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Three-dimensional numerical modelling and analysis of complex stress variations and deformations at Malmberget mine, Sweden

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Abstract

LKAB's Malmberget mine is not only one of the largest SLC mines in the world, but it is also one of the most complex, where between 10 and 15 orebodies are mined simultaneously. The subvertical orebodies are generally stacked, where one orebody is on the footwall or the hangingwall of the other. This results in complex stress interactions and deformation patterns when these orebodies are mined simultaneously. Keeping the entries into the respective orebodies open is a critical part of daily mine planning at the Malmberget mine and the ability to predict stress changes and associated damage to these entries contributes significantly to this planning. To develop an effective empirical tool for predicting mining-induced stress changes and associated entry deformation and damage, a two-year monitoring program was initiated in 2019 to record those stress changes and their consequences. These results are described in other papers written by the authors for this same symposium. This paper, however, focuses on the numerical modelling component of this work, where a series of numerical modelling was done using FLAC3D with monitoring data as the basis for model calibrations. Given the extent of the mining operations at Malmberget mine, the stress changes are global in extent on the scale of kilometres and extend from 100 to 200 m below the active mining front. The field data collected in the entries are local and do not necessarily reflect the global extent of stress changes. Nevertheless, through numerical modelling it is possible to build a global model to observe stress changes and the resulting deformations as neighbouring orebodies are mined.

Keywords: *3D modelling, monitoring, stress changes, deformations*

1 Introduction

The Malmberget mine is LKAB's second largest SLC mine after the Kiruna mine in terms of production capacity. However, Malmberget is the largest in terms of areal occupation, where over 20 orebodies, comprising magnetite and hematite, are spread over an area of roughly 12 km^2. Currently between 10 and 15 of these orebodies are mined simultaneously, resulting in about 18 million tonnes of ore being produced annually.

The challenge for ground control at the Malmberget mine is multifaced. The first challenge is the manner of the spatial distribution of the orebodies. The orebodies are subvertical and generally bedded or stacked one above the other, leading to one orebody being located at the hangingwall or footwall of the other, with waste rock in between. Thus, the simultaneous mining of these orebodies has a domino effect on each other in terms of ground response. The second most important factor is the highly variable lithology, often observed as intermixing of various rock types particularly close to orebody contacts. Since one orebody is the hangingwall or footwall of the other the lithology between them can be best described as a broth of different rock types. Even more intriguing is the dominant presence of biotite schist either as part of the rock broth or as a single unit occurring as bands and lodes along the hangingwall and footwall as well as within the orebodies. The biotite schist is the most troublesome rock unit in terms of its impact on ground deformation (and ore dilution) and it plays an important role in mine design and layout at the Malmberget mine. The third factor for ground control at the Malmberget mine are the complex stress distribution patterns resulting from the domino effect of mining simultaneously. The complexity of the stress distribution is further amplified by the broth mixture of rock types and different principal rock units throughout the mine with distinct deformation behaviours. For example, a biotite unit may find itself locked in between magnetite on one the side, rock broth on the other and strong leptite immediately next to the rock broth. This example is not far-fetched as it is typically encountered at the Malmberget mine at the entries into the orebodies. Hence, the stress and deformation patterns can be distinctly variable within a single entry. These observations are described in Jones & Saiang (2022a, 2022b & 2022c).

This paper presents the numerical modelling component of an investigation conducted at the Malmberget mine to observe stresses and associated deformation patterns at the crosscuts. The aim of this monitoring campaign and analyses was to develop a methodology for predicting deformation and damage at the entries. The results of the monitoring campaign are reported in Jones & Saiang (2022b) and the empirical prediction method is reported in Jones & Saiang (2022c).

Because of the size and complexity of the mine the continuum method of numerical modelling was utilised in 3D simulations. Both versions of Itasca's FLAC3D version 6 (Itasca 2019) and version 7 (Itasca 2020) were used in the numerical modelling and simulations.

2 Monitoring

As this paper is one of three papers published in this conference concerning deformation in complex geological environment at the Malmberget mine, the monitoring program is also described in Jones and Saiang (2022b & 2022c). However, to make this paper as standalone as possible the monitoring program is briefly summarised here. Monitoring was conducted in the crosscuts of two orebodies, Printzsköld and Alliansen (Figure 1) on levels 996 and 1023 in Printzsköld and on levels 1051 and 1080 in Alliansen (Figure 2). Figure 2 shows the instrumentation setup in the crosscuts, which are located on the opposite side of the contact between the magnetite ore, biotite-schist and leptite in the footwall. 10 m long multi-point borehole extensometers (MPBX) with 4 anchors are located in the roof centreline and right shoulders, 7 m long MPBX with 3 anchors in the right wall (from footwall entry). Digital Hollow Inclusion (HID) stress cells were installed 4.5–4.8 m deep in the right shoulders in magnetite ore, biotite-schist (on the contact) and leptite in the footwall. The instrumentation setup is meant to measure deformation and stress changes in the different geological units as mining advanced towards the instrumented crosscuts.

It is also to be noted that mining in Alliansen is proceeding two levels ahead of Printzsköld, which means the instrumentation in Printzsköld is likely located in disturbed ground.

