

The LKAB transformation: approaches for greater depths and a changing world

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Abstract

As we approach the middle of the 2020s a few things are clear: (1) The world's population is increasing, and along with it, the need for raw materials. (2) The planet is changing, and we need to adapt our processes to the new realities we face. (3) The demands of society require that we develop better techniques that limit our impact on the people living around us. These three challenges combine to create a 'Perfect Storm' for the mining industry – not only should we produce more, which requires faster rates, greater depths, and higher stresses, but we must do so with less waste and fewer emissions, while minimising seismicity and surface subsidence, all at the same time. These challenges can only be met through a total transformation of the way we operate, something that Luossavaara Kiirunavaara AB (LKAB) has accepted with open arms. The first challenge is being addressed through new mining methods and layouts developed and tested in full-scale to find new ways to produce. At expected depths of up to 1,900 m, more than 50% deeper than LKAB's present mines, and production rates expected to be significantly higher than today's, entirely new ideas are necessary. The second challenge is met through total electrification. This is much more than simply changing out diesel for electric, but includes new ideas about ventilation, energy storage, and redefining the very foundations of our processing technologies, a path that will reshape the entire region around the mines. The third challenge is especially important and requires finding new ways to control seismicity and subsidence and minimise the use of tailings dams, while implementing environmentally friendly techniques and holding continuous dialogue with the community to ensure all stakeholders are satisfied from day one. This paper provides a glimpse of the path LKAB is following and how we hope to reshape our industry.

Keywords: *transformation; mining methods, electrification, seismicity, mine design*

1 Introduction

Over the preceding decades, the mining industry has identified its main challenges as being those associated with shrinking natural resources. Those deposits that were located near the surface have been progressively mined out, leaving only deeper, harder to access material. In many cases and in many ways, the days of easy mining are over. We are left with a situation where new resources are harder to find, more expensive to locate and define, and present greater risk to the companies attempting to economically extract them. These issues are not new.

At the same time, the population of the world has risen from 4.4 billion in 1980 to 6.1 billion in 2000 and 7.7 billion in 2020, while the average global life expectancy has risen from roughly 62.6 to 72.7 years over the same period (<https://datacommons.org/tools/timeline>). This naturally results in increased requirements for natural resources. To make matters more complex, the average level of industrialisation in developing countries is increasing, meaning that not only are there more people who are living longer, but a greater percentage of them have access to and can afford to purchase material goods (roughly 78% increase in global constant-dollar per-capita gross domestic product during the same period (<https://data.worldbank.org>)).

Let us not forget that while the mining industry works to meet the world's demands for natural resources, and it must do so in riskier and more cost-intensive ways, it *also* faces the necessity of meeting these challenges with greatly increased global focus on environmental, social, and governmental responsibility (ESG). Protection of the environment through minimisation of waste, reduction of emissions into the air and water, and prevention of lost habitat are identified as critical. The populations living in the areas in which the mining industry operates demand greater respect, less disturbance, and well-deserved consideration for their history, ecology, society, and compensation for their contributions and sacrifices. There is no wiggle-room left. The mining industry must change.

2 Beginning of a transformation

In 2016 Luossavaara Kiirunavaara AB (LKAB) began consideration of a plan that would alter the entire foundations of the company. How do you take a 132-year-old company responsible for the two largest sublevel caving mines (SLC) in the world (Kiruna and Malmberget) plus its Svappavaara surface mine (LKAB 2021), a company that produces roughly 27 million tons of finished high-grade iron ore products per year between its three mines, and turn it into a CO₂-free operation? How do you take a company that is well established on the world stage as a leading producer of iron pellets, and eliminate the fossil fuels required to make those pellets?

The answer is a fine balance of productivity, economies of scale, investment in new technologies, investment in higher efficiency operation, and fundamental research into new methods used across the entire value chain.

As usual, the beginning of the solution must start with the geology and the resources under our control. It was identified early on that to make this transformation happen the company would need to prove that it has the resources in the ground necessary to pay for such a large transformation program. To establish this, the company has developed one of the largest exploration drilling programs in the world, completing an average of 210 km of exploration drilling each year between 2019 and 2021. Mining these materials has meant developing plans to extend both underground mines from today's existing main levels on 1365 m (Kiruna) and 1250 m (Malmberget) down to 1900 m in both mines (Figure 1) (actual operational depth in both mines is roughly 100–150 m less than the level numbering implies). In addition to this, plans are under way to take the Svappavaara surface mine and extend it underground for the first time, and the company is also working on a nearby green-field orebody called Per Geijer, which could play a major role in the future of the company.

