Seismic tomography as an instrument for structural evaluation in the Printzsköld and Alliansen ore bodies, Malmberget

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Abstract

The Malmberget deposit is one of the major apatite iron ores in Europe, located in northern Norrbotten. As the mining in Malmberget proceeds deeper more challenges with the stability have been faced. When the stress distribution of a rock mass exceeds the rock strength energy in form of seismic waves is released. In Malmberget, a monitoring system consisting of 200 geophones is installed which detects all seismic waves in the area. Based on data received from the monitoring system, LKAB has achieved to generate a seismic tomography model over the velocity variations of the seismic waves as they propagate in the rock mass.

The present study evaluates how the seismic tomography model can be used as a tool for reconstructing the structural characteristics of the two ore bodies Printzsköld and Alliansen. The aim is to clarify how seismic tomography can be combined with structural data to increase the geological knowledge of the Malmberget mining area.

Based on structural measurements from the mine in combination with geotechnical data (RQD, Jr, Ja) two structural geological models were constructed. One model visualizing the orientation of the foliation and the other presenting brittle joints and fractures. The models were constructed in order to compare them with the seismic tomography model to outline structures and characteristics in the rock mass.

The foliation in Printzsköld has a steep NE-SW orientation. In the eastern part where Printzsköld connects to Alliansen, the orientation changes to NW-SE, indicative of a fold structure. The joints and fractures in the study area appeared as 4 sets. One set appeared parallel to the foliation and one perpendicular to it. The two other sets were oriented E-W almost perpendicular to each other with a shallow dip. The rock quality in Printzsköld shows a pattern of increasing quality deeper down with zones of lower quality following the magnetite ore body. The previous identified deformation zone DZ031 appear as an important structure for unstable zones in Printzsköld.

The current results suggest that the seismic tomography model needs more investigation but shows promising results as an indicative instrument delineating large scale structures and large zones with lower rock quality.
Sammanfattning


I studien granskas hur den seismiska tomografin kan användas som ett verktyg för att utvärdera geologiska strukturer i de två malmkropparna Printzsköld och Alliansen. Syftet är att klargöra om seismisk tomografi kan kombineras med strukturdata för att öka den geologiska kunskapen i Malmbergets gruvområde.

På basis av mätta strukturer i gruven i kombination med geoteknisk data (RQD, Ji, Jα) konstruerades två strukturgeologiska modeller i syfte att jämföra modellerna mot den seismiska tomografin.


Utvärderandet av resultaten tyder på att den seismiska tomografin behöver fortsatt mer undersökningsarbete men visar lovande resultat av att fungera som ett vägledande instrument för att definiera storskaliga strukturer och större områden med sämre bergskvalité.
Acknowledgements

This master thesis is the final part of my Master´s degree in Civil Engineering in Natural Resources with specialization in ore and minerals. The Master´s degree corresponds to 30 credits and has been carried out at LKAB in Malmberget and the department of Civil, Environmental and Natural resources engineering at Luleå University of technology.

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Linus Jonsson
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{is}$</td>
<td>Arrival time for s-wave</td>
</tr>
<tr>
<td>$t_{ip}$</td>
<td>Arrival time for p-wave</td>
</tr>
<tr>
<td>$E$</td>
<td>Young’s modulus</td>
</tr>
<tr>
<td>$v$</td>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Rock density</td>
</tr>
<tr>
<td>$z$</td>
<td>Depth below ground surface</td>
</tr>
<tr>
<td>$V_p$</td>
<td>Velocity of the p-wave</td>
</tr>
<tr>
<td>$V_s$</td>
<td>Velocity of the s-wave</td>
</tr>
<tr>
<td>$D_i$</td>
<td>Distance to geophone</td>
</tr>
<tr>
<td>$m_L$</td>
<td>Local magnitude</td>
</tr>
<tr>
<td>$M_0$</td>
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<tr>
<td>$G$</td>
<td>Shear modulus</td>
</tr>
<tr>
<td>$A$</td>
<td>Area</td>
</tr>
<tr>
<td>$D$</td>
<td>Average shear displacement</td>
</tr>
<tr>
<td>$W$</td>
<td>Weighting factor in Terzaghi weight</td>
</tr>
<tr>
<td>$J_r$</td>
<td>Joint roughness</td>
</tr>
<tr>
<td>$J_a$</td>
<td>Joint alteration</td>
</tr>
</tbody>
</table>
1. **Introduction**

1.1. **Background**

The northern Norrbotten mining district hosts several of the most important ore deposits in Europe. In the region both Europe’s largest and second largest underground mines are located, the Kiirunavaara and Malmberget apatite iron ore deposits as well as the biggest open pit operation in northern Europe, the Aitik Cu-Au-Ag-(Mo) deposit (Figure 1). The deposits in northern Norrbotten are related to Paleoproterozoic volcanic successions consisting of porphyries, greenstones and clastic metasediments intruded by several generations of granites and pegmatites (Bergman et al., 2001). The area has experienced extensive hydrothermal alteration and has been affected by at least two events of deformation (Bergman et al., 2001; Wanhainen et al., 2012).

![Figure 1. Simplified map of the Gällivare area with the Nautanen Deformation Zone (NDZ) in the east and the Fjallasen-Allavaara Deformation Zone (FADZ) in the west (Bauer et al., under review).](image-url)
The Malmberget ore field is approximately 5 km long and 2 km wide. It is owned by the company LKAB (Luossavaara Kiirunavaara Aktiebolag) and the total mineral reserve at Malmberget is estimated to 346 Mt with 42.5 % Fe (LKAB, 2015). The underground production is currently concentrated to about ten of the twenty ore bodies including Printzsköld and Alliansen which are among the largest ones (LKAB, 2015).


In Malmberget the mining method sublevel caving is used which causes cavities to form around the orebody. As the mining proceeds deeper down more seismic events have occurred and more challenges with the stability have been faced. This could be a result of geological structures in combination with more stress redistribution in the rock mass which can lead to stress controlled rock bursts and/or movements along fracture planes (Larsson, 2015). When these events occur a sudden release of energy from the stored potential energy in the rock is emitted as seismic energy waves. The seismic waves are recorded by a monitoring system constituting of about 200 geophones placed on different ground levels and around the Malmberget area creating a connected 3D network (Wettainen, 2010; Andersson, 2013). Based on the data collected from the geophones it is possible to calculate the position where the energy release occurred and the velocity of the wave (Larsson, 2005).

The system has been active since August 2015 and collecting data from micro seismic events generated in the mine. From the information, LKAB has achieved to create a tomographic model over the velocity variations of the seismic waves. Tomographic models have successfully been used in other studies to model structures (Rawlinson et al., 2010) and it will serve as a support for the structural modelling in this study.

This project was initiated by LKAB to get a better control on brittle structures that contribute to instability in the Malmberget mining area of Printzsköld and Alliansen. In addition, the seismic tomography will serve as a basis for evaluation on how it can be used for geological interpretations.
1.2. Aim and objective of the thesis

The objective of this thesis is to create a robust structural geological 3D model over the major geological structures in the two ore bodies Printzsköld and Alliansen. The model will be built in the 3D modelling software Leapfrog Geo and should be based on structural geological data in combination with lithological, seismic and rock mechanic data. This independent model will then be evaluated against the seismic tomography model to identify incompetent rocks or deformation zones.

The target area, the Alliansen and Printzsköld ore bodies, was chosen because of the complications experienced with stability there. Both ore bodies have been closed several times due to high seismic activity and as the mining proceeds deeper there is an increasing demand on understanding the origin of the seismic activity there. This study focuses on evaluating and defining structures from seismic tomography as support for the model.

