

Re-thinking deep bulk mining

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ABSTRACT

The current plan for LKAB's Kiruna operation is to bulk mine to depths of more than 1300m by SLC, extending mine life to 2050 and beyond. The goal is safe, reliable production based on a plan incorporating the constraints of a seismically active mine.

A substantial effort is underway to improve SLC performance as part of the safe, reliable production initiative, building on experience from LKAB's mines and other analogous operations. The effort has two components: one technical and one behavioural. The technical focus is developing SLC sequences, layouts, support systems and procedures required for a successful deep mine. Behaviour focuses on ensuring that the technical tasks and processes can be assimilated into the day-to-day organisation. Though the technical aspects of mining at depth are significant, the challenge of changing how things are done is perhaps more so.

On paper, technical change is easy, but a transition process requires management systems and, more importantly, behaviours to be adapted to meet the rigour and discipline required for deep mining. What has worked in the past is not necessarily appropriate for the future. Technical and behavioural changes cannot be done in isolation. Robust communication is required so everyone involved understands the issues and the part they play. This takes time. Meanwhile, the operation must continue to produce in a way that does not compromise the changes required. The paper describes the challenges Kiruna is facing together with the solutions required to meet the goals of safe, reliable production.

1 INTRODUCTION

Kiruna operations are mining at depths of around 1,000m to 1,100m with a plan to mine 300m deeper to recover the Reserves down to the 1365L, the main level for transfer of the ore to the crushers and shaft system. The mining method is predominantly transverse SLC with localised longitudinal SLC to recover high-grade lenses. Production is along an approximately 4km essentially flat front. A description of the operations is given by Wimmer & Nordqvist (2018).

A large seismic event occurred in 2020 with a measured magnitude of 4.2. The event caused considerable damage, but fortunately, due to the time of day, there were no personnel in the

vicinity. Thus, there were no injuries. However, the event was a warning that the mine must improve stress and seismic management (Boskovic, 2022; Dineva et al., 2022).

Higher stresses and increased seismic hazard levels will be encountered as the mining progresses toward the 1365L. The challenge is sending the promised tons safely and reliably to the mill under the operational constraints associated with deeper mining. The first part of the challenge is having an achievable plan that incorporates the consequences of deeper mining, essentially managing the effect of ground conditions on production. The second challenge is implementing the plan to provide the stated metal forecast safely.

Experience at other operations has shown that depth is not forgiving and has a significant downside that must be carefully managed. Going deeper requires discipline and an organisation focussed on overall production reliability (safety is a given), where people fully understand roles, accountabilities, and responsibilities: a planned and integrated process that is scheduled rather than a daily reactive firefighting process.

2 OVERVIEW

Strategic planning provides the framework for achieving safe and reliable production down to the 1365L based on the premise that mining at depth is a fragile process that requires the “right plan” and a disciplined approach to production, the “right behaviour”. The plan's core is production reliability, a function of Footprint Reliability (drawpoint to tippel) and Material Handling System Reliability (tippel to surface stockpile). Reliability depends on the performance of the physical assets in the mine (excavations, fixed and mobile plant, e.g., chutes, crushers, rail, loaders, etc.), the prevailing culture (behaviour) and whether the focus is on producing tonnes or following the agreed production plan.

Excavations represent a considerable investment and are a cave operation’s largest physical *Asset* outside the orebody. As such, it must be managed like all other significant assets (fixed and mobile equipment) to achieve the goal of Footprint and Production Reliability. Drawpoints and their associated extraction drives are thus major mine assets.

Production resilience refers to a system's functionality for managing and mitigating production interruptions. Within this framework, resilience is calculated based on the time it takes the system to return production to the target rate after an event that disrupts production.

The improvement processes that identify and manage constraints are fundamental to reliable production. Behaviour and production reliability are intimately linked (Moss et al., 2024). Behaviour must be adapted if reliable production is to be obtained, Figure 1.

