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Preliminary results from tests using sublevel caving with 40 m sublevel height at LKAB

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Abstract

LKAB operates two underground iron ore mines located in the northern part of Sweden, both using sublevel caving as the mining method. Common sublevel heights vary between 25–30 m. Tests with 40 m sublevel height is ongoing in a fairly small orebody called Konsuln located close to the main Kiruna orebody. LKAB has developed three sublevels (436, 486 and 536 m) in Konsuln to test sublevel caving with 40 and 50 m sublevel height. The objective with these tests is to assess the applicability of large sublevel heights in some of the LKAB future production areas. The production started in March 2021 at level 436, and it is currently the only level in production. Development work with the ramp started in 2018. Production drilling is ongoing at the second level (486 m) with 50 m sublevel height and drifting is being completed at the third level (50 m sublevel height). About 0.8 Mt has been produced so far from blasted rings at level 436. Preparations necessary for planning and for the assessment of the performance of these large sublevel heights includes:

1. *Measurements of blasthole and raise hole deviations.*
2. *Installation and detection of smart markers.*
3. *Measurements of iron grades in selected blastholes.*
4. *Opening blast tests.*
5. *Scanning of eventual open cavities.*
6. *Blast performance assessment.*

Follow up of the performance of the rings involves collection of data from loaded buckets, recovered markers, blast function (vibrations) and visual inspections as well as laser scanning when appropriate. This paper describes the preparations and the results achieved so far for blasted rings using 40 m sublevel height.

Keywords: *sublevel caving, field tests, caving mechanism*

1 Introduction

1.1 Sublevel caving and the Kiruna mine

LKAB operates two underground iron ore mines located in the northern part of Sweden in Kiruna and Malmberget. Both mines use sublevel caving as the mining method, see Figure 1.

Common sublevel heights at LKAB vary between 25–30 m. This paper focuses on tests using 40 and 50 m sublevel height in a small orebody called Konsuln located close to the main orebody in Kiruna.

Sublevel caving (SLC) is a mass mining method based upon the utilisation of gravity flow of blasted ore and caved waste rock (Kvapil 1998). The scale has changed substantially during the years, see Figure 2.

The actual SLC ring design is essentially affected by gravity flow aspects. The Kiruna mine applies a silo-shaped design which favours primary recovery. It reflects well with the marker trials made at the late 1990s in which flow was found to occur within a relatively slim vertical zone (Larsson 1998; Quinteiro et al. 2001).