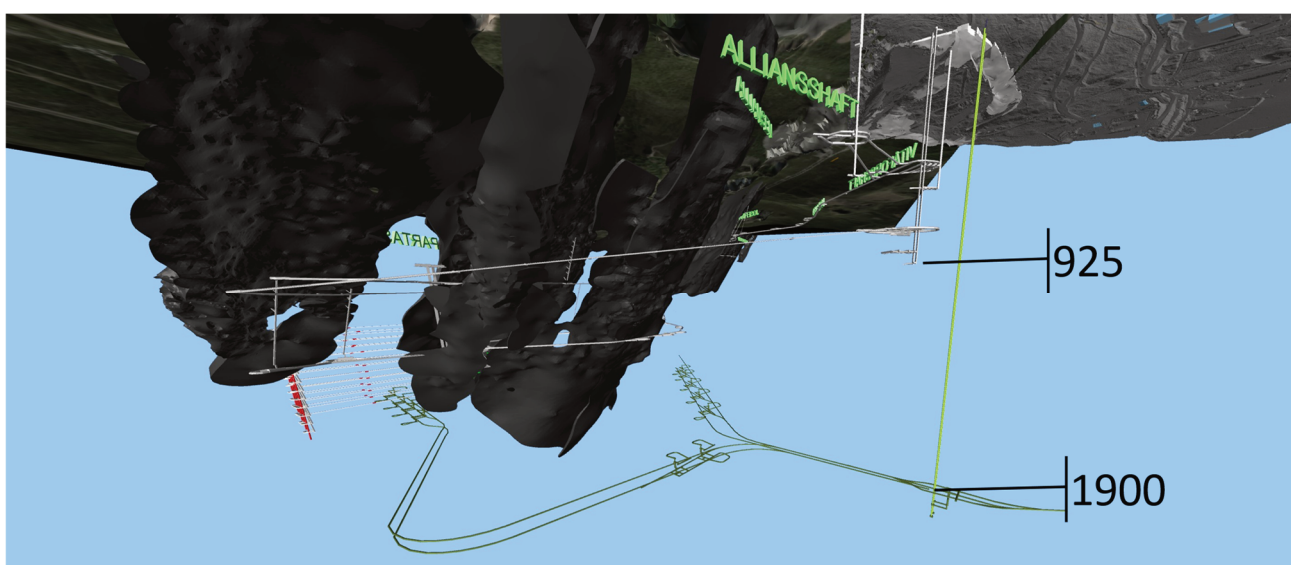


Figure 1 Representation of new Malmberget hoisting shafts to level 1900 compared with a set of existing shafts down to level 925. A proposed train haulage level at the bottom for primary ore transportation would maximise productivity

The company is developing a more effective and environmentally responsible method of ore processing. Rather than simply extracting the iron content out of the rock, work is under way to expand the processing capabilities to recover both apatite (phosphorus) and rare earth elements from the same ore. Such a process not only has the potential to improve the bottom line, but also to make better use of the energy expended during mining, to reduce the quantity of tailings produced, and to recover the raw minerals required for many chemical, food-production, and high-tech uses.

Once the processes to recover the minerals have been identified, it is another matter to extract them. To finance the transformation, it was decided to aim for a much larger interval between main levels. Historic main levels in Malmberget were built at 300 m, 400 m, 500 m, 600 m, 815 m and 1,000 m, and currently the 1250 m level. As stated, the plan is to create the next main level at 1900 m (Figure 1). This larger interval will reduce the infrastructure development cost compared to the smaller level intervals.

