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Geotechnical role models and the delivery of geotechnical expertise

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ABSTRACT

LKAB operates four iron ore mine sites using Sub-Level Cave (SLC) and open pit mining methods. Traditionally its geotechnical models were absent, however, it now has developed a geotechnical data collection and modelling system at scale using the latest geotechnical methods of collection and modelling.

Until development at greater depths and stress-related instability became an issue, no need existed for a geotechnical model. Classification system papers are available - thus logging is reverse-engineered from the system used - with well-described case studies. However, the overall what and why of the doing needs help from experience. LKAB engaged and learned from experienced geotechnical expertise, bridging the gap of raw data to knowledge with lessons learnt – including the 90 million tonne (Mt) stable pillar in Block 22.

The development of a geotechnical model is well described by Read and Stacey (2009). In the last three years, LKAB systematically generated the primary data needed to make reliable geotechnical models - with the help of external experts and the development of an in-house team. The in-house team learned from the consultants engaged in the set-up of the system and learnt lessons from the problems encountered along the way - and the solutions needed.

This paper provides a discussion of the overall components of the LKAB geotechnical model, describes LKAB's geotechnical system with major lessons learned, and concludes with an assessment from one of the end-users of the final geotechnical product.

1 INTRODUCTION

This paper is for companies operating without a geotechnical model. Mines without a geotechnical model tend to be production focused, using tonnage and, or grade as performance metrics. As will be demonstrated, operating without a geotechnical model is an unacceptably large risk which can convert resources into losses. There exists a gap between the desire for a geotechnical model and its actual implementation, where that gap contains problems deemed too difficult or too expensive. Yet frequently, the company is forced to contend with seismicity and ground support issues which often result in a reduction in resources or reserves or unachievable production targets. As a direct consequence (as in the case of LKAB) companies realise the importance of geotechnical controls on mining performance and thus refocus their attention on geotechnical data collection and rock mass characterisation. To achieve this objective, companies are typically required to rapidly expand their geotechnical teams yet are limited by their existing expertise and experience. To this end, LKAB has engaged subject matter experts (SMEs) to transfer their knowledge and experience and assist in the development of the systems and processes required to ultimately develop a reliable mine geotechnical model.

For informed mine design, a representative geotechnical model is imperative (Read & Stacey, 2009), however, across the mining industry mines and mining companies are operating without such models. The mining stalwart and one of Sweden's oldest industrial companies, LKAB, until recently, did not have a geotechnical model (Matthias Wimmer, personal comms).

The perception that geotechnical data collection and geotechnical modelling are complex, complicated, expensive, and require specialist expertise are common misconceptions and justifications for not undertaking such activities.

In theory, it should be easy to compile relevant information on geotechnical data collection, rock mass characterisation and geotechnical modelling from publications, However, the overall 'what, how and why' of the developing and implementing these processes is best facilitated with help from experienced SMEs. LKAB found that to quickly bridge the gap from information to knowledge, a useful strategy to adopt is to learn from several prominent industry SMEs. Learning from SMEs was seen as an instrumental strategy in developing competencies within the small geotechnical team at LKAB's Gruvteknik department. Structural changes within LKAB have now spread the geotechnical working groups across sections and departments, while Gruvteknik retains the central role of co-ordination and incremental improvements of the system.

In three years LKAB has systematically developed geotechnical models for all its deposits. In the next section, the geotechnical ideal is described as it currently is in 2024. Proceeding sections cover LKAB's systems and expectations from a geotechnical model, with lessons learnt, including its Block 22 90 Mt ore body write-off. Finally, obstacles which may prove common to other mine sites are listed.

2 ROCK MASS CHARACTERISATION & GEOTECHNICAL MODELS (IN MASS MINING)

To understand and predict the rock mass response to mining presumes that we have good knowledge of the rock mass throughout the extent of the mine. To this end, a reliable and representative, three- dimensional geotechnical model is imperative; where the model comprises detailed information on the geology, structural, geotechnical and hydrogeology characteristics, i.e. detailed rock mass characterisation. Read and Stacey (2009), described the development of a geotechnical model as an amalgamation of key individual models (components) as depicted in Figure 1, namely:

• Lithology or rock type, • Alteration, • Geological structure (at all scales), • Rock strength (typically the uniaxial strength of intact rock), • Fracture frequency, • Joint condition, • Hydrology.	Rockmass rating (using one or several of the classification systems),

Figure 1 Components of a geotechnical model.

