

# Raise caving: a novel mining method for (deep) mass mining

**T Ladinig** *Montanuniversitaet Leoben, Austria*

**M Wimmer** *LKAB, Sweden*

**H Wagner** *Montanuniversitaet Leoben, Austria*

## Abstract

*Raise caving is a novel mining method, which is based on the raise mining method. Raises are central and utilised for different purposes. Here only those directly related to the extraction of the orebody will be discussed. The main objective of raises is to utilise them for creating de-stressing slots, large drawbells and large stopes in an efficient manner. Remote-controlled or automated machinery is operated in raises. Further objectives of raises comprise monitoring and preconditioning. Depending on the field of application two different variants of raise caving can be distinguished, namely a de-stressing variant and a block caving variant.*

*In the de-stressing variant, narrow slots are created first with the objective of providing stress shadows for mining activities in the subsequent production phase. Creating the slots in the de-stressing phase is high stress mining. Hence, massive pillars are left between slots to control the stress situation for de-stress raise development and mining-induced seismicity. After the de-stressing phase is completed, large-scale mineral extraction commences in de-stressed zones. In the production phase large drawbells are developed from raises and large stopes are extracted. During stope blasting only the swell of each blast is mucked so that blasted rock mass provides temporary support to the stope walls. After blasting is completed, the stope is drawn empty and the hanging wall is allowed to cave and caved hanging wall rock mass fills up the stope successively. The massive pillars are extracted in the course of large-scale stoping in the production phase too.*

*In the block caving, variant raises are utilised for drawbell development, undercutting, preconditioning and monitoring purposes. Large drawbells are developed from raises. As drawbells are developed in upward direction, the roof area of the drawbells is enlarged constantly until continuous caving is initiated. Due to the integration of several key activities the block caving variant of raise caving is also referred to as integrated raise caving.*

*This paper highlights the background and motivation for raise caving and it describes both raise caving variants. Steps for the implementation of the methods are outlined and advantages of the individual methods are outlined briefly. Key issues for the implementation of raise caving are highlighted and discussed, and an outlook on currently ongoing research and development activities, which include in situ tests of the method and machinery, is provided. Dedicated accompanying papers provide more information on the ongoing research and development.*

**Keywords:** *cave mining, mass mining, deep mining, stress management*

## 1 Introduction

Mass mining is characterised by large production volumes exceeding 10 kt/day or 3 Mt/year (Nordlund 2008). In order to achieve large production volumes, large production stopes and a large spatial extent of stoping activities are necessary. Moreover, a high productivity method is preferred to keep mining costs low. For this reason, mass mining methods are commonly applied in low grade deposits.

The deposit size and shape are determining parameters as to whether mass mining methods can be applied. Principally, two different situations can be distinguished, namely:

- *Narrow tabular deposits of large areal extent:* These deposits have typically a relatively small thickness of several metres and extend over many kilometres in strike and dip direction. The relatively small thickness demands a large areal extent of mining activities to reach a large production volume. An example of mass mining in such deposits is large-scale longwall mining in coal.
- *Thick tabular deposits and massive deposits:* These deposits are characterised by a large extension in all three spatial directions, which enables the extraction of large stopes. Hence, for mass mining the size of stopes is critical, whereas the areal extent of mining activities is typically smaller than in the first situation described above. Typical mass mining methods in such deposits comprise large-scale longhole open stoping, block caving and sublevel caving.

Mass mining in narrow tabular deposits and massive deposits is different. The deposit characteristics call for different mining methods, mine layouts and mining sequences. These different methods take into account different operational and rock mechanics constraints, which are strongly related to the differences in size and shape of the deposits. It is beyond the scope of this paper to discuss these differences, the individual methods and their individual issues. Instead, this paper concentrates on mass mining in thick tabular and massive deposits by means of cave mining methods.

## 1.1 Attractivity of cave mining methods

Cave mining methods rely on caving of the rock mass by means of gravity or stresses. The main objectives of caving are to fragment the rock mass and to fill up mined-out areas. Depending on the method, caving is initiated on purpose in the orebody and the hanging wall or in the hanging wall only. In block and panel caving operations the orebody is undercut and caving is initiated in the orebody. Caving fragments the ore, propagates due to drawing of caved rock mass and finally caving propagates into the hanging wall, which fills up mined-out areas. In sublevel caving operations the ore is fragmented by means of drilling and blasting and the hanging wall is allowed to cave in order to fill mined-out areas consecutively.

The advantage of cave mining methods for a mass mining application is that a regional support system comprised of pillars or backfill is not required, because the hanging wall is allowed to cave. A further advantage of block caving is fragmenting the ore by means of stress and gravity. Consequently, the processes required for extraction can be reduced and consequently a high production, high productivity and low mining costs can be achieved. The wide application of cave mining methods for mass mining purposes underpins their attractivity.

## 1.2 Specific challenges faced in cave mining

Despite their attractivity and suitability for mass mining, cave mining methods face challenges, which limit their applicability or which endanger the continuation of an operation. These challenges comprise operational and rock engineering aspects. Major issues are:

- *Long development times before achieving planned production and associated high upfront costs:* In order to achieve a high production and productivity, significant amount of infrastructure pre-development and preparatory activities, such as preconditioning or undercutting are necessary before production can commence. Consequently, the capital costs are high and the lead time, until stable production meeting the set target is achieved, is long; see for example Araneda (2020) or Casten et al. (2020).
- *Inflexibility:* Due to the required pre-development work, cave mining methods are very inflexible. The mine layout and mining sequence are mostly fixed at an early stage during mine planning. At this stage the knowledge regarding rock mass properties and rock mass behaviour is mostly relatively limited. Furthermore, changes after infrastructure development commenced are either not possible or associated with considerable additional costs.

