar layout with yield or crush pillars. Depending on the ore
body, thickness room and pillar methods or sublevel stoping methods are applied for ore extraction [29, 30].

Principally, raise caving is based on the application of de-stressing slots, massive pillars, and extraction in de-stressed ground. Hence, raise caving makes use of the well-proven deep mining approach in deep South African gold mines.

3. Raise Caving Method

3.1 Utilization of the Raise Mining Principle

Raise caving relies on the raise mining method. Raises are the central element in raise caving and are used for the development of initial de-stressing slots and for the extraction of ore in stopes in de-stressed ground. Stopping removes regional support pillars leading to hanging wall caving and subsequent filling of mined-out stopes with caved rock mass. Raises are developed by means of conventional raise boring techniques and serve as the basis for slot and stope mining activities. Drilling and blasting are carried out from a platform, which is moved with a shaft hoist system inside the raise. The platform and hoist system are installed after raise boring has finished. Slots and stopes are blasted from bottom to top. Therefore, blast hole fans are drilled parallel to the existing excavation roof (Fig. 2a). Drill fan layouts control the shape of the excavation and roof inclination. After a fan is drilled and charged, the hoist platform is retracted to the top for blasting so that blast damage is avoided (Fig. 2b). Blasted rock mass falls into the excavation, and there has to be enough free volume to absorb the volume increase resulting from blasting (Fig. 2c). Before the next blast round can be fired, enough blasted rock mass has to be drawn from the excavation so that a free volume is present for the next blast. Routine work done in the raises should be carried out remote controlled or automated. Repair and maintenance of machinery can be carried out at the top of the raise when the platform is retracted. Hence, the presence of mining personnel in raises can be kept to a minimum for, e.g. routine raise inspections or special, irregularly occurring work which cannot be done by installed machinery on the platform. As manual work might be required in raises and as machinery in raises must be protected from rock falls, raises must be stable. If rock mechanics conditions require raise support, support can be installed from the platform. The platform construction itself provides additional protection for miners. The circular cross-section of the raise is an even and simple excavation shape, which enables, together with the platform positioning via the hoist system, an easier drill hole detection and identification compared to irregular drift shapes in conventional mining situations. This drill hole detection is critical for automation (Fig. 2).

Summing up, the utilized principle of raise mining is a modern, large-scale approach. It differs largely from raise mining conducted in past, such as Alimak mining or Horodiam mining, which are described for example by Makinen and Paganus [31] or Ran and Mfula [32]. The above-described modern, large-scale raise mining method has been successfully applied in Alpine mining conditions for several years [33, 34]. Moreover, these mining operations have come along with a considerable degree of remote control and automation. A similar concept of modern raise mining was outlined by Gipps et al. [35] and Gipps and Cunningham [36] and called ROES. However, the ROES was not implemented.

3.2 Raise Caving Layout and Mining Sequence

Fig. 3 provides a schematic overview of the raise caving method, which is comprised of two different phases, referred to as “de-stressing phase” and “production phase”. The amount of infrastructure for the development of de-stressing slots in the de-stressing phase is kept to a minimum. These slots create stress shadows, which are used for protection of infrastructure in the production phase. The infrastructure required for de-stressing is also called slot infrastructure and infrastructure required for stoping is termed production infrastructure. Although both phases have different purposes, namely creation of stress shadows in the de-stressing phase and bulk extraction of ore in the production phase, they cannot be seen as individual, independent phases. Rather both phases must be designed together to form a functionally integrated and applicable raise caving method. From a system point of view, raise caving is a hybrid method starting from a pillar supported method in the de-stressing phase, converting to an artificially supported, shrinkage stoping method during the production phase, and ending up in a caving method as stopes are drawn empty. For these reasons and especially due to similarities to shrinkage stoping, the terms stoping and stopes describe the extraction process in raise caving better than just caving (Fig. 3).
3.2.1 Infrastructure, Elements, and Levels

Different types of slot and production infrastructure, elements, and levels are necessary for the implementation of raise caving. Individual elements and their purpose are described in the following. Bracketed abbreviations refer to Fig. 4 and 5 and 6.

- **Slot raise (SR):** Slot raises are utilized for the extraction of de-stressing slots. Up to several hundred meters in length, slot raises are developed between individual raise levels and the slot development level, respectively. The raise boring method is used therefore. Depending on ore body shape, rock mass conditions, and mining directions, slot raises can be situated in the ore body or in the contact areas of the ore body with surrounding rock mass formations. Raises can either be vertical or inclined.