Furthermore, this thesis will serve as an introductive work for LKAB to gain better understanding of how seismic tomography can be combined with structural data to increase the geological knowledge of the Malmberget area. The results of this study indicate that seismic tomography has the potential to act as an integrated tool in the mine planning process.
2. Geological setting

2.1. Regional geology

The geology in Northern Sweden, as seen today, is the outcome of a complex geological evolution affected by subduction processes, rifting events, repeated arc collision events and metamorphism (Bergman et al., 2011; Martinsson, 2004; Lahtinen et al., 2005; Weihed, 2005; Martinsson, 2016). The basement rocks of the northern Norrbotten area are characterized by a sequence of Archean (>2.5 Ga) tonalitic to granodioritic rocks outcropping in the northernmost areas. The basement rocks formed at approx. 2.83 Ga and were subject of metamorphism and recrystallization around 2.7 Ga (Bergman et al., 2001; Martinsson, 1999, 2004). The Archean basement is discordantly overlain by a cover of 2.5 to 2.0 Ga Karelian and c. 1.9 Ga Svecofennian units (Figure 2). The stratigraphic lowest unit of the Karelian rocks is the Kovo Group, comprising quartzites and conglomerates followed by andesitic volcanic rocks and volcaniclastic deposits (Bergman et al., 2001; Martinsson, 1999, 2004). This layer is covered by a 2 to 4 km thick unit of tuffites, basalts and chemical sedimentary rocks that form the Kiruna Greenstone Group. The Kiruna Greenstone group is overlain by Svecofennian supracrustal rocks which are divided into two separate groups based on their chemical composition (Martinsson and Perdahl, 1995; Bergman et al., 2001; Martinsson, 2004):

The first group, the Porphyrite Group, comprises mainly metavolcanic rocks with calc-alkaline composition. They formed at 1.89 to 1.86 Ga and generally have low Ti- and Zr-contents (Bergman et al., 2001; Martinsson, 2004; Sarlus, 2016). According to Martinsson (2004) these calc-alkaline rocks have formed as a result of a north-east directed subduction in a compressional setting.

The second group, referred to as the Porphyry group, formed at 1.88 to 1.86 Ga and comprises of volcanic and volcaniclastic rocks with calc-alkaline to alkali-calcic character (Witschard, 1984; Bergman et al., 2001; Sarlus, 2016). The rocks of the Porphyry group contain generally high Ti and Zr which separates this group from the Porphyrite rocks (Bergman et al., 2001). The Porphyry group is regarded to have formed in a back-arc environment as the result of a continuous north-eastward subduction related to extension of a mature continental arc (Martinsson, 2004, 2016).

Intrusive rocks in the area formed mainly from two phases of intrusive activity (Sarlas, 2016). In the first phase, the Porphyrite Group was generated. Slightly later, the Perthite monzonite
suite (PMS) was formed co-genetically with the Haparanda suite. Both the Porphyrite and the PMS group are suggested to form in an extensional setting, probably in a back-arc environment (Sarlus, 2016). The Haparanda suite ranges from dioritic to granodioritic compositions and show almost identical ages with the PMS around 1.88 Ga (Sarlus, 2016). The PMS includes diorite, gabbro, syenitoids and granites with mainly syenitiodic compositions (Bergman et al., 2001).

The Hauki Quartzite represents the youngest Svecofennian unit and comprises mainly feldspar arenite in combination with sedimentary breccia and conglomerates closer to the base. The depositional environment is interpreted as small, tectonically active grabens (Bergman et al., 2001; Martinsson, 2004).

During late stage magmatism of the Svecofennian orogeny S-type magmas referred to as the Lina-type granite was generated, 1.81-1.78 Ga (Sarlus, 2016). According to Weihed (2002) the heat source that generated the Lina suite formed from an eastward subduction followed by a compressional event which resulted in a second deformation and metamorphic event in Northern Norrbotten. Lina granites are widespread in the Northern Norrbotten showing variation from granitic to pegmatitic in composition (Martinsson, 2004).

The Northern Norrbotten region is strongly metamorphosed and most of the rocks have been recrystallized and deformed during the Svecokarelian orogeny (Bergman et al., 2001). The metamorphic facies vary from upper greenschist to amphibolite and in general the metamorphic grade decreases from high in the east to low in the west (Bergman et al., 2001).
2.2. Local geology

The geology of the Gällivare area includes two major supracrustal units with rocks of volcanioclastic origin occurring in the eastern part whereas volcanic rocks of intermediate composition dominates to the west (Martinsson and Wanhainen, 2004; Martinsson et al., 2013; Lynch et al., 2015). The volcanic rocks have been intruded by multiple generations of igneous intrusives (Haparanda suite, PMS and Lina suite) and are overlain by arenitic sediments in the south-western parts (Bergman et al., 2001; Martinsson et al., 2013; Sarlus, 2016).

Both the Aitik and Nautanen deposits are hosted within a succession of volcano-sedimentary rocks associated within the Svecofennian rocks (Bergman et al., 2001). The Malmberget deposit is hosted within metavolcanic rocks belonging to the Kiirunavaara (Kiruna Porphyry) group (Martinsson et al., 2013). The character of the rocks varies from trachyandesitic to rhyolitic with occasionally basaltic intercalations (Martinsson et al., 2013). The primary textures are rarely preserved but amygdaloidal and porphyritic rocks have been identified (Geijer, 1930). The Aitik deposit is hosted within the Muorjevaara (Porhyrite) group. Minor
dioritic to granodioritic intrusions of the Haparanda suite are present and show a porphyritic, high-level intrusive character at Aitik (Wanhainen et al., 2012; Martinsson et al., 2013).

The Malmberget apatite iron ore field comprise about twenty different sized ore bodies (Figure 3). The ore bodies cover an area of five kilometers in west-east direction and two kilometers in the north-south direction (Geijer, 1930). The underground mining operations are currently concentrated to about ten of the orebodies (LKAB, 2015). The stock shaped, massive to semi-massive, magnetite ore bodies show minor occurrence of hematite and contain 51 to 61% Fe with varying content of phosphorus (<0.8%; Lund, 2013). The ore at the Malmberget deposit is considered similar to the Kiruna ore but it has experienced higher metamorphic overprint and ductile deformation (Bergman et al., 2001; Lund 2013; Lundh, 2014; Bauer et al., under review). The gangue minerals are mainly occurring as apatite, pyroxene, amphibole and biotite. The host rocks of the ore bodies are of volcanic origin and locally refered to as leptites. The volcanic rocks have a felsic to mafic composition and differ in color from red to grey (Geijer, 1930). Amygdules are sporadically occurring, indicating primary extrusive origin comparable to the Kiruna Porphyries (Martinsson et al., 2013). In the host rocks and the ore, granite and pegmatite dykes are commonly encountered (Debras, 2010). Some of the pegmatite dykes contain coarse-grained hematite together with apatite and titanite (Martinsson et al., 2013). Close to the iron ores breccias with high Fe-content are found which are spatially related to enrichment of K-feldspar and/or amphibole in the host rock (Debras, 2010; Martinsson et al., 2013; Bauer et al., under review). Due to the ductile deformation, the breccias are strongly flattened and the ore may appear as banded ore (Geijer, 1930).

