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The Kiruna seismic event: important insights from the geotechnical model

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Abstract

Luossavaara-Kiirunavaara Aktiebolag's Kiirunavaara Mine is an iron ore mine located in Sweden's Lapland. On 18 May 2020, a seismic event of moment magnitude ($M_{w)}$ 4.2, calculated on the Swedish National Seismic Network (SNSN) and international systems, caused extensive damage to tunnel infrastructure and halted production in Block 22. A study was conducted to investigate the causes and evaluate how to safely restart mining. As discussed in this paper, the study included detailed reviews of existing datasets of core logging, drift mapping, and damage mapping following the event. In addition, new data was collected from drillholes targeting the interpreted area of the seismic source. Geotechnical data interrogation, structural modelling, and rock mass characterisation served to characterise the seismic source area in greater detail, leading to a full description of the crush zone: a zone of weaker rock mass which obliquely cuts the orebody – interpreted as an early extensional fault breccia of probable hydrothermal origin. The crush zone is identified to be susceptible to damage resulting from the seismic event. Associated with the crush zone, strong porphyry intrusions have resulted in complex lithological–structural relationships. This paper highlights the investigation into the source area of the seismic event and demonstrates how geotechnical data integration can give important insights to major mine planning decisions.

Keywords: *seismic event, geotechnics, modelling*

1 Introduction

The iron orebody at Kiirunavaara is operated by Luossavaara-Kiirunavaara Aktiebolag (LKAB) in Sweden's Norrbotten county which is a major mining district. LKAB exploits the Kiirunavaara orebody using sublevel caving (SLC) mining method. Its strike length is divided into 11 mining macro blocks, overall producing magnetite ore at a rate of 27 million tonnes (Mt) per annum. The Block 22 (B22) mine area (Figure 1) is host to a complex orebody shape, major structures, and crosscutting intrusions.

A working group and umbrella project known as Bergsäkerhet KUJ was established to investigate the cause and assess the damage from the M_W 4.2 seismic event, provide guidance, and help restart mining. The geotechnical setting was identified as a key component to understanding the event. Data available to the project were seismic data gathered continuously from the geophone network, subsidence data gathered from continuous InSAR satellite and surface Global Positioning System (GPS) measurements, and drillhole and mapping geotechnical data. It was found that the geotechnical dataset of B22 was limited, comprising rock quality designation (RQD) and rock mass classification (Q' system) from drillholes, and joint data and geological strength index (GSI) from drift mapping. Therefore, the working group commissioned a geotechnical core drilling program to collect detailed geotechnical data from the seismic event source area.

Figure 1 shows the main orebody with production area Block 22, ore passes, and simplified infrastructure. The B22 hanging wall consists of rhyolite-rhyodacite lavas and pyroclastic flows, while the footwall comprises intermediate-mafic volcanic units. In addition, B22 contains late crosscutting diabase dykes, and geometrically complex bodies of dyke porphyry (DP). The hypocentre of the seismic event was interpreted to be located at or very near the intersection between the stiff DP dyke and the crush zone. A central question is to what extent do the dyke porphyries act as pillars to support the block. And another question follows, what led to the significant seismic event?

