Petrophysic of the Host-rock to the Ore in the Lovisa Mine, Bergslagen

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Abstract

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The Bergslagen region has three base-metal mines operating today, and one of them is the Lovisa mine, which host a Zn-Pb-Ag deposit. The Lovisa mine is located in the Guldsmedshyttan area north of Lindesberg. The mine is part of in the X-Mine H2020 project that includes four different mines with the aim of an improved environmental resource management. The project aims at reducing the environmental impact from transport, ore processing and chemical handling as well as result in lowering the costs per produced amount of metal.

The purpose for this thesis is to determine the petrophysical characteristics of the host rocks to the thin tabular mineralised units in the Lovisa mine with petrophysics. Petrophysics is used to obtain information about the physical properties of rocks, which is then is integrated with geophysics and the geology, to obtain an improved understanding about the different geophysical anomalies. The petrophysic methods used here, reviled three different physical properties of the rocks: density, magnetic volume susceptibility and natural remanent magnetization. These properties were measured on five different drill cores and correlated with the literature data and lithologies of the core.

The lithologies close to the ore correspond to literature data for volcanic siltstone, volcanic sandstone, massive rhyolite, skarn (calc-silicates) and dolomite. Dolomite is not present in the cores and corresponds to breccia, volcanic sandstone and skarn. My conclusion for this method, is that in order to do a lithological interpretation based on the measured petrophysical properties, is that a good knowledge of the lithologies as well as a good understanding of the geological processes that have affected the rocks in the investigated area are required.

Key words: Petrophysics, density, magnetic volume susceptibility, natural remanent magnetization, Bergslagen, lithology

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Sammanfattning

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Resultatet visar att det malmnära sidoberget korrelerar med litteraturdata på vulkanisk siltsten, vulkanisk sandsten, kalksilikat, ryolit, skarn och dolomit. Dolomit finns inte i kärnorna utan representeras av bl.a. breccia, vulkanisk sandsten och skarn. Min slutsats är att det går att bestämma lithologin med dessa fysikaliska egenskaper, men man måste ha en god kännedom om vilka bergarter som förväntas att förekomma i området samt vilka geologiska processer som påverkat dem.

Nyckelord: Petrofysik, densitet, magnetisk susceptibilitet, naturlig magnetisk remanens, Bergslagen, lithologi.

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1. Introduction

The Bergslagen region is located in the south-central Sweden (figure 1) and covers the Västmanland, Värmland, Dalarna, Uppsala, Stockholm and Östergötland counties and is one the most important mineralisation provinces in Sweden (Stephens et al., 2009). In the Bergslagen region there are three base-metal mines in operation, the Lovisa mine, Garpenberg and Zinkgruvan the latter being the largest ore deposit in the region and is also one of the largest in Europe (e.g, Jansson et al., 2018).

In 1985 LKAB and BP minerals Ltd was exploring the area around the Håkansboda deposit and discovered the Lovisa Zn-Pb-Ag sulphide deposit. At that time the companies deemed the deposit to be small to be mined by them and in 1989 the deposit was sold to a consortia of private investors and small scale, irregular production started in the mid 1990’s.

Since 2004 the deposit has been owned and operated by Lovisagruvan AB. It is a small-scale operation compared to other active mines in Sweden (Stephens et al., 2009).

The ore body is a very thin tabular body approximately 0.8 m steeply dipping and has been identified down to 400 m but is open at depth. The ore is mined with a special method customised to mine thin layers of ore in a cost-efficient way. The size of the ore body was initially estimated to be 400 000 tonnes of pure ore with high grades of zinc (22 wt %), lead (14 wt %) and additional silver. Until the end of 2017, 446 000 tonnes of ore has been mined and the current reserves sum up to 700 000 tonnes which at current production level equals to another 17 years of mining. Currently about 40 000 tonnes of ore is mined annually grading 9 wt % zinc and 6 wt % lead (Lovisagruvan AB, 2017).

The purpose of this thesis is to characterize the petrophysical properties of the host-rocks to the ore at the Lovisa mine. The measurements on five drill cores from Lovisa mine were conducted at the Geologic Survey of Sweden. The petrophysical data has been correlated with rocks with similar physical properties and with the lithologies obtained from the drill core logs. This thesis is conducted as a part of the H2020 X-MINE project financed by the EU commission. X-MINE is a large-scale project that aims to get a better resource characterisation in 3D but also to improve ore extraction. Four small mines participate in the project and X-MINE to increase the
existing recourse potential and to decrease the environmental impact (X-MINE, 2018).