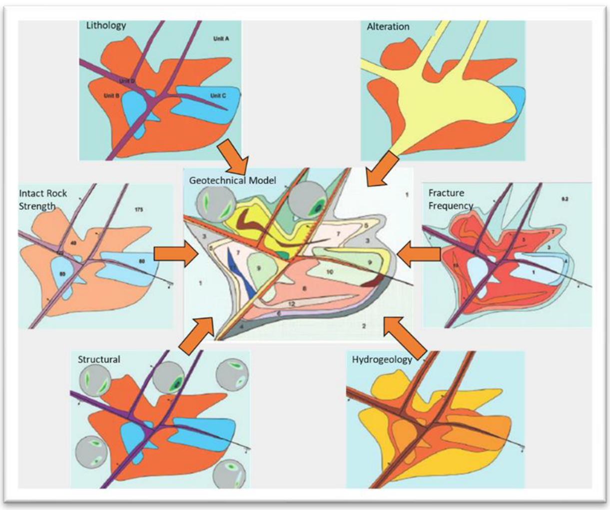

Figure 2 Geotechnical Model components, after Read and Stacey, 2009.

It is important to understand that the reliability of the geotechnical model is dependent on the maturity of the model, i.e. the quantity and type of data that is available to build the model. As more good quality data becomes available, more rigorous assessments of the data can be undertaken to better define representative rock mass parameters and their variability. Thus, the process of developing a reliable model must be understood in the context of the phase of the study/operation (i.e. exploration, order of magnitude, prefeasibility, feasibility, construction and development and finally, operations), as indicated in Figure 2.

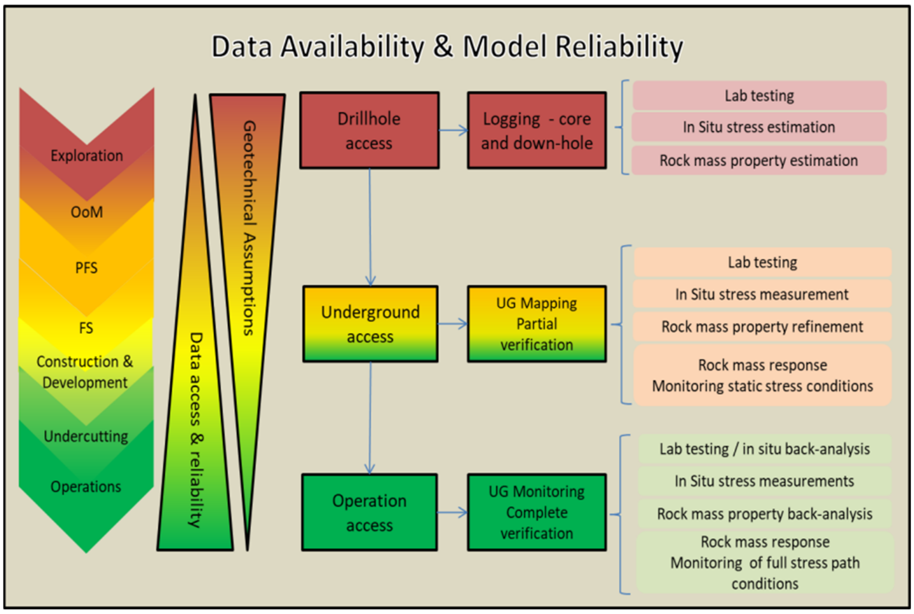

Figure 3 Model reliability as a function of data availability, after Kaiser and Bewick, 2015.

However, not only must the phase of study/operation be considered when deciding on the level of geotechnical effort required but it is also important to appreciate that as mining progresses, the stress environment may also change and hence the rock mass response to mining may deviate from past experiences. For this reason, reliance on past mine performance as a substitute for ongoing geo-data collection and geotechnical modelling is problematic and the reason why many operations still suffer from unforeseen, catastrophic geotechnical events. All of this is to say that rock mass characterisation and geotechnical modelling is an ongoing process that should continue through to mine closure.

3 LKAB's GEOTECHNICAL DEVELOPMENT

LKAB have contracted knowledge and know-how from consultants and existing networks to build the best models available at that time. The progress of LKAB's in-house geotechnical knowledge has pivoted from a position of limitation to one of ever-increasing awareness of the geotechnical processes and modelling. The LKAB-SME journey started with a do-it-for-you (DIFY) approach. For example, in 2014 SRK logged/ relogged 13,175 m of diamond drill hole (DDH) core at Malmberget, and reported on individual projects. In 2020 a do-it-with-you (DIWY) approach started. The DIWY system assisted two new geotechnical geologists to create and implement the geotechnical logging, while consultants provided early-stage geotechnical models.

Geotechnical logging and testing required reverse-engineering to efficiently provide the required rock mass characterisation values. Hiring was outsourced and required a platoon (20 – 40 persons) of geotechnical geologists - divided into four squads. One in-house geotechnical geologist was to oversee each major deposit. In all the team at LKAB's Gruvteknik controls the geotechnical data 2.6 billion tonnes of ore out of a total resource inclusive of reserves if 4.6 billion tonnes of ore (source, LKAB website: LKAB - Documents and instructions (mediaflowportal.com)).