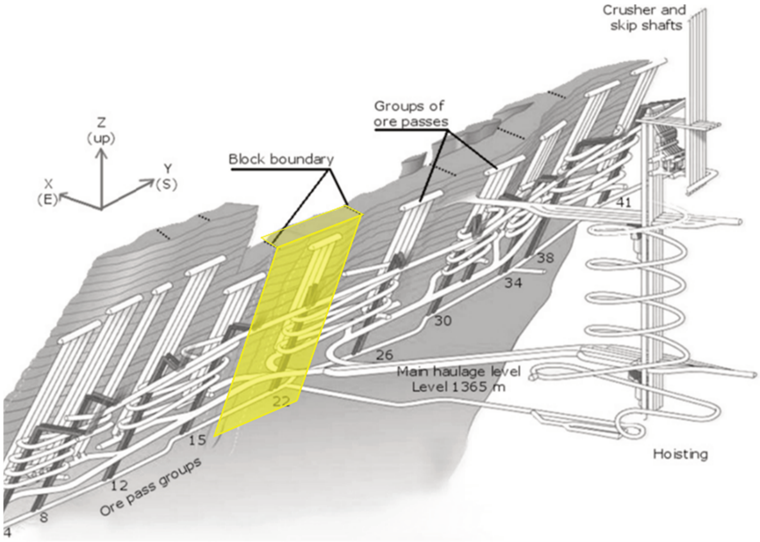

Figure 1 Sketch of the Kiruna mine orebody, with production area Block 22 of Kiirunavaara Mine highlighted. Three ore passes are located within the block. The event's hypocentre is interpreted to be located at the northern orepass

2 Short description of the M_W 4.2 event with aftershock sequence

On 18 May 18 2020, a large M_W 4.2 (based on international recordings) seismic event occurred in B22 of LKAB's Kiirunavaara Mine (Dineva et al. 2022) accompanied by widespread tunnel failures and loss of equipment. Fortunately, there were no injuries to mine personnel.

Seismic data are sourced from a mine-wide internal geophone network and regional stations. The effect of the event was felt up to several thousand kilometers (km) away and the geophone network recorded aftershocks for 15 days. There was an event increase up to five times the average frequency, with 20,662 seismic events of magnitude ranging from -3.3–1.4 during the first 24 hours after the main event. This is in comparison to a typical background daily average of about 5,000 seismic events (Boskovic 2022).

The mine's seismic network consists of 253 geophones of 4.5 and 14 Hertz (Hz) uniaxial and triaxial sensors, located in grouted boreholes in the orebody and country rock (Boskovic 2022). The seismic data analysis, processed by the Institute of Mine Seismology (IMS), calculated the location of the hypocentre, which is the accepted initial point of the event (Dineva et al. 2022). Foreshocks grouping, aftershock clusters, and studies to identify correlations or causations used mXrap™ modelling software (Harris & Wesseloo 2015). In combination with mine geology, development, and production data the seismic knowledge allows spatial correlations and back-analysis to the mechanism types (Boskovic 2022; Dineva et al 2022).

Summarised by Boskovic (2022), numerical modelling was used to visualise differential stresses around the Block 22 orepass group and the high footwall stresses. Several possible failure mechanisms were identified (Boskovic 2022).

3 Geotechnical understanding at the time for the event

In the northern part of the Fennoscandian Shield, the Kiruna iron oxide–apatite (IOA) deposit is of Paleoproterozoic age and emplaced in a succession of metavolcanic rocks, on top of an Archean basement and an early Paleoproterozoic rift-related volcano-sedimentary formation (Bergman et al. 2001; Martinsson 2004). The orebody's footwall comprises mafic-intermediate volcanic units (Hopukka formation) of the Kiirunavaara Group, while the hanging wall consists of rhyolitic-rhyodacitic metavolcanic rocks, largely pyroclastic flows, both with ages in the interval 1.90–1.87 giga annum (Ga) (Westhues et al. 2016; Allen 2021). Located between the volcanic Hopukka and Luossavaara formations, the Kiirunavaara deposit has a strike length of 4–5 km and a thickness varying between 0–200 m (Andersson & Rutanen 2016). The orebody strikes almost north–south and dips on average 60° east. The latest mineral resource estimate for the Kiirunavaara deposit is 713 Mt at 60.1% Fe and an additional mineral reserve, which sits outside of the resource, of 737 Mt at 41.5% Fe. Massive magnetite-apatite ore contains generally sharp contacts, but many variations exist. The range of mineralogical, structural, and alteration types opens a debate as to the genetic model of ore formation and ore emplacement (Andersson & Rutanen 2016; Andersson et al. 2021).