Petrophysical characterization is carried out for numerous reasons and can provide information in ore exploration. Borehole samples can be used to characterize lithologies and the physical properties of various rock types. Petrophysics provides different physical properties that the rock possesses for example density, magnetic susceptibility and magnetic remanence (Schön, 2004).

Petrophysical data is also intergraded in seismic measurements were the density of the different lithologies need to be known for depth conversion of the different layers shown seismic diagrams (Cannon, 2015). Lithology classification can be obtained by different methods and petrophysics is one of them, where measurements can be done on samples from surfaces or from boreholes.

The classification of the physical rock properties can also be used to understand the reason for geophysical signatures for example airborne or ground gravity, density and magnetic measurements. Petrophysical data of known lithologies in a specific area is therefore used as correction factors for the geophysical data (Morris & Tschirhart, 2015).

1.1 Limitations

The limitations in this work are related to time allocated to this project but also related to the number of samples. The time limitation restricted the number of samples that could be analysed and as a consequence only an overview picture of the lithologies has been obtained and important layers might have been missed. The measured samples were not orientated and therefore only partial information of the magnetic remanent magnetisation analysis have been obtained that otherwise would give paleomagnetic information. The petrophysic measurement methods were also limited to only density, magnetic volume susceptibility and natural remanent magnetization and a better characterization of the lithologies require measurements of additional properties in order to correlate with existing data of particular rock types.
2. Geological background

2.1. Regional geology

The Bergslagen region is located in central Sweden, in the south-western part of the Svecokarelian orogen of the Fennoscandian shield. The area has endured medium to high grade metamorphism. The dominating rocks in the area have a felsic compositions (Allen et al., 1996) and where formed between 1.9-1.8 million years ago during the Svecokarelian orogeny (Stephens et al., 2009). The oldest exposed rock in the Bergslagen region comprises metasedimentary rocks that is overlaid by a thick unit of felsic metavolcanic rocks. The lower part of the volcanic stratigraphy contains pyroclastic flow deposits and subvolcanic intrusions and the upper part is dominated by ash-siltstone and ash-sandstone with interbedded banded iron formations, marble and volcanioclastic mass flow deposits (Jansson et al., 2018). The metamorphic grade in the eastern part of Bergslagen is generally in amphibole facies reached during the Svecokarelian orogeny whereas greenschist and granulite facies prevails locally (Stephens et al., 2009). During the different stages of the Svecokarelian orogeny, the rocks in Bergslagen were affected by deformation in either ductile or brittle regimes. The most dominant structures are ductile and brittle shear zones, L2 lineation and tight isoclinal fold subsequently refolded producing fish-hook interference pattern (type 2) during a switch in the orientation of the maximum principle stress (Allen et al., 1996). The F1 folds are steeply dipping and in the southwestern part of Bergslagen trending mainly east-west and in the western part of the region they are mainly trending northeast to northwest. The stretching L2 lineation is plunging to the east (Allen et al., 1996).

The Bergslagen region is intensely mineralized and hosts a large number of different ore deposits, like W-skarn, stratabound Zn-Pb-Ag-(Cu-Au) sulphide ores, iron oxide skarn, apatite iron oxide, banded iron-formation, and carbonate-hosted iron ores. The ore deposits are most commonly found in metamorphosed hydrothermally altered volcanic rocks and are often associated with skarn and metalimestone layers (Allen et al., 1996).

The geology indicates that the bedrock was formed in a magmatic back-arc region inboard an active continental margin i.e. an extensional setting within the continental crust. The early crustal forming events developed during a magmatic-extensional-compressional cycle with magmatism, crustal extension and thermal doming followed by a decrease of extension, thermal subsidence, a change from extensional to compressional deformation, structural inversion and metamorphism (Allen et al., 1996). The volcanic evolution is divided into three stages: the first stage with intense volcanism and extension, second stage with waning volcanism and the third stage with sedimentation and thermal subsidence (Allen et al., 1996). During the intense volcanic stage, the depositional environment was shifting between below to above wave base. The volcanic activity in this stage resulted in an 8 km thick volcanic succession (Allen et al., 1996). The felsic volcanism produced poorly bedded breccia and volcanic sandstones (Stephens et al., 2009).
The waning volcanism stage is related to a period of continuous subsidence with deposition below wave base in a calm shallow marine environment, resulting in a wide distribution of distal rocks (Allen et al., 1996). The volcanic rocks are laminated or planar volcanic ash-siltstone or sandstone, occasionally interbedded with carbonate rocks (Stephens et al., 2009). It was also during this stage that most ore deposits were formed. A period of decreasing volcanism and continued subsidence characterized the third sedimentary and thermal subsidence stage (Allen et al., 1996).