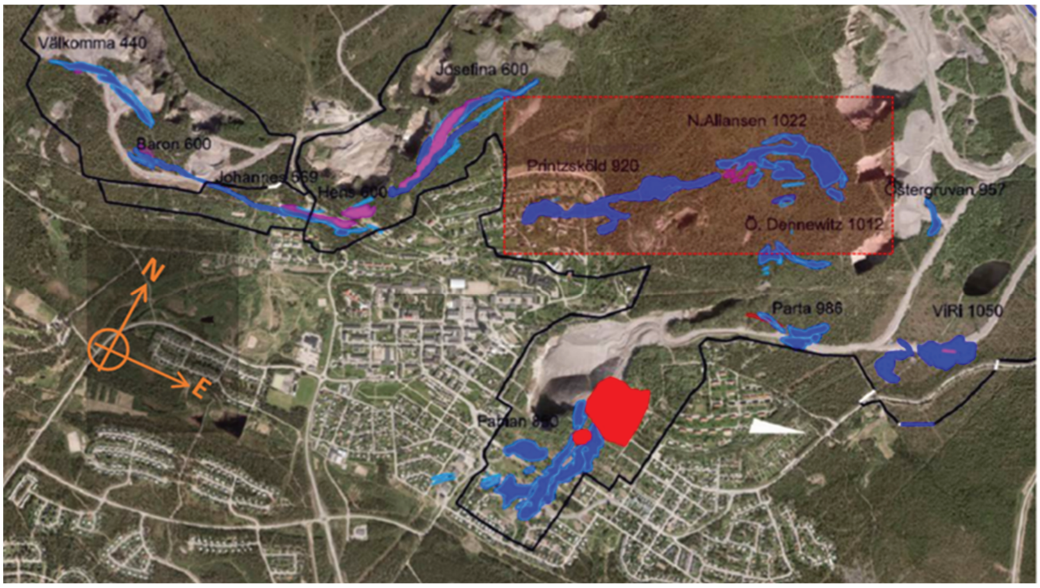


Figure 1 Printzsköld and Alliansen orebodies (boxed in) where the investigation was conducted

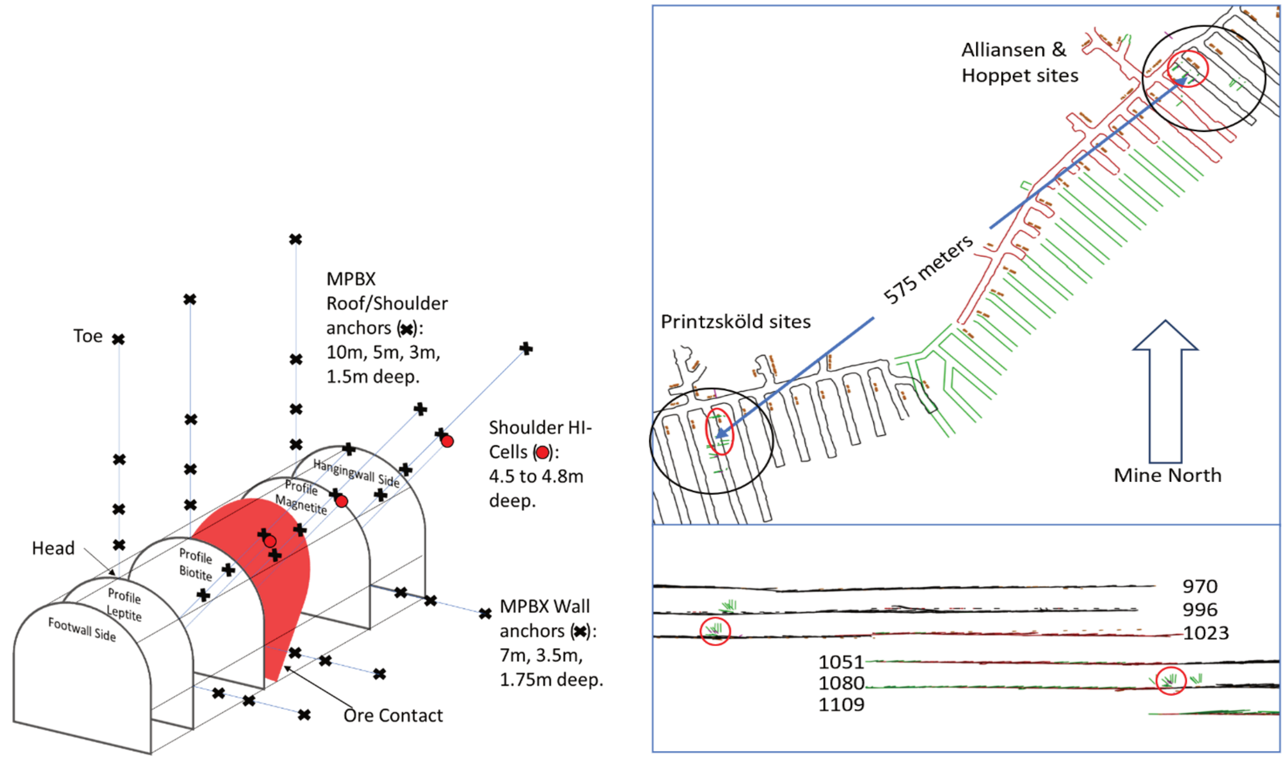


Figure 2 Instrumentation of the crosscuts at monitoring sites underground

3 Model setup

3.1 Model area

The FLAC3D model was constructed to include monitoring areas in Alliansen and Printzsköld orebodies in one model. Both Alliansen and Printzsköld are part of the eastern group of orebodies (Figure 1). Printzsköld is a non-daylighting orebody and therefore does not have an exposure on the surface like Alliansen. The two separate orebodies eventually merge at a depth of around 1,000 m, into more or less a single orebody. The orebodies generally strike northeast and dip southeast.