- *Control of rock pressure*: Rock pressure related problems are commonly experienced in cave mining. These problems comprise stress related damage to pre-developed infrastructure (e.g. Fernandez et al. 2010; Gomes et al. 2016; Campbell et al. 2020) and the occurrence of mining-induced seismicity and associated rockburst damage (e.g. Araneda & Sougarret 2008; Dahnér et al. 2012). The root of these rock pressure problems is often the development of significant abutment stresses combined with the necessity to place pre-developed infrastructure into abutment zones and to conduct extraction activities in the abutment zones (Ladinig et al. 2022). Rock pressure problems on the one hand impose a safety hazard and they result in operational issues such as a lower production rate or increased extraction costs due to required repair work.
- *Issues related to cave initiation and propagation*: These issues comprise poor caveability, which may result in slow or stalled cave progression, slow production rate, significant amounts of secondary breaking or airgap formation (e.g. van As & Jeffrey 2000; Hebblewhite 2003; Ngidi & Pretorius 2010) and deviation of the planned direction of cave progression, which may have unplanned, adverse effects on the surface or which may cause early dilution with waste material (e.g. Parsons et al. 2018). Moreover, stopping drawing earlier than planned due to intolerably high dilution may cause significant ore losses.
- *Surface subsidence*: Surface subsidence occurs usually due to large-scale caving operations. This issue of caving operations is specific to operations where the surface is required for other purposes; see for example Villegas et al. (2011).
- *Issues related to ore flow*: Ore flow considerations and the therefrom deduced draw strategy are critical for ensuring a high extraction ratio and for preventing early dilution with waste rock. Improper understanding of the ore flow mechanisms, improper draw strategy or improper draw control can manifest themselves amongst others in early dilution, in air blast and inrush risk, in significant loads on the production level and associated damage and in extreme situations in early abundance of the operation; see for example Stegman et al. (2018).

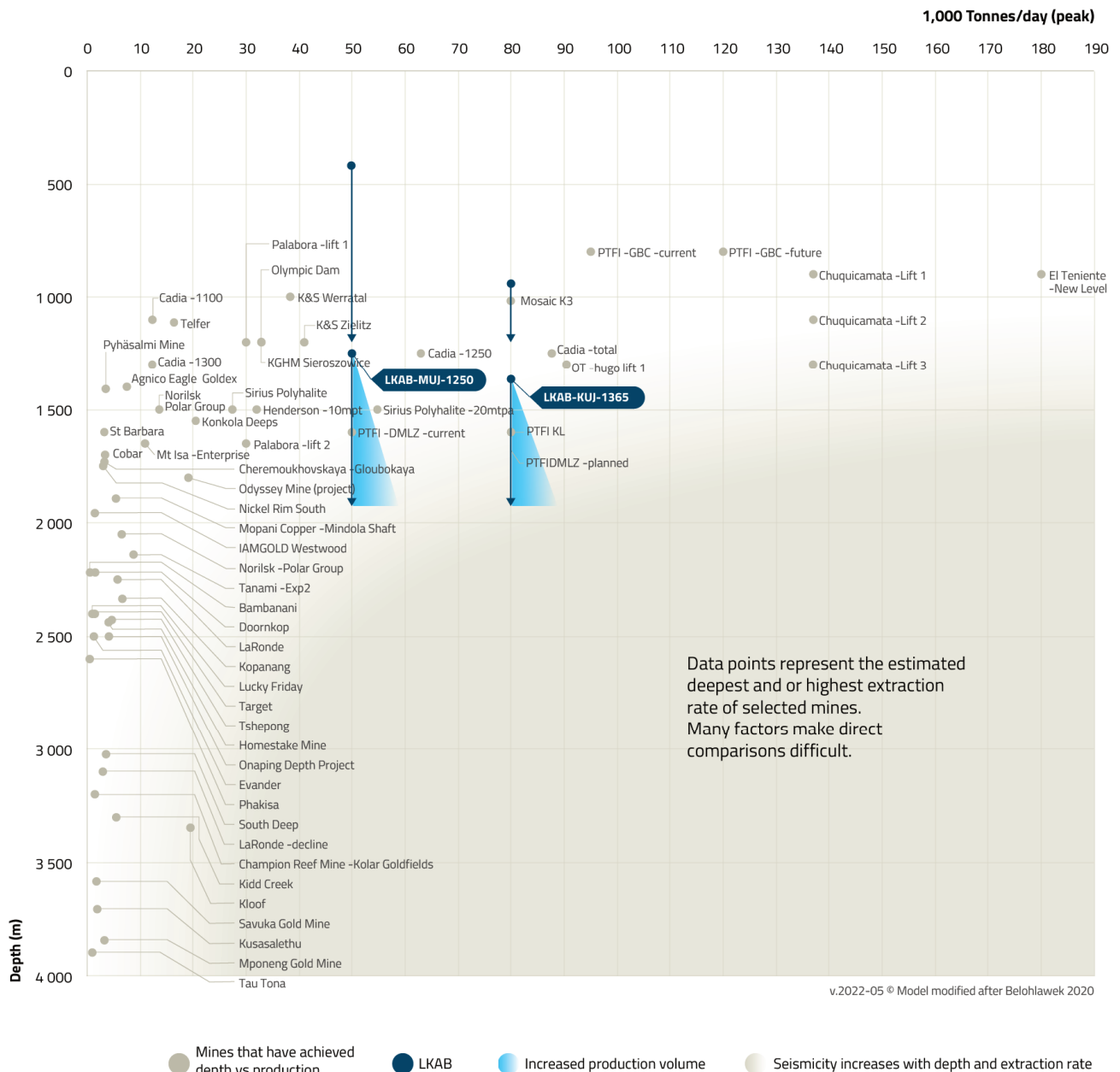
Aforementioned issues are strongly related to the utilised mining methods, mine layouts and mining sequences. They can be addressed best in the planning phase of the operation. In this stage main design parameters such as the mine layout, the mining sequence, the undercut size and the draw strategy are fixed. However, at this stage data, information and knowledge regarding the prevailing geotechnical environment is low and often very limited. Due to this circumstance and the inflexibility of caving methods, the risk associated with cave mining is high.