Behaviour	Description	Outcome
Reliable	Reliable integrated production system with a plan-driven way of working	Reliable revenue stream
Planned	Increased management of the downside through improved design, asset management and proactive behaviour	Sub-optimum revenue stream
Reactive	Poor reliability of critical assets with reliance on a large portfolio to make production call. Firefighting of disruptions.	Interruptions to revenue stream

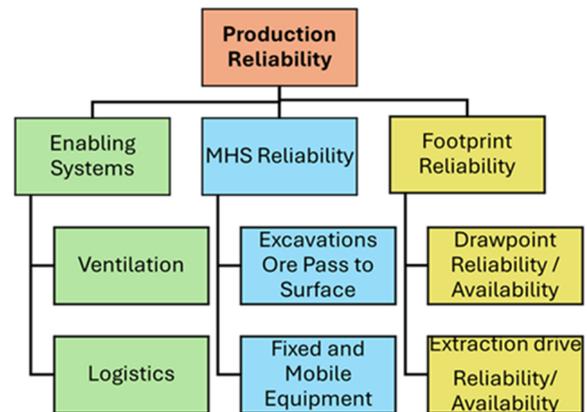


Figure 1 Connections, behaviour, and reliability.

The plan thus has two themes: a technical theme that outlines the improvements required for production reliability through managing ground conditions as mining progresses to the 1365L, the “right plan”, and a behavioural theme that describes the need for proactive, plan-driven behaviour, the “right behaviour”.

Several findings shaped the strategy:

1. Depth is not forgiving; production is vulnerable to mining-induced stresses and seismic activity. Having an achievable plan that incorporates the constraints of ground conditions is critical.
2. The mine is seismically active and has experienced significant stress and seismically induced damage.
3. Time influences strategy. For example, there is insufficient time to change to a new method and meet production targets for the present mine down to 1365L. Therefore, the operation must adapt SLC

- to manage the expected ground conditions safely.
4. A large pillar is to be left in block 22. This represents a substantial investment, dividing the mine into two independent operations, Figure 2.
 5. SLC draws some 20,000m³ of ore daily, resulting in a large active mining volume in the abutment areas, increasing areas of overstress and seismic hazards as mining progresses deeper.
 6. The ore passes have already experienced stress-related challenges, and further stress-induced damage is anticipated.
 7. Forecasts indicate that the 1365L haulage level will experience damage by the early 2030s, including an increased likelihood of floor heave and disruption to train operations. The production capacity will, therefore, be challenged due to the impact of mine-induced stress damage and seismicity on the Material Handling System (MHS) functionality. Plan-driven, proactive behaviour is required to achieve reliable production.

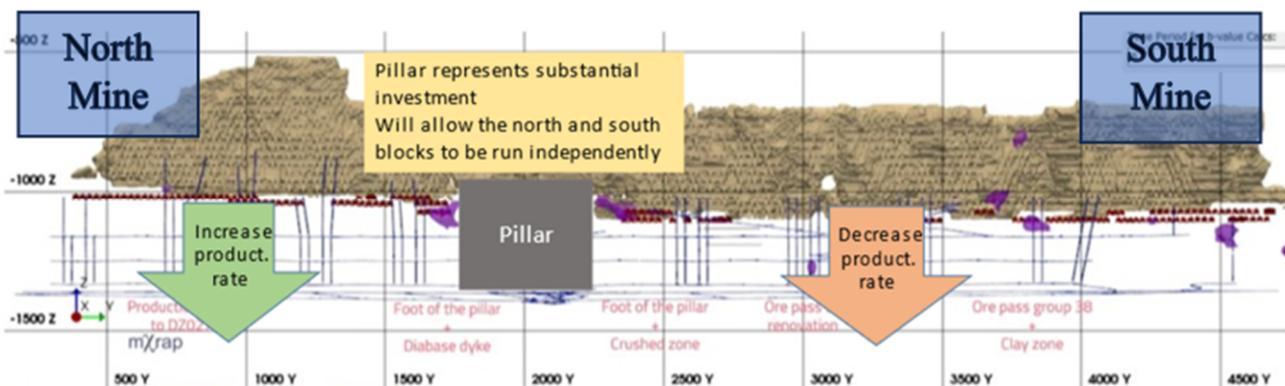


Figure 2 Longitudinal section of Kiruna operations showing placement of strategic pillar.