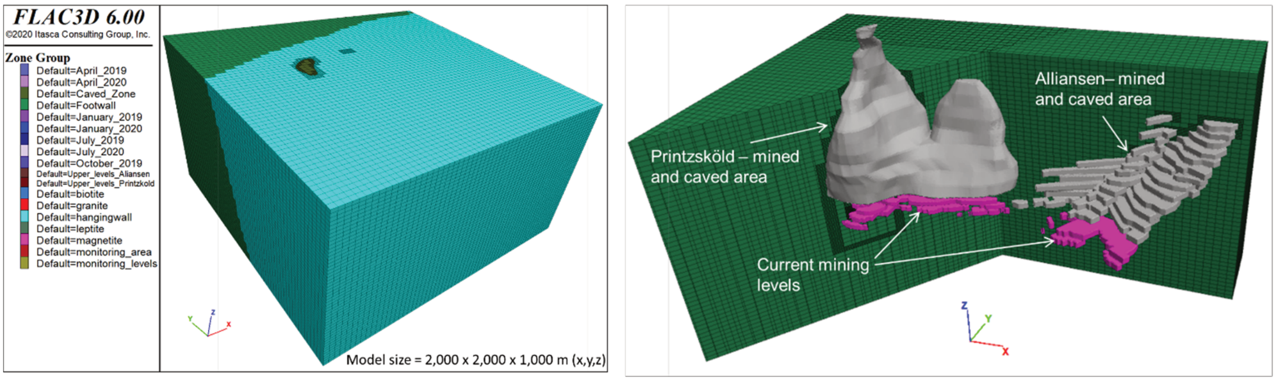
3.2 Model geometry and boundary conditions

Figure 2 shows the *FLAC3D* model geometry and the two mining areas of Printzsköld and Alliansen. At 2,000 × 2,000 × 1,000 m in x, y, and z directions, it is significantly large and sufficiently covers both monitoring areas and the extensions of the two orebodies. The height of the model extends to level 400, which encompasses the large Printzsköld upper horizon that was mined and caved (Figure 3a). There are other orebodies surrounding Printzsköld and Alliansen, but the model did not cross into those orebodies.

Given the size of the model the mesh was refined in the monitoring areas and geological boundaries, elsewhere the mesh was coarse. The zones are as small as 0.5 × 0.5 × 0.5 m at the crosscut entries and geological boundaries and as large as 30 × 30 × 30 m cubes farther away.

Roller boundaries were applied to all six walls: top, bottom and the four sides.

Figure 3 shows the cross-sections, from the FLAC3D model, through the crosscuts that were monitored in Printzsköld and Alliansen. Note that mining in Alliansen is advancing one to two sublevels (20 to 50 m) ahead of Printzsköld. The target for the instrumentation was to place them within the different lithological units at the footwall contact.



(a) (b)

Figure 3 (a) FLAC3D model geometry and (b) Model extends from -1,400 mL (bottom) up to -400 mL (top) and covers the previously mined areas as well as the current mining areas

3.3 Inputs

3.3.1 Pre-mining stress

The pre-mining stress regime used is based on hydro-fracturing stress measurements conducted by Ask et al. (2009) at depths between 1,000 and 1,200 m. Sjöberg (2010) reported the summary of these measurements as shown below and refers to the data as the accepted understanding of the pre-mining stress conditions for the entire Malmberget ore field.

$$\sigma_H = 0.0358z \text{ (maximum horizontal stress (MPa))}$$

$$\sigma_h = 0.0172z \text{ (minimum horizontal stress (MPa))}$$

$$\sigma_v = \rho g z \text{ (vertical stress (MPa))}$$

Where z is depth below the ground surface (m), ρ is the density (kg/m^3) and g is gravity (m/s^2). The orientation of the maximum horizontal stress (σ_H) is 130.6° southeast, relative to local mine north.

3.3.2 Rock parameters

The input parameters for intact rock and the rock mass are shown in Table 1. The cave material was assigned the following material properties after Villegas & Nordlund (2013); E = 200 MPa, c = 0, ϕ = 35 and σ_t = 0, and was assumed as Mohr–Coulomb material.

Table 1 Rock parameters

Basic rock parameters	MGN	GLE	RLE	RGL	BSF	GRA
Intact UCS (MPa)	104	115	170	133	62	190
Intact Young's modulus (GPa)	59	57	72	43	47	76
Hoek–Brown parameter, m_i	29	30	30	30	15	32
Geological Strength Index (GSI)	65	60	60	40	30	65
Disturbance factor, D*	0.8	0.8	0.8	0.8	0.8	0.8
σ_{3max}**(MPa)	20	20	20	20	20	20
Rock mass parameters						
Cohesion, *c* (MPa)	6.7	5.2	5.9	3.7	1.5	7.0
Friction angle, ϕ (°)	44	38	41	30	14	45
Tensile strength, σ_t (MPa)	0.126	0.097	0.143	0.02	0.006	0.237
Rock mass Young's modulus, *E* (GPa)	13.6	9.4	11.9	2.8	1.5	17.1
Rock mass Poisson's ratio	0.25	0.25	0.25	0.25	0.3	0.25

D* Mining disturbance factor 0.8 because of regional disturbance created by cave mining and has also been tested as part of model calibration.

σ_{3max}** is the maximum value of the minor principal stress area monitoring. This stress was determined by an elastic stress model and was measured after the upper Printzsköld horizon has been mined.

Rock units: MGN = Magnetite, GLE = Grey Leptite, RLE = Red Leptite, RGL = Reddish-Grey Leptite, BSF = Biotite-Schist, GRA = Granite

3.4 Constitutive models

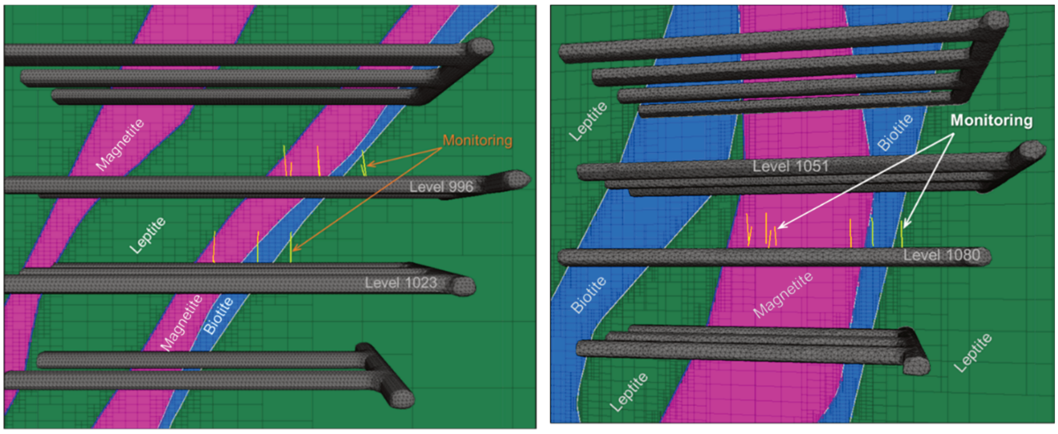
All geological units are treated as Mohr–Coulomb materials and therefore Mohr–Coulomb was utilised as the standard constitutive model for the simulations. However, the biotite-schist was assigned Mohr–Coulomb strain-softening constitutive model, which best captures the strain softening characteristics of the biotite-schist. Table 2 shows the strain-softening parameters used for the biotite-schist.