The common alterations minerals are characterized by amphiboles, magnetite-apatite, biotite, K-feldspar, albitisation and biotite-chlorite associations (Bergman et al., 2001; Debras, 2010; Lund, 2013; Bauer et al., under review). The K-feldspar exist in both the hanging wall and foot wall and overprints the amphibole alteration (Debras, 2010). The biotite alteration occurs mainly in the metavolcanic rocks and form dominant biotite-rich shear zones (Kearney, 2016; Bauer et al., under review).
2.3. Local structures

The Gällivare area is bound by two crustal scale structures, the Nautanen Deformation Zone (NDZ) in the east and the Fjällåsen-Allavaara Deformation Zone (FADZ) in the west (Figure 1). This divides the area into specific structural domains (Lynch et al., 2015; Sarlus, 2016; Bauer et al., under review). The NDZ is characterized by ductile structures and hosts the Nautanen Cu-Au±Fe deposit (Bergman et al., 2001; Martinsson and Wanhainen, 2004; Lynch et al., 2015). Associated with these two NNW-SSE trending major structures are local high strain zones and second order structures (Bauer et al., under review). Related structures can also be observed in the two ultramafic-mafic intrusions, the Dundret and the Vasaravaara complex (Figure 1), found in the southern parts of the Gällivare area as rounded to sub-rounded formations (Martinsson et al., 2013; Sarlus, 2016).

At least two compressional events have deformed and metamorphosed the rocks in the Gällivare area under upper greenschist to amphibolite facies conditions (Wanhainen et al., 2012; Bauer et al., under review). The first compressive event at approx. 1.88 Ga (D1) produced a distinct penetrative foliation (S1) resulting from a NNE-directed shortening (Lynch et al., 2015; Sarlus, 2016; Bauer et al., under review). The S1 fabric forms the
dominating gneissic cleavage in the majority of the rocks and the ore bodies of Malmberget and can be seen in the orientations of biotites and amphiboles.

The second compressional event at approx. 1.80 Ga (D$_2$) was east-west directed but resulted in folding of the pre-existing S$_1$ foliation with localized spaced cleavage instead of generating a penetrative tectonic foliation (Lynch et al., 2015; Bauer et al., under review). The folding event also resulted in transposition of the Malmberget ore bodies into an open synform system with a SW-plunging fold axis. The Printzsköld ore body is located on the western limb of this synform whereas the Alliansen ore body is located in the fold hinge. The reason why D$_2$ did not produce any new foliations was suggested to result from upper-crustal, low pressure conditions (Bauer et al., under review). As a result of the low pressure and high temperature conditions during D$_2$, Bauer et al. (under review) suggests that brittle structures might have formed synchronously during folding. Additionally, a third deformation phase, (D$_3$) created brittle fractures and fissures that often occur as open cavities in varying scales.
2.4. The ore bodies

2.4.1 Printzsköld

The Printzsköld ore body is dominated by massive to semi massive magnetite with minor hematite and is situated between the eastern and western part of the Malmberget deposit (Figure 2). The tabular ore body strikes ENE and dips 70° to the SSE (Lund, 2013). The ore body is irregular but measure an average width of 50m with a length of 400m at the top where the mining started. On the production level 920m the body has extended and covers a width of 900m (Wettainen, 2010). A model of the ore body visualized in Leapfrog can be seen in Figure 4. Today the mining is conducted on a level of 996m.

![Figure 4. Screenshot from Leapfrog showing the Printzsköld ore body A) horizontal view and in B) top view.](image)

In 2007, a 3D model of the biotite-bearing zones in Printzsköld and Alliansen was constructed (Magnor and Jacobsson, 2007). The results indicate that the biotite zones are mainly following the foliation parallel to the ore but also occur inside the magnetite ore. The occurrence of biotite also seems to fade out to the west which could contribute to the reduced
incidents of stability problems in this part (Wettainen, 2010). The surrounding rocks in the area are primarily dominated by granites and grey- to red leptites.

2.4.2 Alliansen

The Alliansen ore body is folded into an open closed synform with an enveloping surface oriented ENE-WSW with a dip to the south (Magnor and Mattsson, 2010). The ore body appears thickened within the fold hinge and shows a distinct crenulation as a response to folding (Bauer et al., under review). The fold hinge at the ground level shows a distinct M-folding pattern (Geijer, 1930). The orebody is approximately 60m wide and 700m long (Figure 5). The mining is today conducted on a level of 1052 m.

![Figure 5. Screenshot from Leapfrog showing the Alliansen ore body A) horizontal view and in B) top view.](image)

2.5. Deformation zones

Magnor and Mattsson (2010) created a structural model of the geological deformation zones in Malmberget. It was based on new structural field mapping and geophysical measurements together with historic data. In the report, they include a description of every deformation zone identified in the Malmberget mining area. According to Magnor and Mattsson (2010) a deformation zone is defined as a linear structure in the bedrock caused by a geological deformation. It can be a ductile, brittle, cemented or an open structure.
The deformation zones (DZ) that have been identified in the vicinity of the Printzsköld and Alliansen ore bodies are presented in Table 1 and their spatial distribution in space is shown in Figure 6. An overview of the structures extrapolated to the surface can be seen in Figure 7.

![Deformation zones identified in close relation to the Printzsköld and Alliansen ore body by Magnor and Mattsson (2010) visualized in Leapfrog.](image)

*Figure 6. Deformation zones identified in close relation to the Printzsköld and Alliansen ore body by Magnor and Mattsson (2010) visualized in Leapfrog.*

<table>
<thead>
<tr>
<th>Name</th>
<th>Ore body</th>
<th>Strike [°]</th>
<th>Dip [°]</th>
<th>Probability of existence</th>
<th>Reliability of orientation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DZ031</td>
<td>Printzsköld</td>
<td>003</td>
<td>90</td>
<td>Medium</td>
<td>Medium</td>
<td>Brittle structure. Length 900 m, width 15 m</td>
</tr>
<tr>
<td>DZ032</td>
<td>Printzsköld</td>
<td>167</td>
<td>68</td>
<td>High</td>
<td>High</td>
<td>Brittle joint/zone. Length 500 m, width 5 m</td>
</tr>
<tr>
<td>DZ050</td>
<td>Printzsköld</td>
<td>315</td>
<td>70</td>
<td>High</td>
<td>High</td>
<td>Brittle structure. Length 400 m, width 5 m</td>
</tr>
<tr>
<td>DZ015</td>
<td>Alliansen</td>
<td>134</td>
<td>25</td>
<td>High</td>
<td>High</td>
<td>Fault associated with the foliation. Length 1200 m, width unknown</td>
</tr>
<tr>
<td>DZ033</td>
<td>Alliansen</td>
<td>195</td>
<td>88</td>
<td>High</td>
<td>High</td>
<td>Brittle structure. Length 1000 m, width 10 m</td>
</tr>
</tbody>
</table>

*Table 1. Description of the deformation zones in close relation to Printzsköld and Alliansen from Magnor and Mattsson (2010).*
2.6. Previous structural identification

Wettainen (2010) studied the deformation zones DZ031, DZ032 and DZ050 in detail. The structure DZ031 was identified by geological logging, geophysical methods and by seismic events and it responded clearly to be seismic active. In the vicinity, an increased number of seismic events were documented. The structure DZ032 did not give rise to any distinctive seismic character. The deformation zone DZ050 was located outside the mining area during their study and did not show any evidence of increased seismic activity (Wettainen, 2010).