3 THE PLAN

The objective is to achieve the “right plan” through the “right behaviour” matched to the

challenges associated with deeper mining. The plan is predicated on four sequential phases constrained by time, as illustrated in Figure 3.



Figure 3 Key phases in strategic plan.

3.1 Phase 1: Setting the Scene

The mine has successfully produced at high production rates when the mining depth and seismicity were not significant production constraints. The past is not a reliable indicator of the future. The likelihood of stress-induced damage and associated production interruptions increases with depth. The 2020 seismic event emphasised that stress and seismic management are major performance drivers as the depth of production increases.

Figure 4 presents a schematic of the production system. The system consists of drawpoints, sublevel and footwall drives, tipples, ore passes, chute galleries and a rail haulage system on the 1365L. Damage will reduce the functionality of key excavations, resulting in production delays and interruptions. These excavations can be divided into two broad groups:

1. Temporary development is the drawpoints, sub-levels and footwall drives that constitute the production footprint.
2. The fixed facilities, the tipples, ore passes, chute galleries, and haulage drifts comprise the MHS.

The two groups are vulnerable to the impacts of stress-induced damage. The consequences are, however, different in terms of impact on production. The production footprint represents a reasonably robust system due to the number of drawpoints available for production, thus optionality. The temporary loss of a few drawpoints due to damage will not significantly impact production. The haulage system, by way of contrast, is fragile. There are no options if the haulage level is damaged but to repair, directly impacting production.

The mechanical capacity of the MHS is approximately 35Mtpa, and the loading system is slightly less. Production will, however, be determined by the impact of mining-induced stress on the excavations that form the backbone of the production system rather than the installed capacity of the MHS.

The depth of mining will constrain production. The “burning platform” is managing and mitigating the rock engineering and operational challenges that will occur as production progresses to the 1365L.