- **Production raises (PR):** Production raises are utilized for the large-scale mineral extraction in stopes. Hence, they are also called stope raises. Production raises are developed by raise boring as well. Production raises are positioned in the stress shadows provided by slots and start slots. Raises can either be vertical or steeply inclined.

- **De-stressing slots or short “slots” (SL):** Slots are tabular shaped excavations and are created from slot raises with the raise mining method in the de-stressing phase. Slots are situated at the hanging wall contact. The purpose of slots is to provide a stress shadow for a protection of the production infrastructure from high stresses and seismic energy releases. Neighboring slots are separated by substantial barrier pillars. Slots are operated in a shrinkage mode, where only the swell of each blast is drawn before the next blast. The blasted rock mass in slots provides a temporary support for the slot sidewalls.

Fig. 3: Schematic overview of the raise caving method

Fig. 4: Overview (a) and vertical cut perpendicular to strike (b) of the de-stressing phase in an early stage
- **Start slot (STSL):** Start slots are tabular shaped excavations, too, but in contrast to slots, start slots are wider. The purpose of start slots is to de-stress the ground near production levels. Therefore, the start slot is continuous. Either no pillars or pillars small enough to yield and crush reliably are left between the start slots. The reason is that stable pillars are stress raisers which could damage the draw level infrastructure situated behind the start slots. The start slot extends to a height which de-stresses production levels appropriately. Above this height, the width of the start slot is reduced to the width of de-stressing slots.

- **Raise level (RL):** The top levels of slot and production raises are referred to as raise levels. The vertical spacing of raise levels could be up to several hundred meters. After slots passed by raise levels, they can be used to create additional draw points into slots facilitating ore flow in slots. Moreover, raise levels can be converted to intermediate draw levels in the production phase.

- **Production levels (PL):** The production levels are used for the development of production raises and for the extraction of ore from stopes. Using large drawbells may require two production levels to realize an appropriate positioning of draw points. Ore drawn at production levels is then transferred to the main haulage infrastructure.

- **Slot development level (SDL):** The slot development level is used for the development of slots and start slots at an early stage in the de-stressing phase. The purpose of the slot development level is that start slots extend deeper than production levels so that the production levels are not exposed to high abutment stresses, which form at the bottom of start slots. The slot development level is no longer needed once drawpoints into slots are created at the raise or production levels situated above, and it can then be abandoned.

- **Intermediate draw level (IDL):** If the ore flow to the production levels cannot be guaranteed due to ore body shape or ore body inclination, the installation of intermediate draw levels is necessary. Additional draw points are developed into blasted stopes at intermediate draw levels to facilitate ore flow and to guarantee a high extraction ratio. It is suggested that these intermediate draw levels are developed after the stope roof has passed by so that abutment stress damage is avoided.

- **Pillars (PI):** Massive pillars are left between de-stressing slots to stabilize the hangingwall in the de-stressing phase and in the early production phase, to create a favorable stress environment for developing slot raises and to control stress magnitudes and seismicity around de-stressing slots. As stoping progresses, pillars are extracted as part of the stoping process and hanging wall is allowed to cave.

- **Stopes (ST):** Stopes are used for the large-scale mineral extraction. Hence, stopes are large excavations created with the raise mining method. Therefore, long blast hole fans are drilled from production raises. Depending on local requirements, blast holes could either be flat or inclined. After a blast, only the swell is mucked at draw points providing enough free volume for the next blast. Accordingly, the stope is operated similar to a shrinkage stope. The blasted rock is a temporary stope wall support and thus slows down hanging wall caving and dilution. The formation of an air gap is prohibited further. Extraction of stopes weakens and subsequently removes most of the substantial pillars between slots. Furthermore, extracted stopes provide stress shadows for further production.

- **Drawbells (DB):** Drawbells are developed from production raises and used for the large-scale mineral extraction. Raise caving enables the use of large drawbells, which should offer improvements related to ore flow, such as a more even draw point spacing and improved flow characteristics.

- **Drawpoints (DP):** Drawpoints are used to draw ore from slots, start slots, and stopes, and they are developed at individual levels.

- **Ore passes (OP):** Ore passes are developed by means of raise boring and used to transport ore from the intermediate draw levels to the main haulage infrastructure. Ore passes can be developed delayed in the production phase, and hence they can benefit from provided stress shadows or can be protected from regional abutment stress magnitudes.