The main difference in production systems between Kiruna and Malmberget can be used as an example of this benefit. In 2015 the Malmberget mine considered creating a new main level at 1500 m, though those plans were abandoned. At that time analysis determined that the higher OPEX and lower CAPEX involved with creating a truck haulage level was better when compared with using ore trains as a haulage method given the amount of ore in that 250 m interval. In Kiruna, where there was more ore within the 320 m interval between main levels at 1045 m and 1365 m, a cost per ton evaluation showed that it was more beneficial to accept the higher CAPEX with significantly lower OPEX associated with train transportation (Systecon 2022). The expectation is that the current plan to move both mines up to 650 m down to 1,900 m will decrease the development cost per ton of available ore and will finance the installation of an exceptionally efficient transportation level, even considering the cost of construction at these great depths. It will support the company's overall strategy and long-term environmental and efficiency goals, creating a cost-effective, low-energy usage system.

3 Increasing productivity at depth

Today's mines extract approximately 25 Mtpa run-of-mine ore at Kiruna, 17 Mtpa at Malmberget and 7–9 Mtpa at Svappavaara to depths of up to 1100 m and 1150 m respectively at Kiruna and Malmberget and 160 m from the Svappavaara open pit. These production rates, while substantial, are not considered sufficient for the future. To help meet the increased resource demands of our customers, and to help offset the costs of the transformation, LKAB is aiming to increase overall productivity by 50% before the end of the transformation in 2045.

Productivity is a ratio of output versus input, and LKAB expects to both increase the extraction rate and reduce costs at the same time. The company is collaborating with the Montanuniversitaet Leoben to develop and refine new mining methods for deep mass-mining which should allow for higher extraction rates at lower costs. One of these methods, raise caving, is a promising bottom-up method of extraction where the orebody is divided into primary and secondary stopes of up to several hundred metres high, with horizontal cross-sections of up to 50 m × 50 m. A raise-drilled opening is developed and automated drilling and charging equipment is used in the raise to blast the rounds in an upwards fashion (Ladinig et al. 2022). The stopes are operated in shrinkage mode – always filled with broken rock mass. Blasted ore is drawn from an underlying extraction level and the hanging wall caves and fills the stope gradually after blasting each finished raise segment. Additionally, a slot-pillar system is created before stoping commences to control the rock pressure systematically and strategically by creating a stress 'shadow'. The raise cave method offers opportunities in the form of improvements in automation and safety by removing people from the extraction area and offers some of the best options under consideration for active and passive stress control for mining at greater depths and production rates.

We believe that raise-based vertical mining, together with a de-stressing concept and newly developed machinery will enable deep mass-mining in a high stress environment. It also has great potential for cost reduction because of lower requirement for tunnel development into the orebody. The key to success will be the design for the de-stressing slot-and-pillar system with the purpose of protecting the production raises

and other infrastructure (Figure 2). For more information the reader is directed to Ladinig et al. (2022). The drilling capacity for the automated machine will also be an important productivity factor.