In recent years there has been an ongoing trend towards developing deeper caving operations and towards more competent rock masses. Furthermore, there has been a rising interest to develop cave mines in deposits with a smaller footprint and in deposits which are narrower. In such conditions the risks further increase. Caving is more difficult to initiate in competent rock masses and cave progression is typically slower. Of particular relevance are rock mechanics aspects in deep cave mines. The increasing primary stress magnitudes result in higher abutment stress magnitudes and increased seismic activity. Furthermore, higher stress magnitudes may impact cave propagation adversely, as clamping stresses in the cave back, which prevent detachment of rock mass, may be larger. The protection of long-term and critical infrastructure becomes central for a successful caving operation at great depth. Another commonly experienced disadvantage at increasing depth is less geotechnical knowledge, which impacts negatively on mine planning and hence increases the risk further.

Summing up, mining experience highlights that current cave mining methods, layouts and sequences are associated with significant operational and rock mechanics difficulties; see for example Stegman et al. (2018). Issues become particularly prominent at depths exceeding 1,000–1,200 m or in competent rock mass conditions.

(Belohlawek, pers. comm. 2020) provides an illustrative graph highlighting this issue. Figure 1 outlines the peak production of mining operations over the average extraction depth. It can be seen that the mass mining

operations (production larger than 10 kt/day) have barely exceeded depths of 1,500 m and the majority just went below 1,000 m, whereas mines with a lower production have been exceeding this depth by far. The grey shaded area indicates an area in terms of extraction depth and production, where mining activities are either not present or very seldom. Hence, operations advancing into this grey shaded area enter new ground. However, at this point it is noted that Figure 1 is only illustrative, because there are inherent simplifications and assumptions, which comprise that a differentiation between different mining environments (stress situation, rock mass conditions) is not made and that the size, shape and footprint of the deposit are not considered. All these aspects could have a significant impact on the peak production and the transition to deep mining conditions, in which the control of rock stresses and seismic energy release become decisive for success.



**Figure 1** Peak production over extraction depth of specific operations (Belohlawek, pers. comm. 2020)

### 1.3 Initiatives

The challenges and risks in cave mining and the particular issues related to great depths and competent rock masses have long been recognised. In order to address them considerable research and development efforts

have been conducted. The major caving studies (Laubscher 2000; Brown 2003, 2007; Brown & Chitombo 2007; Laubscher et al. 2017) financed by major mining houses are therefore mentioned representatively. Examples for proposed, trialled or implemented initiatives against faced issues are:

- Installation of very heavy support and reinforcement systems (e.g. Jacobsson et al. 2013; Campbell et al. 2020).
- Rehabilitation of unstable ground conditions (e.g. Stegman et al. 2018; Holder et al. 2020).
- Extensive and large-scale preconditioning (e.g. Catalan et al. 2017a, 2017b; Nugraha et al. 2020; Orrego et al. 2020).
- Implementation of specific seismic risk management plans (e.g. Chester et al. 2018; Rojas & Balboa 2017).
- Adaptions but no major changes of the layout and sequence (e.g. Tawadrous & Preece 2015; Quinteiro 2018, 2020; Parades et al. 2020).

However, the above-mentioned initiatives do generally not address the root of experienced problems, which are strongly linked to the applied mining methods, mine layouts and mining sequences. Principally, the methods, layouts and sequences have largely remained the same. Significant changes have not been introduced or proposed. Hence, these initiatives can mostly be considered as reactive and passive. Active, foresighted initiatives, which address the root of problems, are mostly absent.

The raise caving method, which is presented and discussed in the following section, addresses the latter shortage of active, foresighted approaches. The main objective of raise caving is to address issues actively, whilst still enabling high production and productivity as well as keeping the extraction costs at a low level.

## 2 Existing technologies used in raise caving

The raise caving method relies on two well-established and successfully applied technologies, namely:

- Modern raise mining method.
- Active stress management.

Both technologies are outlined in the following briefly.

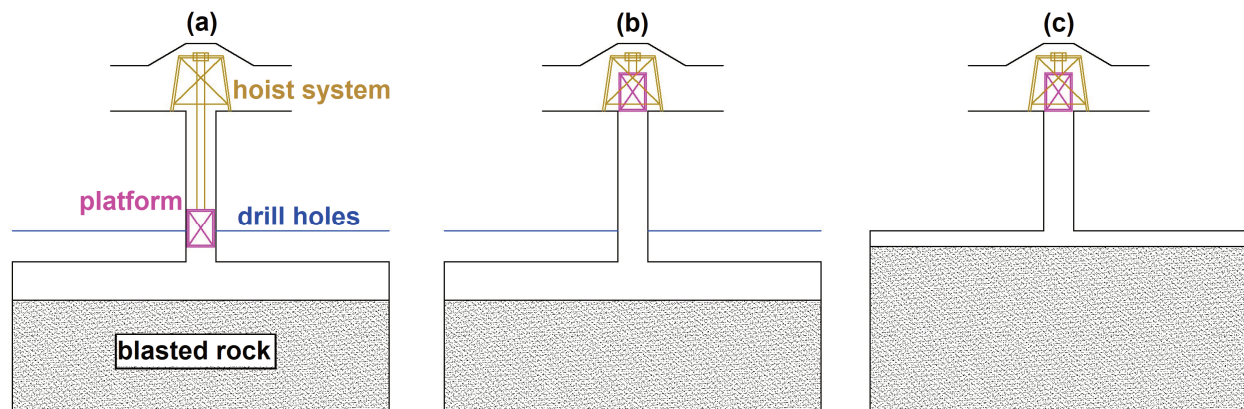
### 2.1 Modern raise mining

Raise mining relies on raises, from which drilling and blasting is conducted for stope extraction. Different raise mining variants have been utilised for many decades, which can be grouped into mechanised and non-mechanised.

- *Non-mechanised raise mining*: Best known are the non-mechanised, small-scale and low productive variants such as Alimak mining or Horadam mining; see for example Makinen & Paganus (1987) or Ran & Mfula (2012). These non-mechanised variants are not suitable for a modern mass mining approach.
- *Mechanised raise mining*: A modern approach of raise mining, which provides a high productivity and a high degree of mechanisation, remote control and automation, has been developed and implemented in the last two decades. This applied modern raise mining approach is well suited for the application in mass mining. The ROES concept proposed by Gipps et al. (2008) and Gipps & Cunningham (2011) is a similar concept. However, the ROES concept was not implemented.