Table 2 Strain softening parameters for biotite-schist

Parameter	Initial strain $\varepsilon_1 = 0\%$	Dilation strain $\varepsilon_1 = 0.5\%$	Residual strain $\varepsilon_1 = 1.0\%$
Cohesion (MPa)	0.97	0.5	0.5
Friction (°)	10	5	5
Tension (MPa)	0.006	0	0

3.5 Simulation

The sequence of extraction is properly executed in staged mining sequences to distribute the stresses down to the monitoring levels. This involved numerically mining and filling the mined areas with caved material (Figure 4). The sequence involved, mine out the first block and cycle to equilibrium. Prior to mining the next block, the recently mined block is filled with caved material and then cycle to equilibrium, and so forth. All the crosscuts and other developments were fully excavated following the sequence of mining.



(a) (b)

Figure 4 (a) Section through crosscut 4080 in Printzsköld with monitoring on levels 996 and 1023 and (b) Section through crosscut 2780 in Printzsköld with monitoring on level 1080. Note that the crosscuts are 3D objects and not to section taken to show location of instrumentation

The simulation was divided into two parts. The first part involved mining the upper horizons prior to the period of monitoring which started in January 2019. The second part involved excavating in 3-month periods during the monitoring phase.

So, firstly the upper Printzsköld was mined and filled (grey volume in Figure 5a), which was done in two stages. Then the upper Alliansen was mined along with levels above 900 m in Printzsköld (green volume in F) and finally the blocks that were mined as of January 2019 excavated (purple volume in Figure 5a). From January 2019 to July 2020 the mining was conducted in three-monthly increments (see Figure 5b). After each excavation the model was run to equilibrium and then backfilled before the next excavation was done and so forth.

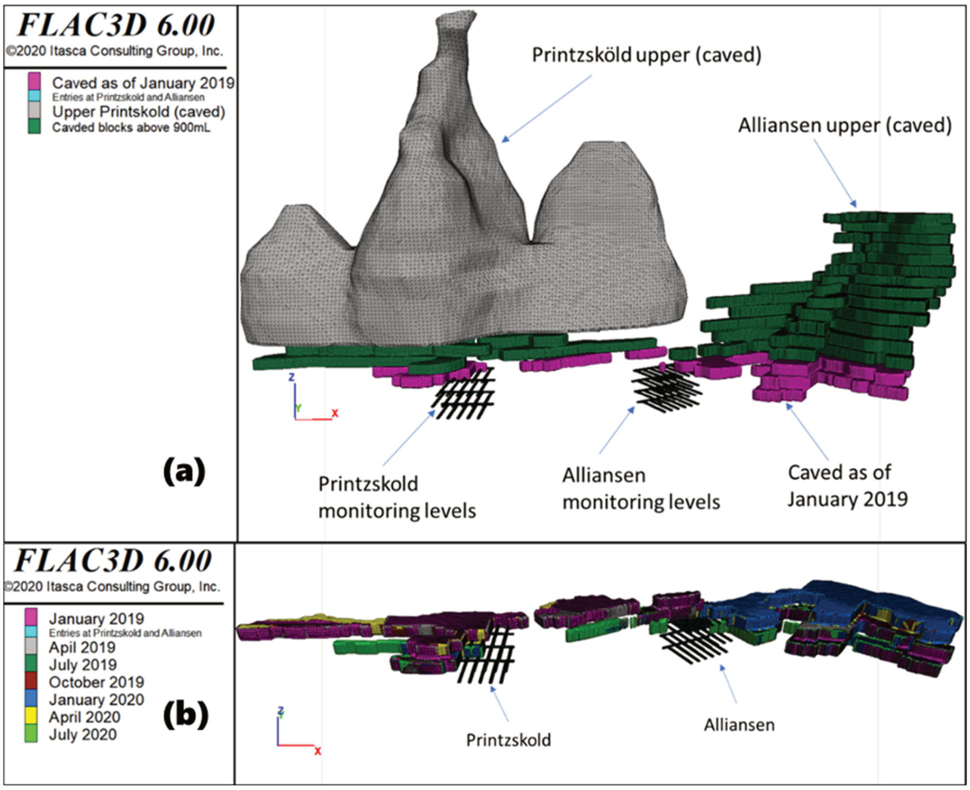


Figure 5 (a) Caving blocks for staged numerical excavation and (b) blocks for three-monthly excavation increments from January 2019 to July 2020

The Mohr–Coulomb model is applied to all the rock units, except for the biotite schist where the Mohr–Coulomb strain-softening model is utilised.

3.6 Numerical measurement points

Figure 6 shows the history points where the stress and displacements were monitored. They correspond to the location of the Digital Hollow Inclusion HID cells and Multi-Point Bore-Hole Extensometers (MPBX), which monitored the stress changes and displacements respectively. The numerical measurement points were located at least 1.5 m behind surface, which corresponded to anchor number 2 on the MPBX. A total of 53 history points were located in both areas (Printzsköld and Alliansen) to track the histories of stresses and displacements throughout the various stages of the mining during monitoring period.

The specific monitoring areas were (Figure 6):

- Printzsköld on level 1023, crosscut 1048 and level 996, crosscut 4090.
- Alliansen on level 1082, crosscut 2800 and level 1082, crosscut 2780.