2.2. Local geology
Lovisa deposit is located in the western part of central Bergslagen (figure 2) in the Guldsmedshyttan area (Stephens et al., 2009). This area is intensely deformed resulting in several ductile and brittle structures. The Lovisa mine is located on the south to southwest plunging “Lovisa anticline” that is a parasitic fold on the western limb of the Guldsmedshyttan syncline. The syncline is interpreted to be a first generation fold, related to the dominant N-S to NE-SW trending tectonic fabric (Jansson et al., 2018). Cross folding is also present in the area, related to the second generation folding. There are several shear zones transecting the Lovisa mine stratigraphy, which results in stacking of the stratigraphy by almost vertically displacement (Jansson et al., 2018). These shear zones are often cross-cut by vertical faults including the N-S to NW-SE Lovisa fault.

2.3. Stratigraphy in the Lovisa area
The dominating rocks in the Lovisa area are felsic subvolcanic intrusions (Stephens et al., 2009) and volcanic sediments deposited below storm wave base by dilute turbidity currents in a suspension settling far away from the source volcanoes (Jansson et al., 2018). Storsjön formation in the lower part of stratigraphy comprises massive plagioclase- and quartz-phryic, fine grained metavolcanic rocks that are locally affected by magnesium alternation and contains variably skarn-altered units (Stephens et al., 2009). Overlying the Storsjön formation is the Usken formation that comprises a large portion of reworked rocks in addition to BIF, rhyolitic metavolcanic rocks dolomitic and calcitic marble. The Usken formation is succeeded by the Mårdshtyttan formation that comprises clastic metasedimentary rocks (Jansson et al., 2018; Lundström, 1983).

The upper part of the stratigraphy in the Lovisa mine (figure 3) is divided into three sections: the stratigraphic footwall, the ore zone and the stratigraphic hanging wall. The footwall contains a large number of different rock types that together form a complex stratigraphy. The unit between the metalimestone and rhyolitic siltstone-sandstone is weakly affected by sericite-chlorite alternation and other levels in the stratigraphy shows silicification caused by hydrothermal alternation (Jansson et al., 2018). Dolomitic marble of the Usken formation is found in the bottom of the footwall (Jansson et al., 2018; Lundström, 1983). It is locally intercalated with rhyolitic ash-siltstone layers and in the upperpart of the dolomitic marble section is interbedded with calcitic marble, skarn and rhyolitic siltstone (Jansson et al., 2018). Higher up in
the stratigraphy, there is a massive magnetite-skarn unit that can be correlated with the magnetite iron formation at Håkansboda and Lekeberg mines located north of the Lovisa deposit. The magnetite iron formation is overlain by grey rhyolitic siltstone and feldspar-quarts-phyric sandstone and skarn followed by a 50-70 m thick succession of coarse grained volcanoclastic material that contains sandstone and pumice. This section has a sharp boundary to a 20-30 m unit of rhyolitic siltstone followed by a rhyolitic quartz-feldspar sandstone unit with pyrite porphyroblasts. Pyrite are gradually more abundant and the sandstone more fine grained upwards in the stratigraphy (Jansson et al., 2018).

The massive sulphide ore is surrounded by a strongly banded grey and red rhyolitic siltstone that contains more Ca-rich feldspars then the other siltstones in the stratigraphy. The ore is divided into a the lower and an upper layer of which the upper layer is the main ore body. The upper layer consists of galena and sphalerite and the lower layer of only sphalerite. The stratigraphic hanging wall is superimposed on the ore zone. The unit in contact to the ore zone is a section of ash-siltstone followed by an 80 m thick layer of coarse grained-rhyolitic volcanoclastic rocks, 80 m of massive rhyolitic siltstone unit that is interbedded with marble and a section of interbedded pink-grey rhyolitic ash siltstone (Jansson et al., 2018).

Figure 2. Map showing parts of the Lindesberg area and the location of Lovisa mine. Source: SGU map generator.
2.4. Petrophysics and its integration with ore prospecting

Petrophysics is also called rock physics and describe the physical behaviour of rocks as well as properties related to the “experimental and theoretical aspects and methods, fundamental and practical questions connected with applications in geophysics, geology, reservoir and geotechnical engineering and related disciplines” (Schön, 2004).