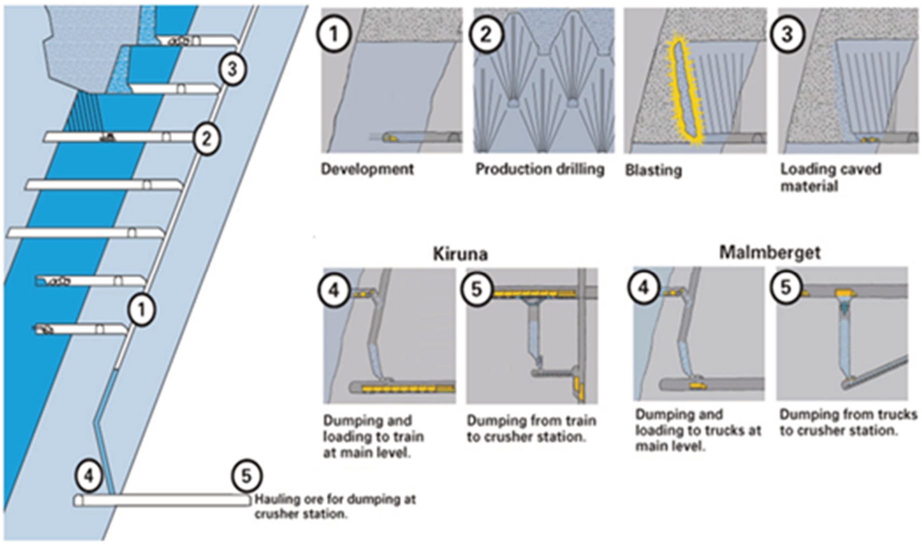


Figure 1 Sublevel caving in LKAB's iron ore mines

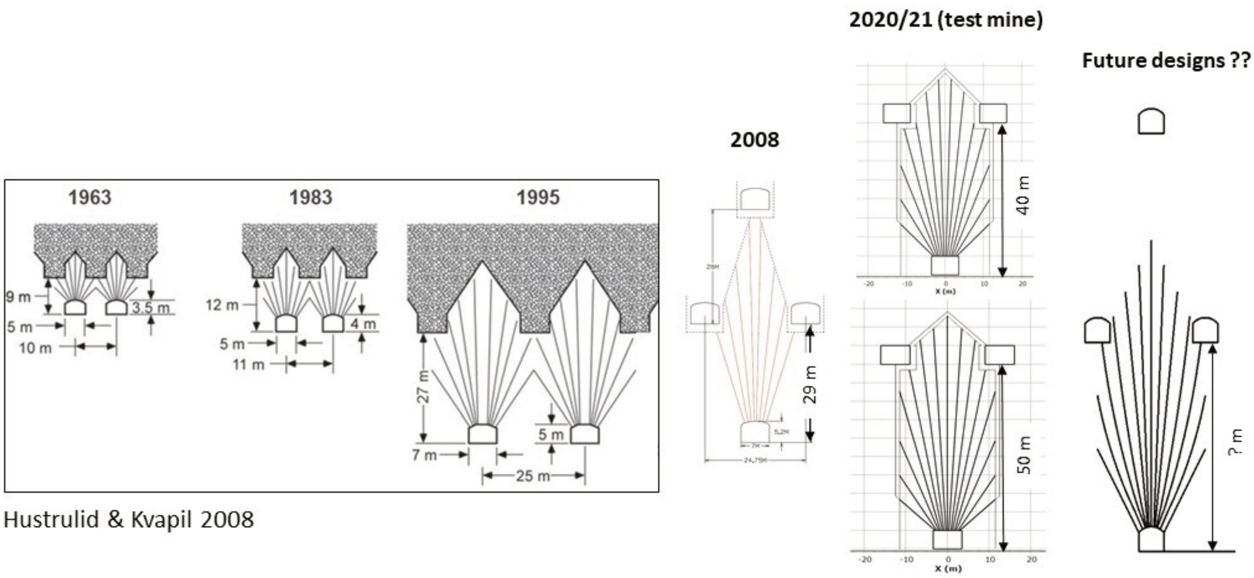


Figure 2 Evolution of scale and design for SLC rings, Kiruna mine

1.2 Testing sublevel caving with higher sublevels to meet future challenges

LKAB has been investigating underground mining under current main levels for a few years now. One of these studies started in 2017 and was concentrated mostly to Kiruna and Malmberget mines. Mining in a safe, productive, and sustainable way even at greater depths were the main targets. The mining depth for these studies were down to around a level of 2,000 m. This depth is about 700 m below current main levels for both Kiruna and Malmberget mines. One important conclusion of the study in 2017, regarding mining with sublevel caving, was the negative impact of the increased mining depth on the long-term stability of infrastructure situated around the production areas such as ore passes and longitudinal access drifts. This has led to the development of the fork-layout for sublevel caving at depth and the proposal to test sublevel caving using 40 and 50 m high sublevels (Quinteiro 2018).

A full-scale mining test was designed in the Konsuln mine, located south of the Kiruna mine, involving three sublevels: 436, 486 and 536. The first sublevel using 40 m and the last two using 50 m sublevel height. The Konsuln orebody has a dip of about 75° to the east and a complex geometry. The thickness of the magnetite orebody varies from 15 m to 50 m. At the end of 2018, the LKAB Board approved the execution of the mining test and development work started with an extension of the current ramp to the lower levels. These tests are part of the program called SUM (Sustainable Underground Mining) at LKAB.

By Q1–2020, development of the first mining level 436 was completed, the second level 486 was under development and level 536 was about to start development. The selection of the layout for the production rings was based on the previous experience with the fan layout and the availability of production drilling rigs. Blasting tests for the opening layouts were also under preparation under Q1–2020 (Quinteiro 2020).

The current situation (April 2022) with the three sublevels to be mined in Konsuln is as follows: level 436 is under ore production with 40 m sublevels; level 486 is under production drilling and level 536 is completely developed and production drilling will start soon. There is no hoisting system for ore transport in the Konsuln test mine.

Blasted ore is transported from underground to the crusher situated at the surface level by using a fleet of 44 ton capacity diesel trucks. Mucked material from the cave with low iron content is transported to the waste dumps at the surface. At the crusher station the material is crushed below 200 mm, screened and sorted using magnetic separation into concentrate and waste. The ratio between the tonnage of products to the concentrating plant and the tonnage of crude ore into the crusher gives a good indication of the quality of the crude ore sent to the crusher from the blasted rings. The ratio between the mucked material that is sent to the waste dumps and the total material mucked from the rings gives a good indication of waste dilution. The decision to send a truck to the crusher or to the waste dumps is based on the weight of the LHD (load-haul-dump) buckets. A lower scoop weight is an indication of waste, and a high scoop weight is an indication of ore (good iron content). The performance of each blasted ring in these mining tests is based on the measurements of tonnage of material sent to the crusher and tonnage of material sent to the waste dumps. The performance of all blasted rings in a time period is based on the measurements of the tonnage of material sent to the crusher, the tonnage of products sent to the concentrating plants and the tonnage of waste from the magnetic separation. In addition, it is also important to quantify the in situ tonnage of ore and waste of the drilled rings. This information is dependent on the block model of the orebody. Since the orebody in Konsuln has a complex ore geometry, it is expected that this could be a potential problem for an accurate estimation of performance of the rings in terms of ore recovery. This factor will be considered when carrying out the final analysis of the results. In this paper we are using the values given by the current block model. The performance of the rings will also be evaluated based on the recovery of installed smart markers. It is hoped that these markers will give information about the ore flow towards the brow leading to estimation of primary, secondary and tertiary recovery. Other important information is the width of draw. Markers installed at certain pillars at level 396 are expected to give additional details about the width of draw.

This paper describes the preparation tests, measurements, and installations necessary for the planning and assessment of tests with SLC using 40 m sublevel height at Konsuln mine, LKAB. In addition, this paper summarises the results achieved so far for blasted rings using 40 m sublevel height.

2 Tests

2.1 Blasting test cuts

Blasting long openings is the key for successful SLC mining. Three 50 m long cuts were blasted before the planned production drilling started. A summary of the results is shown in Table 1.

Test 2 showed the best results. However, the number of tests is limited so the results are only indicative. It was decided to use mainly the test 1 layout for production drilling of long openings. This layout is easier to plan and to drill compared to test 2 layout. The test 3 layout is used mainly for shorter openings.

Table 1 Summary of results from blasting three test cuts

Test	Cut length (m)	Cut area (m^2)	Number of raise holes	Raise hole diameter (m)	Number of blastholes	Blasthole diameter (mm)	Full area advance (m)	Max advance (m)
1	50	8	2	0.75	13	115	39–40	44–45
2	50	6	2	0.75	10	115	49–50	49–50
3	50	4	1	0.75	8	115	20*	49–50

* Cut area reduced to about 50% between 20–49 m.

2.2 Ring layout

An example of the ring layout used at level 436 is shown Figure 3. This layout is used in the southern part of the Konsuln orebody which has a spacing between crosscuts of 22 m. This layout has 13 boreholes with a diameter of 115 mm. Drilling is carried out using a rig having the Wassara water hammer technology. The maximum borehole length in this example is about 52 m. This is about the same maximum borehole length in the silo layout used today at the Kiruna mine. The inclination of the ring is 80° from horizontal and the burden between rings is 3 m. These two parameters are the same as the ones used today at the Kiruna mine. The side angle of the first borehole is 49°. The tonnage included in the ring is about 12,500 tonnes and the total drilled metre is about 410 m. The tonnage drilled per metre is about 30.