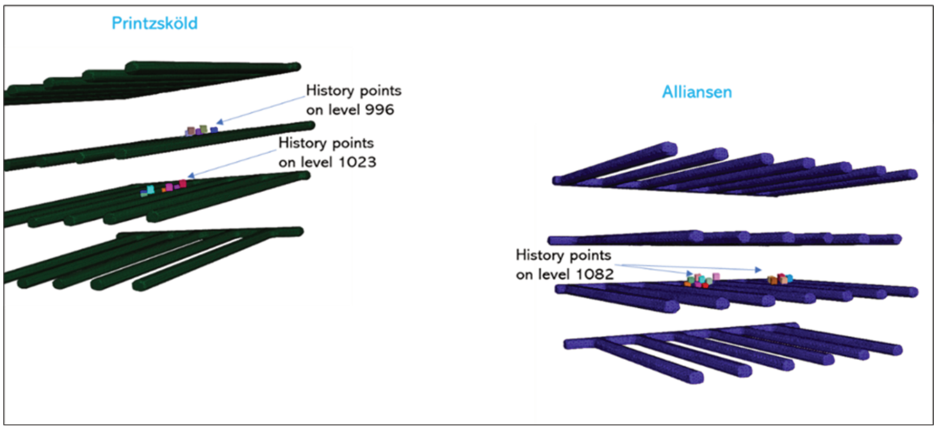


Figure 6 Location of history points in the *FLAC3D* model, which correspond to the locations of the HID stress cells and MPBX, in Printzsköld and Alliansen orebodies

3.7 Model calibration

The first step in model calibration was using the standard inputs and comparing the numerical modelling outputs against the measured data. The results of the standard model did not match all the results measured in both orebodies. Even more so the results in the same crosscuts but in different geologies did not match well. Hence, a series of models were run with following cases to try and get results that were closer to the observation:

- Test constitutive models, namely Mohr–Coulomb and Mohr–Coulomb strain-softening for biotite, since biotite has been known to be the most highly deforming lithology and observed to be time dependent. Creep test has been performed on biotite as part of the work and the results show very little indication of creep.
- Varying the disturbance factor, D, from ranges of 0 to 1. Since intact rock parameters were obtained from laboratory testing, these were not varied. The rock mass parameter, namely RMR-89, for different rock types was obtained from Malmberget mine’s rock mass models.

The model calibrations led to following conclusions:

- The biotite was best simulated using the Mohr–Coulomb strain-softening model.
- Inputs obtained applying a disturbance factor 0.8 resulted in outputs that were closer to the observations.

- It was not possible to calibrate the model for each measured observation, as it would mean tweaking input parameters with unrealistic values.
- Calibration against measured displacement did not yield the same outcome for the measured stresses or vice versa.
- However, the stress observation in biotite presented a case considered to be reliable for model calibration.

As noted above, the HID measured stress in the biotite showed results that were somewhat consistent in behaviour in both Printzsköld and Alliansen (Figures 7 and 8). In Printzsköld a constant stress of ~20 MPa is attained by March 2019 after monitoring began in January 2019. In Alliansen a constant stress of ~50 MPa is attained by March 2020 after monitoring began in March 2019.

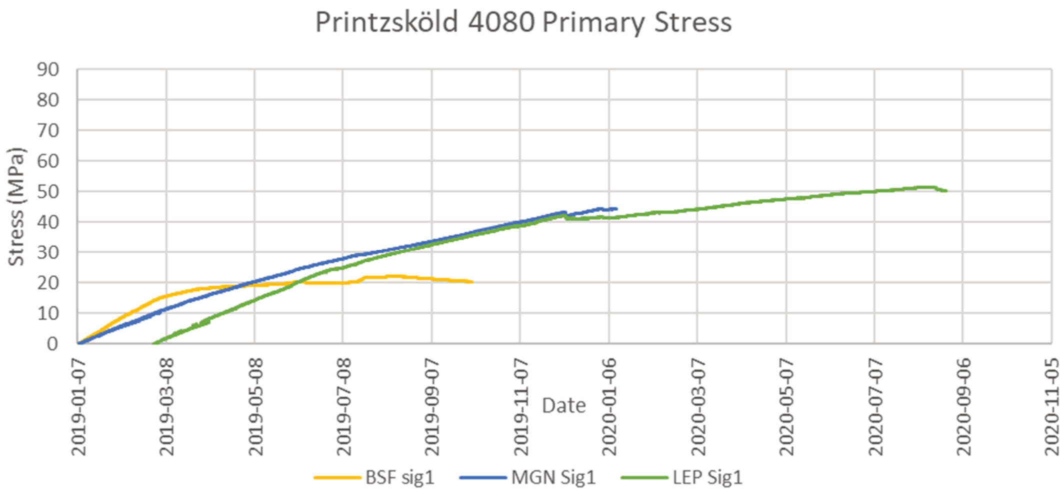


Figure 7 Sigma 1 magnitudes measured in biotite (BSF), magnetite (MGN) and leptite (LEP) in Printzsköld on crosscut 4080