Investment in LKAB's in-house team has led to incremental continuous improvements. LKAB's gruvteknik department continues to engage consultants and has now evolved to a do-it-yourself (DIY) model.

For example, a recent, large, surface drill campaign aimed to map the hangingwall structures and rock mass characterisation to better understand the effects on hangingwall subsidence, cave propagation, and seismicity. Significant issues surround the proximity of Kiruna's residential building and old-town and ground deformations. The orebody extends to the north, with a moderate plunge, where current production is heavily focused. How will the crown pillar react, and will hydraulic fracturing be necessary in the future? Development work is needed for this SLC-related topic.

4 USE OF GEOTECHNICAL MODELS AT LKAB – MINE DESIGN AND MINE PLANNING

Along with geotechnical models, numerical models aid design by predicting rock mass behavior (Zvarivadza, 2023). Various numerical techniques are used to compute a mathematical model where designs may be tested, and the effect of high stress conditions against planned development and infrastructure. Numerical models have been used to adjust design decisions when planning in high stress environments. On analysis by Itasca, a numerical model (FLAC3D) used the ore body geometry, biotite schist geometry and maximum stress models to determine the stresses of the rock mass at the planned location, Figure 4. A charging station, Laddstation AL992, was moved from its original position to a deeper location of improved geotechnical rock mass, Figure 5.

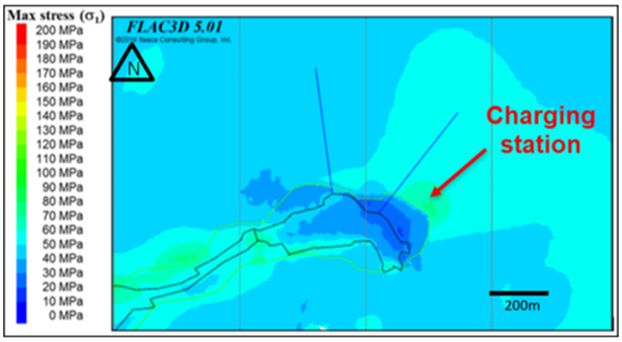

Figure 4 Plan view of the planned charge station, laddstation AL992, against the max stress numerical model. Green line is biotite schist, black line is the Alliansen ore body. (Perman. F, 2018).

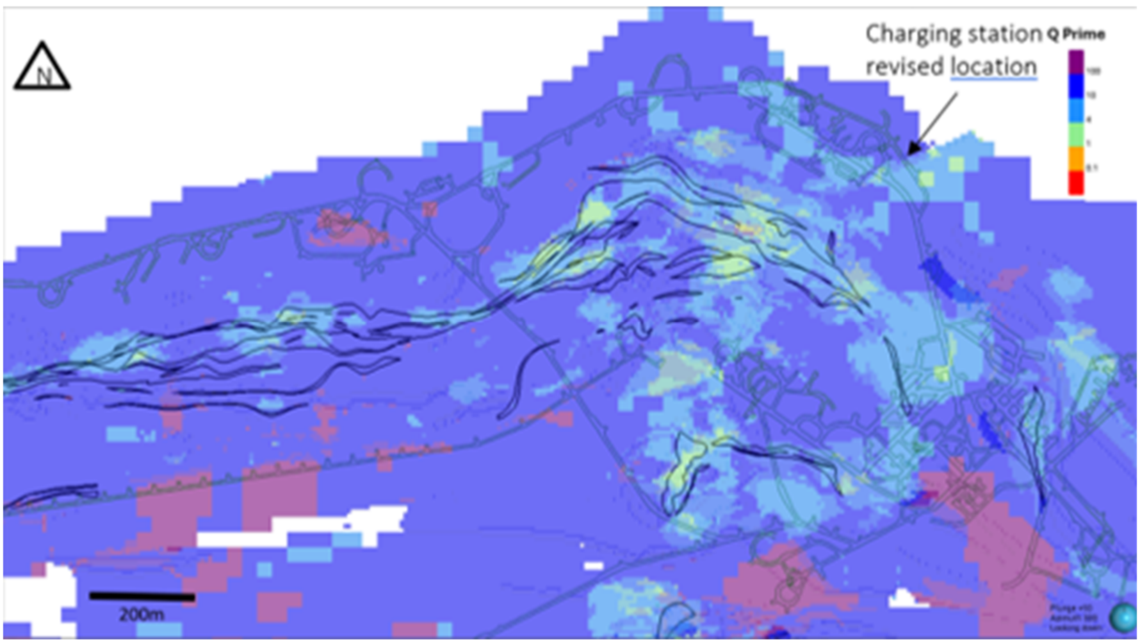

Figure 5 Alliansen orebody at level 1000 showing the geotechnical block model. Magnetite as black outline.