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**Fig. 5:** Overview (a) and vertical cut perpendicular to strike (b) of the de-stressing phase in a more advanced stage. First production infrastructure is already developed.
Fig. 4 and 5 and 6 show the steps of implementing raise caving by means of a conceptual mine layout and mining sequence. Fig. 7 shows a possible raise caving layout and mining sequence in a steeply dipping, thick tabular deposit. In the figures, the infrastructure and excavations in the extraction area are shown. For simplification, the other main infrastructure, such as hoists, main haulage drifts, or workshops, are not shown. The outlined excavation dimensions are based on preliminary analyses. They provide a rough estimation of dimensions in raise caving.

3.2.2 De-stressing Phase

Fig. 4 provides a schematic overview of the de-stressing phase at an early stage. First slot raises, start slots, and slots are developed. Active levels are the slot development level, where the blast swell of slot advance is drawn, and raise levels. The minimum amount of infrastructure required in the de-stressing phase is clearly visible. Moreover, the development of infrastructure at the production level has not been started, yet. The shown slots have a striking extension of 50 m and a thickness of 10 m. The slot raise center spacing is 100 m leaving 50 m wide and 10 m “high” pillars between the slots. Start slots are continuous and have a vertical extension of approximatively 100 m. Slot raises have a diameter of 4 m.

Besides the outlined method of creating de-stressing slots from raises with the raise mining technique, other alternative methods for slot extraction are under investigation (Fig. 4).

Fig. 5 shows the de-stressing phase in a more advanced stage. More slots and start slots are developed in the strike direction, and the height of slots is increased. First production infrastructure at the production level is developed in stress shadows provided by the slots and start slots. In areas where draw points into slots are available at the production level, the slot development level is no longer required and is abandoned (Fig. 5).

3.2.3 Production Phase

The production can first be started after de-stressing slots have advanced a certain distance. The background is that regional consequences on the stress situation and seismicity result from stope and subsequent pillar extraction. Regional abutment stresses develop increasing stress levels in nearby pillars, which would affect the slots and de-stressing infrastructure adversely. Thus, slots development must lead production (stope extraction) by a certain number of slots. Currently it is estimated that a lead of two to three slots is appropriate.

Stopes are blasted from production raises, which are developed in de-stressed rock mass, and the swell is drawn at draw points. As stoping advances from bottom to top, the installation of intermediate draw levels and associated infrastructure at the footwall sides of stopes may be necessary. The background of these intermediate draw levels is to draw more ore at the footwall side of the stope, which could be required to maintain an even ore flow and to avoid early dilution in inclined stopes. The stope inclination and ore body shape determine the number and position of intermediate draw levels. This additional production infrastructure is developed after stoping passed by, so it can benefit from stress shadows provided by stopes and does not suffer damage from abutment stresses, which form around extraction areas. Fig. 6 schematically shows the production phase in raise caving. De-stressing activities lead some slots, and stopes are mined behind the slots in stress shadows. Whenever necessary, intermediate draw levels and ore passes are developed with some delay in the stress shadow of stopes. Several stopes are in production at the same time, but there is some vertical distance between roofs of neighboring stopes in order to avoid negative interrelations. Stope cross-sections of more than 1000 to 2000 m² seem to be possible at the moment. Stopes are up to several hundred meters high. It has to be noted that in Fig. 6 only one production raise is shown behind every slot. In a massive deposit, several production raises are required behind a slot without exceeding technical drilling limits or stope stability limits (compare Fig. 7). The position of production raises can be chosen freely as long as they are situated in de-stressed ground provided by slots and neighboring stopes. Moreover, blasted stopes increase the de-stressing effect because they block stresses from another direction.

Pillar weakening and extraction is possible in several ways. One option would be to blast pillars actively from production raises. Another option is to degrade the pillar strength and facilitate pillar yielding and crushing. This degradation could be done for example by decreasing the pillar width-to-height ratio due to blasting of stopes behind neighboring slots or by pre-conditioning techniques, such as hydraulic fracturing, which are applied inside pillars. Crushed pillars are de-stressed and hence can be extracted from another production raise, which is then situated in the crushed, de-stressed pillar. Pillar extraction removes their temporary hanging wall support function causing the caving of hanging wall. Caved material starts to flow into the stope. After stopes are fully blasted and in the process of drawing empty, broken hanging wall rock mass fills up stopes completely. The draw strategy and draw control are critical to avoid early hanging wall dilution (Fig. 6).