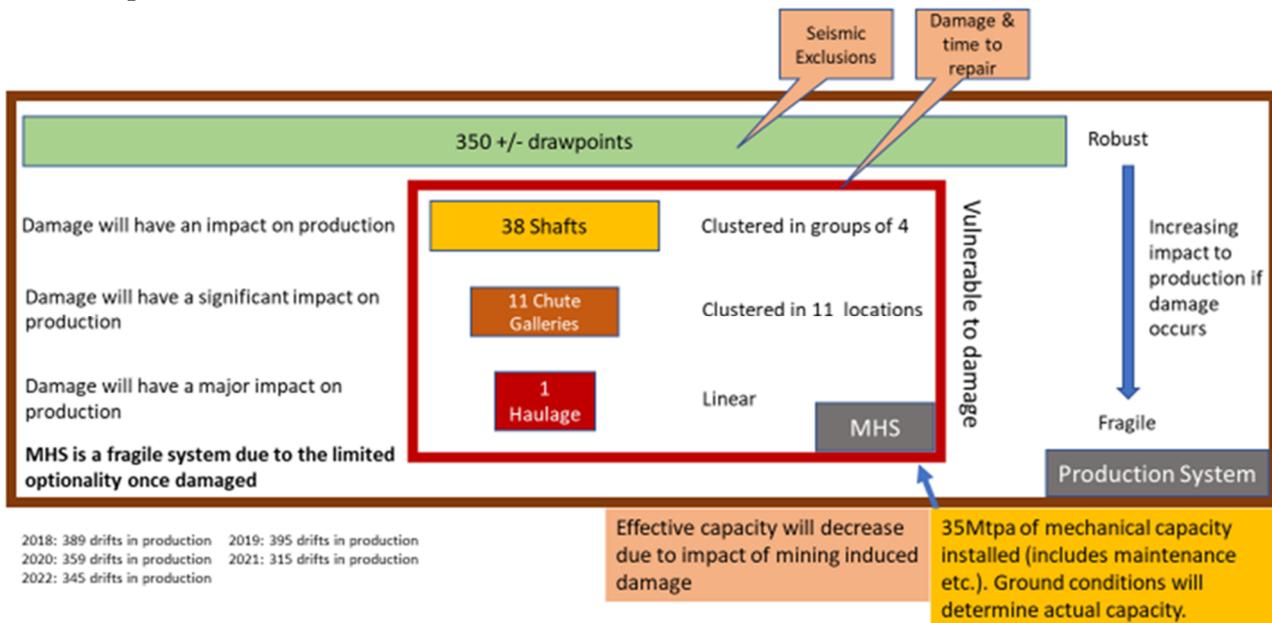


Figure 4 Schematic of the production system.

3.2 Phase 2: Surviving the Present

Several alternate mining methods were examined to determine if they could provide safer and more reliable production than SLC. It

was found that there was not enough time to change methods and maintain production. The decision was made to continue with SLC, focussing on determining which layouts and sequences would result in better stress and

seismic management at acceptable production rates.

The approach adopted is summarised in Figure 5. There are four major tasks:

1. SLC improvements and production controls.
2. Securing the MHS.
3. Transition planning and execution.
4. Modifying behaviour to move from reactive to proactive.

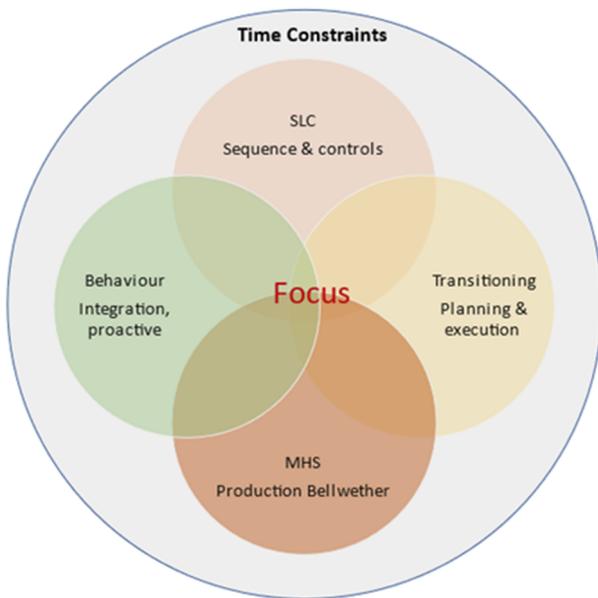


Figure 5 Key tasks for Phase 2.

Improving SLC requires the “right plan” to be developed based on robust Orebody Knowledge (OK). The SLC sequence and layout changes are necessary to manage the anticipated ground conditions better.

The decision has been made to leave a regional load-bearing pillar in place in Block 22, the location of the 2020 seismic event. This pillar effectively divides the mine into two independent production areas: the North Mine and the South Mine, see Figure 2. Historically, the North Mine has been more forgiving, with fewer ground-related problems than the South Mine, an outcome of the South's more complex geology and ore geometry. In addition, the North Mine has considerable resources below the 1365L, while the South Mine has limited resources. The strategy is, therefore, to have the

North Mine as the prime producer and the South Mine as the “swing” producer.

Several strategic options exist to improve a SLC’s ability to manage stress and seismicity. The first is to shape the mining front, moving from the current flat front to a chevron shape. A chevron front provides better stress management but will take time to execute and can lead to even earlier damage to the haulage level.

The second option is to leave additional regional load-bearing pillars in place. Not only can these provide stress management, but they will increase the number of independent production areas. This can be an effective means of managing risk.

Further work is required to develop a plan that balances stress management, productivity, and production requirements. Numerical modelling is being carried out to investigate the advantages and disadvantages of these two options.

There are several tactical options to locally manage stress, including locally orientating the front to cross faults at an appropriate angle, changing the footwall layouts and reducing drive size for better stress management, adopting a just-in-time philosophy for development and production drilling to minimise exposure to the stress changes that occur in the abutment. Finally, the application of Production Governance to ensure the appropriate controls, plans and metrics are in place and that there is acceptable compliance with ground control requirements and operating rules.