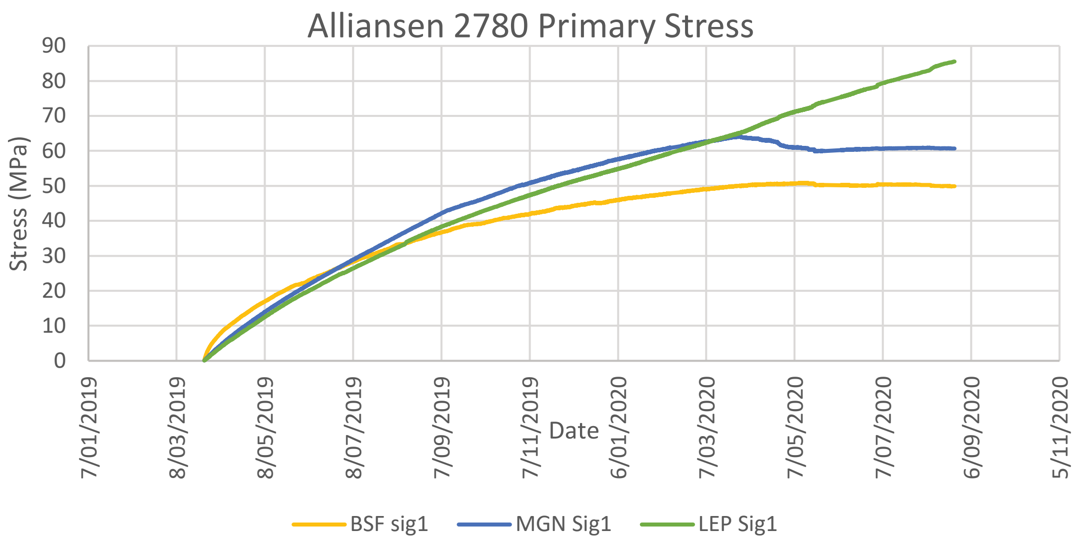


Figure 8 Sigma 1 magnitudes (σ_1) measured in biotite (BSF), magnetite (MGN) and leptite (LEP) in Alliansen on crosscut 2780

Hence, for model calibration the biotite stress results from Printzsköld were used. Figure 9a shows the results from uncalibrated model and Figure 9b shows the results from the calibrated model. The calibrated model stress is about 25 MPa, a significant improvement uncalibrated model which was about 32 MPa. Similar observations are made for stresses in leptite and magnetite for uncalibrated and calibrated cases.

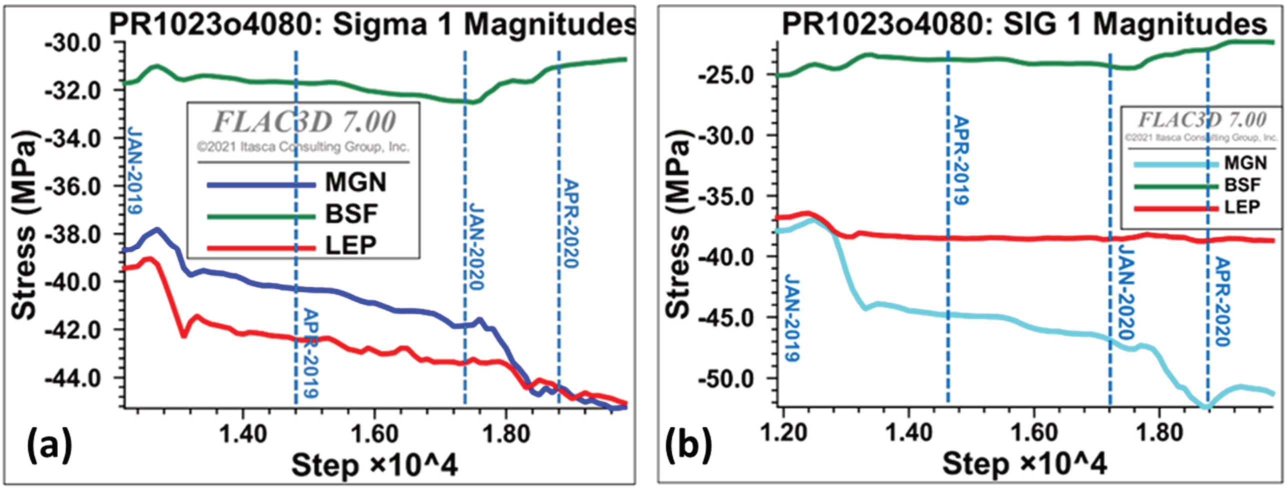


Figure 9 **Modelled σ₁ magnitudes in biotite (BSF), magnetite (MGN) and leptite (LEP) in Printzsköld on crosscut 4080, (a) is the uncalibrated case and (b) is the calibrated case**

4 Results

4.1 Stress behaviour

The behaviour of the maximum principal stress (σ_1), tracked during the monitoring period January 2019 to July 2020, are shown in Figure 10a for Printzsköld and Figure 10b for Alliansen. The negative values imply that the stresses are compressive. The high negative value means high compressive stress and low negative value means low compressive stress.

In Printzsköld, the maximum principal stress (σ_1) did not vary significantly in biotite schist (BSF) and Leptite (LEP). But in magnetite (MGN), maximum principal stress (σ_1) increased. This is confirmed with monitoring data which shows σ_1 increasing to about 45 MPa in January 2020 (Jones & Saiang 2022a) in MGN. In biotite, the HID measured stress reached about 20 MPa in March 2019 and remained constant until terminated in November 2019. In the leptite, the stress reached about 50 MPa.

In Alliansen, the maximum principal stresses (σ_1) were decreasing constantly during the monitoring period in all the rock units. This is anticipated, as Alliansen is advancing at least 1 to 2 levels (25 to 50 m) ahead of Printzsköld. Therefore, as mining approaches the monitoring level in Alliansen, the stress should decrease as destressing would occur. However, the HID stress measurement shows continuous stress increase, which is expected since the HID cells were measuring relative stresses, that is, from zero from the time of installation. That means the values would increase until the stress no longer changes.