Fig. 7 shows a raise caving layout in a steeply dipping, thick tabular deposit. Infrastructure and excavations in the de-stressing and production phases are outlined. De-stressing and large-scale mineral extraction advance from left to right. The slots are oriented in strike direction and situated at the hanging wall contact. Extraction of stopes commences some distance behind slot development. The stopes behind the slots are mined-out first. Consequently, the pillar width-to-height ratio is reduced and pillars crush and de-stress. Crushed pillars are then extracted with production raises placed inside them some distance behind. Furthermore, large drawbells are outlined. These large drawbells facilitate and improve the ore flow characteristics in the stope, which enables a better recovery and lower dilution (Fig. 7).
3.2.4 Flexibility and Adaptability

Raise caving is quite a flexible method allowing for changes in the mine layout and mining sequence on short to medium notice. The position of slots, stopes, raises, and other infrastructure can be adapted to local ore body shapes and rock mass properties. Cross-sections of stopes can be trimmed to ore body boundaries by adapting the length and orientation of individual drill holes. Changes in the mine layout, infrastructure position, and mining sequence can be made on a short to medium term notice because raise caving requires a minimum amount of infrastructure pre-development. This circumstance is a powerful possibility to dynamically adopt the mine design to experiences gained. However, rock mechanics considerations limit flexibility. For example, production raises must be placed in de-stressed ground or pillars must be large and strong enough to separate slots effectively. The flexibility in raise caving is a major advantage to existing caving methods, which do not allow changes at all or which have very limited or expensive possibilities for adaptions, after infrastructure development has started or caving has been initiated, respectively.

3.2.5 Application Potential of Raise Caving Elements in Existing Mining Systems

Certain elements of the raise caving method can be applied in other ways as well. For example, de-stressing slots developed from raises can be applied as a de-stressing element in existing mining methods or for de-stressing and protection of critical long-term infrastructure. Neighboring stopes mined by raises can also replace a traditional flat undercut in block and panel caving. In this case, the size of the drawbell roof would be increased until caving is initiated. This variation of raise caving is referred to as “integrated
raise caving” [37]. Moreover, raises equipped with appropriate machinery above an active cave would provide possibilities for pre-conditioning, cave advance monitoring, facilitating cave advance, and steering of caving direction. Finally, the successful application of raise mining as a variation of open and sublevel stoping is described by Siefert [33] and IMA Europe [34].

4. Pre-study of Raise Caving in LKAB’s Kiruna Iron Ore Mine

Iron ore has been mined in Kiruna mine for several decades by means of sublevel caving. Continuous improvements to the mine layout and upscaling of the methods have resulted in an increased productivity whilst maintaining low mining costs [38]. Because of the increasing mining depths, rock pressure problems, particularly rock bursts, started to occur and have been imposing a safety risk and operational problems [6, 39, 40]. The control of rock pressure is considered decisive in future, and LKAB has been investigating mining methods for mining at greater depths below the current main level. A part of these investigations was a pre-study analyzing the application potential of raise caving in Kiruna mine from a rock mechanics perspective [41]. Furthermore, the effects on productivity, the potential for automation, and safety were analyzed. A brief summary of the study can be found in Ladinig et al. [37]. Study results show that raise caving can make use of the considered deep mining approach that raise caving is applicable from a rock mechanics point of view and that raise caving seems to offer considerable advantages compared to existing caving methods. In case of sublevel caving, which is currently used in Kiruna mine, these advantages are:

- releasing seismic energy distant from active infrastructure;
- allowing for adaptions in mine layout and mining sequence to control seismicity and to improve infrastructure stability;
- offering significant automation potential;
- resulting in safety improvements;
- decreasing infrastructure development effort considerably and enabling the majority of infrastructure to be situated in de-stressed areas; and
- reducing mining costs significantly.

5. Further Development Steps

In the light of the promising results of the pre-study, a decision was taken by LKAB to set up a comprehensive, detailed, and structured joint R&D program to investigate open rock engineering questions and to look into the development of technological infrastructure to enable automated and remotely controlled mining operations. The program emphasizes on key issues of the raise caving method. Central points in the program are investigations on pillars, ore flow, hanging wall caving and surface impact, regional stress and energy changes, production and logistics, the machinery inside the raise, ventilation, and blasting. Overall, the conducted activities aim at evaluating the application potential of raise caving as well as at designing a layout and sequence for a raise caving operation at greater depth in Kiruna mine.