Figure 2 provides an illustrative sketch of the principle of the modern, mechanised raise mining method. On top of a vertical or inclined raise, which is typically developed by means of raise boring, a small, specifically designed shaft hoist system is installed. With this system a platform is lowered into the raise. Machinery on the platform conducts the drilling and charging work (Figure 2a). The simple circular geometry of the raise in

combination with positioning of the machinery through the hoist system provides ideal conditions for remote-controlling or automating the work in the raise. Drill holes are drilled parallel to the roof of the excavation and the drillhole length and orientation can be used to excavate stopes of different dimensions and geometries. The roof of stopes will be inclined in practice to improve roof stability and the breakage during blasting. After drill holes were charged, the platform is retracted to the top at a safe position during blasting (Figure 2b). The blasted rock mass falls into the excavation and fills up the free volume below the roof (Figure 2c). Before the next blast can be fired, sufficient blasted rock mass must be drawn from the stope to provide enough swell volume.



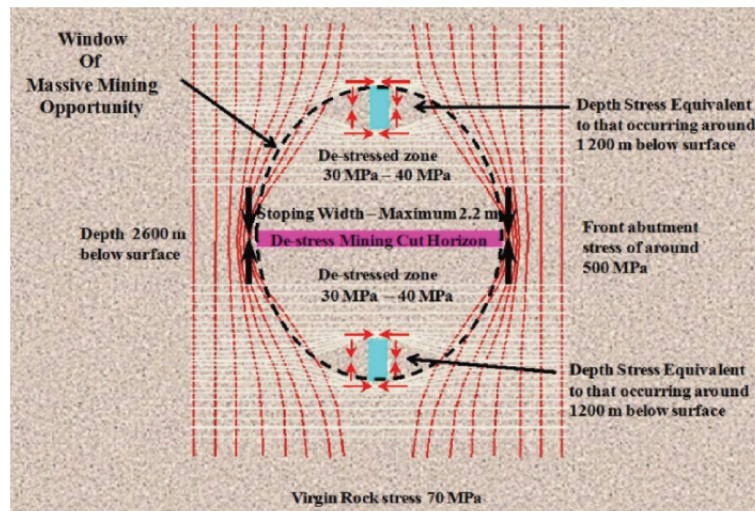
**Figure 2** Vertical cross-section showing principle of modern raise mining; (a) Drilling and charging of holes; (b) Platform retracted for blasting; (c) Freshly blasted roof

## 2.2 Active stress management

An active stress management addresses potential sources of rock pressure problems and aims at eliminating them. Practical examples are providing stress shadows before the development of infrastructure, limiting abutment stress magnitudes or releasing seismic energy distant and controlled from active mining areas. The mine layout and mining sequence as well as providing flexibility for changes in them are critical for the application of an active stress management (Ladinig 2022). Contrary, a passive stress management emphasises on the alleviation of consequences of high rock pressure and mining-induced seismicity. Examples are increasing the strength of the support systems and the repair of occurred damage. As outlined in the introduction the passive stress management is dominant in cave mining currently.

Overall, the active stress management is considered superior over the passive stress management. Potential sources of rock pressure problems are addressed and hence, mining can advance to greater depth safely. Mining experience in deep South African gold mines underpins the advantages of an active stress management (Durrheim 2010). Specifically designed mining layouts and mining sequences have been developed and successfully applied over many decades and up to a depth of 4,000 m; compare Jager and Ryder (1999). Most of these layouts and sequences are applied in narrow reef mining and with conventional, non-mechanised methods. An exception is South Deep mine, in which a reef package is extracted with massive, mechanised methods. In order to apply these methods, a de-stress cut is extracted in a first phase, followed by large-scale stoping in the de-stressed ground in a second phase. An overview of the de-stressing techniques and their evolution in South Deep mine is given by Watson et al. (2014) and Andrews et al. (2019). Figure 3 outlines the stress reduction and effectivity of the de-stress cut schematically.





**Figure 3 Schematic sketch of stress reduction resulting from a de-stress cut (Watson et al. 2014)**

The de-stressing variant of raise caving (see Section 3.1.) makes use of some elements of the active stress management in deep South African gold mines. The approach of South Deep mine comes thereby closest to the approach in raise caving. However, specific adaptations and modifications are necessary. Some of these adaptations are central for a successful application of raise caving and they will be highlighted in the section dealing with key issues.

### 3 Raise caving method

Raises are central in the raise caving method and utilised for different purposes. These purposes comprise the extraction of large stopes, the creation of large drawbells, the extraction of de-stressing slots, monitoring of excavation conditions and implementation of preconditioning. Characteristic for the raise caving method is that either the orebody and the hanging wall or only the hanging wall is allowed to cave as mining progresses.