However, at LKAB's mines, some decisions resulted in sub-optimal outcomes. Of these missteps, which may be common across operational environments, noticeable issues are long (up to 10 years) lead times between development and production due to unforeseen changes or seismicity present unique issues in predicting the rock mass quality over long time-spans, and ore body sterilisation – the location of offices and a restaurant within ore bodies due to poor definition of ore body boundaries, Figure 6 and Figure 7. At level 1250 at the eastern fields, infrastructure development co-insides to the Östergruvan orebody. Essential infrastructure is placed within the Östergruvan ore body due to previously poorly understood ore body boundaries and complex geometries.

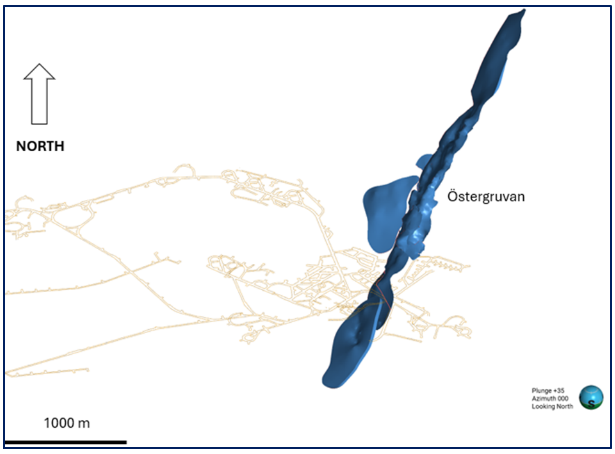

Figure 6 **Ore as grey polygons and tunnels as line drawings, Malmberget mine.**

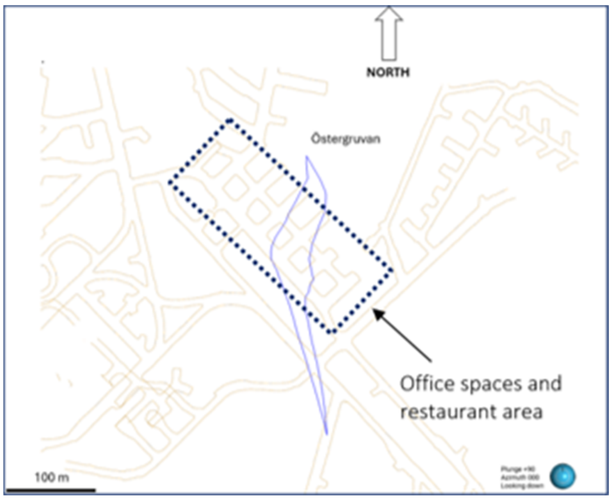

Figure 7 **Main extraction level 1250 and magnetite orebody as blue solid outline.**

In addition, difficulties in drift stability arise when developing a production layout in parallel to a structure or contact. At the Printsköld orebody, drift geology mapping on level 1023 shows the drift aligned parallel to a contact of biotite schist and a very stiff red leptite, Figure 8 inset. In this case, the biotite schist half of development experiences squeezing ground, whereas the red leptite half experiences rock bursts. A large competency contrast between biotite schist and red leptite is unfavourable for development and layout such of been adjusted prior to development by moving into either the red leptite or the biotite schist.

Each of these issues may have been avoided with accurate rock mass characterisation contained in reliable geotechnical and numerical models. Poor decisions on infrastructure led to increased costs, delays, haphazard sequencing, and loss of reserves.

Across LKAB's deposits, future mine designs to depths below the current main levels are undecided and liable to change. Below current main levels, the Extended Life Of Mine Plan (E-LOMP) has yet to be converted into reserves, Figure 9. An important factor in deciding the mining method, mine designs and minable reserves will be the quality and quantity of geotechnical data, the thematic models resulting from these data, and a good grasp of the uncertainties. Critical for the recovery of the E-LOMP will be reliable rock mass characterisation through deep drilling and associated deep geotechnical testing.

The stand-up time is considered a major factor and subsequent changes to the geotechnics or geotechnical model over time – how does one study time lag from layout development to production on large scale SLC operations.