In the mine production area of Block 22, structural measurements from tunnel mapping and drillcore allow the description of three main fracture sets and one minor, reported by Boskovic (2022). One major set runs close to east–west dipping intermediately to the south (40–80°) and the other two close to north–south, dipping steeply east or west. A minor set also runs E-W, dipping north. This structural pattern is essentially consistent with that for the entire mine (Andersson & Jokelainen 2020). In other parts of the mine the three major sets are known to include extents of >10 m, where those running north–south tend to have a higher percentage of slickensided surfaces (Berglund & Andersson 2013; Björnell et al. 2015). During seismicity, the stability of development areas in B22 is affected by these extensive brittle fracture sets.

4 Damage mapping

Tunnel damage mapping findings confirm varied damage types and confirm a strength contrast in the footwall areas. Tunnels mapped for damage used a damage scale of R0 to R5 (Heal 2010): R0 represents zero perceivable damage grading to R5 indicating total collapse or failure. Explosive ejections (rock bursts) in the dyke porphyry occur when shotcrete and rock are thrown into tunnels. Within the dyke porphyry, back-analysis of ejections with 35 m of travel have resulted in calculated ejection speeds of 40 m/s.

Complete failure of footwall – crosscut intersections are common on several levels. The dimensions of the fallen rock blocks clearly show (i) some blocks have been released along discontinuities to their smallest block size (Figure 2), a function of the penetrative fracture sets and veins in the rock mass, and (ii) blocks and fragments with fresh failure surfaces which has been exposed to enough high stresses to almost achieve complete fragmentation without blasting. Once fragmenting, the back continues to fail along existing fracture sets until a stable arch is achieved (Figure 2). The height of the now stable back can be more than 10 m – inaccessible to personnel – but, where, possible these voids are scanned with drones.

Other blocks are large enough to show unbroken, internal discontinuities (Figures 3 and 4). The block face of Figure 4 represents the ore-parallel fracture set used by the block to fail into the development. The vertical shear fractures guide the failures of some damage areas and can accommodate large vertical displacement. Utilising the vertical, ore-parallel shear fractures, large blocks drop into a development, completely sealing the crosscut tunnel (Figure 4).

Figure 2 Level 1079 footwall drift looking north showing fragmentation from the back and a void above the rock pile

Figure 3 Level 1079, Y202 crosscut looking west, fragmentation and oversized boulder

Figure 4 Level 1079 crosscut Y204 looking west, complete sealing of development

5 Drilling investigations and updated geotechnical understanding

To investigate the seismic source area, an NQ3-sized orientated diamond drillcore program was initiated. In total, 23 drill holes along two footwall drift levels drilled a total of 2,106 m. All holes were drilled from the footwall towards the east, in the direction of the orebody, at positive and negative dips. Drillhole spacing ranged between 60 and 180 m with a greater density in the north and central areas of the block (close to the seismic source). Logged data included geology, alteration, minerals in veins or fractures, orientation fractures, and the attributes to calculate rock mass ratings. In addition, 2,986 structural orientation readings were captured using the Reflex IQ logger. Parameters recorded were joint orientations, cemented joint orientations, joint conditions, and mineral fill. IQ logger data were validated against manual Ezy Logger measurements in accordance with internal quality assurance, quality control (QAQC) protocols. These data compliment the mapped structures from tunnel-drift mapping. Several drill holes encountered hole collapse in anticipated weak zones, core loss – again in the weak zones – and voids. One drillhole was extended to penetrate the orebody and hanging wall. Point load test (PLT) data to International Society for Rock Mechanics standards for diametral testing were routinely collected. In addition, samples of the major rock types were sent to a commercial laboratory (Stress Measurement Company Oy, Finland) for triaxial tests across a range of confining pressures. To summarise, the new datasets are considered of good quality and consequently attached to these is a high level of confidence.

Data capture and drillhole validation was performed in the software AcQuire GIM Suite 4™. Drillhole data QAQC and data processing used Leapfrog™ version 2021.2.4. Combining these new data with seismic locations, lithology model, orebody model, drift mapping data, and the underground workings void model, produced a geotechnical model. The geotechnical model was constructed in Leapfrog including data of rock mass rating systems of RQD (Figure 5), Q', GSI, RMR_{89}, $IRMR_{L\&J}$, fracture networks, orientated structural data, and a detailed description of the crush zone – a major structure in Block 22.