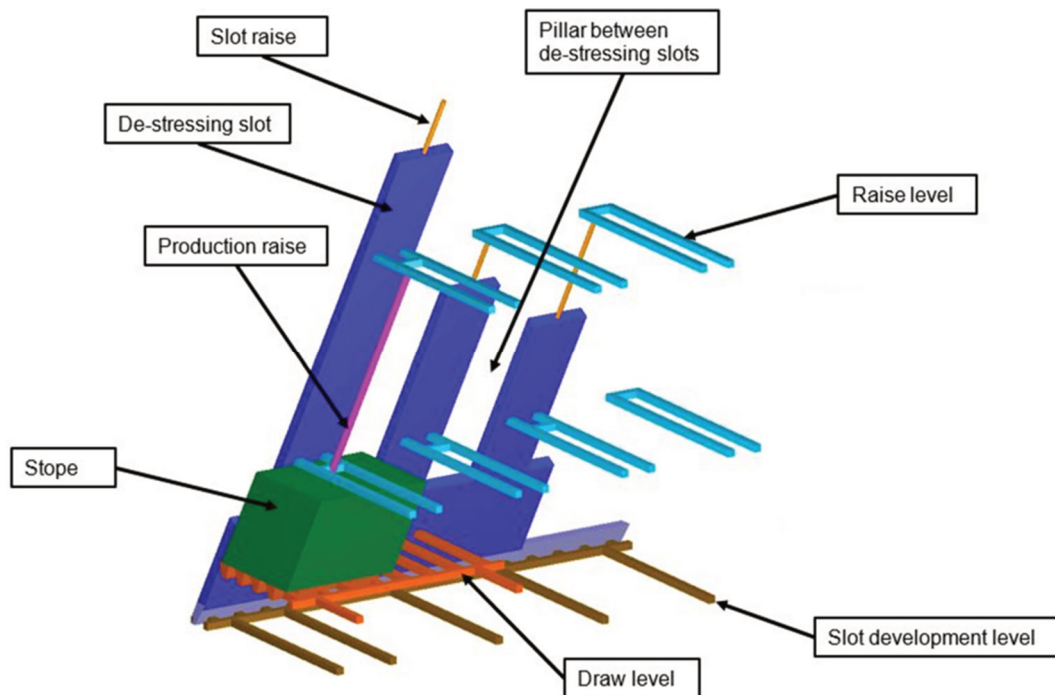


Figure 2 Simplified schematic overview of the raise caving method (from Ladinig et al. 2022)

The raise caving method will be trialled in either Malmberget or Kiruna within the next two years. The trial site will be built with the purpose of further developing the de-stressing concept. At least two full size de-stressing slots and one pillar will be constructed under today's mining levels, in a seismically active environment. The pillar and seismic behaviour will be monitored with the purpose of gathering data necessary for the calibration of numerical models, allowing further development of the de-stress design concept.

LKAB also operates the Konsuln test mine and uses it for development and refinement of new mining techniques and equipment. The mine is a satellite orebody of the Kiruna mine that produces around 1.5 Mtpa of run-of-mine ore while serving as a test bed for mine automation, system design, and mining method trials. It is planned to be the site for testing the proposed new raise drilling and production machinery.

Another promising mining method under consideration for LKAB's future is SLC mining with 50 m sublevel heights (SLC-50). Since 1963 LKAB has progressed from 9 m up to 30 m heights. Each increase in sublevel height means more ore extracted for fewer development metres. The limiting factor has typically been the drilling technology available at the time. Now, LKAB is working with its subsidiary, Wassara, to develop new equipment and techniques that blend aspects of directional drilling, new drill head design and the elimination of standard drill steels to create a system capable of reliably drilling holes up to 60 m long for primary blasting.

These drilling techniques, as well as new SLC crosscut opening methods have also been progressively trailed in Konsuln and in Malmberget. Recent advancements have included new footwall drift and crosscut designs (Quinteiro 2018, p. 433) that better withstand the greater stresses developed when the sublevel spacing increases. Efforts towards SLC-50 are ongoing and mining has proceeded from SLC-30 up to SLC-40 with the method showing promising results. The next step is to trial SLC-50 using the new drilling technology to achieve the required hole lengths with directional accuracy. This spacing will allow 50–60% more ore to be extracted for the same number of development metres (Quinteiro 2020, p. 936).

LKAB puts tremendous resources into the development of these methods in the form of field trials. When developing new mining methods, nothing proves viability better than progressively building larger and larger-scale versions of the method and attempting to mine in a controlled fashion. This allows for problems to be

identified and resolved, for the method to be refined, and the technology to be developed in a stepwise fashion, decreasing risk while increasing confidence. The process also builds trust in the safety, viability, and robustness of the method prior to putting it into full production.

Field trials alone don't tell the entire story though, and a great deal of work goes into planning and preparing for mining at depth in the form of numerical modelling. LKAB uses advanced tools to better understand the expected impact of our mining on the underground infrastructure, the surface deformation, and the seismic impact we have on our own operations and on the community. One of the most important outcomes from this work to date is a technique using a coupled *CAVESIM-FLAC3D* model developed by Itasca (Sharrock 2021; Itasca 2019), that can produce calibrated deformation models that show the expected impact of our mining activities on both the ground surface and underground infrastructure. The models work by using an iterative process to model the expected cave after each future year's production based on the long-term plan, and then use the result to feed into a stress model. The stress model then updates the stresses for the next year's cave model until the entire mine life has been simulated. These models are used to develop critical standoff distance lines accurate to ± 20 m (Figure 3) and predict which areas of the host-rock are likely to be most suitable for constructing future infrastructure and which areas should be avoided (Figure 4) (Theofanis et al. 2022). Of course, most production activities take place inside these critical standoff distances, but this knowledge allows the planned design to minimise exposure, reduce total metres within critical areas, and improve the predictability of the mining system as a whole.