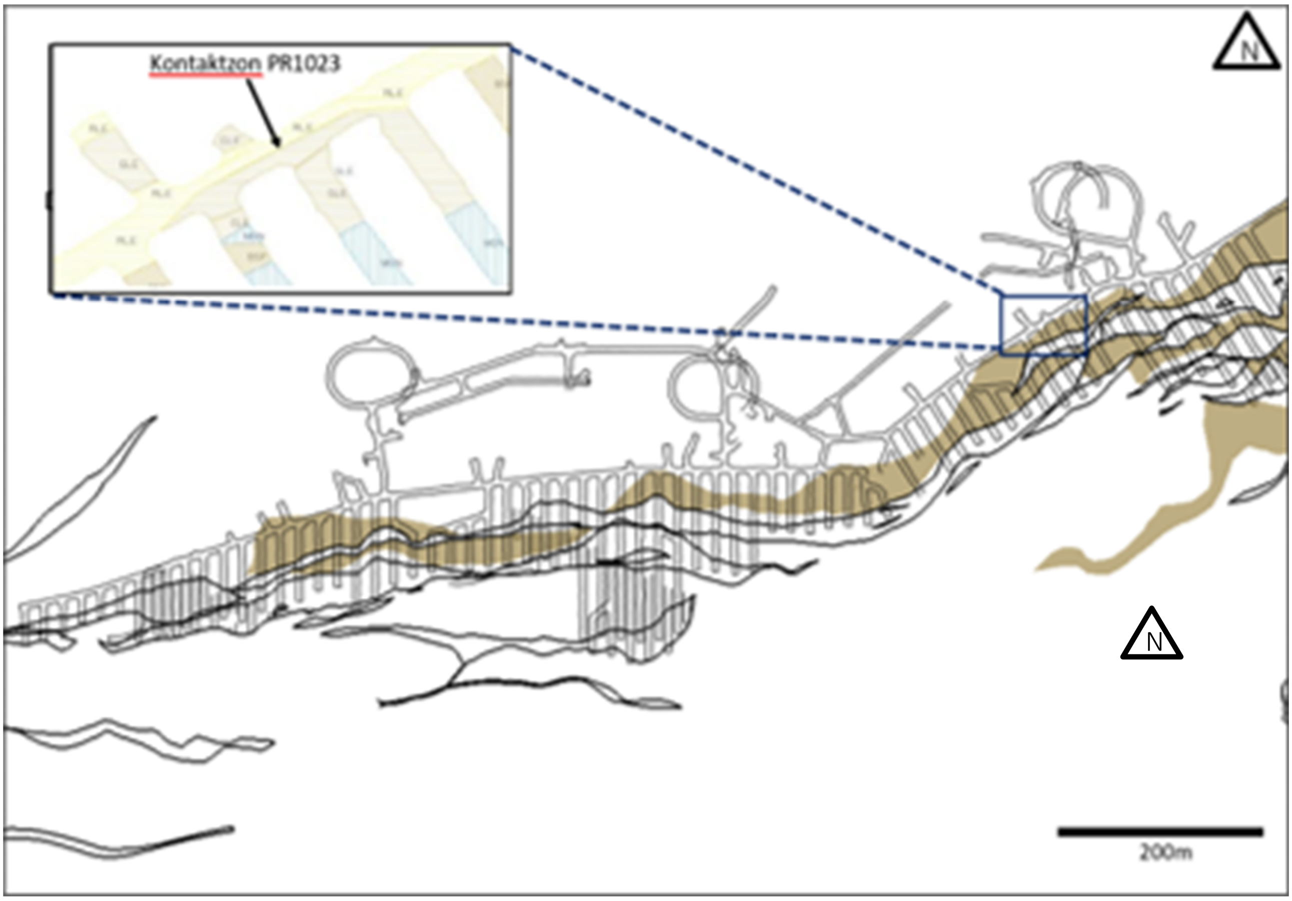

Figure 8 **Printsköld ore body, level 1023. Biotite schist as brown solid, magnetite as black outline. Inset: Drift aligning to a major boundary. Source Thomas Wettainen, LKAB.**