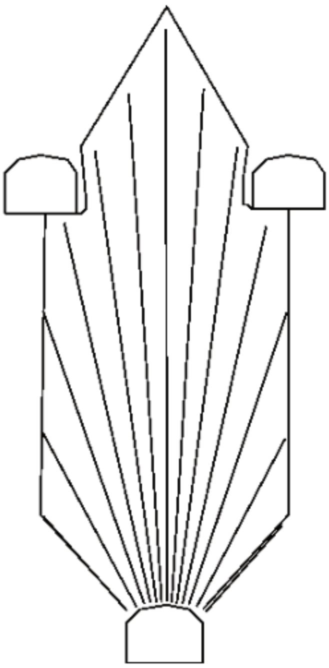


Figure 3 Example of a drilling pattern for a full-size ring at level 436 in Konsuln (40 m sublevel height)

2.3 Fe content in blastholes

The orebody in Konsuln is rather small and the geology is complex and somewhat uncertain especially in the northern part. Therefore, it was decided to develop a borehole logging system for measuring the iron content in blastholes with 115 mm diameter. The device measures the magnetic susceptibility: technical data is shown in Table 2.

Table 2 Technical data for the magnetic susceptibility probe

Diameter (mm)	Length (cm)	Weight (kg)	Range (SI units)	Sensor	Response time (s)	Inter coil – spacing (cm)
80	130	16	0.0001–5	Two coil system	< 0.5	30

The probe has been calibrated using six plastic barrels (volume 220 L) filled with varying content of magnetite and waste (0, 20, 40, 60, 80 and 100%). The particle size was 0–8 mm for magnetite and 0–4 mm for waste. The barrels have been carefully filled with small portions of magnetite/waste with known weight and then manually packed thereby reducing the porosity to about 20–30%. A plastic pipe with diameter of 100 mm was centred in the barrels when the filling started. After completed filling, the probe was inserted into the plastic tube and the output (CPS = Counts Per Second) from the probe was recorded. Three readings were obtained, one in the centre of the barrel and the other two about +/- 10 cm from the centre. The variation between these three readings was found to be negligible. This procedure enabled the construction of a calibration curve i.e. the relation between the Fe content (weight%) and the output from the instrument (CPS), see Figure 4. Note the non-linear behaviour appearing especially towards high Fe grades. It should also be mentioned that the calibration curve is valid only for magnetite.

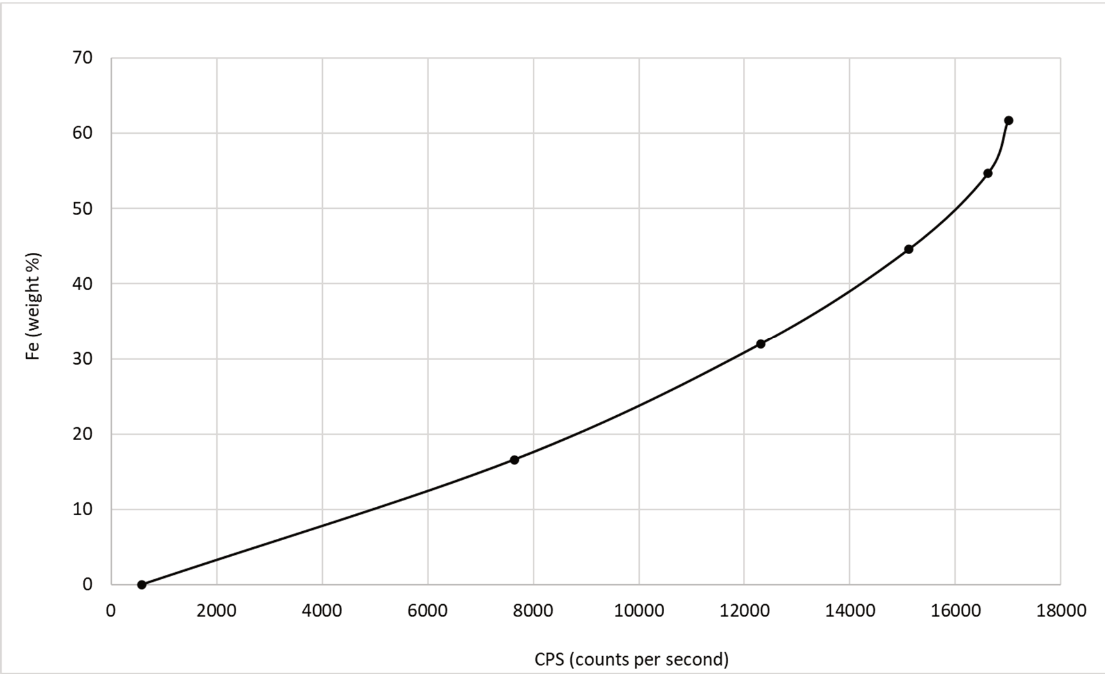


Figure 4 Calibration curve for the magnetic susceptibility probe for magnetite

It was decided to measure every second blasthole in every second ring as a general guideline. However, the full-size rings after the second opening are of special interest. We also decided to measure two to six consecutive rings after the second opening.

The response time for the probe is <0.5 s. The logging speed is about 10–12 m/minute, so we get a reading about every 10 cm along a borehole. The measurement system is installed on a special measurement truck which enables very efficient logging.

2.4 Borehole deviation measurements

Knowledge about blast- and raise hole deviations is important especially when using extreme sublevel heights (40 and 50 m) and blasting large openings. A new technique utilising very fast and high-quality laser scanning is used. The scanner is mounted on a tripod standing on the drift floor, the distance from the scanner to the borehole collar is normally about 5–6 m. Reduced scanning data is transferred wirelessly to a tablet directly after scanning which enables a quick view of scanned data in the field. This facilitates finding a perfect position for the scanner i.e. in line with the borehole.

2.4.1 Raise holes

Scanning is normally repeated about four to six times at slightly different positions when surveying a raise hole (diameter 0.75 m). The scanner is moved about 0.2–0.4 m between each scan. Each additional scan is automatically aligned to the previous by a software. The resulting point cloud from multiple scans, see Figure 5, is then geo-referenced enabling estimates in the mine coordinate system.