2.7. Rock quality

To classify the rock quality, some parameters from the Q-system (Barton et al., 1974) have been used. Rock quality designation (RQD) is used to gain a better understanding of the rock quality (Bienlawski, 1979) and $J_r$ and $J_s$ to sort out natural cracks and joints from synthetic and to characterize the roughness and frictional characteristics of the joints. $J_r$ stands for joint

<table>
<thead>
<tr>
<th>DZ034</th>
<th>Alliansen</th>
<th>022</th>
<th>90</th>
<th>Medium</th>
<th>Medium</th>
<th>Unknown character. Length 200 m, width unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>DZ035</td>
<td>Alliansen</td>
<td>158</td>
<td>83</td>
<td>High</td>
<td>High</td>
<td>Brittle joints. Length 1200 m, width 10 m</td>
</tr>
<tr>
<td>DZ039</td>
<td>Alliansen</td>
<td>358</td>
<td>90</td>
<td>Medium</td>
<td>Medium</td>
<td>Unknown character. Length 400 m, width unknown</td>
</tr>
<tr>
<td>DZ052</td>
<td>Alliansen</td>
<td>330</td>
<td>90</td>
<td>Low</td>
<td>Medium</td>
<td>Brittle structure. Length 600 m, width 0.1 m</td>
</tr>
</tbody>
</table>

Figure 7. Deformation zones around Printzköld and Alliansen extrapolated to the surface (Magnor and Mattsson, 2010).
roughness and is determined on the roughness of the joints. J is a shortening of joint alteration and is based on the alteration grade as well as the character of the joint infill. See Appendix A for definition of RQD and classification of J and strain intensity.
3. **Mining seismology**

3.1. General theory

When a rock mass is fractured energy is released in form of seismic waves. During
deformation, a conversion from potential stored energy to elastic seismic energy occurs and
this conversation of energy drives the seismic process. The greater the energy conversion the
greater the energy transformed to seismic energy becomes (Shearer, 2009).

The seismic energy is mainly released in form of two types of body waves, p-waves and s-
waves (Figure 8 and 9). P-waves (also mentioned as longitudinal waves or pressure waves)
have the highest velocity of the two and therefore expand fastest from the source. The
velocity for the p-waves is generally in the interval of 5.5-6km/s for solid rocks (Shearer,
2009). The s-waves (also mentioned as transversal or shear waves) propagate slower than the
p-and have a velocity in the interval of 3.0-3.5 km/s (Shearer, 2009).

![Figure 8](image_url)  
*Figure 8. A p-wave where the particles moves parallel to the propagation direction (Shearer, 2009).*

![Figure 9](image_url)  
*Figure 9. An s-wave where the particles move perpendicular to the wave direction (Shearer, 2009).*

3.2. Positioning

To determine the position of a seismic event with reasonable accuracy, at least four
geophones at different levels need to record the occurrence (Wettainen, 2010; Andersson
The geophones record the arrival time of the s-wave and the p-wave (Figure 10) and the basic principle to locate the seismic event is to solve the system with four unknown parameters \((T_0, x, y, z)\) described by Martinsson (2012).

![Figure 10. Different arrivals times registered for the s-wave and p-wave propagated from the same source (Hudyma et al., 2003).](image)

3.3. Magnitude

The size of the seismic events is measured in the logarithmic Richter scale. The magnitude of the events is determined by the highest energy released (the ratio of the amplitude) of the seismic wave and a correction coefficient for the distance to the epicenter (Andersson, 2013).

In Malmberget a local magnitude scale is applied \(m_L\) and is calculated by (5).

\[
\begin{align*}
m_L &= A \cdot \log E + B \cdot \log M - C \\
E &= \text{the elastic energy transmitted from the seismic event and is proportional to the amplitude squared (Shearer, 2009).} \\
M &= \text{a measurement of the plastic deformation. The constants } A, B \text{ and } C \text{ are corrections coefficients for the distance and are in Malmberget defined as:} \\
A &= 0.272 \\
B &= 0.392 \\
C &= 4.630
\end{align*}
\]

\(E\) is the elastic energy transmitted from the seismic event and is proportional to the amplitude squared (Shearer, 2009). \(M\) is a measurement of the plastic deformation. The constants \(A, B\) and \(C\) are corrections coefficients for the distance and are in Malmberget defined as:

\[
\begin{align*}
A &= 0.272 \\
B &= 0.392 \\
C &= 4.630
\end{align*}
\]

\(M\) is the seismic moment and is given by (6).

\[
\begin{align*}
M_0 &= GD\ A \\
G &= \text{the shear modulus, } D \text{ is the average shear displacement and } A \text{ is the area affected by the seismic event (Larsson, 2015).}
\end{align*}
\]

Below is a table with descriptions on how different levels of magnitudes are felt in the mine, table 2.
Table 2. An approximation of how the magnitudes are felt in the mine (Larsson, 2005).

<table>
<thead>
<tr>
<th>(M_L)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.0</td>
<td>Significant ground shaking. Felt as good thumps or rumbles. Can be felt more distant from the source of the event (i.e., more than 100 meters away). Should be detectable by the seismic monitoring system.</td>
</tr>
<tr>
<td>-1.0</td>
<td>Is often felt by workers throughout the mine. Major ground shakings or air blasts. The vibration is felt like distant underground secondary blast.</td>
</tr>
<tr>
<td>0.0</td>
<td>The vibration and air blast can be felt and heard throughout the mine. Bumps is commonly felt on surface (hundreds of meters away) but may not be audible. The vibration can be felt on the surface.</td>
</tr>
<tr>
<td>1.0</td>
<td>Felt and heard very clearly on the surface. The vibration is felt on the surface is similar to a major production blast. It can be detected by regional seismological sensors located hundreds of kilometers away.</td>
</tr>
<tr>
<td>2.0</td>
<td>The vibration felt on the surface is greater than large production blasts.</td>
</tr>
</tbody>
</table>

3.4. Seismic tomography theory

The basics behind seismic tomographic imaging involves finding the solution of some physical parameter alongside a pathway throughout the medium a wave travels (McMechan, 1983). For instance, the accumulated travel time of a seismic ray emitted from a source to a receiver can be expressed as the integrated slowness along the distance. If the velocity variation in the medium is assumed to be small, all ray paths are estimated to straight lines. However, for mining induced seismic events the variations are large and paths are curved around voids, mined out parts and fracture zones. The straight-line assumption likewise realistic for homogenous mediums like disseminated deposits and deposits with little velocity variation.
The tomographic image of the area is created from iterative reconstruction of forward modeling. Forward modeling is used to generate artificial data of the identified material that is used in the evaluation of the inverse processing (McMechan, 1983). The character set used in both inverse and in the forward problems can be seen in Figure 11. The medium in Figure 11 comprise of nine discrete square elements in which the $i$:th element has constant slowness $s_i$ (=velocity$^{-1}$). Considering the seismic ray path AB consisting of three square segments; distance $d_1$ in slowness $s_7$, $d_2$ in $s_4$ and $d_3$ in $s_1$. The total travel time (TAB) can then be written as:

$$TAB = d_1 s_7 + d_2 s_4 + d_3 s_1$$  \hspace{1cm} (1)$$

This set of ray equations (x) can be expressed as a matrix.

$$Ds = T$$  \hspace{1cm} (2)$$

Figure 11. The character set used in inverse and forward problems. The area imaged are divided into square elements. In the $i$:th element, the value ($s$) of the parameter to be imaged is constant. Ray paths (AB, AC and AD) are each made up of adding series of segments regarded as $d_i$. Each ray segment traverses one model element (McMechan, 1983).

where $D$ is an $N \times M$ matrix comprised of distance increments $d_i$, $N$ is the total numbers of rays, $M$ is the total number of slowness in the region, $s$ is the vector of slowness (length $M$) and $T$ is the vector of travel times (length $N$). For the travel time of the three rays AB, AC and AD equation 2 is:
\[
\begin{bmatrix}
  d_3 & 0 & 0 & d_2 & 0 & 0 & d_1 & 0 & 0 \\
  0 & d_7 & d_8 & d_9 & d_8 & d_6 & 0 & d_4 & 0 \\
  0 & 0 & 0 & 0 & d_{11} & d_{12} & d_9 & d_{10} & 0
\end{bmatrix}
\times [s_1 s_2 s_3 s_4 s_5 s_6 s_7 s_8 s_9]^T = [TAB TAC TAD]^T
\]

where raised T is transpose.