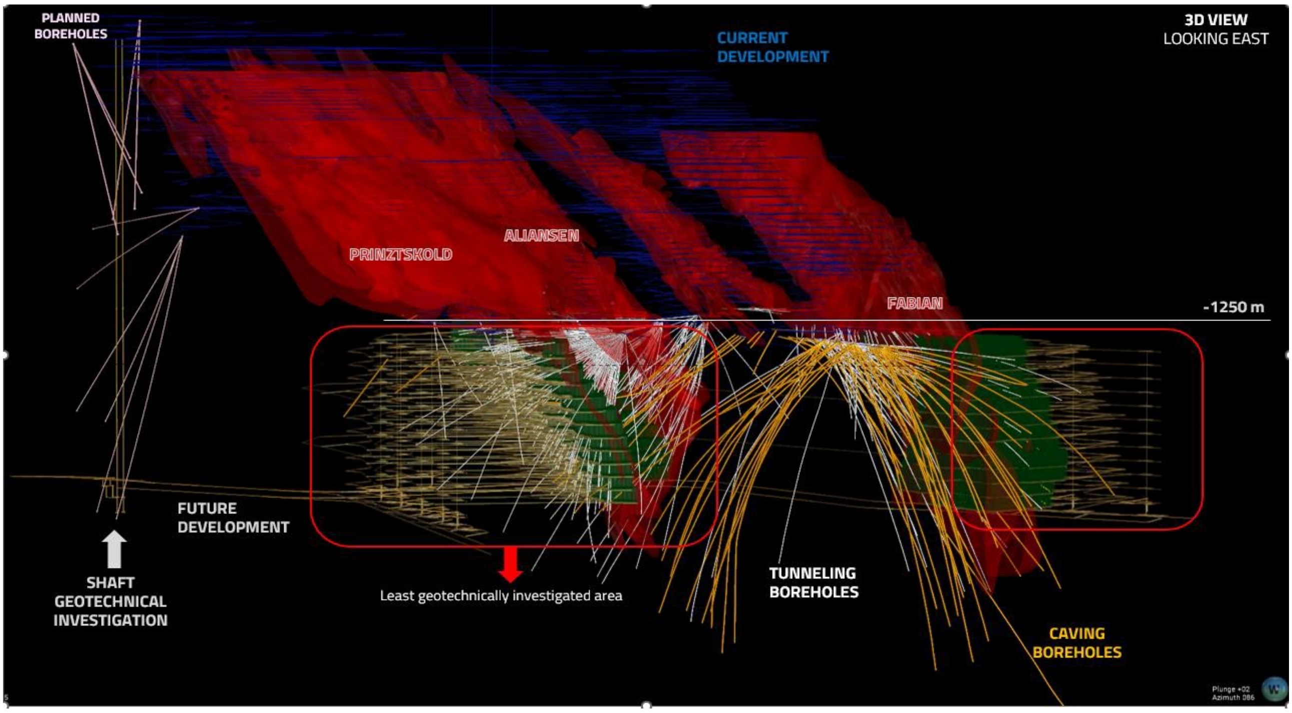

Figure 9 **Malmberget's Printsköld and Fabian future mines investigation. Ore bodies in solid red, planned development in shaded yellow and green. Boreholes in solid yellow. Source: Nikolas Grendas, LKAB.**

LKAB's expectations for its remaining production levels follow the Base LOMP (B-LOMP) to the current main levels. Following the B-LOMP presents a challenge and still has far to go with many potential changes. In specific areas, go/ no go decisions for pillars and hangingwall lenses will be based on the deciding factors of stability, cave flow, and cave propagation – each requiring detailed geotechnical modelling.

However, recent improvements have been made. Adjustments to specific horizontal level layouts now consider structures, and how a structure reacts to stress changes due to mining. With respect to Kiruna, results may be achieved with analysis of proposed standard layouts, Figure 10(a), with the local geology, the history of rockfalls, and seismicity. Where necessary the application of an adjusted, hybrid layout (Lundgren, T, 2023) is recommended and an application for a layout change is submitted to the mine's management group (KG). A hybrid layout is a tailored layout, as in the case of Block 15, level 1194 (15/1194), Figure 10(b). The aim of a hybrid layout is to destress the level by using smaller sized drifts to a maximum of 6.5 m, moving the footwall drives deeper into the footwall, and by changing the footwall drive headings to avoid interacting with weak structures. Once the hybrid layout is adopted and developed, the anticipated results are greater stability in production areas and fewer disturbances on the tunnel walls.