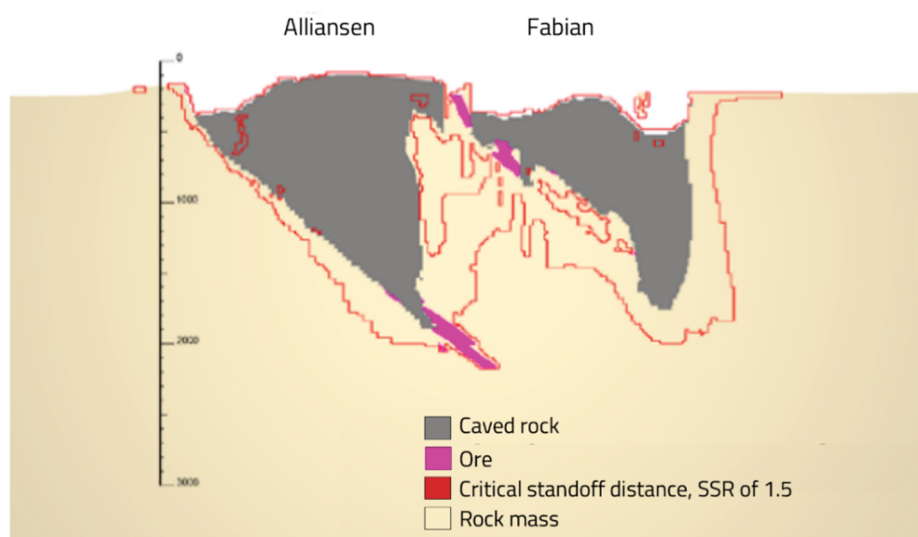


Figure 3 Critical standoff distance on a section through Alliansen and Fabian orebodies, Malmberget Mine (Theofanis et al. 2022)

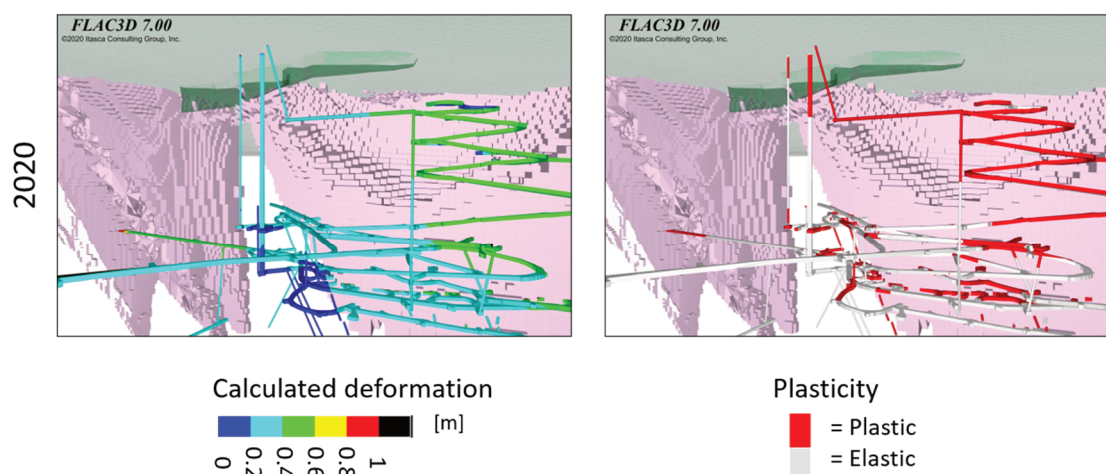


Figure 4 Effect of cave mining on the underground infrastructure for the year 2020 (Jonsson 2021)

LKAB uses deformation prognosis, stress, and seismicity analysis to ensure a safe working environment. To enable mining at greater depths, we are constantly trying to understand our mines by using different numerical and analytical approaches. By using these methods, we can look at historical seismic events caused by our mining method and use these to attempt to predict and avoid large seismic events, unfavourable geometries, and poor stress conditions.