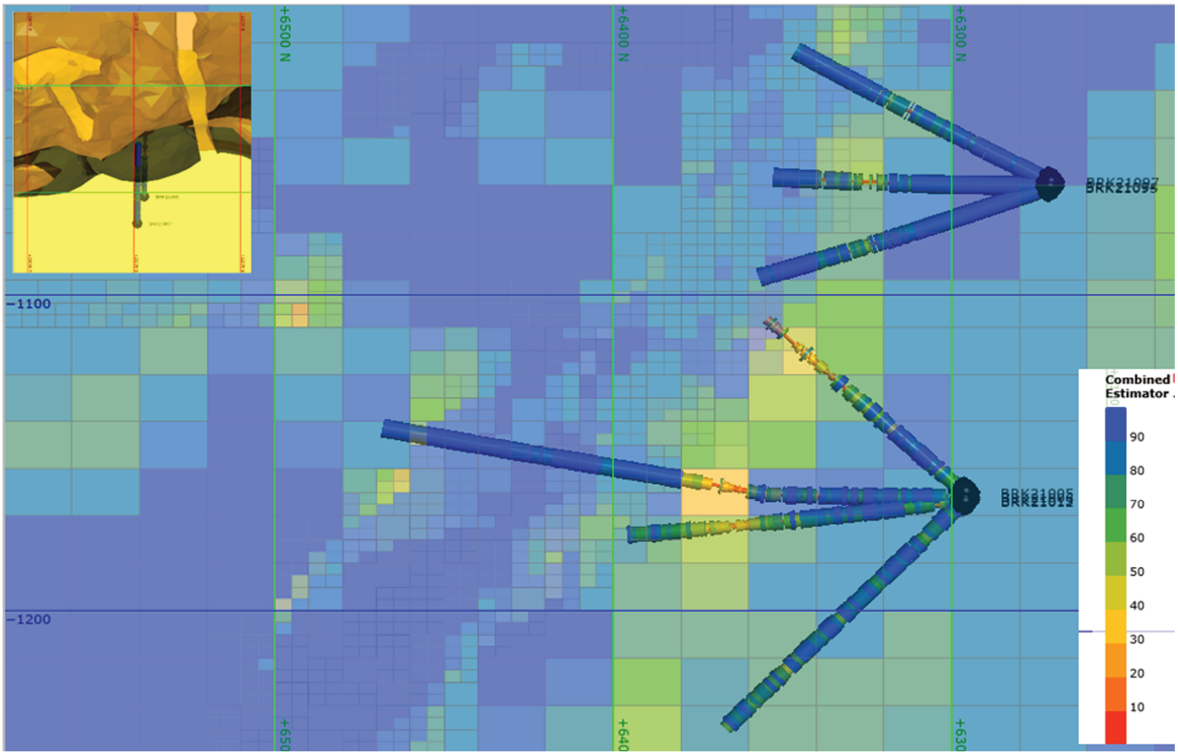

Figure 5 RQD block model cross-section of B22 at Y2100 with drill holes BRK21005, BRK21006, BRK012, BRK21013 from lower level, and drill holes BRK21094, BRK21095, and BRK21097 from the upper level. RQD shown on drill trace and model. Inset, plan section showing drillhole positions with yellow footwall units, dark ore, and orange hanging wall units

6 Discussion

6.1 Crush zone

The crush zone was described and delineated, based on the information from the drill program, and confirmed by damage mapping when viewed in the updated geotechnical model. The triple tube method gives protection to the drillcore resulting in the recognition of fine clays as shear faults. Shear structures were previously unlogged due to the removal of fines during the drilling process. Furthermore, other features preserved are the fault seal minerals. The crush zone is recognised as hydrothermal brittle fracture zone. First identified by the operations rock mechanic engineers in the footwall, the crush zone was further delineated by the geotechnical geologists by connecting drillhole low RQD zones. In their assessment of alternative mining methods, photo-logging by SRK Consulting identified the same fracture zone in the footwall subparallel to, then obliquely cutting, the orebody. In summary, the level of detail obtained in the triple tube campaign has significant impact on the assessment of major structures and geotechnical models.