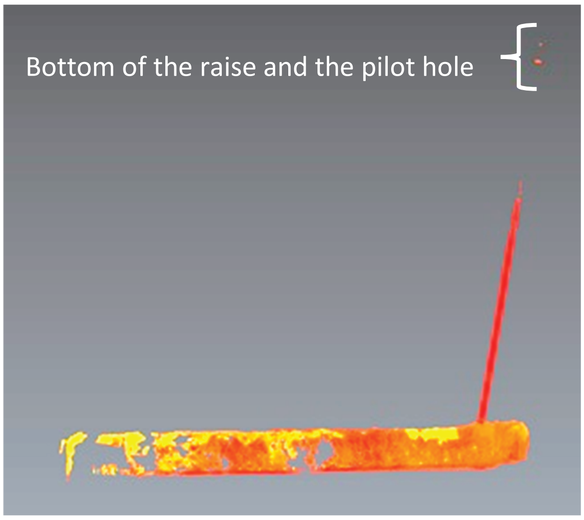
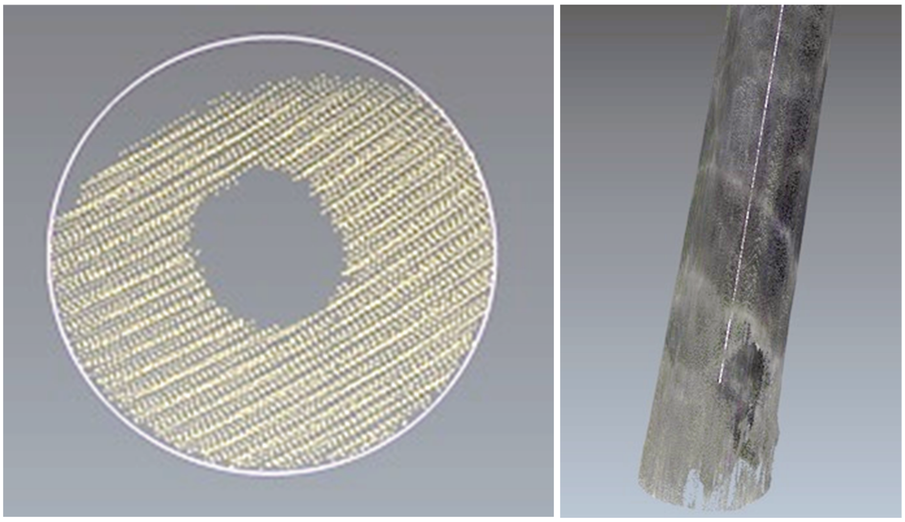


Figure 5 Example of a point cloud from laser scanning of a raise hole, length 30 m and diameter 0.75 m The bottom of the raise and the pilot hole is also clearly visible

Two to three layers of mesh is installed for safety reasons at the raise hole collar soon after drilling. This will, of course, reduce the number of scan points inside the raise hole. However, many raise holes have been scanned in these conditions with good results. The bottom of the raise hole is clearly visible in all scans and in many cases also the pilot hole, see Figure 6. This enables an accurate estimate of the end point by fitting a circle to scanned data. The raise centre line (neutral axis) is estimated by software. The result is a polyline starting close to the collar and ending at about 10–25 m depth. A point at the collar is taken from the scan. Together with the centre line and the endpoint this enables an estimate of a 3D polyline for the entire hole.



(a) (b)

Figure 6 Evaluating a scanned raise hole: (a) Fitted circle at the bottom of a raise hole; (b) Part of a scanned raise hole and the calculated centre line

2.4.2 Blastholes

A couple of different working methods have been used. The most common method today is using a long telescopic stick which is inserted a short distance into a blasthole. This determines a proper position for the scanner i.e. in line with the hole. Normally each blasthole is scanned just once, an example of a scanned ring is shown Figure 7. Good data around the circumference is often obtained 1–3 m into the hole.

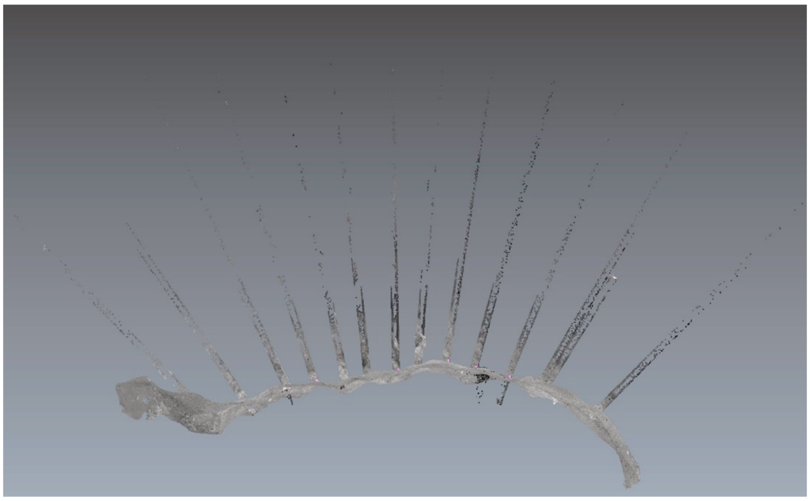
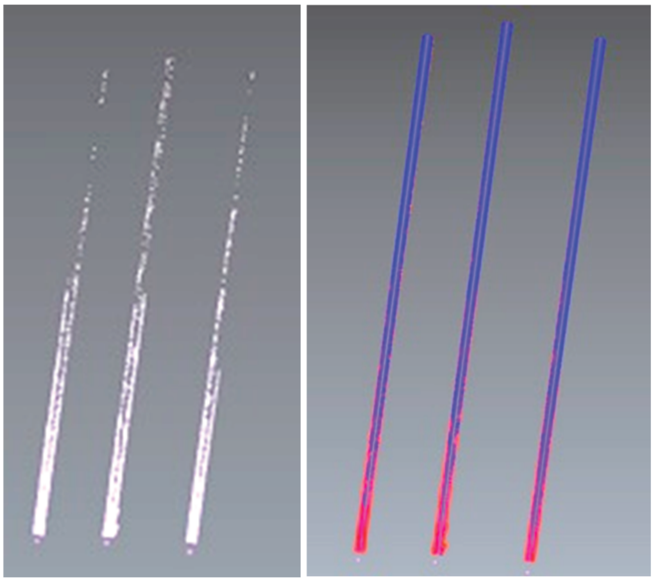


Figure 7 Scanned blastholes in a ring

The start direction of a blasthole is estimated by fitting a cylinder to scanned data (Figure 8).