The SLC layout and sequence improvements are significant and could take several years to implement. Transition planning is essential to maintain production continuity, efficient allocation, and effective risk management.

As mining progresses, the MHS will be increasingly vulnerable to mining-induced stresses and seismicity. This is an outcome of key components of the system, the passes, haulage level and chute galleries, being located close to the production front. Numerical modelling has been carried out to investigate the potential impact of the stress re-distribution that

occurs as mining progresses. Further work will be carried out on this aspect.

Ore pass performance has had a significant impact on the production rate. Some 10 to 25% of the passes, mainly in the South Mine, can be down for repair at any given time. The repair cost is estimated to add some USD2/t to OPEX, but the more critical is the time to repair. A pass can be out of commission for up to 9 months as repairs are carried out. Conditions are not expected to improve as mining goes deeper. A planned approach to ore pass care and maintenance is required, with strict rules on ore levels in the passes and repair schedules. These will be implemented as part of the transition phase.

Damage occurred near Chute Gallery 30 due to seismic activity in early 2023. This event resulted in floor heave, leading to a derailment. Forecasts indicate significant damage to the southern portion of the haulage system by 2030/2 and to the northern portions by 2036.

Floor conditions will likely impact production before any wall and back damage. Floor heave changes track geometry, increasing the

likelihood of derailments and the need to run the ore trains at slower speeds. Options for floor management include re-ballasting the track, installing support in the floor (akin to the walls) and shaping the floor to provide a geometry more amenable to stress management. A cost-benefit analysis will be undertaken to select the most appropriate option.

Ore pass and haulage level performance are not simply a function of ground conditions only. They are connected to the entire production system. For example, ore pass instability tends to be triggered when passes are emptied. Emptying of passes can occur when trains empty the passes quicker than the loaders can fill the passes, a mismatch between loader productivity and train productivity. In this instance, the focus needs to be on the drivers of loader productivity, Figure 6.

Comprehensive monitoring of the MHS has been initiated, building on previous work. Monitoring includes condition mapping, deformation mapping using LIDAR scans, depth of wall damage as a function of distance to active production and system availabilities, productivities, and maintenance cycles.