Investigations show the crush zone to be a brittle hydrothermal breccia with a structurally controlled alteration halo of sodic-fine grained iron oxide–red brick alteration. Small local shears, as chloritic clays in fault gouge, indicate movement. Cemented joints are often anhydrite and open fracture surfaces contain gypsum. The hydration of anhydrite to gypsum is estimated by the logging crew to take place within a year. Irregular micro defects are present, can contain gypsum, and concentrate in sections with the most alteration. The crush zone has, thus, degraded the rock mass, but less so in passing the dyke porphyry. The latter therefore remained a source of relative high strength in the rock mass.

The crush zone strikes subparallel to the orebody. In the south of Block 22, it starts 100 m deep in the footwall and travels north to obliquely cut the orebody (Figure 6). At the intersect between the orebody and crush zone the orebody is heavily brecciated, and drilling shows regular core loss. Complex lithological geometries of the orebody and dyke porphyries are significant in Block 22 (Figures 6 and 7).

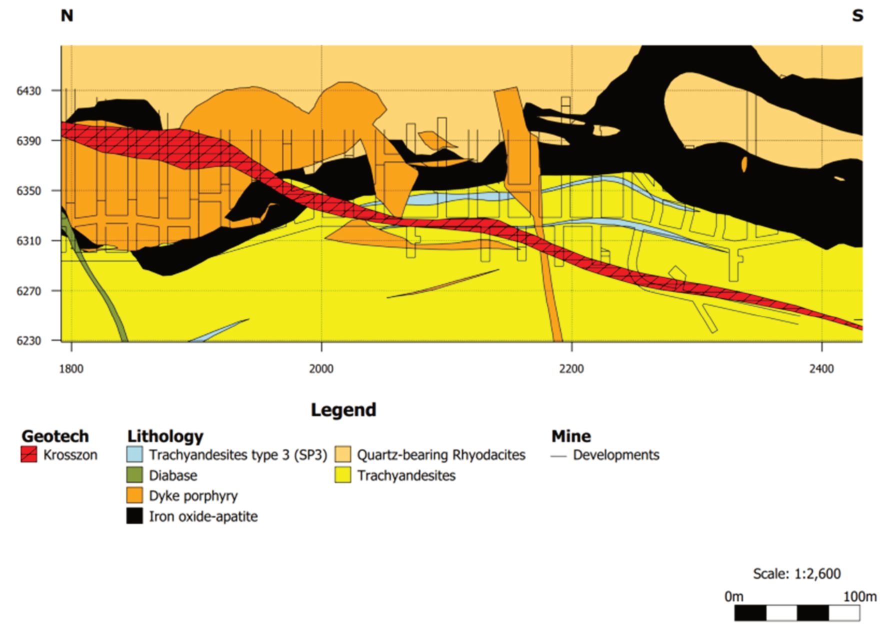

Figure 6 Block 22 geology at Level 1079, showing a thin orebody, country rocks, and the crush zone in red hatch