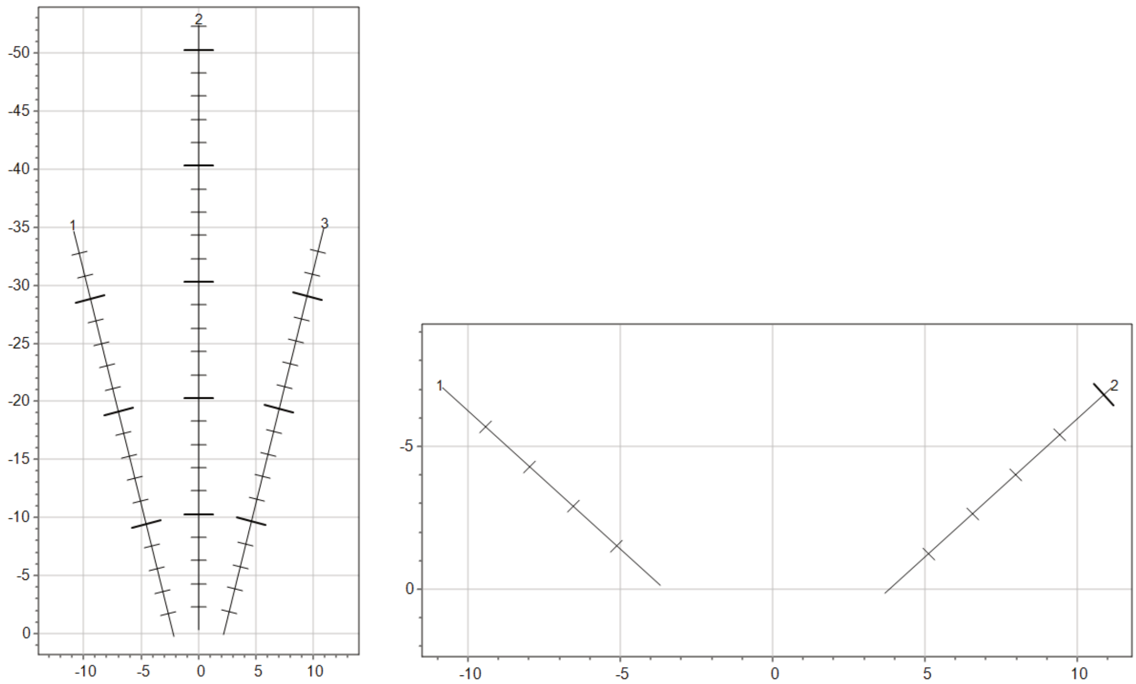
(a) (b)

Figure 8 Processing scanned blastholes. (a) Cleaned holes from scan and selected point at the collar; (b) Fitted cylinders in blue

Processing scans enables estimation of collar coordinates and the start direction. The borehole trajectory is measured using a gyro-based measurement technique.

2.5 Gravity flow: marker trials

A holistic approach was adopted in two previous marker trials in Kiruna. The setup for these tests has been presented by Nordqvist & Wimmer (2014), with results from the tests by Nordqvist & Wimmer (2016) and Nordqvist et al. (2020). Three marker rings were drilled in each burden and a total of about 200 smart markers were installed. The number of studied rings were ten in each trial. This test setup gave a detailed description of the draw and how it developed during extraction, but limited tests gives less information on the variability. A somewhat different approach is adopted in this project. Three full size marker rings are drilled in each crosscut in the middle of each burden. These rings are located after the second opening and consist of three holes. Another three marker rings are drilled in each crosscut. They are small and located closer to the hanging wall, the markers are intended to be detected at the level below (486 m). Figure 9 shows both a typical full size marker ring and a small marker ring. The layout of these marker trials will give valuable information about the SLC performance including variability.



(a) (b)

Figure 9 Typical marker rings at level 436 m. (a) Full size marker ring drilled after the second opening; (b) Small marker ring drilled closer to the hanging wall; markers are intended to be detected at the level below (486 m)

Installed markers in six neighbouring crosscuts are shown in Figure 10.

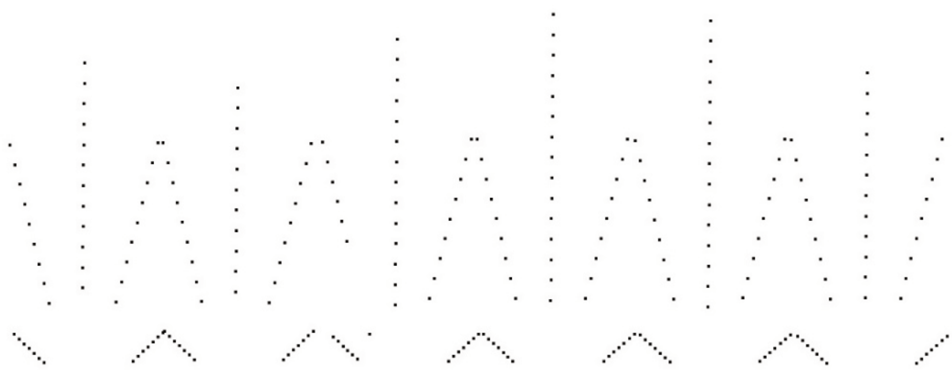


Figure 10 Installed markers in six neighbouring crosscuts at level 436 m

In total, 353 markers were also installed at the level above (396 m) in the southern part of the orebody. Horizontal marker holes were drilled through the pillar between crosscuts.

2.6 Blast performance

The blast performance is monitored using two triaxial borehole geophones located at level 536 m. The geophones were grouted in 4–5 m long vertical (down) boreholes with diameter 76 mm. The distance to the blasts varies between about 30–250 m. Monitoring is automatically activated only during the night when blasting occurs, this reduces the number of unwanted non-blast events. A special focus is on monitoring and evaluating opening blasts since they are critical for successful mining.

2.7 Draw control

During the mucking process, careful bookkeeping is kept of the tonnage drawn from each drift and ring. This procedure is the same as in the Kiruna mine. The same software, called Giron, for collecting and processing mining data is also used. LHDs are equipped with a weighing device for the scoops and this information is used to classify the mucked material as ore to the crusher or waste material. In Konsuln, this classification is done on a truck basis, about two to three scoops per truck. LHDs used in Konsuln have a capacity of 15 and 22 tons. The information is stored and available for all blasted and mucked rings in the Giron system.