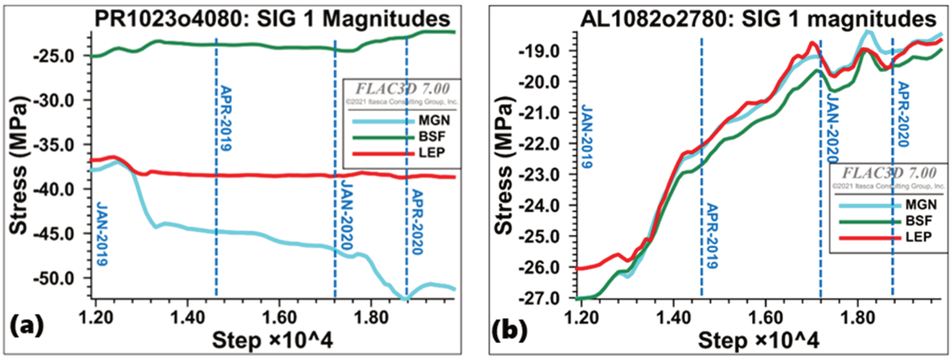


Figure 10 Behaviour of the maximum principal stress (σ_1) in (a) Printzsköld and (b) Alliansen. The results are from the monitoring period January 2019 to April 2020

4.2 Displacements

Figure 11 shows the cumulative displacements measured in crosscut 4080 on level 1023 in Printzsköld (PR1023o4080) and Figure 12 shows the cumulative displacements measured in crosscut 2780 on level 1082 in Alliansen (AL2780o1082). The measurements were taken in the roof, the shoulder and wall and coincided with locations of the MPBX anchor #2.

During the monitoring period (January 2019 to July 2020) the displacements in Printzsköld continued to increase in a stepwise manner. In Printzsköld, the stepwise behaviour is more pronounced than in Alliansen. The sharp increases in the displacements are associated with periods where most SLC rings were blasted. Displacements in Alliansen increased constantly during the monitoring.

The displacements recorded by the MPXs in these locations are much less, in fact ten times lower in the points where the numerical measurements were taken.

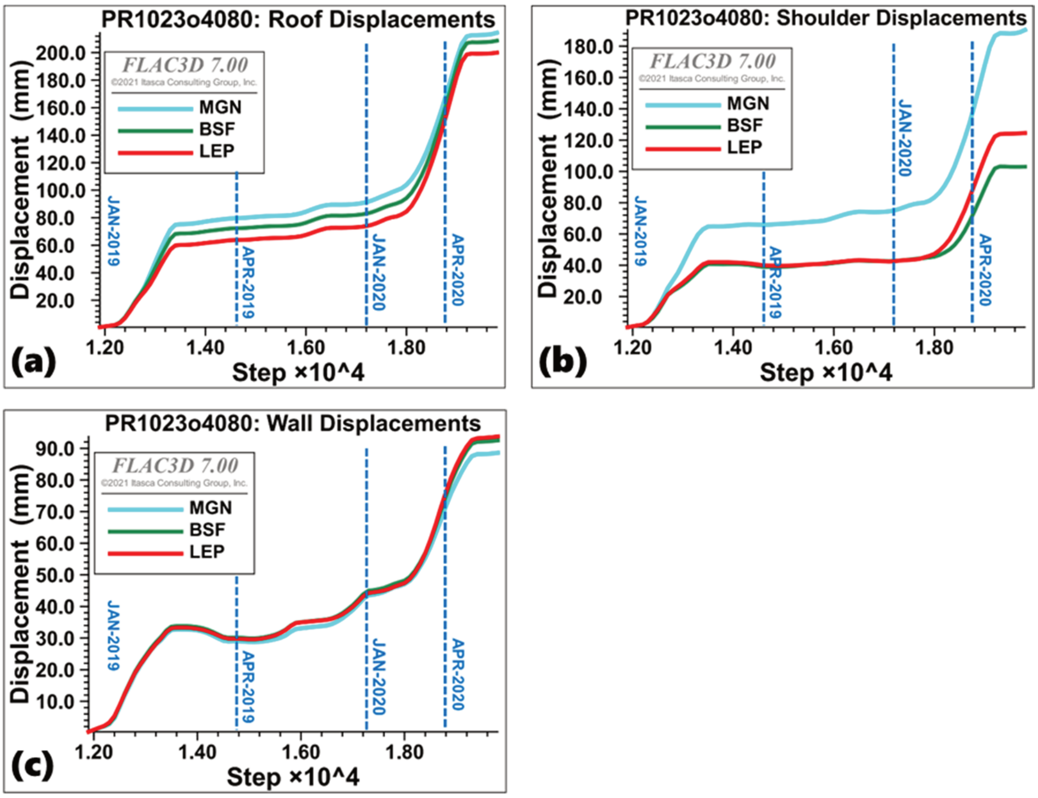


Figure 11 Displacements in Printzsköld at crosscut 4080 on level 1023 from January 2019 to July 2020 in (a) roof, (b) shoulder and (c) wall, with strain softening of biotite