The program was started in 2020. The Chair of Mining Engineering & Mineral Economics at Montanuniversitaet Leoben concentrates on the rock engineering aspects and design, and LKAB focuses on the machinery and mine planning aspects. For the machinery development, LKAB is currently partnering with LKAB subsidiaries Wassara and Kimit, NECAB North Engineering Consulting AB, and ABB. Fig. 8 shows exemplary one of the concepts currently under investigation and development (Fig. 8).

Moreover, the principles of raise caving are going to be tested in large scale tests in designated sites in Kiruna or Malmberget mine. Detailed planning of the test site is currently ongoing, and construction is planned to start in summer 2022.

6. Conclusion

Raise caving is based on existing and successfully applied modern, large-scale raise mining method and deep mining approaches. This contribution describes the raise caving method and its approach to address encountered rock mechanics issues in existing caving methods at great depth. Raise caving enables the de-stressing the ore body with a minimum amount of infrastructure and bulk extraction of the ore body in de-stressed ground. Thus, it is expected that raise caving is better suited for deep cave mines than other available caving methods. Moreover, raise caving should allow a higher degree of remote control and automation. A pre-study dealing with the application of raise caving in Kiruna mine supports the application potential of raise caving from a rock mechanics point of view and outlines considerable advantages in terms of rock mechanics and mine operation compared to the currently applied sublevel caving method. A comprehensive research project aiming on
the development of the raise caving method including a full scale test of raise caving is ongoing.