4 Total electrification

The conversation around electrification is often limited to the discussion of switching out diesel-powered equipment for electrically powered equipment. That view is narrow in scope, yet it is what many focus on because it is easy to make big strides quickly when it comes to CO₂ reduction. In reality, the conversation encompasses so much more. To become CO₂-free it is also necessary to eliminate the petroleum products used to heat our pelletising plants and the fuel oil used in our ventilation heating facilities. The most challenging of these is changes in the ore processing. Creating pellets from our iron ore fines allows us to create a high-quality product that has excellent quality control, is easily transportable, and is easy for the customer to use. For these reasons, it brings a price premium that has allowed LKAB to profitably mine iron ore underground at a much higher cost than most companies in the world who do so via lower cost surface mining.

LKAB's current processing techniques utilise either fuel oil or coal to heat the raw ore to 1,250°C during the creation of iron ore pellets. This process will be replaced by focusing on creating Hot Briquetted Iron (HBI) sponge iron instead (Figure 5). Today's typical HBI processes utilise natural gas or coal to process the ore to remove oxygen, converting it to iron metal without melting it. The process is more energy efficient than other methods of iron ore processing and allows downstream mills to make steel using much less fuel than traditional blast furnaces. This further improves the environmental footprint of the mine's finished product.

However, for LKAB and its partners to use HBI as a means of creating the world's first fossil-free value chain for steel creation, a major hurdle to overcome is current HBI processes typically utilising coal or natural gas in the production process. LKAB's goal is to develop a hydrogen-based direct reduction process to replace this. LKAB has built the joint-venture company HYBRIT with steel manufacturer Svenskt Stål AB (SSAB) and power provider Vattenfall to facilitate this process. This will replace the natural gas required for the direct reduction with hydrogen and an inert gas, and in combination with switching from coal or oil-based heating to electric heating, will enable the total elimination of CO₂ from our processing. This process has been successfully demonstrated at pilot-scale and a full-scale processing plant is planned for 2026 in Malmberget.



Figure 5 Hot Briquetted Iron sponge iron as a replacement for iron pellets

To achieve these goals, LKAB will need to enter an entirely new industrial segment so it can produce enough hydrogen to process our planned ore production. The process will require design and construction of hydrogen generation plants, massive underground high-pressure hydrogen storage facilities (up to 1,000,000 m³), and hydrogen transportation capability. The electrolysis for hydrogen will become the main consumer of electricity in the company, with the entire transformation process eventually requiring an estimated 72 TWh/y of energy. This is roughly half the current annual consumption of Sweden, or twice the current annual consumption of Denmark (Figure 6) (<https://www.statista.com/statistics/1260553/eu-power-demand-country>). The most effective and efficient method of generating this electricity has been determined to be via wind turbines, though roughly 1,200 new wind turbines would need to be constructed to meet the need. This requires close cooperation with local, national, and European energy providers and will require a restructuring of the power grid in the entire northern portion of Europe. One anticipated benefit is that the production and storage of so much hydrogen will allow the process to act as a tremendous power storage cell, providing significantly lower costs for operation than on-demand hydrogen production.

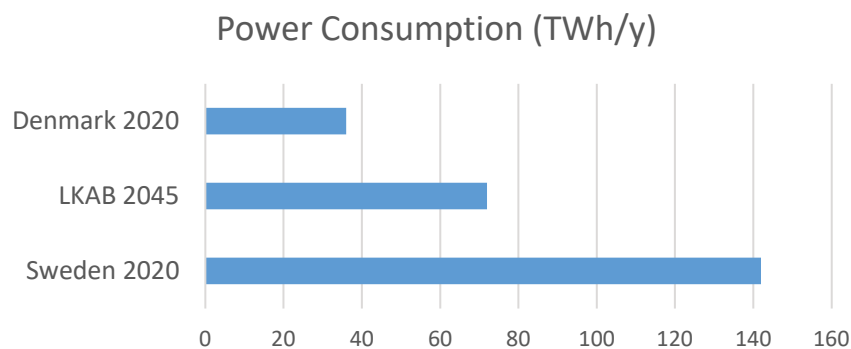


Figure 6 Illustration of expected energy needs due to LKAB's transformation (<https://www.statista.com/statistics/1260553/eu-power-demand-country>)

When eliminating CO₂ from the production process, the ventilation of the underground mines also requires new ways of looking at current operations, especially with respect to heating, cooling, and ventilation system efficiency. Malmberget and Kiruna present an uncommon situation from a heating and cooling point of view. The virgin rock temperature is quite low relative to many other deep mines – even at a depth of 1,900 m, the rock is considered a heat sink. The primary heat sources are auto-compression, fans, and heat from other equipment which, through modelling, result in temperatures of over 40°C in the working face. Thus, the air itself is the heat source, rather than the cooling medium and pushing more air to the production areas will not contribute to cooling. Alternative cooling ideas are being considered because traditional bulk cooling of large air volumes above-ground, far away from the heat sources, would be cost intensive and ineffective.