When executing the forward computations, \( D \) and \( s \) are known parameters while the vector elements \( TXX \) have to be calculated. In executing the inverse, the value of \( D \) is known, \( TXX \) are observed and the value for \( s \) is computed (McMechan, 1983). As \( M \) and \( N \) can consist of very big sets of data making it both time consuming and requirement handling of large storage. An alternative option for this is to use an iterative method when solving for \( s \) as this method treats only one equation (one ray) at the time.

3.5. The impact of stress for the velocity in rocks

Rocks show a strong behavior of nonlinear stress-strain indication. This implies that residual or applied stress in the rocks affect the velocity of the wave significantly (Huang et al., 2001) and can be seen from figure 12.

![Figure 12. Experimental and theoretical results of the velocity of the compressional wave propagating in the X-direction against the normal stress in X-direction in the cycle ABCD (Huang et al., 2001).](image)
As a result of the mining proceeding deeper down, the rocks volumes are experiencing a higher degree of stress which can develop increased velocities for the waves propagating deeper in the ground.

In rocks, the changes in velocity are explicitly connected with stresses (Huang et al., 2001). Therefore, a change in stress could be considered as zones with changes in velocity. Areas with low velocity can by this indicate defect rocks or joints as these decrease stress in rock volumes (Huang et al., 2001).
4. Geological modeling

Implicit 3D modelling of the structures in combination with seismic, rock mechanic data and seismic tomography data have been carried out and visualized with the modeling program Leapfrog geo.

4.1. Leapfrog™ Geo software

Leapfrog Geo version 4.0 developed by the Applied Research Associated of New Zealand (ARANZ) was used to develop 3D models for this thesis. Leapfrog is an implicit 3D modelling software that allows the development of conceptual geological models from raw drill-core data (Cowan et al., 2002). The method allows handling of large data sets utilizing a rapid interpolation technique (Leapfrog, 2017).

To create surfaces from a discrete set of known data points implicit modelling uses an approximation to interpolate the gaps where there is no data (Cowan et al., 2002). Interpolation is a process to determine or produce an estimate of a quantity that is unknown from already obtained values. The more traditionally explicit modeling, involves more manual work constructing polylines and polygons to produce a surface (Cowan et al., 2002).

The interpolation method behind Leapfrogs implicit models is called FastRBF™ (Leapfrog, 2017). It combines linear and spheroidal interpolation to assign values weighted based on the distance from the chosen point that the estimate is computed for. The method is comparable to the variogram models used to perform kriging (Leapfrog, 2017). The linear interpolant values, closer to the computed point are more important than data far away. Additionally, the spherical interpolant also assign weighted values an importance based on their distance. But, as the values reach a defined distance called the “range” all values are assigned roughly the same importance no matter how far away they are from the point to be estimated (Leapfrog webpage, 2017).

4.2. Implicit modelling

An implicit model of a solid is based on the technique where the surface and volume is described as isovalues of a volumetric scalar field (Vollgger, 2015). The scalar field is generated with the help of a global interpolation function adjusted to data points (Figure 13a). The interpolation function creates a volumetric scalar field that connects every point in space to a scalar value (Figure 13b). From the isovalues in the scalar field isosurfaces can be generated which can be used to visualize 3D bodies of 2D lines (Figure 13c).
Figure 13. A 3D implicit modelling workflow with (a) various types of data spatially interpolated by an implicit function that defines a scalar field (b). From the scalar field, implicit surfaces can be generated (c). The surfaces can then be used to visualize lithological data, assay data and structural data (Völlgger, 2015).

As the models are implicit the surfaces are not constructed directly as with triangulation in explicit models. Explicit models rely on manual digitization and definition of geological boundaries to generate 3D bodies and surfaces while the implicit surfaces are instead a finite approximation of surfaces with infinite detail (Cowan et al., 2002).

4.3. Limitations

The calculations behind the RBF with linear weights are similar to dual kriging (Cowan et al., 2002). In situations where the variogram cannot be obtained like in sparse sampling situations or when interpolating across different domains the results from RBFs are almost identical with conventional kriging (Cowan et al., 2003). RBFs can therefore be used as a valuable technique for resource estimations in certain situations (Völlgger, 2015). Furthermore, in implicit models the spacing of data points is a limiting factor for the size of the objects and structures. It can be resolved in the implicit models but may result in not showing small-scale features.
5. Terzaghi weighting

Terzaghi weighting is a method that can be applied to rosette plots and contour plots to account for the sampling bias potentially introduced by collecting orientation data along traverses. When structural measurements are collected, a bias is initiated in favor of the structures and features which are oriented perpendicular to the surveying (Meller, 2012). An illustration of the theory can be seen in Figure 14 illustrating three joints identically spaced along a scanline.

Figure 14. Measurements along the scanline will favor joints of Set A more than Set C in a density contour plot. To compensate for this bias a weighting factor, W, is calculated and applied to each measurement (Rocscience webpage, 2017).

To calculate the geometric weighting factor, W, following method is used (Figure 15):
The Terzaghi weighting have been used on the structural measurements in the roof of the Printzsköld ore body to a depth of approximately 600 m to make sure no sets of structures were disregarded due to the direction of the drilling survey.

An effect of the weighting procedure can be seen in Appendix B. The results of the method did not show any structures masked by abundant structural data.
6. Methodology
This thesis is based on compiled existing data sampled by LKAB that includes drillhole data, seismic events and seismic tomography, geotechnical data and structural measurements. Additionally, structural data from Bauer et al. (under review) was incorporated. All data were imported into Leapfrog™ Geo v. 4.0.

6.1. Geological logging
A total of 20 047 structural measurements collected from earlier drillings from the 1000m level in the Printzsköld ore body was provided by LKAB. The structural measurements included geotechnical characterization of the cores involving RQD, strain intensity, and Q-system for rock mass classification. LKAB did also provide drill core data of 5 214 structures and geotechnical data in 23 boreholes from a drilling campaign in the roof of the Printzsköld ore body.

A total of approximately 340 structural measurements were carried out by Bauer et al. (under review) on the 500m, 590m, 900m, 980m, 1000m, 1020m and 1080m levels around and in the west of the Printzsköld ore body.

6.2. Development of the foliation model
In order to construct a foliation model, the first step was to create query filters. The filters were categorized to only include the foliation structures from the structural measurements. The filtered data was then interpolated using Leapfrogs tool “Form Interpolant” to build isosurfaces between the input data in the model. The resolution for the surfaces was set to 20 with a distance set at -1, -0.5, 0, 0.5 and 1 for the isosurfaces. The direction of the trend was set to Directions (0, 0, 90) with Ellipsoid Ratios (1, 1, 1). The model can be seen in Figure 17.