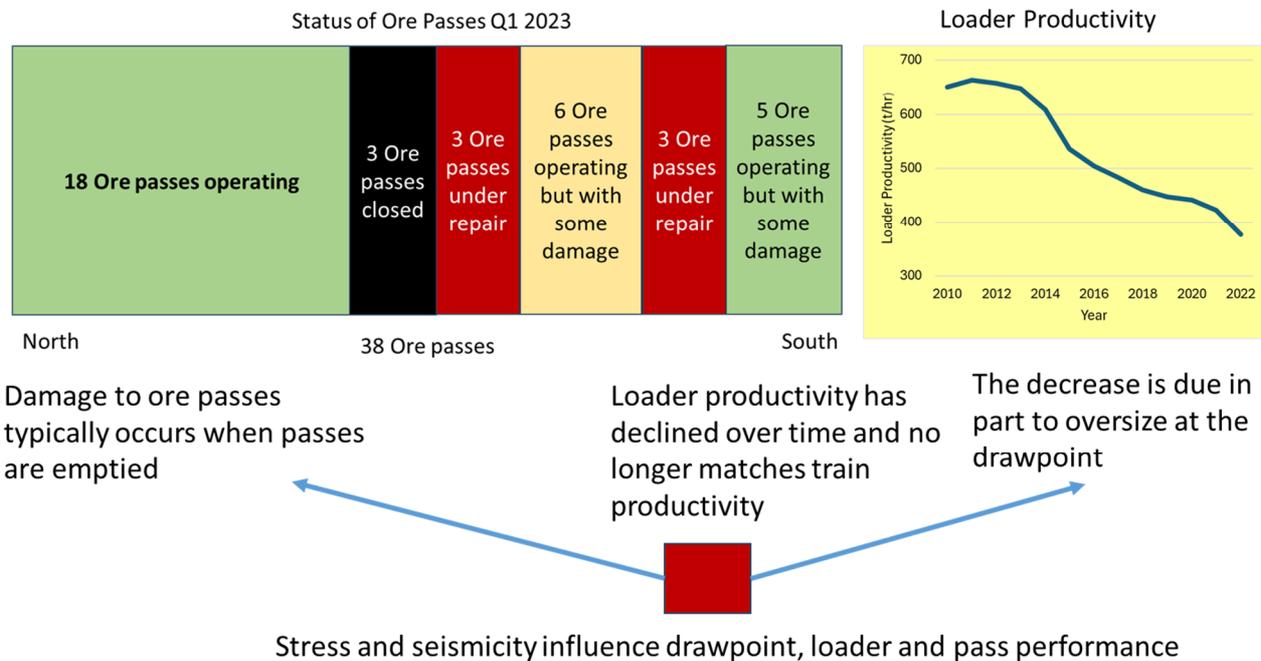


Figure 6 Connections, pass damage train and loader productivities.

Once modelling results are obtained, production simulations and scenario planning will be undertaken to understand better the implications of MHS damage to production. Particular attention should be given to floor behaviour due to the potential impact of heave on train performance. An anticipated outcome of this work will be the potential for stress shielding of key components of the MHS and a program of Preventive Support Maintenance (PSM) (Kaiser & Moss, 2022)

3.3 Transitioning to the Future

The focus will be on plan execution, improving SLC and operational aspects of managing stress and seismic hazards.

Transition planning builds on the analyses and studies carried out during the previous phase. The process starts with transition planning focused on scheduling the changes in abutment shape and sequencing required to progress to the 1365L. The transitioning process must be examined in detail as it may negatively impact production. Trade-off studies will be required.

Experience elsewhere has been that the transition process takes time and requires a dedicated team. Contingency plans must be in place to deal with the anticipated conditions and must incorporate the resources required for monitoring ground conditions and PSM.

Developing the discipline is necessary to mine at depth. The challenge is to change thinking from a “get tonnes to today” to one that “looks after tomorrow’s tonnes” from a reactive firefighting approach to a proactive, plan-driven behaviour. This will require changes in priorities based on good communication and collaboration between all parties. Education, mentoring, metrics, and better integration of key functions are important factors.

The objective is to move from reactive behaviours to proactive and resilient behaviour. The outcome is improved operational efficiency and production reliability, as illustrated in Figure 7.

Experience at other operations has been that changing behaviour requires a substantial

management effort over an extended period, 3 to 5 years, as opposed to a short-term effort of 6 months or less. The process must be well planned.

Associated with a behaviour change is the need to develop an organisation that can respond to complex challenges efficiently and effectively. Figure 8 shows two different structures. The first reflects the more traditional mining organisation, with Engineering providing a service to Production, reflecting a hands-on production-driven approach. Experience with bulk mining at depth has found that the system is fragile due to limited optionality. This suggests that a plan-driven structure is required where Engineering creates achievable plans that Production implements, Figure 8.

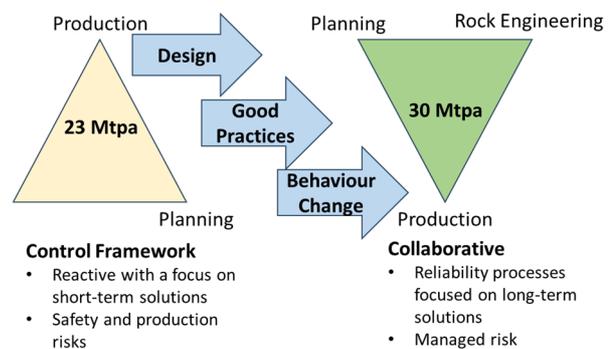


Figure 7 Organization.