2.8 Laser scanning when a cavity exists

Scanning is possible when a cavity exists i.e. in a hang-up situation. A laser scanner is placed at the end of a very long (16–20 m) boom on a telescopic handler, four to six scans are normally taken at different positions. More recently, drones have become a valuable tool for scanning in these conditions.

3 Results

3.1 Studied rings

The performance of sublevel caving using 40 m sublevels is best assessed by studying full size rings i.e. rings passing the level above. Due to the geometry of the orebody, the rings at the beginning of a crosscut will be smaller and their behaviour could be affected by other factors such as absence of caving. Therefore, in this analysis, we have decided not to include these smaller rings. The selection of the rings in this analysis was carried out by taking only those rings reaching the level above and located after the opening. An important parameter for mined rings is the extraction ratio i.e. the ratio between mucked and blasted tonnage. This information is readily available in the Giron system.

Additional information is the tonnage mucked from the ring that was classified as ore and sent to the crusher and the tonnage classified as waste. In this study waste ratio is defined as the ratio between waste and total tonnage mucked in a ring. It is desirable to achieve a high extraction ratio and a low waste ratio in these studied rings.

At the time of writing this paper, the total tonnage of material mucked from level 436 was about 0.8 Mt. However, despite this tonnage, mining had not as yet produced many rings classified as full height. Therefore, the results presented here should be taken as an indication of behaviour rather than the final behaviour of 40 m sublevel height. Also, we have not carried out, for this paper, a thorough analysis of the performance of the rings. We have focused mostly on those important parameters described above to assess the overall behaviour of the rings so far.

A total of 39 mined rings fall into the classification above and will be used in this analysis. These rings are from nine different crosscuts at level 436 in Konsuln. Mucking operations in these rings have produced about 500 kt of material. About 84% of this material was transported to the crusher as ore and 16% of this material was transported as waste to the waste dumps. The tonnage of ore transported to the crusher was then 420 kt. The average extraction ratio for these 39 rings is 107%. These 39 rings have an in situ dilution of 10% (iron grades lower than 20%), according to the current block model. The absolute waste ratio increase was 6%. The in situ material classified as ore in these rings is therefore about 420 kt. Note that the in situ dilution in the rings will be checked later against the measurements of grades described in section 3.3 in this paper.

If needed, adjustments will be made to the grades for the final analysis. Without consideration of the grades, one can observe by the numbers above that the overall performance of these 39 rings is good. On average, about the same tonnage of ore blasted as the in situ tonnage in the ring was sent to the crusher from these 39 rings: 420 kt. This is an indication that the rings are performing well.

However, as mentioned before, the Konsuln orebody has a complex geometry, especially in the north part of orebody. The north part is characterised by lower grades and irregular geometry. Also, in general, the last two rings in a drift might be influenced by other factors such as contact zones between waste and ore, and different drilling patterns that could affect the performance of the rings. If rings from the northern part of Konsuln and the last two rings in a drift situated in the southern part are excluded, one would have a group of 27 rings out of those 39 rings. These rings are from six different crosscuts. This analysis is an attempt to observe how the performance could be in an orebody that is thick enough and with homogeneous orebody geometry. These 27 rings produced about 385 kt of material. About 90% of this material was transported to the crusher as ore and 10% was transported as waste. The tonnage transported as ore to the crusher was about 347 kt. The average extraction ratio for these 26 rings is 123%. These 27 rings have an in situ dilution of 5% according to current block model. The absolute waste ratio increase was 5%. The in situ material classified as ore in these rings is about 300 kt. Thus, on average, more tonnage of ore was sent to the crusher from these 27 rings than the blasted ore tonnage: about 47 kt more. This is also an indication that the blasting and caving functions of the rings are performing well. The flow of blasted ore in the rings towards the drawpoints is monitored by detecting smart markers previously installed in the rings, as discussed above in this paper. Detected markers are also showing the same behaviour, see Figure 11. Table 3 summarises the results of the analysis of data from the selected rings.

Table 3 Summary of the rings used in this study

Dataset	Number of rings	Number of drifts	Mucked (kt)	Extraction ratio (%)	Crushed (kt)	Waste ratio (%)	In situ waste (%)	In situ ore (kt)
All rings	39	9	500	107	420	16	10	420
Subset	27	6	385	123	347	10	5	300