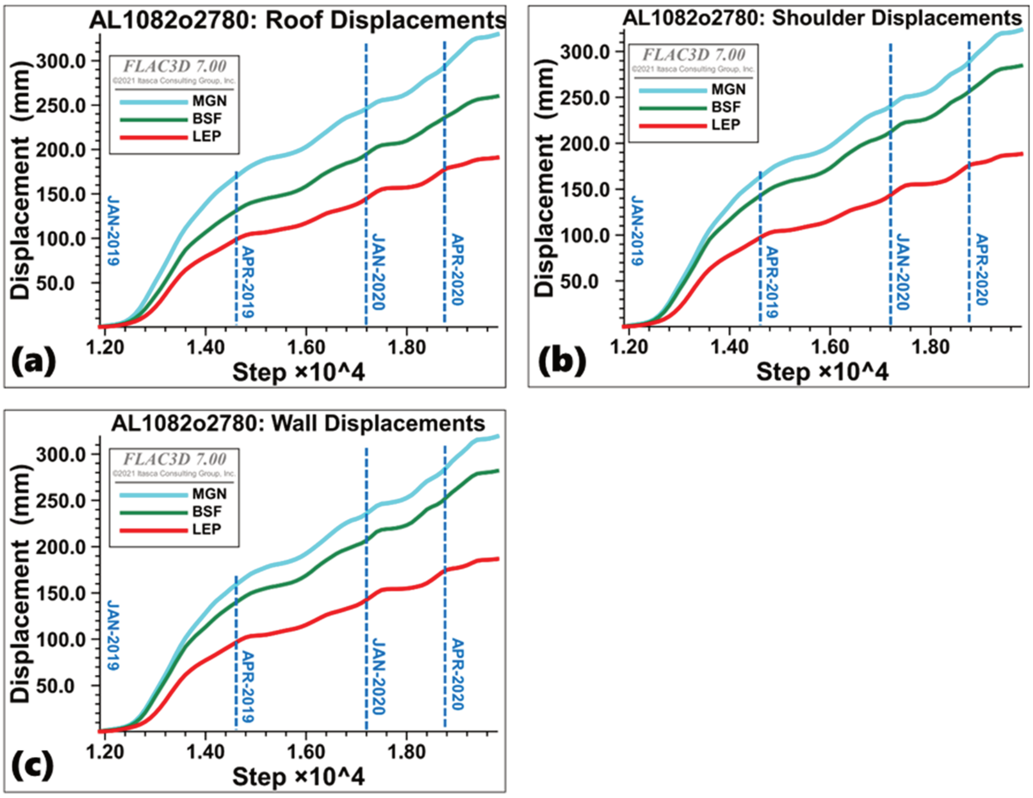


Figure 12 Displacements in Alliansen at crosscut 2780 on level 1082 from January 2019 to July 2020 in (a) roof, (b) shoulder and (c) wall, with strain softening of biotite

4.3 Regional influence

Figure 13 shows the scale of regional disturbance resulting from mining on level 870 in Printzsköld before monitoring began on level 1023. It implies that the monitoring was likely conducted in disturbed rock mass. The displacement contours extend beyond level 1023, the monitoring level.

The confining stress (σ_3) is also notably affected at least 2 levels below level 870, i.e. approximately 50 m. Between 50 and 100 m (or roughly 3 to 4 levels below level 870) the stresses are moderately affected. And between 100 and 150 m the stresses are minimally affected or gradually returning to in situ stress conditions. Beyond 150 m they are close to or equal to the in situ stress conditions. This meant that the monitoring was conducted in the disturbed ground.

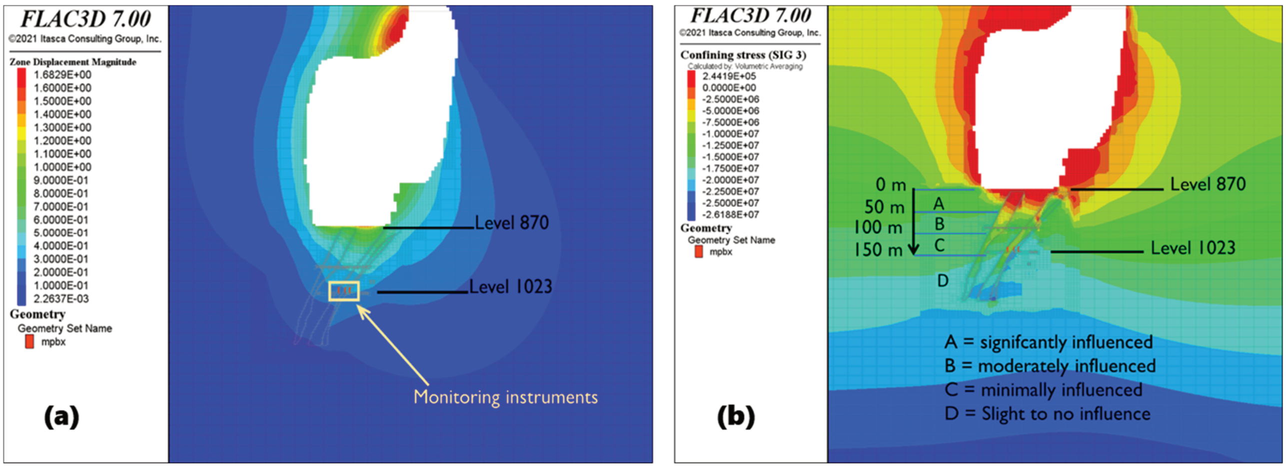


Figure 13 (a) Displacements resulting from mining on level 870 and above in Printzsköld (b) Status of the confining stress (σ_3) with mining occurring above level 870 m in Printzsköld

5 Discussion and conclusion

It was not possible to obtain a model that is universally calibrated based on the measured results combined. The HID measured stresses in biotite appear to show consistency in both Printzsköld and Alliansen and were therefore used as the basis for model calibration. The calibrated model is then used to simulate the observations. The results obtained are reasonable considering the complexity of the geology, the mining environment and success of the measurements. Since the numerical models were based on absolute stresses the execution of models was done following mining sequences in order to arrive at the stress levels being monitored by the HID stress cells which are relative to the time of installation. The HID measured stress and FLAC3D modelled stresses deviated by about 5 to 10 MPa, which is again is reasonable considering the scale of mining at Malmberget.

The measured displacements were rather lower than the modelled displacements by about 5 to 10 times. Nevertheless, this is in the order of millimetres. The difference could be related to a number of reasons including the fact that rock supports were not installed in the FLAC3D model. Another reason is that in the FLAC3D model the displacements were monitored based on excavations happening on a quarterly basis, while the MPBXs started monitoring displacements on a daily basis from the time they were installed. It is also possible that much of the displacements may have already occurred before the installation of the MPBXs.

One of the main objectives of the FLAC3D modelling in this work was to compliment the empirical modelling in order to see how best to model and track stress changes and associated displacements during various mining stages. Another aim was to observe how the stresses and displacements behave in a single crosscut where different lithologies with different behaviours occur. The Malmberget mine often experiences room closures of up to 2 m in a single crosscut, even though the measurements in this work did not yield such observations.

It has also shown that while other lithological units were exhibiting the behaviour of Mohr–Coulomb material, the biotite on the one hand was exhibiting a strain-softening behaviour. This distinct behaviour has been responsible for much of the stress dependent deformation observed in biotite at the Malmberget mine.

With regards to future investigation the monitoring should be conducted in undisturbed ground, so that any correlation and calibration of stresses can be based on in situ stress values. This means conducting measurements at least four to five levels below active mining horizon in the case of Malmbegert mine.

Acknowledgement

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