3.4 Phase 4: The New Age

An outcome of the work in Phases 1 to 3 is to have a reliable production system, focussing on the “right production” plan supported by the “right behaviour”. A focused effort, together with a sense of urgency, is required in implementing the plan given the short time frame before the impact of deeper mining will impact production. It is critical to recognise the constraint of time, which, once spent, cannot be recovered.

Initially, the focus will be on improving the SLC and maintaining the functionality of the MHS. There will be trade-offs. Investigating the feasibility of developing a new MHS for the resources/reserves in the North Mine must be given attention.

As mining progresses to 1365L, overstress and seismic hazards will increase, damaging the

production footprint and the MHS and constraining production. Damage to the MHS is more likely to impact production than damage to the production footprint because of limited options to bypass (note: in both instances, it is assumed that controls are in place to minimise the risk to the workforce).

The production curve is asymmetric (see Figure 9). The upside limit is the installed capacity of the MHS; the downside limit is substantial due to the production system's vulnerability and fragility to disruption. As discussed earlier, events such as floor heave can reduce train productivity, while ore pass stability can impact the quantity of ore available to the trains. It is the potential for production downside that must be managed. Figure 9 encapsulates the strategy.

The strategy is to improve the SLC to manage stress better, reducing the likelihood of seismic hazard and damage. Damage will occur, however, with forecasts indicating significant damage to the MHS. This will impact production. The operation must prepare for this.

A comprehensive programme of deformation monitoring must be implemented. The results will be used to schedule PSM, as warranted.

Contingency planning is required to establish the options available to maintain the functionality of the MHS.

4 WORK PLAN

Several tasks must be executed to achieve the strategy, and the enabling processes are summarised in Figure 10.

The first task is “just do it”, comprising the various practices that govern deep mining. These can be started immediately. The tasks include developing and implementing the Ground Control Management Plan (GCMP), Targeted Action Response Plans (TARPs), the Cave Management Plan (CMP) and the metrics required to monitor production performance. This work should be done as a matter of urgency. These should follow the practices and standards that are in place within the mining industry.

Subsequent tasks focus on obtaining the necessary Orebody Knowledge for designing

and planning the SLC sequences and layouts for stress and seismic management, a key step in attaining safe, reliable production. The mine health centre currently being developed (Pulse) is important.

The next step is to “right size” the production plan through improved mine designs and contingency planning, in essence, process improvement. This will be an iterative process between the rock engineering and planning groups as different layouts, including additional strategic pillars and sequences, are tested for production and stress management. It is anticipated that the final layout will be a compromise between these two objectives. Nevertheless, will result in significant sequence changes and the possibility of additional pillars.

The MHS will constrain production. Specific analyses of the impact of mining on the functionality of the MHS, as mining progresses down to the 1365L, must be undertaken, together with the work required to maintain the MHS. The option exists in the North Mine to bring forward the new MHS required for reserves below 1365L. MHS planning is urgent, given the damage forecasts.

Behaviour has been identified as a key aspect of successful mining at depth. Changing behaviour from a reactive, firefighting approach to a proactive, plan-driven approach will require education, collaboration, and communication. Experience at other operations shows such changes take time but are central to safe, reliable production. Detailed planning of the processes required to change behaviour must be done and implemented in stages.

The Mine's Rock Engineering Centre (REC) is crucial in the proposed changes. The Centre will provide real-time data on the reliability (health) of the operation. Initially, this is around the spatial and temporal distribution of seismicity used to manage exclusion and re-entry protocols required through seismic ground motion alerts and important seismic parameters such as potency. The Centre's role will be expanded to handle deformation data from Lidar scans of critical development and excavations (e.g. the haulage system) and ore pass status, ultimately

integrating with production systems. The data will feed into Trigger Action Plans to determine when additional support (PMS) is required, real-time ore pass management and, more broadly, production reliability and critical asset (excavation) management, necessary to managing mine performance at depth.

5 CONCLUSIONS

As mining progresses to 1365L, overstress and seismic hazards will increase, damaging the production footprint and the MHS and thereby constraining production. Damage to the MHS is more likely to impact production than damage to the production footprint because of limited options to bypass (Note that in both instances, it is assumed that controls are in place to minimise the risk to the workforce). Safety is paramount in all these discussions.