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References

1. Laubscher, D.H.: Cave mining—The state of the art. J. S. Afr. Inst. Min. Metall. 94(10), 279–293 (1994)
2. Gomes, A.R.A., Rojas, E., Ulloa, J.C.: Severe rock mass damage of undercut and extraction level pillars at El Teniente Mine. Geomech. Tunn. 9(5), 529–533 (2016)
3. Campbell, R., Mardiansyah, F., Banda, H., Tshisens, J., Griffiths, C., Beck, D.: Early experiences from the Grasberg block cave: A rock mechanics perspective. In: Castro, R., Báz, F., Suzuki, K. (eds.) Proceedings of the Eighth International Conference and Exhibition on Mass Mining, University of Chile, pp. 115–126. (2020)
4. Holder, A., Wolmarans, A., Mzimela, B., Beck, D., Tukker, H., Boshoff, P., Matoba, T., Phahla, T.: A block cave construction process realigned to minimise predicted deformation in a weak mining zone: A rock mechanics perspective. In: Castro, R., Báz, F., Suzuki, K. (eds.) Proceedings of the Eighth International Conference and Exhibition on Mass Mining, University of Chile, pp. 140–154. (2020)
5. Araneda, O., Sougarret, A.: Lessons learned in cave mining at the El Teniente mine over the period 1997–2007. In: Schunnness, H., Nordlund, E. (eds.) Proceedings of MassMin 2008, Luleå University of Technology, Luleå, pp. 43–52. (2008)
6. Dahneţ, C., Malmgren, L., Bošković, M.: Transition from non-seismic to a seismically active mine: Kirunavaara mine. In: ISRM International Symposium—EUROCK 2012, Stockholm (2012)
7. Malovichko, D., Cuello, D., Rojas, E.: Analysis of damaging seismic event on 24 December 2011 in the Pilar Norte sector of El Teniente mine. In: Potvin, Y., Jakubeck, J. (eds.) Proceedings of the Fourth International Symposium on Block and Sublevel Caving, Australian Centre for Geomechanics, Perth, pp. 637–650. (2018)
8. van As, A., Jeffrey, R.G.: Caving induced by hydraulic fracturing at Northparkes mines. In: Girard, J., Lieberman, M., Breeds, C., Doe, T. (eds.) Pacific Rocks 2000, Balkema, pp. 353–360. (2000)
9. Ngidi, S.N., Pretorius, D.D.: Impact of poor fragmentation on cave management. In: Potvin, Y. (ed.) Proceedings of the Second International Symposium on Block and Sublevel Caving, Australian Centre for Geomechanics, Perth, pp. 593–601. (2010)
10. Parsons, J., Hamilton, D., Ludwicki, C.: Non-vertical cave and dilution modelling at New Gold's New Afton mine. In: Potvin, Y., Jakubeck, J. (eds.) Proceedings of the Fourth International Symposium on Block and Sublevel Caving, Australian Centre for Geomechanics, Perth, pp. 323–334. (2018)
11. Laubscher, D.H.: Block Caving Manual, Prepared for International Caving Study. Julius Kruttschnitt Mineral Research Centre, The University of Queensland, Brisbane (2000)
12. Brown, E.T.: Block Caving Geomechanics, 1st edn. Julius Kruttschnitt Mineral Research Centre, The University of Queensland, Brisbane (2003)
13. Brown, E.T.: Block Caving Geomechanics, 2nd edn. Julius Kruttschnitt Mineral Research Centre, The University of Queensland, Brisbane (2007)
14. Brown, E.T., Chitombo, G.P.: Underground Mass Mining by Caving: The Way of the Future, Sustainable Minerals Institute, Julius Kruttschnitt Mineral Research Centre, The University of Queensland, Brisbane (2007)
15. Flores, G., Karzulovic, A., Brown, E.T.: Current practices and trends in cave mining. In: Karzulovic, A., Alfaro, M. (eds.) Proceedings of MassMin 2004, Chilean Engineering Institute, Santiago, pp. 83–90. (2004)
16. Power, G., Just, G.: A review of sublevel caving current practice. In: Schunnness, H., Nordlund, E. (eds.) Proceedings of MassMin 2008, pp. 155–164. Luleå University of Technology, Luleå (2008)
17. Chitombo, G.P.: Cave mining—16 years after Laubscher's 1994 paper "Cave mining—state of the art." In: Potvin, Y. (ed.) Proceedings of the Second International Symposium on Block and Sublevel Caving, pp. 45–61, Australian Centre for Geomechanics, Perth (2010)
18. Laubscher, D.H., Guest, A., Jakubeck, J.: Guidelines on Caving Mining Methods, The Underlying Concepts. W.H. Bryan Mining and Geology Research Centre, The University of Queensland, Brisbane (2017)
19. Jofre, J., Yáñez, P., Ferguson, G.: Evolution in panel caving undercaving and initiation methods. In: G. (ed.) Proceedings MassMin 2000, pp. 249–260. Australian Institute of Mining and Metallurgy, Melbourne (2000)
20. Rojas, E., Molina, R., Cavieres, P.: Preundercut caving in El Teniente Mine, Chile. In: Hustrulid, W.A., Bullock, R.L. (eds.) Underground Mining Methods Engineering Fundamentals and International Case Studies, pp. 417–423. Society for Mining, Metallurgy and Exploration Inc, Littletown (2001)
21. Catalán, A., Onederra, I., Chitombo, G.: Evaluation of intensive pre-conditioning in block and panel caving—Part I, quantifying the effect on intact rock. Min. Technol. 126(4), 209–220 (2017a)
22. Catalán, A., Onederra, I., Chitombo, G.: Evaluation of intensive pre-conditioning in block and panel caving—Part II, quantifying the effect on seismicity and draw rates. Min. Technol. 126(4), 221–239 (2017b)