6.3. Development of the discontinuity model
To construct the model of brittle structures, query filters were created to sort out intervals with RQD-values less or equal to 25%. Since the intervals of low RQD did not contain any structural orientations due to the fractured rocks, 10 m was added to the beginning and the end of the RQD intervals to determine the dominating orientations in that sections. The orientation data was then plotted as poles to planes in lower hemisphere, equal area stereographic projections to evaluate the sets in that interval area. The dominating sets established from the stereographic projections were illustrated in Leapfrog as planar structures. From these planar structures meshes were created with the help of Leapfrog to visualize the direction of the
brittle plane passing through these structural orientations. The constructed planes can be seen in Figure 19.

6.4. Seismic events
Seismic data have been provided by LKAB, covering the time interval from 2010-01-01 to 2016-12-31. The seismic data consist of recordings of seismic events in the Malmberget area with a lowest magnitude of -3.2 to a highest of magnitude of 2.38. The seismic data have been evaluated in combination with the other data to find relations with the seismic tomography model.

6.5. Seismic tomography
Seismic tomography data from August 2015 to February 2017 gathered in the Malmberget area have been provided by LKAB. The data contains records of the velocities of the seismic waves that have travelled from the releasing source to the receiving sensor. Altogether, the data forms a pattern in the recording area of the velocity contrasts in the rock volumes. The recordings have been measured by 200 geophones distributed throughout the underground mine. The seismic events were grouped in clusters of 25x25x25 meter. To create a cluster, at least one seismic event must be recorded from that volume.
7. **Results**

7.1. **Structural geology**

7.1.1. **Ductile structures**

The tectonic foliation observed in the western part of Printzsköld shows the average an orientation of 170/65 (dip-direction/dip). Figure 16 shows a stereographic projection of the biotite foliations (FOL) and gneissic cleavages (MINFOL) measured in drill cores in the boreholes 7520-7551 (in blue) and 7812-7814, 7815B, 7816-7829, 7830C, 7831B, 7832-7834 (in green). The red data points are the structures from Bauer et al. (under review) from the 500m, 590m, 900m, 980m, 1000m, 1020m and 1080m levels around and west of the Printzsköld ore body.

![Figure 16. Lower hemisphere, equal area stereographic projection with poles to foliation measured in the Malmberget area.](image)

Based on the foliation measurements, a foliation model was constructed (Figure 17). The model shows that the strike of the foliation changes from NE in the west to SE in the east, indicative of a folding of the foliation. The Printzsköld ore body is situated in the western part of the model whereas the Alliansen ore body is situated in the eastern parts where the foliation starts to fold.
7.1.2. Brittle structures

Figure 18 shows a stereographic representation of joints and fractures. The structures plotted in green color have been measured in drill core numbers 7521-7551. The orientations marked with blue are from brittle structures in boreholes 7812-7814, 7815B, 7816-7829, 7830C, 7831B and 7832-7834 and the structures in brown are measurements from the 500m, 590m, 900m, 980m, 1000m, 1020m and 1080m levels.

Figure 19 shows the discontinuity model based on low RQD intervals and structural measurements. The model show the four interpret planes, A (pink), B (green), C (grey) and D
The planes correlate with the dominating structural direction seen in Figure 18. The structures that control the low RQD intervals are shown in Figure 20-23 as great circles in red.

Figure 19. The constructed planes A, B, C and D with the structural measurements in green, yellow or red depending on their level of reliability. A) View to north. Figure B) View to east showing a cross-section of the planes.

Figure 20. Lower hemisphere, equal area stereographic projection of structures that correlate with plan A. The red plane illustrates the direction of plane A. Measurements for each interval: 7816 n=52, 7821 n=4, 7824 n=28, 7818 n=44, 7823 n=10, 7828 n=18, 7830C n=2, 7832 n=22, 7812 n=13.
Plane A has an approximate orientation of 190/40 and is located in the roof above the Printzsköld ore body.

Plane B (Figure 21) from the discontinuity model with an average orientation of 010/20.

Plane C with an average direction of 150/80 located in the roof above the orebody Printzsköld.
Figure 23. Lower hemisphere, equal area stereographic projection of structures that correlate with plane D. The red plane demonstrates the created plane D. Number of measurements from each interval; 7524 n=63, 7526 n=27, 7528 n=7, 7529 n=4, 7530 n=38, 7535 n=42, 7541 n=131, 7548 n=49, 7549 n=85, 7551 n=24.

Plane D in the discontinuity model based on a drilling campaign from the 1000m level (Figure 23). Plane D dips 70 degrees towards 160.

A table of characteristics of the structures used for creation of the planes in the discontinuity model was compiled (Appendix C). To evaluate the uncertainty of the planes, a reliability number (1-3) was assigned to each structure; number of sub-parallel structures, $J_r$-values, $J_a$-values, $J_r/J_a$-ratio, approximate dip estimated from core photos (Appendix D) and mineral alteration. The classification for each category can be seen in Table 3.
Table 3. Uncertainty classification for the brittle structures. The total sum gives an indication of the uncertainty of the structure. 3 (green) = Highest level of reliability, 2 (yellow) = medium reliability, 1 (red) = low reliability.

<table>
<thead>
<tr>
<th>Classification</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-parallel structures</td>
<td>0 to 2</td>
<td>3 to 5</td>
<td>≥6</td>
</tr>
<tr>
<td>(J_r)-value</td>
<td>≥3</td>
<td>2</td>
<td>≤1.5</td>
</tr>
<tr>
<td>(J_s)-value</td>
<td>≤2</td>
<td>3</td>
<td>≥4</td>
</tr>
<tr>
<td>(J_r/J_s)</td>
<td>≥1</td>
<td>0.51 to 0.99</td>
<td>≤0.5</td>
</tr>
<tr>
<td>Mineral infill</td>
<td>Unaltered, skarn, epidote or calcite with medium to low intensity</td>
<td>Skarn, magnetite or calcite infill with high intensity</td>
<td>Biotite, chlorite, anhydrite or clay infill with any level of intensity</td>
</tr>
<tr>
<td>Approx. dip from core photos</td>
<td>Differ by ≥ 30°</td>
<td>Differ by 11–20°</td>
<td>Differ by ≤10°</td>
</tr>
<tr>
<td>Total sum</td>
<td>6 to 9</td>
<td>10 to 14</td>
<td>15 to 18</td>
</tr>
</tbody>
</table>

The overall rock quality in Printzsköld is very high with and average RQD of 90.4%. The small regions with low rock quality (RQD ≤ 25%) mainly occur in the roof above the Printzsköld orebody at a depth of 100-600m. The zones with RQD less than 25% appear to be decreasing as the quality of the rock generally gets better deeper down.

7.2. The seismic tomography

Figure 24-30 show the seismic tomography model on several Z-levels within the study area. Plane A, B and C from the discontinuity model (Figure 19) have been investigated to find probable correlations with the variation in velocity.

For the Z-levels between 300-600m, a scale of Lower=5400 km/s and Upper=5800 km/s was used. The general velocity increases with depth so in order to enhance the variation in the velocity at the 1000-1200m levels the scale was narrowed down to Lower=5700 km/s and Upper=6000 km/s.
Figure 24. The seismic tomography model from a horizontal view at the 301-m level. The black volumes are mined out parts and cavities. The red planes are deformation zones (Magnor and Mattsson, 2010). The planes in pink (A), light green (B) and grey (C) are the discontinuity model.

Figure 25. The tomography model at the 401m level. The black volumes are mined out parts and cavities. The red planes are deformation zones (Magnor and Mattsson, 2010). The planes in pink (A), light green (B) and grey (C) are the discontinuity model.
Figure 26. The tomography model at the 501m level. The black volumes are mined out parts and cavities. The red planes are deformation zones (Magnor and Mattsson, 2010). The plane in pink (A) and grey (C) are the discontinuity model.