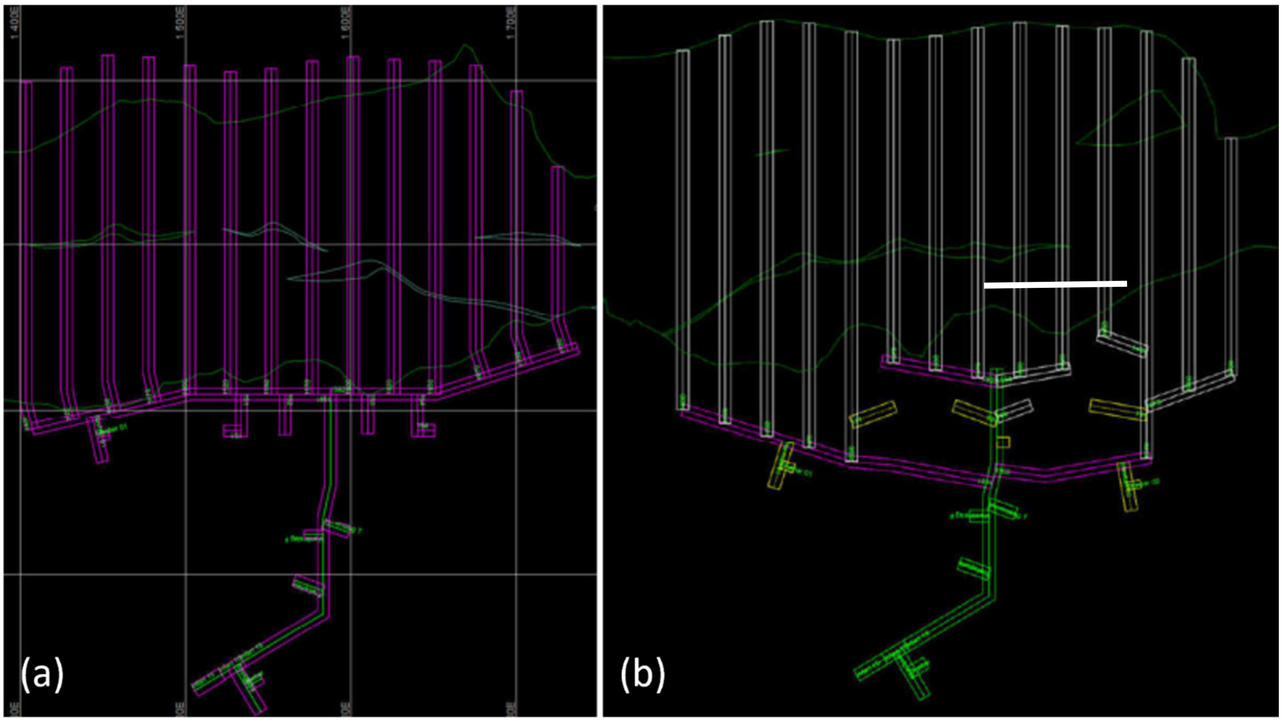

Figure 10 (a): Kiruna standard layout plan, Block 15/1194. (b) Kiruna hybrid layout plan. Source: Theresa Lundgren, LKAB. Ore body outline in green.

Other examples of B-LOMP changes are horizontal sequencing adjustments (L. Jonsson, 2023, personal comms). Structures identified by the Kiruna mine geologist were, at a later stage, compared with seismic data, confirming the presence of a potentially active structure together with numerical modelling. Where seismically active structures ran across the orebody strike in E-W direction, the mining sequence was changed to not interact with a structure at a low angle. The revised mining sequence then intercepts the structure at a higher angle to decrease the probability of triggering movement along the structure. To make changes, adjusted mining sequences were then sent to the mine planning department. Sequence changes occurred in the following areas: Block 15 due to nearby diabase rock types, Block 26/1108 and Block 30/1108 due to stress concentrations, and in Block 38 due to nearby clay zones. The changes in sequencing have resulted in positive outcomes and decreased seismicity.

In summary, the use of empirical and numerical models with a specific sequence and consideration to a layout, and their interaction with structures, may lead to improvements in stability and seismicity.

5 DISCUSSION

The experiences of LKAB's KGE and Gruvteknik departments are discussed, with recommendations for operational mines. A long-term approach to geotechnical data requires patience. A wide collection of rock mass parameters seems to be the right approach to accommodate the many classification systems. Many uncertainties exist yet on the actual use, in particular use in the far future. However, geotechnical data should be regarded as an investment, adding immense value to the assets of mine infrastructure. In addition, organisational changes to departments make continuity difficult to plan for, especially where these data 'pay-off' is far away. Through quality control, quality assurance (QAQC) a standard can be set and through ongoing QAQC protocols standards are maintained.

Rock mass is highly changeable in 4D. Rock mass classification is often done a long time in advance – where development and mining influences it greatly and needs to be kept in mind. In particular, the very long lead times inherent for an SLC system (from development to actual production) makes rock mass degradation a complicated factor to account for, Figure 11. Observation based changes (condition mapping) and comparison to original geotechnical models and model predictions (e.g. numerical modelling on the mining impact) are important. Further, it is important to document and utilize learnings e.g. from the development to full extraction of a block.