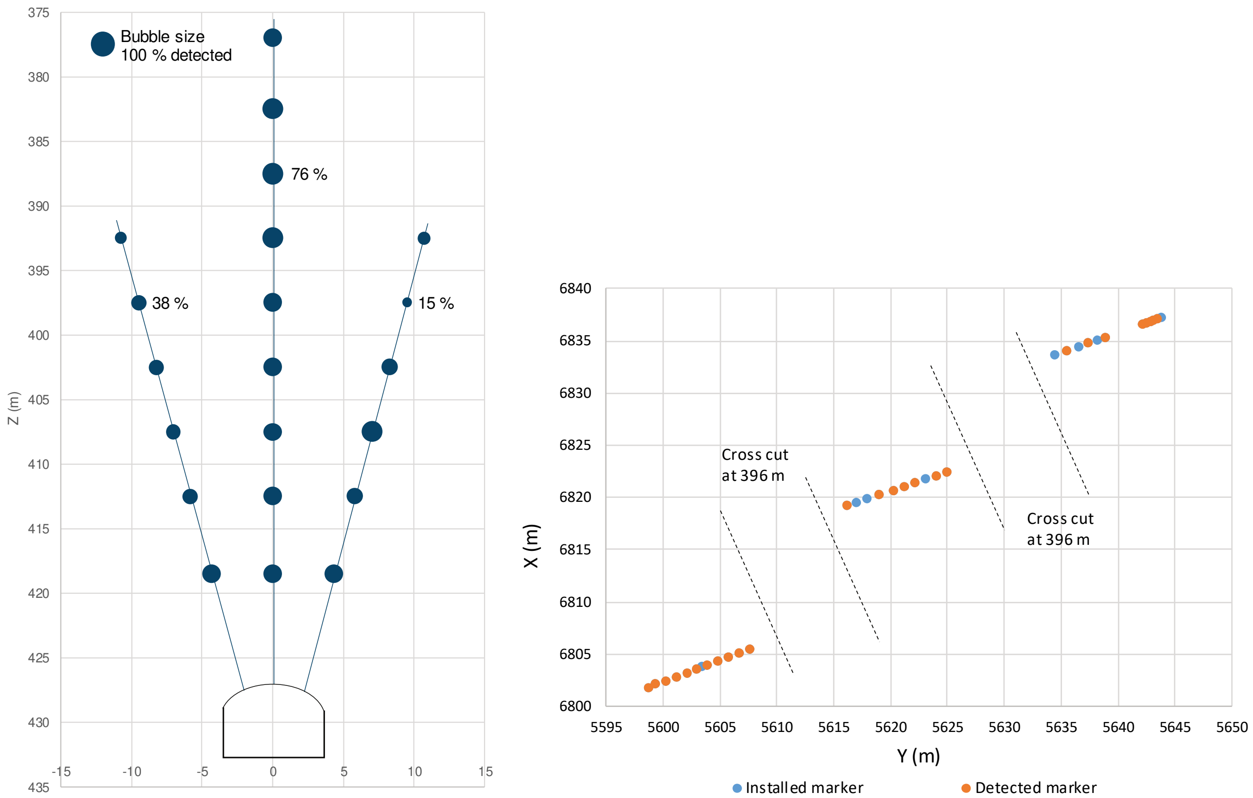
Finally, it is also possible to quantify the quality of the ore being sent to the crusher, since this crusher handles only ore from the Konsuln test mine and it is equipped with magnetic separation for sorting waste and ore. The product of the crusher is material under 200 mm and sorted in coarse and fine fractions. Both fractions produce concentrate and waste. The ratio between the tonnage of concentrated product and the total tonnage passed through the crusher gives an indication of the quality of the ore. The higher the ratio, the better the ore quality. In the first four months of 2022 this ratio was about 63%. This number indicates that good ore quality is coming from mining with 40 m sublevel height. Monitoring this ratio over time will give us valuable information about the tests. Work is ongoing in this area.

Even though the test is showing good numbers, we are trying to get it to work even better. An area of focus is the openings for the 40 m sublevel height. The ore recovery in the openings is low due to poor mobility of the blasted material towards the drawpoint. The results so far indicate that this poor mobility is not influencing the behaviour of the rings after the openings. However, we are planning to carry out new tests for different types of openings to improve this situation. Another area for possible improvements is fragmentation of the blasted rings. We have already planned two drifts with decreased burden (2.5 m) to observe its impact on fragmentation.

In conclusion, data from mucking of 39 rings from nine different crosscuts reaching 40 m sublevel height at Konsuln test mine is showing an initial good average performance of the rings independent of the way they are grouped. Data shows good extraction ratio and low relative waste ratio. In addition, data from the crusher indicates good ore quality. All this data indicates that mining with 40 m sublevel height is working properly so far. With the current mining front, we have at least six drifts under caving operation using 40 m sublevel height, based on our measurements and observations. As more rings are blasted, mucked, crushed and sorted from level 436, more information will be available to improve the knowledge and increase the performance of these rings.

3.2 Gravity flow

Mining at level 436 m was in progress when writing this paper. However, there are five crosscuts in the southern part of the orebody where mining has passed the marker rings. Detection of more markers installed from these drifts is not expected at this level. There are three full size marker rings in each crosscut, 15 rings in total. Markers in these rings have been summarised by boreholes and the Z-coordinate since the layout of the rings are identical. Grouping of markers is based on 5 m long intervals in the vertical (Z) direction. The number of installed and detected markers has been estimated for each Z-interval and borehole respectively. Figure 11a shows the marker recovery in a modified bubble chart including three examples of actual recovery values. The area of a bubble represents the marker recovery. Markers have previously been installed at the level above (396 m). Horizontal marker holes were drilled through the pillar between crosscuts. A top view of installed and detected markers are shown in Figure 11b.



(a) (b)

Figure 11 Marker recovery: (a) Summarised for 15 rings (crosscut 557–564, 436 m); (b) Top view showing installed and detected markers at the level above (396 m)

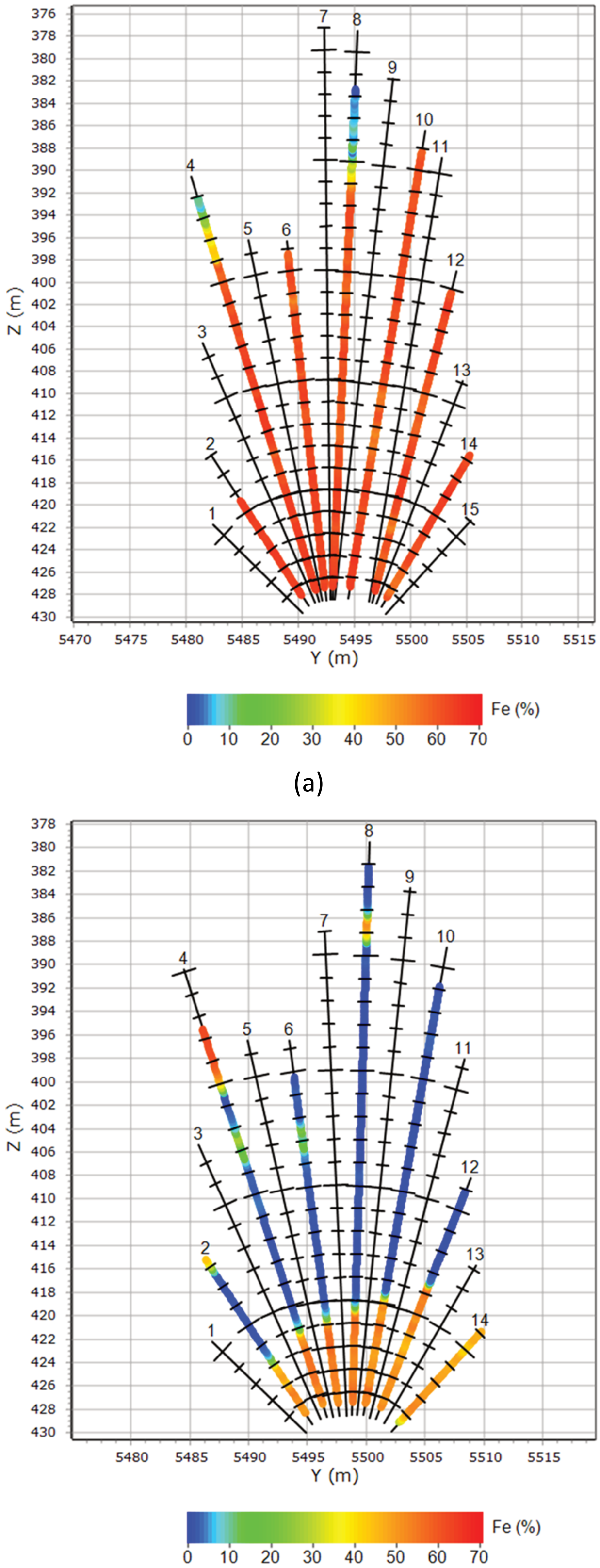
The average marker recovery for the 15 rings is 50%, 40% in the left hole, 61% in the middle hole and 43% in the right hole. However, we have failed to detect some markers due to power failures, broken antennas, and other problems. The true recovery is therefore somewhat higher.