23. Nugraha, N., Bastlwarman, R., Edgar, I.: Initial setup of hydraulic fracturing in Deep Mill Level Zone (DMLZ) underground mine, PT Freeport Indonesia, Papua, Indonesia. In: Castro, R., Báz, F., Suzuki, K. (eds.) Proceedings of the Eighth International Conference and Exhibition on Mass Mining, University of Chile, pp. 239–248. (2020)
24. Jacobsson, L., Töyrä, J., Woldemedin, B., Krekula, S.: Rock support in the Kirunavaara Mine. In: Potvin, Y., Brady, B. (eds.) Proceedings of the Seventh International Symposium on Ground Support in Mining and Underground Construction, pp. 401–409. Australian Centre for Geomechanics, Perth (2013)
25. Potvin, Y., Wesselo, J., Morkel, G., Tierney, S., Woodward, K., Cuello, D.: Seismic risk management practices in metalliferous mines. In: Joughin, W. (ed.) Proceedings of the Ninth International Conference on Deep and High Stress Mining, pp. 122–132, The Southern African Institute of Mining and Metallurgy, Johannesburg (2019)
26. Wagner, H.: Deep mining: a rock engineering challenge. Rock Mech. Rock Eng. 52, 1417–1446 (2019)
27. Wagner, H., Salamon, M.D.G.: Strata Control Techniques in Shafts and Large Excavations. Association of Mine Managers of South Africa Papers and Discussions., pp 123–140 (1973)
28. Durrheim, R.J.: Mitigating the risk of rockbursts in the deep hard rock mines of South African: 100 years of research. In: Brune, J. (ed.) Extracting the Science: A Century of Mining Research, pp. 156–171. Society for Mining, Metallurgy and Exploration Inc, Denver (2010)
29. Watson, B.P., Pretorius, W., Mpuuni, P., Du Plooy, M., Mattheyson, K., Kuijpers, J.S.: Design and positive financial impact of crush pillars on mechanized deep-level mining at South Deep Gold Mine. J. S. Afr. Inst. Min. Metall. 114(10), 863–873 (2014)
30. Andrews, P.G., Butcher, R.J., Ekkerd, J.: The geotechnical evolution of deep level mechanized distress mining at South Deep. In: Joughin, W. (ed.) Proceedings of the Ninth International Conference on Deep and High Stress Mining, pp. 15–28. The Southern African Institute of Mining and Metallurgy, Johannesburg (2019)
31. Makinen, I., Paganus, T.: Stability of hanging Walls at the Viscaria Copper Mine. In: 6th ISRM Congress, Montreal (1987)
32. Ran, J., Mfula, C.: Geomechanical aspects in Alimak stoping at Barrick’s Bulyanhulu Mine. Min. Technol. 121(1), 1–10 (2010)
33. Siefert, M.: Erfahrungen mit innovativen Abbaukonzepten im alpinen untertägigen Bergbau. In: „Bergbau Gestern – Heute – Morgen“ Ehrenkolloquium aus Anlass des 90. Geburtstages von em. O. Univ.-Prof. Dr.-Ing. Dr.h.c. mult. Günter B.L. FETTWEIS und des 75. Geburtstages von em. O. Univ.-Prof. Dipl.-Ing. Dr. mont. Horst WAGNER. Montanuniversität Leoben, Leoben (2014)
34. IMA Europe: IMA Europe announces the winners of its 2016 Recognition Awards in 4 categories. https://www.ima-europe.eu/award/sites/ima-europe.eu.award/files/Press%20release%20IMA-Europe%202016%20Awards.pdf, Accessed 19 Apr 2020
35. Gipps, I., Cunningham, J., Cavanough, G., Kochanek, M., Castleden, A.: ROES®—A low-cost, remotely operated mining method. In: Proceedings Tenth Underground Operator’s Conference, pp. 147-156. The Australasian Institute of Mining and Metallurgy, Melbourne (2008)
36. Gipps, I., Cunningham, J.: ROES®—Automated rock extraction. In: Proceedings Second International Future Mining Conference, pp. 35–39. The Australasian Institute of Mining and Metallurgy, Melbourne (2011)
37. Ladinig, T., Wagner, H., Bergström, J., Koivisto, M., Wimmer, M.: Raise Caving—A new cave mining method for mining at great depths. In: Proceedings of the 9th International Future Mining Conference, pp. 368–384. The Australasian Institute of Mining and Metallurgy, Melbourne (2021)
38. Wimmer, M., Nordqvist, A.: Present-day sublevel caving functionality uncovered—What’s next? In: Schunnesson, H., Johansson, D. (eds.) Proceedings of the 12th International Symposium on Rock Fragmentation by Blasting, pp. 469-480. Luleå University of Technology, Luleå (2018)
39. Dahnér, C., Dineva, S.: Small-scale variations in mining-induced stresses, monitored in a seismically active underground mine. In: Wesseloo, J. (ed.) Proceedings of the Second International Conference on Underground Mining Technology, pp. 233–246. Australian Centre for Geomechanics, Perth (2020)
40. Sjöberg, J., Dahnér, C., Malmgren, L., Perman, F: Forensic analysis of a rock burst event at the Kirunavaara Mine—Results and implications for the future. In: Sainsbury, D., Hart, R., Detournay, C., Nelson, M. (eds.) Proceedings of the 2nd International FLAC/DEM Symposium, Itasca International Inc, pp. 67–74. (2011)
41. Ladinig, T., Daborer, A., Wagner, H., Maier, T.: Pre-study: Improved Caving Systems in LKAB’s Kiruna Mine (2019). Institute of Mining Engineering, Montanuniversität Leoben, internal report

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