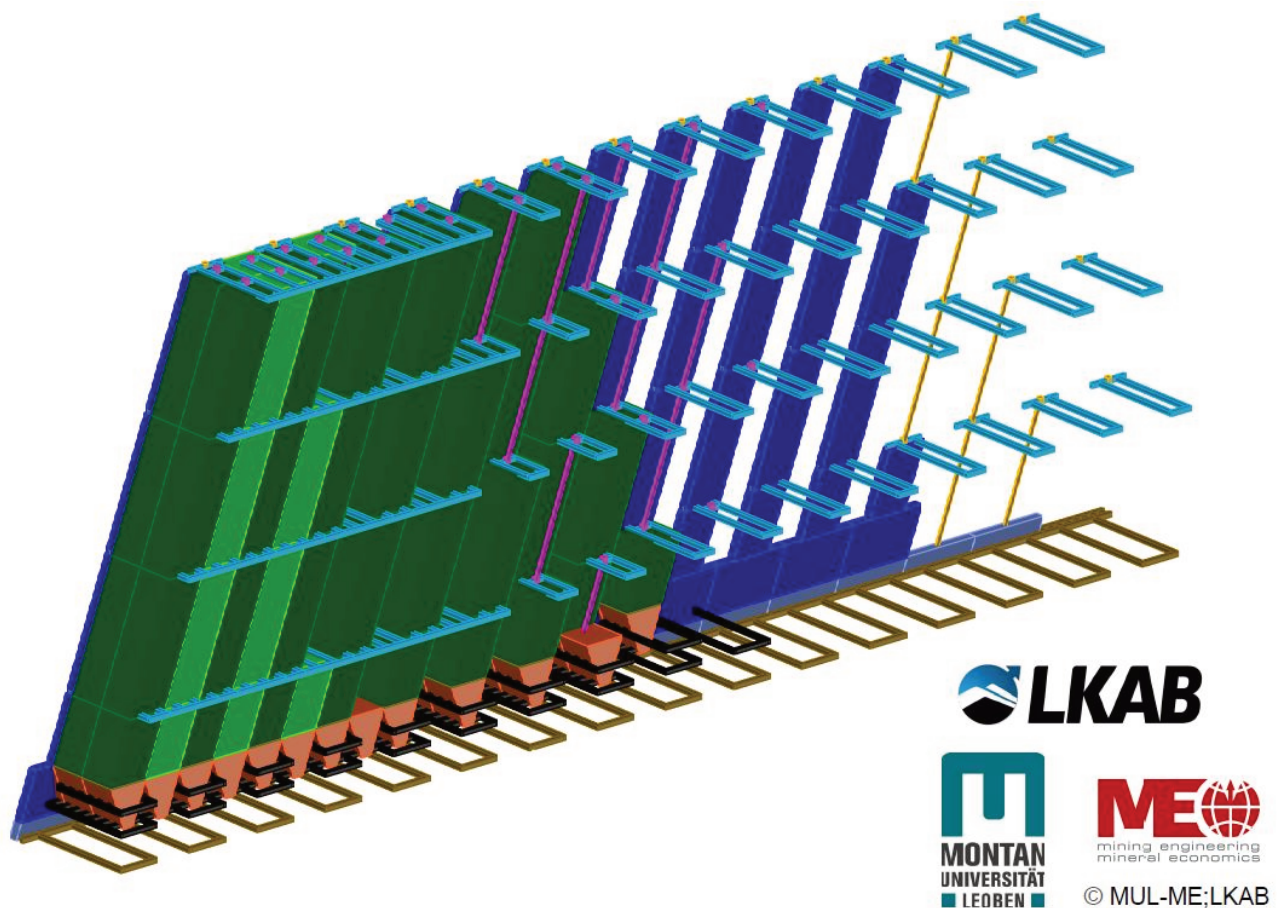
Two variants of raise caving can be distinguished. The applied variant should be chosen according to the prevailing mining environment and production requirements.

- De-stressing variant.
- Block caving variant.

In the following sections a brief outline of both variants is provided. A detailed description of both variants can be found in Ladinig et al. (2021, 2022).

#### 3.1 Raise caving: de-stressing variant

The main objective of the de-stressing variant is making use of an active stress management approach. Therefore, the de-stressing variant of raise caving is comprised of two phases, namely a de-stressing and a production phase. Figure 4 shows a possible layout in a steeply-dipping, thick tabular deposit. Mining advanced from left to right direction in this figure. Infrastructure and excavations required for the de-stressing variant are outlined. Long-term infrastructure, such as ramps, transportation tunnels or hoist shafts are not shown for overview reasons.



**Figure 4** Raise caving layout for the de-stressing variant in a steeply-dipping, thick tabular deposit

### 3.1.1 De-stressing phase

In the de-stressing phase a slot-pillar system is established with a minimum amount of pre-developed infrastructure. The slot-pillar system is comprised of slots, massive pillars and infrastructure required for its development. So-called slot raises, which are used for slot creation, are therefore central. The objective of the slot-pillar system is the implementation of the active stress management approach. Slots provide stress shadows for the subsequently developed infrastructure and for the stoping activities in the production phase. Slots are always filled with blasted rock mass, because only the swell is drawn from slots after each blast. Massive pillars are left between slots to control the abutment stresses near advancing slot roofs and at positions where infrastructure for the development of the next slots is to be established. Moreover, massive pillars are required to control mining-induced seismicity and to prevent premature hanging wall caving. Slot raises are used for the development of slots and they are situated in the abutment zones of slots. For their protection the dimensions of the slot-pillar systems are decisive. Additionally, heavy support systems will be installed in these raises.

The dimensions and orientation of slots and pillars must be adapted to the prevailing mining environment. It is important to note that the creation of the slot-pillar system is high stress mining and hence that rock mechanics considerations govern the layout and sequence in the de-stressing phase. Protecting the infrastructure in the de-stressing phase is of utmost importance. Furthermore, the dimensions of the slot-pillar system must be such that the stoping activities in the production phase can be conducted safely and efficiently. The latter point refers to the spatial extent of stress shadows and the possible extraction scenarios of the massive pillars in the production phase. Based on ongoing development activities slots and pillars are planned to have a cross-section each in the range of 30–70 m × 5–10 m. The dip extension of slots and pillars can be several hundred metres and the spacing between levels is in the range of 150–250 m.



Figure 4 shows the de-stressing phase on the right-hand side. The slot-pillar system is established at the hanging wall contact. Slots are dark blue, massive pillars between slots are left blank, slot raises are yellow and levels used for slot development are brown and light blue. It can be seen clearly that only a minimum amount of infrastructure is required for the creation of the slot-pillar system.

Besides the outlined slot development with raise mining technology further methods for slot development are investigated. One of these methods comprises guided longhole drilling with drill lengths of more than 100 m and neighbouring raises provide the required swell volume. Again, the objective of these methods is to minimise the amount of pre-developed infrastructure, which is exposed to high stress conditions.

### 3.1.2 *Production phase*

In the production phase large-scale mineral extraction commences under the protection of the previously created slot-pillar system. Production raises and production levels are developed in stress shadows provided by de-stressing slots. From these production raises, a large drawbell is excavated. Afterwards stopes are extracted by means of drilling and blasting above drawbells. The cross-section of stopes is in the range of 35–50 m × 35 m–50 m. The stopes are always filled with blasted ore, as drilling and blasting progresses in upwards direction. This implies that only the swell is drawn after each blast. Leaving the stopes filled with blasted ore provides support to stope walls and the hanging wall and it prevents the occurrence from an air blast.