Recovered markers clearly show that the draw has successfully reached the level above. This confirms conclusions based on extraction data.

There are also indications that the draw is wider (> 14 m) in the Konsuln orebody compared with the northern part of the main Kiruna orebody. The reason is probably coarser fragmentation.

3.3 Fe content in blastholes

Figure 12 shows Fe content in two rings, measured using a magnetic susceptibility probe.



(a)

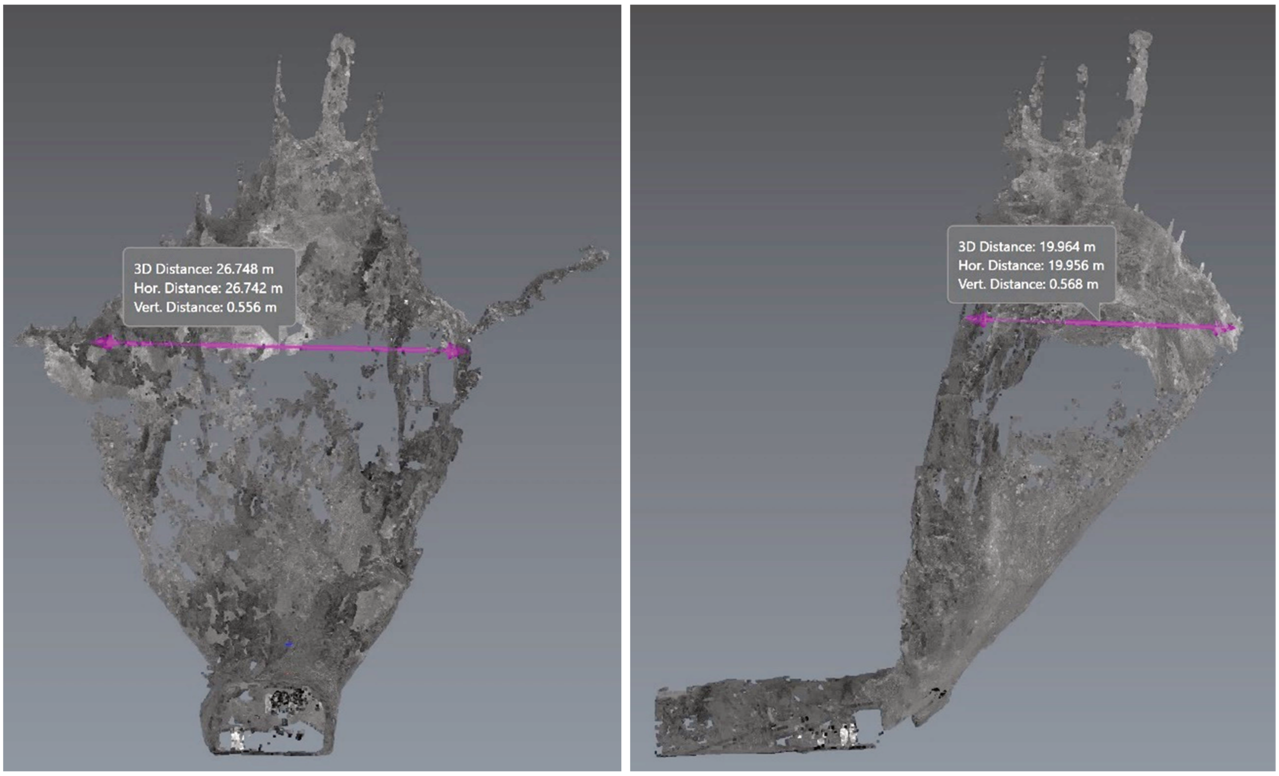
(b)

Figure 12 Examples of Fe content in blastholes measured using a magnetic susceptibility probe: (a) Ring in the rich ore; (b) Ring with a lot of waste in the upper part

Since all data points have estimated 3D coordinates it is easy to construct maps showing the Fe content at an arbitrary level.

3.4 Laser scanning

Laser scanning is carried out in special situations when an open cavity exists. Figure 13 shows a scan after loading a ring directly behind an opening.



(a) (b)

Figure 13 Front (a) and side view (b) of a laser scan after loading a ring directly behind an opening

4 Conclusion

This paper describes measurements and some preliminary results achieved so far from tests using 40 m sublevel height at LKAB. This test is carried out at Konsuln mine, a fairly small orebody located close to the main Kiruna orebody. The measurements and markers installations carried out are essential for the planning and assessment of the performance of the rings with large sublevel heights. The results so far, extraction ratio and marker recovery, indicate that caving is being initiated and ore is flowing down to the drawpoints as desired. The extraction ratio of the rings reaching the sublevel above is good. Data from the crusher station indicates that good ore quality is being mucked from the 40 m sublevels. As mining continues and more rings are blasted and mucked, more information will be available to improve knowledge and possibly also the design and performance of rings and openings.

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