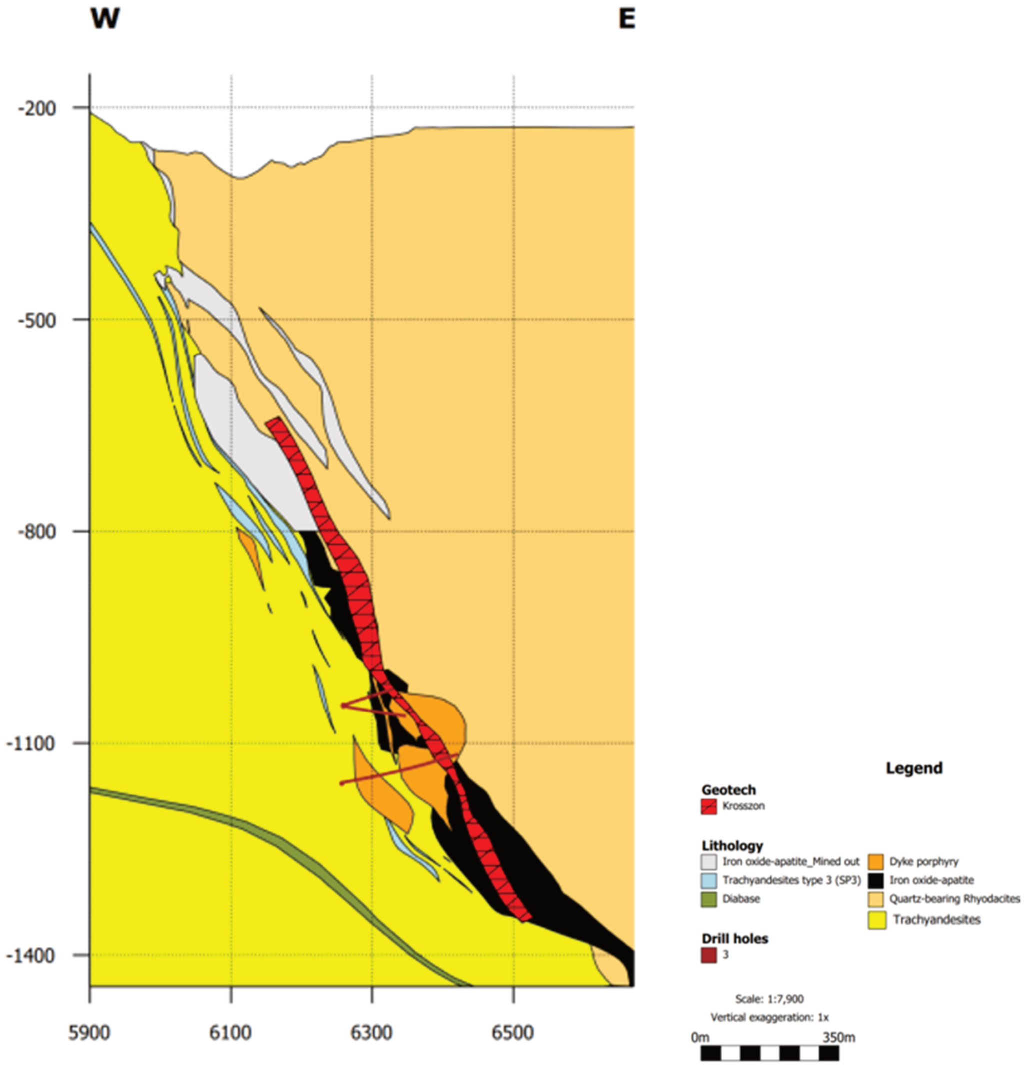

Figure 7 Vertical geological section at Block 22, Y1935, Drillhole traces in brown. Legend as in Figure 2

Within the crush zone, tunnel scans before and after the large event show floor heave, roof sag and overall compression (Figure 8). Reverse and normal faulting have also been documented along ore-parallel structures.