Initially stopes are only extracted behind slots, where slots provide stress shadows for protecting stopping infrastructure. Pillars and their foundations are still highly stressed at this stage and the development of infrastructure in this high stress zones is not possible. However, progressing stope extraction behind slots has an impact on the pillars, namely the cross-section of pillars is enlarged by increasing the effective height of the pillar. From a rock engineering perspective this enlargement is synonymous to reducing the width to height ratio of the pillar. Hence, the pillar strength is decreased and the pillar post-peak behaviour transitions from a strain hardening to a softening behaviour. As a result, pillars are overloaded and they crush. Due to pillar crushing the stresses in the pillar and its foundation decrease and regional stress and energy changes occur. Crushed and de-stressed pillars can then be extracted in the same manner as stopes behind slots by means of raise mining. An alternative may be to extract these pillars by means of natural caving.

From a rock engineering perspective, it is critical to ensure that pillar crushing is stable and thus that violent pillar failure does not occur. The layout of the slot-pillar system and the stope layout and sequence of stope extraction are decisive. Additional options comprise extracting a part of the pillar within the stopes behind slots or conducting preconditioning measures such as hydraulic fracturing or confined blasting in the pillar. Furthermore, the regional stress and energy changes must be handled such that they do not cause adverse effects on the mining system, particularly in areas where de-stressing activities are conducted. As protection measure against potential adverse impacts it is planned that de-stressing activities lead about three slots ahead of first stopping activities.

If the deposit is too thick to be extracted with one row of stopes behind slots and in pillars, additional rows of stopes can be extracted. For these additional rows the first stopes provide stress shadows for the protection of stopping infrastructure.

Once stopes are completely blasted, they are drawn empty. The hanging wall is allowed to cave and fill up stopes at this stage. Besides caved hanging wall rock mass, rockfill may be dumped into stopes at this stage to limit surface impact. The draw strategy and draw control are critical to ensure that stopes are filled consecutively from top to bottom and to prevent early dilution. Different options exist, namely either every single stope is drawn empty after blasting finished or several stopes are drawn empty as a kind of extraction block, after all these stopes were completely blasted.

In Figure 4 the production phase is on the left-hand side. Production raises are pink, large drawbells are orange, stopes behind slots are dark green, stopes in pillars are light green, production level infrastructure is black and further required infrastructure is light blue. Ore passes and progressing hanging wall caving are not shown for overview reasons. It can be clearly seen that the required infrastructure development in the

production phase can be delayed just before its utilisation and hence that the infrastructure can be positioned in the provided stress shadows.

### 3.1.3 *Advantages of the de-stressing variant*

The advantages offered by the de-stressing variant of raise caving in comparison to widely used caving methods are listed below (Ladinig et al. 2021). More information on these advantages can be found in Ladinig et al. (2021).

- Application of an active stress management approach.
- Application of modern raise mining technology.
- Huge potential for automation and remote control.
- Potential for just-in-time infrastructure development.
- Flexibility on short- to medium-term notice.
- Adaptability to local conditions and requirements.

Due to the provided advantages the de-stressing variant of raise caving offers a considerably advantageous alternative for deep mass mining. Particularly, the active stress management approach and the raise mining technology facilitate or, in some instances, even enable the extraction of deep deposits in an efficient and safe manner. An application study conducted in Kiruna mine (Ladinig et al. 2019) and the ongoing raise caving development activities underpin the offered advantages and attractiveness (see Section 5).

## 3.2 *Integrated raise caving: block caving variant*

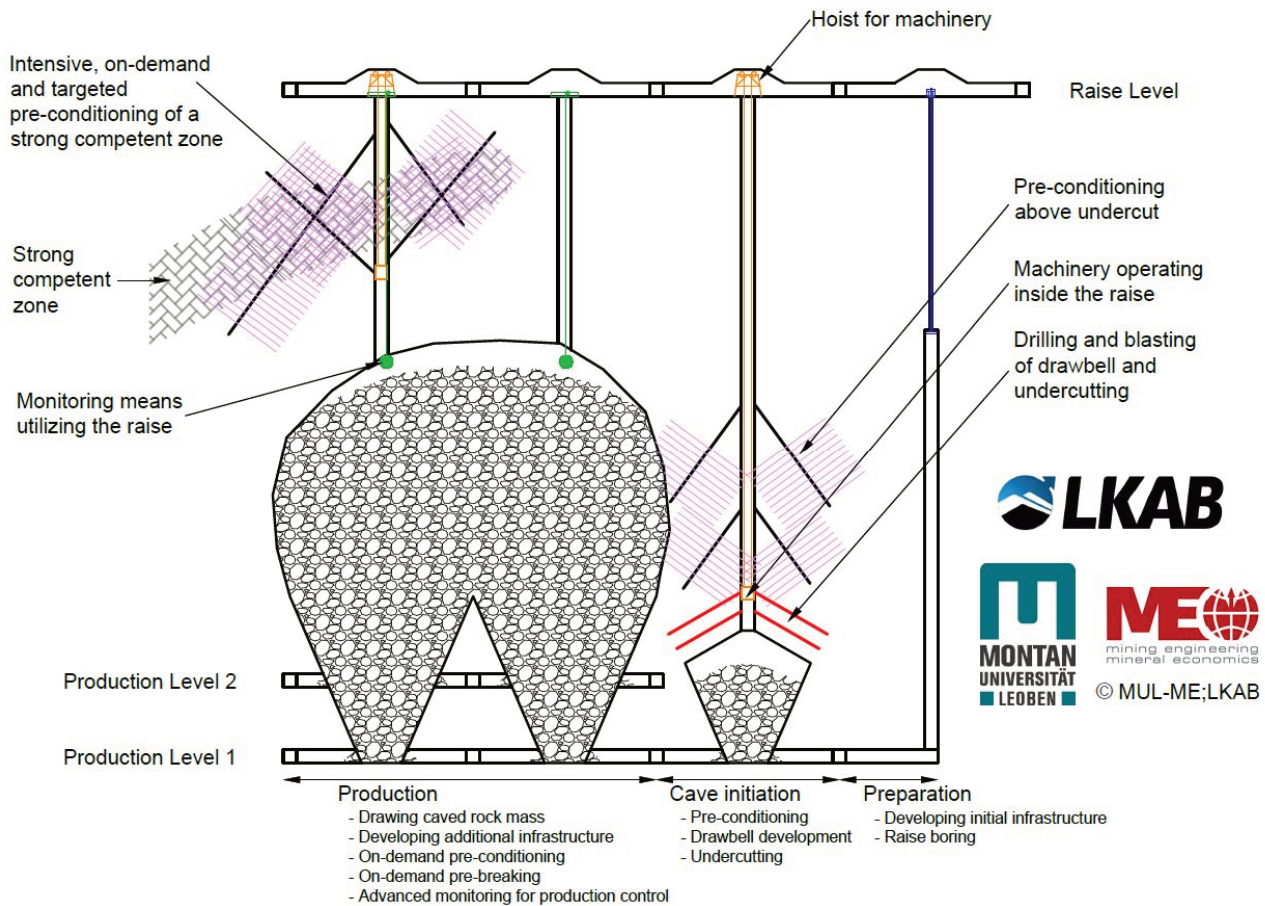
The main objective of the block caving variant is to make use of the raise mining technology for the development and establishment of a large-scale caving operation. Raises are central and used for the main steps in cave establishment, namely, preconditioning, drawbell development, undercutting and controlling of cave propagation. For this reason, the block caving variant is also referred to as integrated raise caving.