Petrophysics is a subject that has attracted increased attention lately because of the growing interest to obtain more information from geophysical measurements. Petrophysical methods origin from the petroleum industry but are applied in several other major exploration industries including mineral resources. It is used for solving and understand the geophysical signatures as they show the physical properties of the rocks (Schön, 2004; Kennedy, 2015). To be able to obtain a reliable image of the subsurface, geophysical data needs to be intergraded with petrophysical data in order to understand and relate them to measured geology i.e. knowledge of the petrophysical properties of the different rock types in the specific area. (Bosch, 1999).
The interpretation process contains three stages; gathering geophysical field data, spatial distribution of corresponding parameter and spatial distribution of interesting parameter. The geophysical field data (gravity, density or magnetic etc.), is used to obtain a model that will represent the spatial distribution of diagnostic properties from the geophysical method applied. The spatial distribution of corresponding properties transforms to the spatial distribution of properties of interest. At this stage the geophysical data is integrated with petrophysical data for correction of anomalies shown, and the final result shows the properties that are significant for a specific geological area, for example porosity, mineral composition, mechanical strength and the lithological variations of the subsurface (Bosch, 1999; Schön, 2004).

The rocks physical properties that can be obtained from petrophysics are density, magnetic volume susceptibility, magnetic remanence or intensity of remanent magnetization, Koenigsberger ratio, magnetic permeability, electric resistivity and conductivity, electrochemical polarizability, thermal conductivity, velocity of compressional waves and coefficient of anisotropy. The properties measured and presented in this thesis are density, magnetic volume susceptibility and natural remanent magnetization.

Petrophysics is used for several purposes in ore exploration, and one of these is to understand the variations in bedrock and its relation to airborne magnetic, spectrometry and gravity measurements, but also the relation to field observations, remote sensing data, height relief data and aerial photographs (Lundin & Bastani, 2007). The geophysical data is often combined with petrophysics for improved correction factors related to real rock properties that are applied to the geophysical data. This is done because the average correction factors are too general and yield incorrect and misleading result of the geology of interest.

Airborne gravity gradiometer measures the gravity from a certain height above the ground and the density contrast between the air and the bedrock is measured. The density of the bedrock varies and a granite is often assigned with a density value of 2670 kg/m³, but for a more detailed and meaningful measurement result, the ground specific density need to be corrected with more specific values in areas were the geology comprises a diverse lithology (Morris & Tschirhart, 2015).

Bedrock mapping is carried out in the beginning of prospecting campaigns to evaluate the economic potential before expensive geophysical measurements are conducted that in turn determine where boreholes will be placed for further data collection (Nationalencyklopedin, 2018). Bedrock mapping is done to illustrate the geology on the surface and show the distribution of rocks and if possible the lithostratigraphic correlations. Bedrock maps constructed for ore prospecting, are often compiled by using several different methods because positive indicators from one particular method may be inconclusive. By combining different methods with petrophysical measurements enables an understanding of the geophysical anomalies and a meaningful bedrock map showing the information of interest can be produced (Nationalencyklopedin, 2018). Petrophysical measurements is of great importance particularly in areas that should be mapped with poor bedrock outcrop density. In such areas petrophysical properties are needed to get a realistic geologic map as
there are to a large extent based on geophysical data. The petrophysical data extracted from boreholes and surfaces are used to identify and characterize the different lithological units. The geophysics methods applied in exploration is determined by the properties of the material, i.e. when prospecting for ores with magnetic properties, magnetic methods are used in order to visualize the magnetic anomalies (Lundin & Bastani, 2007).

2.4.1. Density
Density is a measure of body weight in relation to volume and is determined by the mass divided by volume of the specific body. If a rock volume is homogeneous the gravitational attraction is proportional to the difference in density of the body compared to the surrounding rock (Parasnis, 1971). The density of a mineral or a rock is depending on the chemical composition and internal bonding but also its porosity and pore fluid content. There are two ways to describe the density of a rock related to the degree of heterogeneity and it is either based on the bulk density, or the density of individual minerals. The bulk density is the density of a volume rock and is depending on the mineral compositions, content of enclosed pore or fracture space and different fracture or pore space fillings. For igneous and metamorphic rocks pores and fractures are insignificant and do not affect the density in contrast to sedimentary rocks. This implies that a specific rock can have a widespread bulk density that may cause a problem in rock classification based on density only. In metamorphic rocks the density is related to the composition and density of the protolith but also to the thermodynamic condition and the level of metamorphism they have endured. The density difference can be high between the protolith and the metamorphic equivalent if there is a removal or addition of individual components due to chemical processes that occurred during the metamorphism (Schön, 2004).