A combination of more local, sustainable cooling options are being studied. One of the most promising is using cryogenic liquid air as a cooling medium. This offers many benefits that play perfectly into the company's strategic goals in that the cooling medium itself becomes a method of energy storage. In the winter, the heat created when liquifying the air can help to heat the mines. The liquid air can then be transported underground and released locally where it will cool the atmosphere, act as an additional pressure source, not contribute to auto-compression, and be capable of generating electricity at the same time it is released. The method could significantly reduce the company's footprint and improve efficiency. Other sustainable technologies, such as mine water cooling, absorption refrigeration, and propylene glycol coolth storage are also being evaluated.

Even though most of the ventilation heating requirements have been fulfilled with waste heat from the pelletising plant (in Kiruna) and with direct electric heating in Malmberget, oil boilers are still used to cover for peak demand both in Kiruna and in Malmberget. More sustainable heating options have been identified, with the most likely way forward utilising waste heat from hydrogen production where available. In other areas, heat exchanger systems will provide most of the required heating capacity.

5 Environmental considerations

One of the fundamental challenges in mining remains the way the industry affects the environment and communities that exist around the mine. Gone are the days when a mine could rely on the community to approve of its activities simply because the community wouldn't exist without the mine. The importance of environmental responsibility is understood more fully in the arctic latitudes where LKAB operates, because the impact of global warming can be seen so much more clearly. The arctic regions are warming at a rate three times higher than the global annual average (Arctic Monitoring and Assessment Programme (AMAP) 2021). A person moving to Kiruna only 10 years ago would have been able to see and feel clear differences in the average low and high temperatures every winter and summer even in just that short time. People who live there don't *think* the environment is changing, they *know* that it is changing.

Take a moment to connect some of the ideas from earlier in this paper. LKAB plans to mine between the levels of 1,250 and 1,900 m at increased rates compared to today. The virgin rock stresses at these depths will be up to 50% higher than those at today's main levels. LKAB already has two seismically active mines, and this is expected to become more of an issue with depth. To help address the challenge, it is already known that LKAB is relocating both cities of Kiruna and Malmberget, but this action is primarily being taken to address today's seismicity. In the future, active steps will be taken to mitigate the increases in seismicity.

One of these active steps is hydraulic fracturing which we are currently testing and evaluating in the Kiirunavaara mine. The goal with this test is that the conducted fracturing will have seismically pre-conditioned the rock mass, and the number and magnitude of large seismic events will be reduced as some of the stored energy is already released.

Another active step is the raise caving mining method that is under development (previously described). This is intentionally being designed with the goal of providing stress shadow protection to the working areas underground. The slot-and-pillar design is such that seismicity should be allowed to occur in a slower, controlled fashion. Many small seismic events are preferable to fewer, more energetic events.

Mine subsidence and land use are also being taken into consideration as an environmental impact that may be reduced through careful planning and preparation. The amount of land area accessible to the mine is limited, and in the area above the potential Per Geijer orebody, there is an environmental protection area. This places limitations on the caving mining methods currently used by LKAB.

One possibility under consideration is to mine the Per Geijer orebody with a longhole open stoping method with full cemented backfill, or a combination of sandfill, rockfill and paste (Figure 7). The stopes under consideration would have a footprint of 20 × 20 m and would be 60 m tall. Horizontal sill pillars would be present every 120 m, allowing different portions of the mine to be under production at the same time. The ultimate production rate of this mine would be 15 Mtpa with a stope production rate of 2,500–3,000 tpd per stope. This would be the largest stoping mine in the world and would require the world's largest paste production facilities. The method would allow LKAB to meet the production targets for the mine, while also eliminating the subsidence associated with cave mining. These early-stage plans show promise but are far from being complete. Connection to the nearby (approximately 5 km) Kiruna mine could be made underground to eliminate much of the surface infrastructure necessary for ore transport, going a long way towards the invisible mine concept.