### 3.2.1 *Cave establishment with integrated raise caving*

Figure 5 shows a schematic layout and sequence of integrated raise caving in a vertical cross-section. Extraction advanced from left to right side. Individual, consecutively conducted extraction steps are:

- *Step 1 – Preparation of the operation:* First raises are developed by means of raise boring between a first production level and a raise level. The raise level can be situated above the deposit or distant from production levels, if raises are required during the production (Step 3), or inside the deposit close to the production levels, if raises are only required for cave initiation (Step 2).
- *Step 2 – Cave initiation:* Large drawbells are created from raises in upwards direction. Only a minimum amount of infrastructure on the production level is therefore needed, because the blasted rock mass from drawbell development can be drawn from a few drawpoints. The roof of drawbells forms the undercut and the roof area of drawbells is enlarged continuously until caving is initiated. During undercutting only the swell from blasting is drawn from drawbells. Thus, Drawbells are always filled with broken rock mass to mitigate the air blast risk and to stabilise drawbell sidewalls. Depending on the hydraulic radius and the drilling and blasting capabilities from the raise, several adjacent drawbells may be required for the initiation of caving. If necessary, targeted preconditioning measures can be conducted from raises in this step.
- *Step 3 – Production:* Caving was initiated and it progresses in an upwards direction. Caved rock mass is drawn through drawpoints developed into the large drawbells. A second production level has to be developed due to the large size of drawbells. The large drawbells offer significant advantages respective ore flow (Koch et al. 2022). The majority of the infrastructure on the production levels

can be developed delayed at an early stage of production, because only minimum draw infrastructure is required for drawbell development (Step 2). The raises can be utilised further for the monitoring and controlling purposes. Monitoring devices can be lowered into the cave to observe cave progression, primary fragmentation, the condition of the cave back and the direction of caving. Based on monitoring controlling measures such as an on-demand draw strategy or targeted preconditioning for controlling, the direction and rate of cave progression can be implemented. Additionally, competent zones can still be pre-conditioned from raises during the ongoing production.



**Figure 5 Schematic sketch of integrated raise caving**

### 3.2.2 Advantages of integrated raise caving

In comparison to currently applied block and panel caving methods, the integrated raise caving method offers, amongst others, advantages as listed below (Ladinig et al. 2021). More information on these advantages can be found in Ladinig et al. (2021).

- Enabling shorter development times.
- Reduction of the required infrastructure pre-development.
- Improving the functionality of the undercut.
- Improving ore flow.
- Huge potential for automation and remote control.
- Flexibility on short- to medium-term notice.
- Adaptability to local conditions and requirements.

- Improving monitoring and controlling capabilities.
- Reduction of the abutment stress issues during undercutting.
- Improving the stability of production levels.
- Possible combination with an active stress management approach.

The provided advantages are considerable and address safety, efficiency, flexibility and controllability. In summary, the advantages tackle issues faced in current cave mining methods. Hence, the integrated raise caving is considered to reduce the risk in cave mining considerably and to improve the range of application of cave mining methods.

### 3.3 Development of a novel mining method

Both outlined methods of raise caving are based on well-established technologies, but they are novel in the sense that they have not been applied. Hence, as with any new development there are a number of uncertainties and critical areas which need to be clarified for assessing the full potential of raise caving as well as for introducing raise caving. Critical areas and uncertainties have been identified and they are addressed by targeted research and development. Sections 4 and 5 provide an overview. Moreover, critical areas are updated on a regular basis based on development results to facilitate method development.

## 4 Key issues

Several key issues for the implementation of raise caving have been identified. A key issue is considered an issue or circumstance that can endanger the application of raise caving or imposes a significant risk in raise caving. Hence, key issues require particular attention in the development, design and operation. At this point it is also noted that raise caving is, in contrast to other cave mining methods, a relatively flexible method. The flexibility of raise caving allows to introduce changes into the layout and sequence on short- to medium-term notice, which reduces the risk related to uncertainties resulting from key issues significantly.

A brief outline of key issues is given in this chapter. The emphasis is thereby on the de-stressing variant, because the de-stressing variant is of primary interest for LKAB mines, because of the experienced high stress conditions and the planned depth extensions (Jones et al. 2022). Dedicated, accompanying papers address some of these key issues (Folgosó Lozano et al. 2022; Karlsson & Ladinig 2022; Koch et al. 2022).