Figure 27. The tomography model at the 601m level. The black volumes are mined out parts and cavities. The red planes are deformation zones (Magnor and Mattsson, 2010).
Figure 28. The seismic tomography at a level of 1001m. The white (PZ) and grey (AL) volumes represents the Printzsköld and Alliansen ore bodies. The yellow plane is the discontinuity model. The purple circles are intervals of RQD (≤25%). The black volumes are mined out parts and cavities.

Figure 29. The seismic tomography at a level of 1101m. The white (PZ) and grey (AL) volumes represents the Printzsköld and Alliansen ore bodies. The yellow plane is the discontinuity model. The purple circles are intervals of RQD (≤25%). The black volumes are mined out parts and cavities.
Figure 30. The seismic tomography at a level of 1201m. The white (PZ) and grey (AL) volumes represent the Printzsköld and Alliansen ore bodies. The yellow plane is the discontinuity model. The purple circles are intervals of RQD (≤25%).

Figure 31-33 shows a vertical cross-section of the seismic tomography model on different sections.

Figure 31. The seismic tomography model from a vertical cross-section at x=951 looking to the northeast. The red planes are deformation zones (Magnor and Mattsson, 2010). The planes in pink (A), light green (B) and grey (C) are the planes from the discontinuity model. The black hollow area is the cavity above the Printzsköld ore body. The white volume is the ore body of Printzsköld.
Figure 32. The seismic tomography model from a vertical cross-section at x=1051 looking to the northeast. The red planes are deformation zones (Magnor and Mattsson, 2010). The planes in pink (A), light green (B) and grey (C) are the planes from the discontinuity model. The black hollow area is the cavity above the Printzsköld ore body. The white volume is the ore body of Printzsköld.

Figure 33. The tomography model from a vertical cross-section at x=1401 looking to the east. The red planes represent intervals of RQD (≤25%). Grey planes are intervals with Jr≤1.5 and Ja≥4. The blue volume is the ore body of Printzsköld.

Figure 34 show how the lower rock quality (RQD≤ 50) appear to follow the ore body of Printzsköld and Alliansen.
Figure 34. The ore bodies of Printzköld and Alliansen together with RQD intervals ($\leq 50\%$) in yellow and plane D in blue. A) Top view. B) Is taken with a view toward the north.
8. Discussion

8.1. The structural models

The obtained structural model is comparable to the overall synformal structure (e.g. Bauer et al., under review). The orientation of the foliation is trending NE in the western part of the Printzsköld ore body, whereas, in the east part, comprising the Alliansen ore body, folding of the foliation can be observed in both the foliation measurements (Figure 16) and in the foliation model (Figure 17). This folding has most likely been formed as a result of D2 E-W compression resulting in the folding of the pre-existing S1-foliation into an open F2-synform (Bauer et al., under review). Bauer et al., (under review) suggests this folding event to have happened during low pressure and high temperature conditions.

The S1-foliation is a distinctive structure in the Malmberget area and appears as one of the most important structure controlling unstable zones. The orientation can be seen in both the brittle and ductile measurements which might be explained by reactivation. Foliation parallel planes gets reactivated in brittle conditions and create brittle joints along the foliation. The quality of the foliation is often also characterized by developed biotite and chlorite minerals (Magnor and Mattsson, 2010). These minerals show characteristics to dilate strongly when sheared which can contribute to the decreased stability and increased the possibility of movement or gliding in the rocks in the S1 direction.

Set 1 and 2 from the measured fractures (Figure 18) appear as two steeply dipping vertical sets striking approximately NE and SE respectively. Set 1 is oriented parallel to the dominating orientation of the S1-foliation while set 2 appear perpendicular to it. Fracture set 3 (Figure 18) has a shallow dip oriented E-W whereas set 4 is oriented almost perpendicular to set 3 with similar dip angles. Set 4 was only identified in the measured joints and fractures in the roof above Printzsköld and appear in close direction to set 3. This could indicate set 3 and 4 comes from the same set of fractures but that the direction changes somewhat as the set goes deeper down.

The brittle model was not made by creating form interpolants as the ductile model. It was created with explicit modeling of planar structures placed in the intervals of low RQD (≤25%). Then, based on the created structures orientations, a mesh was interpolated by implicit modelling.
One known limitation of the implicit modelling technique is its use in data-poor environments (Vollgger, 2015). Due to the spatial interpolation that is based on a radial basis function (RBF), the generated surfaces in the foliation model and discontinuity model will always try to create a smooth fit. This may end up in misleading results for areas with no data or control parameters. On the other hand, this problem has impacts on explicit models as well. When working with implicit models this problem can be avoided or at least reduced by limit the workflow to areas with high drill-core density (Vollgger, 2015).

By using implicit modelling to create the interpolation of the foliation model certain areas appear unnatural or “rounded”. These areas are difficult to remove or trim without losing possible data in that area. However, these implications did not affect the visualization of the measured foliation trend as the area was supported by sufficient structural data.

Since every geomodel is based on hypothesis and interpretations and represents a generalization of the reality grounded on assumptions, all models include a certain degree of uncertainties. The two models created in this study are simplifications of the direction of the foliation in Printzsköld and Alliansen and the discontinuity model illustrate how possible fractures are located based on the assumptions and criteria (Appendix C).

The characterization in the discontinuity model (Table 3) is based on the properties of each structure. Structures with characteristics of indicating unstable minerals was assigned a higher value of reliability as these could be controlling the joints and fractures in that area. The category sub-parallel structures were used to give an indication of how many structures in the RQD-interval that was following the same orientation as the discontinuity plane. A higher number of sub-parallel structures correlating with the plane increase the possibility the discontinuity plane follows a dominating structural orientation. The approximate dip category was used as a rough estimation to get an idea of the dip from the zone with low RQD (<25%). A plane with similar dip angle as the low RQD-interval was given a higher reliability as it follows orientation of the crushed rock zone and could be a controlling structure.

From the total sum (Appendix C), plane A and D appear to comprise structures with higher reliability and around 9-10 structures. This indicate that these two planes are more likely to exist. The structures in plane B and C comprise only 5-6 structures and plane B is mainly made from structures with low reliability. This indicate that these two planes are less likely to exist.
In the drillings from the roof and the 1000m level of Printzsköld the rock quality was classified to very high (90,4%). In the interval between 100-600m an increasing number of zones with low RQD (≤25%) appeared (Figure 33). An explanation to this might be that the tension in the rock volume is lower closer to the surface resulting in more open cracks. Additionally, as an effect of the mining method sublevel caving, the roof is exposed to higher stresses as the mining proceeds deeper (Wettainen, 2010) and this extra stress can cause the already open cracks to fissure. Another explanation causing lower rock quality could be an effect of retrograde metamorphose. As the temperature decrease higher up and fluids are circulating in the system replacement of biotite to chlorite can occur (Parry and Downey, 1982). These less stable minerals can then fracture and slip under the effect of high stress and result in zones of fractured intact rocks.

8.2. The seismic tomography

The volume located 300-600m above the Printzsköld ore body is characterized by low RQD (≤25%) and J_r- and J_a-values of smooth and planar structures (Figure 33). The values indicate that the rock in this volume is more fractured and have a lower rock strength. This region correlates well with a lower velocity volume in the seismic tomography model. These results are in line with what is suggested by Huang et al. (2001), fractured rocks contribute to decreased stress which results in lower velocity together with that deeper depths have increased stress which results in higher velocities (Figure 12).