Finally, the waste material balance indicates that the entire tailings production of both the Kiruna and Per Geijer mines would be necessary to create enough paste to backfill the Per Geijer mine. This would mean that LKAB could eliminate the need for future tailings ponds, further reducing the land use needs and environmental footprint of the company. The proximity of the two mines makes this a real possibility.

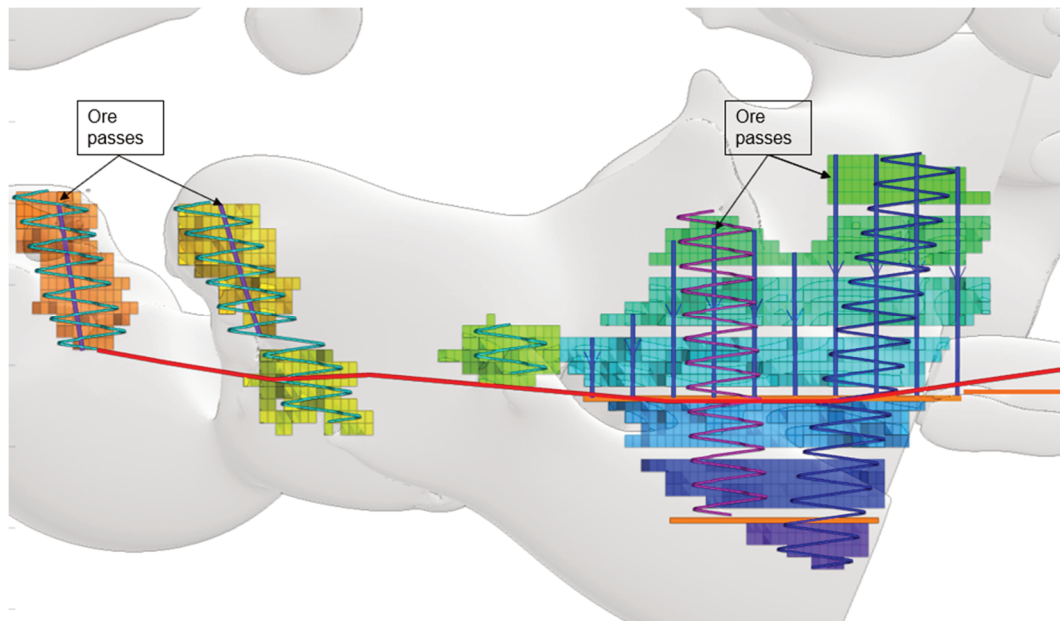


Figure 7 Proposed stope design for the Per Geijer mineralisation

6 Summary

In the next 20 years LKAB will invest 400 billion Swedish crowns (nearly 40 billion euros) to transform the way we do business. This will be the largest industrial investment ever in Sweden and will create between 2,000 and 3,000 jobs annually in the iron ore fields in the north of the country. These changes will transform the entire region and it will be an entirely different company when the process is complete.

For LKAB, the ‘perfect storm’ of challenges has presented an opportunity. In many ways, the three challenges complement one another positively, almost as well as they do negatively. The need to mine deeper and faster requires increased operational capability, as well as leaps of understanding in mining technology. Creating operations that have smaller impact on the land, people and environment can only be done with mining methods that have higher cost. Transitioning the entire corporation to be CO₂-free requires even greater effort.

Producing at higher rates to provide the raw materials desired by society will increase output and providing environmentally friendly iron products will increase prices. These two factors combined will provide the financial security that is necessary to ensure a positive return on investment, even with all the fundamental research and the massive investment that will be necessary. Without mass-mining rates and a large base of resources, such a transformation would not be possible.

For more than 100 years LKAB has been a leader in the mass-mining industry. It has pioneered cave mining technology in many ways and with this transition the company positions itself to continue leading the way in the mass production of underground iron and high-quality and environmentally responsible iron products. The scale of the transition to HBI as a primary iron product will shift the focus of the company. It is possible that the future LKAB could be looked at as an industrial chemical company that also mines iron, rather than an iron mining company that started using hydrogen. Regardless of the outcome, the company will be well-positioned to continue leading the way with technologies, products, and mine life suitable for the next 50 years.

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