### 4.1 Pillars in the slot-pillar system

A detailed understanding of the behaviour of pillars in the raise caving system is essential for the practical implementation of the system. The critical issue is the changing role of the pillars as mining progresses. The initial pillars between the individual de-stressing slots have to be strong and stable in order to control the stress environment during slot raise development. Therefore, these pillars have a high width to height ratio, typically exceeding 10. With the extraction of the orebody in the de-stressed zone behind the de-stress slots the effective height of pillar increases and the effective width to height ratio of the pillar decreases. Associated with this is a decrease in the resistance to deformation of the pillar and a transfer of stresses from the pillars between the de-stress slots to the abutments of the extraction panel. Depending on the thickness of the deposit the effective width to height ratio could reduce from 10 to below 1 and pillar deformation increases significantly. Depending on the magnitude of these changes the characteristics of the pillar system can change from initially stable to locally and/or regionally unstable. This can have significant implications for the system behaviour at an advanced stage of extraction and, in particular, on the development of the seismic hazard. As there is very limited information available on the in situ performance of large hard rock pillars a comprehensive field test program is planned (Karlsson & Ladinig 2022).

## 4.2 Ore flow

In the de-stressing variant of raise caving, ore flow related aspects are especially important. Hang-ups in slots or inflow of caved hanging wall or blasted ore from neighbouring stopes can prevent advancing slots and stopes because of missing swell volumes. Furthermore, the novel large drawbells have an impact on ore flow, which, according to ongoing investigations, is positive and facilitates mass flow (Koch et al. 2022). For this reason, it is decisive to develop a proper understanding of the flow mechanism in slots and stopes to dimension excavations and to design draw strategies.

## 4.3 Further key issues

The key issues related to pillars and ore flow are found to be particularly critical because there is very limited experience available and there are open points on a fundamental level. Besides these two key issues, there are further key issues which are outlined briefly below:

- *Raise stability*: Due to the central role of raises, their stability is critical for the application of raise caving. Instabilities as well as deformations of the raise may prevent the utilisation of the machinery inside the raise. Particularly critical is the period during raise boring because support can either not be installed or only a very limited support behind the reamer head is installed, which leads to a relatively long period where raises are not fully supported. As slot raises must be developed in the (high) primary stress environment and are exposed to high stresses in the de-stressing phase, they are more vulnerable than other raises. Accordingly, slot raise stability may impose a depth limit for raise caving.
- *Hanging wall caving*: Extraction of stopes and pillars in the de-stressing variant removes the support from hanging wall and initiates hanging wall caving. Caving hanging wall may cause dilution or may prevent further blasting of stopes. Hanging wall caving must be seen closely related to the ore flow key issue.
- *Machinery development*: Machinery operating in raises cannot be bought off the shelf currently. Hence, customised solutions need to be developed. Important for these solutions is a high degree of remote control and automation, first to utilise the advantages of raise caving best and second to remove personnel as far as possible from raises, which may require very specific work procedures due to organisational or legal aspects.
- *Ventilation*: The removal of heat and blasting fumes from slots, stopes and drawbells developed from raises may be difficult and call for specific solutions. The reason for this is that they are filled with blasted rock mass and the raise provides only one access with a relatively small cross-section.
- *Change between sublevel caving and raise caving*: Sublevel caving has a regional top down sequence, whereas raise caving has a regional bottom up sequence. As a result, a sill pillar is created between the approaching raise caving operation and a former sublevel caving operation. The (partial) extraction of the sill pillar and the associated regional changes to the overall system are critical. This instance may be rather specific to LKAB mines.
- *Transition to continuous caving*: This point is critical for the block caving variant. As the size of drawbell roofs is increased and the hydraulic radius and continuous caving is approached, local instabilities in the roof have to be expected. These instabilities may prevent further drilling and blasting of the drawbell.
- *Change management*: The potential change of a well-established mining method in a mine has a strong impact on all organisational levels and it must be managed properly from the beginning on. As raise caving is a novel mining method, the change management is particularly relevant.



## 5 Research and development activities

Despite raise caving being based on existing and well proven technologies, there are open points that require further investigation. Open points on key issues were highlighted in the foregoing sections. In order to address these open points and because of the positive results of the conducted pre-study in Kiruna mine (Ladinig et al. 2019), LKAB made the decision to set up a comprehensive research and development project on raise caving.

The objective of the research and development is to develop raise caving towards its implementation. The focus is on the de-stressing variant, because LKAB is currently investigating depth extensions of their mines to depths exceeding 1,500 m. Therefore, open points on key issues are addressed systematically. Main partners on the development of the mining method (rock engineering, extraction technology and production aspects) are LKAB and Montanuniversitaet Leoben. For the machinery development, main partner of LKAB are LKAB subsidiaries Wassara and Kimit, NECAB North Engineering Consulting AB, ABB and Epiroc. Besides desktop studies, in situ test sites for testing the machinery and the mining method are planned in LKAB mines. Dedicated accompanying papers (Folgosó Lozano et al. 2022; Karlsson & Ladinig 2022; Koch et al. 2022) provide more information and results of the ongoing research and development work.

## 6 Conclusion

Raise caving is a novel mass mining method based on the proven and applied technologies of modern raise mining and an active stress management. Based on the prevailing conditions, two different variants are presented, namely a de-stressing variant, which is particularly suited for deep and high stress conditions, and a block caving variant, which is an alternative for currently utilised block and panel caving methods. Overall, the advantages offered by raise caving are considerable. The ongoing research and development activities driven by LKAB and Montanuniversitaet Leoben and the interest of major mining houses in raise caving underpin the attractivity of raise caving. However, despite raise caving being based on existing and proven technologies, there are still key issues which require further investigation. Key issues comprise the strength and behaviour of massive pillars, ore flow, hanging wall caving, the automation of machinery operating in raises and production considerations. These key issues are addressed actively at the moment through targeted research and development as well as through in situ tests of the machinery and the mining method. The aim is to evaluate the applicability of raise caving and to implement design guidelines for raise caving operations.

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