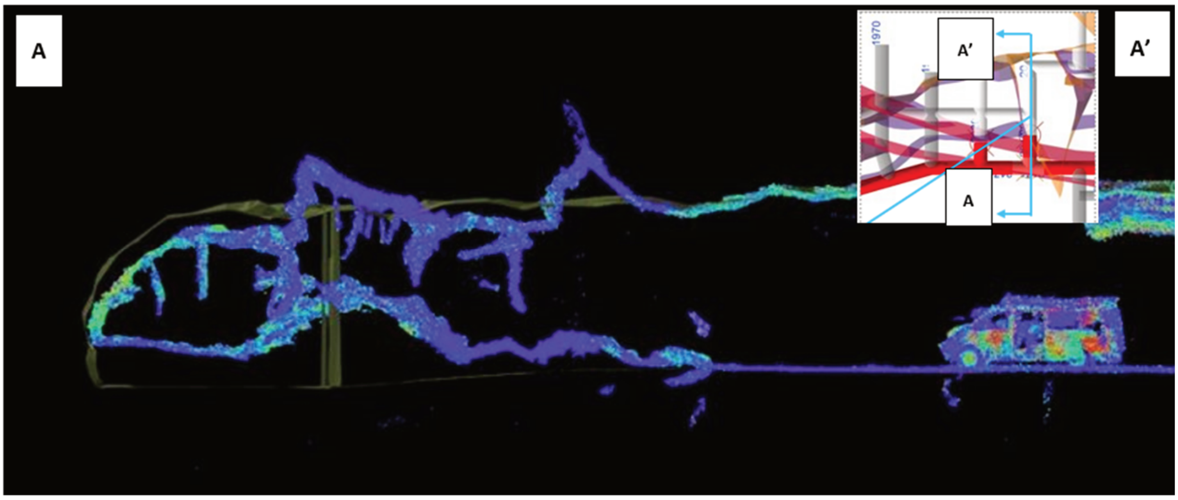

Figure 8 Level 1079, Y22 pre-event and post event scans, looking north. Blue dots, post seismic event show floor heave, roof sag and collapse of back. Scan NGM Automation, D Jatko

6.2 Subsidence

Data sets from three different sources are used in the overall assessment of the Block 22 problem. The sources are seismic data gathered continuously from the geophone network, subsidence data gathered from continuous measurements of interferometric synthetic aperture radar (InSAR) satellite and surface GPS instruments, and geotechnical data from existing and new data sets. LKAB continuously collects these data in normal operations, and a common thread exists to link these independent datasets together – the caveability of the Kiirunavaara hanging wall. The Kiirunavaara hanging wall is continuously caving and subsiding along the orebody's strike to the east. However, one part of the hanging wall appears more stable: the hanging wall of Block 22. Hanging wall stability is high in Block 22 (Figure 9) (Mozaffari & Villegas, pers. comm., 15 June 2022). Irregular mining due to the increased proportion of internal waste rock (and a thinner orebody) creates bridges that affect caving rates of the hanging wall adjacent to the block. This is an area of ongoing investigation.

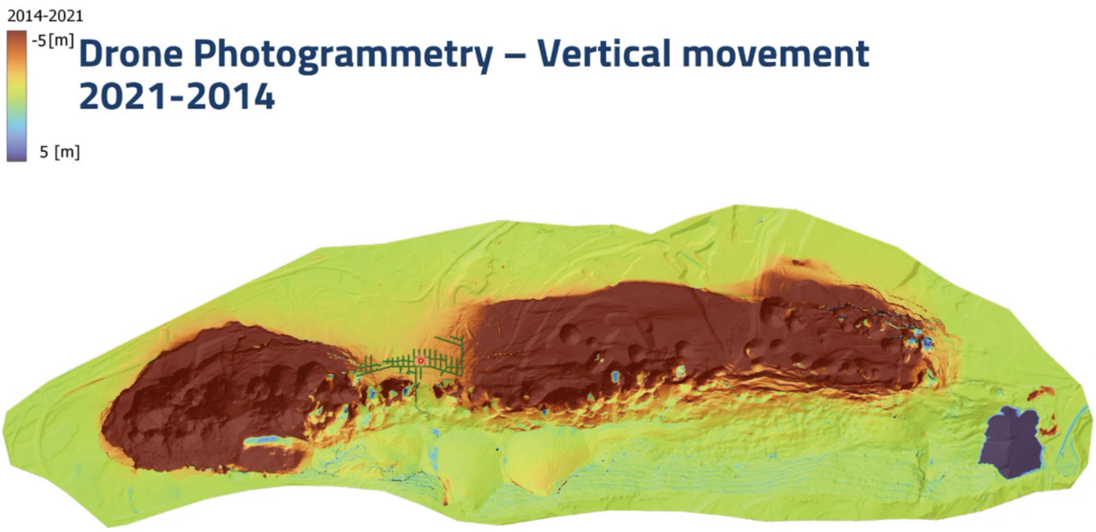

Figure 9 Surface subsidence shows the stalled cave in the Kiirunavaara hanging wall. Block 22's development position, Level -1108 m, in blue and the event hypocentre as a red dot