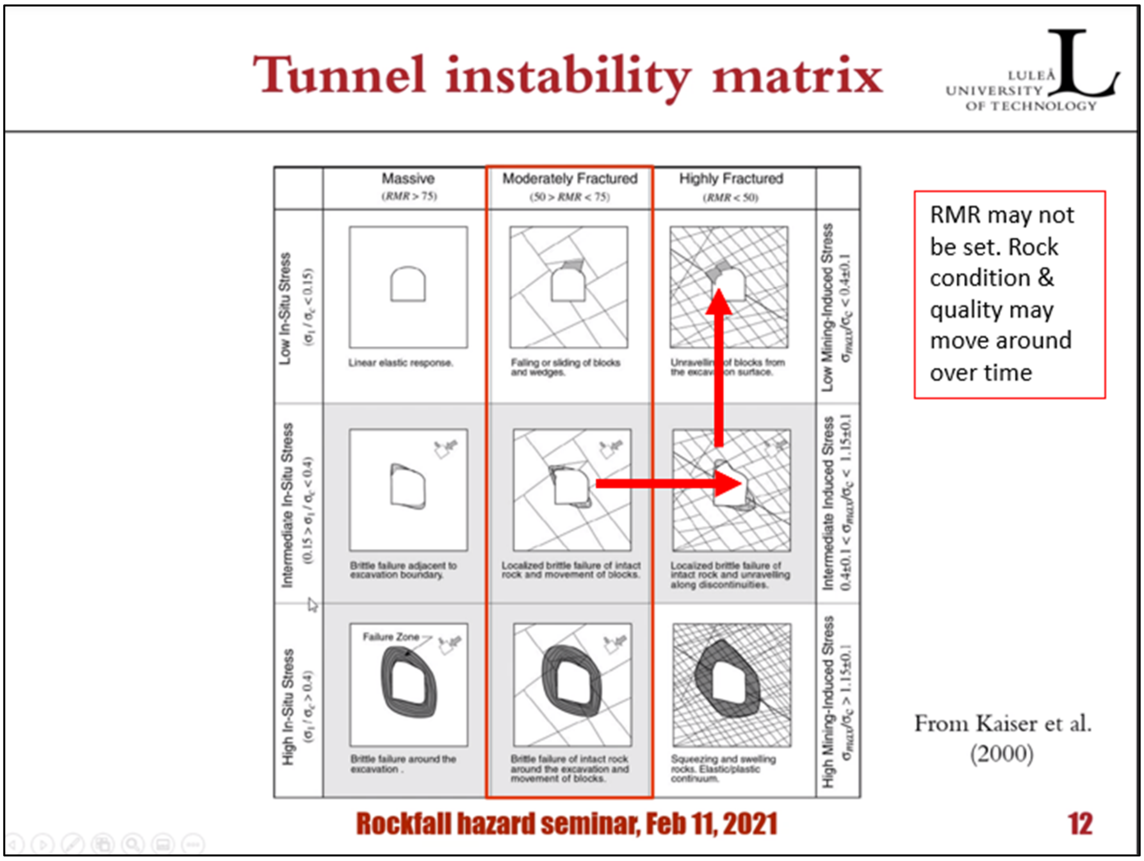

Figure 11 Tunnel Instability Matrix and degradation over time, (Ping, LTU, after Kaiser, 2000). Red arrows show time.

A sound mine design is paramount. Adjustments to mine design need to be done in an agile manner - possible even for an SLC system. Hazard and sound risk (to include exposure and vulnerability) assessments are needed, with the inclusion of levels of acceptable risk. Changes to design can also imply exclusion zones, re-work of support, conditioning the rock mass, etc.

A structural understanding must be achieved and processes where they are actively considered in mine design. Mine design should make more frequent use of geotechnical models. Furthermore, it is important to look beyond production block (precinct) boundaries, but rather think of domains.

Poor planning in the recent past has led to tough decisions in Block 22. A long mining front, seismicity, tunnels damages and unfavourable geology have led to B-LOMP and E_LOMP ore body sterilisation on a grand scale: A total of 90 Mt of magnetite will be left in the ground – potentially for future miners? LKAB needs to foster a collaborative approach with mine-planning.

6 CONCLUSIONS

To conclude, certain findings from LKAB's experiences of geotechnical model development and use are:

- To utilize the full range of SME's with any development plan of geotechnical data collection and modelling.
- To focus on geotechnical data sets with input from geology outlines, alteration, rock mass parameters, structural features, and geohydrological data.
- Using a holistic mine planning approach involves empirical and numerical models where a review process is in place. Geotechnical block models are critical in global design of future mines.

For the reasons discussed, operations must have a geotechnical model. The monetary value to LKAB of sterilising 90 Mt of iron ore reserves is approximately 14 billion USD (approximate cost if all (90 Mt of the estimated mineral resources mineral reserves mined, recovered, and sold at premium pellet price of 160 USD per ton.) And while it still has far to go, the decision to carry on building and improving in-house geotechnical expertise should continue.

How LKAB implemented systematic geotechnical data collection and modelling across all sites will be the subject of the paper 'Geotechnical model making – steps and stories of how LKAB started geotechnical modelling', at the Montreal ACG Deep Mining conference proceedings, September 2024.

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