Planes A, B and C in the discontinuity model pass through the area but appear to be too small-scale structures to be resembled by the seismic tomography model. The tomography model is based on cubes with a volume of 25x25x25 meters but they are varying in size depending on the coverage of each geophone. Smaller cubes mean less rays will travel through the block which will result in less accurate results. In order to get results with reasonable resolution the cubes of 25m were used and in combination with the applied smoothness from the neighboring blocks, added for a more stable convergence, it results in limiting the model to structures above 25m in length. A seismic wave also follows changes of high velocity zones in the rock and can refract together with bending as they propagate. The wave can therefore bounce of sharp boundaries like faults and creating unrealistic tomography models (Julian, 2006).

The model used in this study is based on the first arrival wave and as it is the fastest wave it tends to avoid lower velocity anomalies and favor higher velocity areas (Rawlinson et al,
This problem can contribute to an underestimation of low velocity anomalies. In cases where rays with similar frequency are received, the dominant ray path may cover the more local ones and smear out the anomaly (Rawlinson et al., 2010). But, as the geophones in Malmberget are relatively evenly distributed around the study area and the data recordings are dense, it gives more accurate results and may not be affecting the results in that way.

At the 1000 m level, plane D follows the orientation of the ore body (Figure 28). The constructed plane follows the low velocity areas but crosses through two zones of higher velocity. It also appears as the zones with lower rock quality (RQD ≤50%) follows the orientation of the orebody of Printzsköld (Figure 28) indicating somewhat lower rock quality in the top of the ore body. An explanation might be that the areas with lower RQD (≤40%) are caused by the mining activity and the sublevel caving.

As the velocity increases due to the tension in the rock volumes deeper down (Huang et al., 2001) a questionable subject is what scale in the tomography to use on the different depths. In this study the scale was narrowed down to enhance the heterogeneity of the rocks on the 1000-1200m levels. Consequently, in future studies using the seismic tomography model at depths below 1000m, it is recommended to establish or classify a standard on what scale to use on the different depths to produce the most effective visualisation of the velocity variations in the model.

The deformation zone DZ031 that Wettainen (2010) indicated as seismic active, follows mainly low velocity areas in the tomography model and it correlates with intervals of low RQD (≤25%). The scanning of the cavity above the Printzsköld ore body also follows the orientation of the DZ031 which results in more evidence that the deformation zone exists and is an important structure as for unstable zones in Printzsköld.

As the depth increase from the 1000m level, the ore body and the red high velocity areas coincide gradually. At the 1200m level, the ores of Printzsköld and Alliansen follows the high velocity areas and turn into a SE direction parallels the F2 folding (Figure 32) and the high velocity areas follow the directions of the structural architecture suggested by Bauer et al. (under review). It is tentatively suggested that the high velocity areas might be the continuation of the ore body connecting to Dennewitz and Parta (Geijer, 1930). The shape of the high velocity areas is divided in smaller areas and may be explained by the boudinaged character of the ores proposed by Bergman et al. (2001) and Bauer et al. (under review).

Massive ore have a higher density than surrounding rock and usually gives a higher velocity
for seismic waves. If so, a seismic tomography model over the area could give indications of where massive and dense rocks were to be found and therefore might be considered as an exploration tool.

Mined out parts and cavities show a very good correlation with the tomography model. This is evident as they are large structures and show a great heterogeneity in form of velocity.
9. Conclusions and recommendations

The seismic tomography model gives a rough image of the velocity variation of the study area. It shows promising results to be used as an indicative instrument defining regional scale structures and large-scale zones with lower rock quality. The orientation of the foliation in the ore bodies Printzsköld and Alliansen displays an orientation of NE-SW in the eastern part and fold to the SE in the west. The general rock quality of Printzsköld and Alliansen is high with a pattern of gradually increasing rock quality deeper down in the mine. The previous identified deformation zone DZ031 appear as an important structure for unstable zones in Printzsköld.

Furthermore, it could be interesting to evaluate the seismic tomography in other areas of the mine in Malmberget as well as using a more detailed resolution for the model. The results of this study bring light on how the seismic tomography can be used to identify smaller-scale structures and to provide a better understanding of the structural geology of the area. Another interesting approach using the seismic tomography model is to evaluate the possibilities to use it as a prospecting tool for deeper situated ore bodies. The results from this could give a better geological understanding and be useful for future exploration of the ore bodies in Malmberget.
10. References

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Appendix A

Classifications used in the project.

Table 1. Classification of the RQD (Bienlawski, 1979).

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<tr>
<th>RQD (%)</th>
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<td>Very poor</td>
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<tr>
<td>25-50</td>
<td>Poor</td>
</tr>
<tr>
<td>50-75</td>
<td>Fair</td>
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<tr>
<td>90-100</td>
<td>Excellent</td>
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Table 2. Definition of $J_r$ and $J_a$ for the rock wall contact (Barton et al., 1974).

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<th>Rating</th>
<th>JOINT ALTERATION NUMBER $J_a$</th>
<th>Rating</th>
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<td>Discontinuous joints</td>
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<td>Tightly healed, hard, non-softening, impermeable filling</td>
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<tr>
<td>Rough and irregular, undulating</td>
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<td>Unaltered joint walls, surface staining only</td>
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</tr>
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<td>Smooth, undulating</td>
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<td>Slightly altered joint walls, non-softening mineral coatings, sandy perlakes, clayey disintegrated rock, etc</td>
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<td>Slickensided, undulating</td>
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<td>Silty, or sandy-clay coatings, small clay fraction (non-softening)</td>
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<td>Rough or irregular planar</td>
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<td>Softening or low friction clay, mineral coatings, i.e. kaolinite, mica, Also chlorite, bsd, gyprosum and graphite etc, and small quantities of swelling clays. (Discontinuous coatings, 1 – 2 mm or less in thickness)</td>
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Table 4. Classification of strain intensity (SRK, 2014).

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<td>No alignment of mafic minerals (biotite). Quartz and feldspar grains remain equant.</td>
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<td>Medium-Low</td>
<td>Weak alignment of biotite. Quartz and feldspar grains remain equant.</td>
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<td>Medium</td>
<td>Biotite generally aligned and some stretching/alignment of quartz ± feldspar grains.</td>
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<tr>
<td>Medium-high</td>
<td>All biotite is aligned and quartz is stretched in thin, elongate grains.</td>
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<tr>
<td>High</td>
<td>Extreme stretching of biotite and quartz. Quartz occurs as thin ribbons. Possibly some associated grain size reduction.</td>
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</table>
Figure 35. Definition of how RQD is calculated (Deere, 1989).
Appendix B

Density plots over the structures measurements in the roof above the Printzköld ore body with and without applied Terzaghi weighting.

**Figure 36.** Density plot over the joints and fractures in the roof above the Printzköld ore body with applied Terzaghi weighting.

**Figure 37.** Density plot over the joints and fractures in the roof above the Printzköld ore body without applied Terzaghi weighting.
Figure 38. Density plot over the foliation measurements in the roof above the Printzsköld ore body with applied Terzaghi weighting.

Figure 39. Density plot over the foliation measurements in the roof above the Printzsköld ore body without applied Terzaghi weighting.
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<th>Dip azimuth °</th>
<th>Type</th>
<th>Sub-parallel structures (+/− 20°)</th>
<th>Approx. dip from coreholes (°)</th>
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<th>Ja</th>
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<th>Intensity 1</th>
<th>Fill 2</th>
<th>Intensity 2</th>
<th>Z-Sum</th>
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Appendix D

Approximate dip estimated from core photos