Bridges act as a possible conduit for stresses and stress transfer into the footwall from the stalled caving of the hanging wall. While the DP's geochemistry is identical to the hanging wall felsic rhyolites, texturally it is a coarse feldspar porphyry with large rock blocks, and extremely strong. The dyke porphyry has very high intact rock strengths (average (avg.) 345 megapascals (MPa)), higher than the hanging wall (avg. 225 MPa) and much higher than the ore (avg. 145 MPa), but overlapping with the strongest varieties of the footwall (avg. 370 MPa) (Andersson 2021). Stresses are channelled through the DP, increasing the stress load of the DP. The DP in these bridges is extra stressed/less yielded than the surrounding rock mass. Once a critical value of stress is exceeded – defined by the limit of the rock mass strength of the DP – the DP will fail, and compression occurs.

6.3 Damages

On Level -1079 m, a range of tunnel damages are present. Inspection of the tunnel damages and importantly the resultant failure piles can give insight into the rock behaviour during failure. A high proportion of damages and damaged tunnels exist parallel to the ore which may signal to the orientation of active structures during the large event. From the tunnel damage mapping, complete failure of footwall/ crosscut intersections is common on Level 1079 m and in the damage envelope of Block 22. From inspection of the rock blocks in the failures, it is suggested the rock fails into development areas, using existing fracture sets, as fragmented blocks or large wedge failures. Therefore, it is reasonable to assume that the crush zone and north–south shear fracture sets are the structures which have moved under compression during the large event.

The role of the geotechnical model and the effect of integrating independent datasets of seismic activity, damage mapping, and geotechnical information were assessed to help understand the cause of the seismic event. The block's geotechnical detail is greatly improved for rock classifications systems and new data now allows calculations for IRMR. Classification systems are interpolated onto a block model and used by LKAB in-house departments. In the geological–geotechnical logging, major structures are recorded, e.g. the crush zone. In summary, geotechnical investigations, subsequent data logging and modelling have contributed to clarify the geological factors that may have led to tunnel failures and damages associated with the large seismic event; while the models themselves have assisted in the assessments of applying mining methods such as inclined caving, panel caving or sublevel caving.

7 Conclusion

A hypothesis we can accept, or reject can be: the crush zone is a significant factor in accommodating the compression needed for the M_W 4.2 seismic event.

The proximity of the high strength DP, unmined waste rock pillars, ore passes, and the crush zone were instrumental for the event. The mined-out area in Block 22 is very thin with a low hydraulic radius causing problems for the hanging wall to cave naturally. Pillars are created from the non-mining of waste (DP), and there is a possibility of poor ore recovery causing remnant pillars. Therefore, horizontal stresses are concentrated into B22, i.e. in the stiff dyke porphyry causing a large difference in strain between the dyke porphyry and the adjacent crush zone. Development space from the ore passes allowed the porphyry to yield. An increased yield occurred along the crush zone (Figure 4), and development voids of B22 (Figures 5, 6, and 7). As the poorly caved hanging wall created a bridge to the footwall, Figure 9, a stress transfer took place. On completion, a redistribution of the stresses allowed failure into developments along existing fracture sets. Therefore, the evidence given here seems to support the hypothesis stated above.

Mine planning decisions are based on orebody knowledge and surrounding geotechnical information. The models developed from the seismic source investigation are more complete than previous models, generating a more informed decision. The decision to eliminate panel caving and block caving as future mining methods was based on consideration of the geological and detailed geotechnical model information.

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