The production curve is asymmetric. The upside limit is the installed capacity of the MHS; the downside limit is substantial due to the production system's vulnerability and fragility to disruption. As discussed earlier, events such as floor heave can reduce train productivity, while ore pass stability can impact the quantity of ore available to the trains. The potential for downsides in production must be managed.

The strategic plan has two themes: a technical theme that outlines the improvements required for production reliability through managing ground conditions as mining progresses to the 1365L (the "right" plan) and a behavioural theme that describes the need for proactive, plan-driven behaviour (a disciplined approach: the "right behaviour") necessary for mining at depth.

The operation's "burning platform" is to ensure continued successful mining as depth increases. Depth is not forgiving; production is vulnerable to mining-induced stresses and seismic activity. Having an achievable plan that incorporates the constraints of ground conditions is critical.

Time has a significant influence. There is insufficient time to change to a new method and meet production targets. Therefore, the operation must adapt SLC to manage the expected ground conditions safely.

Plan-driven, proactive behaviour is required to achieve reliable production.

The production footprint represents a reasonably robust system due to the number of drawpoints available for production, thus providing optionality. The temporary loss of a few drawpoints due to damage will not significantly impact production. The haulage system, by way of contrast, is fragile. There are no options if the haulage level is damaged but to repair, directly impacting production.

Operations are production-driven, and a reactive firefighting approach is used to get production to ground control and management. This reactive behaviour gives rise to a system that produces elevated risks of safety incidents and unplanned production interruptions; this system is neither effective nor efficient.

Mining is a combination of engineering and people. People develop solutions, implement plans, and make decisions. Good communication with all stakeholders and the appropriate level of production governance are necessary.

When bulk mining is at depth, a holistic design, planning, and implementation approach is critical. A business improvement approach, The Integrated Process Management System, is recommended as a catalyst for more holistic thinking. This will require allocating resources from different disciplines, including Production, Mine Planning, Rock Engineering, Maintenance, Engineering, and Business Analysis.

ACKNOWLEDGEMENT

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REFERENCES

- Boskovic, M. (2022). Challenges of Resuming the production after a major seismic event at LKAB's Kiirunavaara mine. In 10th Conference on Rockburst and Seismicity in Mines, Society for Mining, Metallurgy & Exploration, Englewood.

- Dineva, S., Dahnér, C., Malovichko, D., Lund, B., Gospodinov, D., Piana Agostinetti, N. & Rudzinski, L. (2022). Analysis of the magnitude 4.2 seismic event on 18 May 2020 in the Kiirunvaara mine, Sweden. In 10th Conference on Rockburst and Seismicity in Mines, Society for Mining, Metallurgy & Exploration, Englewood.
- Kaiser, P. & Moss, A. (2022). Deformation-based support design for highly stressed ground with focus on rockburst damage mitigation. *J. Rock Mech. Geotech. Eng.* <https://doi.org/10.1016/j.jrmge.2021.05.007>.
- Moss, A., Board, M. & Jones, C. (2024). The Challenges of Transitioning to Bulk Underground Mining. Proceedings of MassMin 2024, Kiruna, Sweden.
- Moss, A. & Kaiser, P. (2022). An operational approach to ground control in deep mines. *J. Rock Mech. Geotech. Eng.* <https://doi.org/10.1016/j.jrmge.2021.05.008>.
- Osario, A., Stewart, C., Grivas, A., Lett, J. & Hancock, E. (2020). Integration of Asset Management for Extraction Level Operations. Proceedings of MassMin 2020, Santiago, Chile.
- Read, J. & Stacey, P. (2009) Guidelines for Open Pit Slope Design. CSIRO Publishing, Australia.
- Wimmer, M. & Nordqvist, A. (2018). Present-day sublevel caving functionality uncovered – what`s next? In H. Schunnesson & D. Johansson (eds.), 12th International Symposium on Rock Fragmentation by Blasting (pp. 469-480). Luleå University of Technology, Sweden.