2.4.2. Magnetic volume susceptibility
The magnetic volume susceptibility is measured in K (kappa) and is expressed in unit SI. When a body of any size and shape is under influence of an external magnetizing force it acquires a magnetic moment. This is measured by placing the sample in a space surrounded by a long solenoid carrying an electric current. The volume of the sample influences the measurements, as larger samples have the greater induced moment than smaller, provided that the shape of the sample is comparable. Therefore, the magnetic moment per unit volume is a measure of magnetic ponderability of the body (Paranis, 1971). There are three groups of magnetic materials: diamagnetic, paramagnetic and ferri-, antiferro-, and ferromagnetic materials (Schön, 2004). The diamagnetic materials have an extremely weak susceptibility, therefore not often noticeable when other forms of magnetism exist (Dunlop & Özdemir, 2007). Diamagnetic materials have negative susceptibilities and the paramagnetic materials have a positive susceptibility, normally in the range of $10^{-2}$ to $10^{-4}$ SI (Schön, 2004). Ferro-, antiferro-, and ferromagnetic materials have much higher susceptibility that is related to electron spins of these ferromagnetic
materia, which are metals. Metals have the highest susceptibility because all the electrons spin in the same direction and produces a small magnetic field. Minerals can also be dia, - paramagnetic, and ferro, - ferri, - or antimagnetic. Some diamagnetic minerals can be paramagnetic, albeit the absence of Fe$^{2+}$, Fe$^{3+}$ or Mn$^{2+}$ ions that are the main components providing paramagnetic properties (Schön, 2004).

The magnetic properties of a rock is often given by a very small fraction of the total mineral composition and it is therefore difficult to predict the magnetic property of a given rock. The magnetic properties can also vary within a rock because of the mineralogical inhomogeneity, and conditions that affected the rock after formation. In igneous rocks the minerals susceptibility is depending on the amount of mafic minerals and for sedimentary rocks the content of clay. The percentage of magnetic minerals within a rock volume controls the susceptibility and magnetite that is extremely magnetic and very abundant can be used to correlate the susceptibility with the volume percentage of magnetite within the rock (Schön, 2004). Grain size and grain shape also affects the susceptibility where smaller magnetic grains within a matrix decreases the susceptibility (Stephenson et al., 2007). Worth mentioning is also that temperature and stress also affects the susceptibility. The susceptibility decreases under uniaxial compression and the temperature influence is depending on the different minerals and their characteristic dependence of temperature (Schön, 2004).

2.4.3 Natural remanent magnetization

The field-independent and irreversible part of the total natural magnetization is the natural remanent magnetization (NRM.) The NMR is acquired by the ferrimagnetic minerals in the matrix but also the physical and chemical history affect the phenomena (Schön, 2004).

Intensity of remanent magnetization is the magnetization strength that a body inherit from a previous magnetization (Parasnis, 1971). Orientated samples can give the latitude and the time the rock was formed as the magnetic field has a known direction and intensity at different places on Earth at a specific time. When a magnetic rock is cooling down from above the Curie temperature, the magnetic fields specific properties at the place the rock is formed will be preserved. It can be difficult to determine the direction of the magnetic field recorded by NRM, because different generations of NRM recorded by the a rock since its formation in addition to modern “overprints” must be separated (Dunlop & Özdemir, 2007). For determination of the orientation and direction of the magnetic field, the measured sample must be oriented. The samples in this study were not orientated but the strength of the magnetism was measured without using an external magnetizing force. The magnetic moment per unit volume of the body is measured in ampere per meter (Parasnis, 1971).

There are three different types of NMR, detrial or depositional remanent magnetization (DRM), chemical remanent magnetization (CRM) and thermoremanent magnetization (TRM). DRM is measuring the remanent magnetization of magnetic
minerals deposited in sediments (Dunlop & Özdemir, 2007). The particles align to the magnetic fields direction, which produce a magnetic footprint. Chemical processes below the Curie temperature, for example oxidation, reduction and recrystallization ferri-, ferromagnetic minerals in presence of a magnetic field are also processes of CRM and affects the magnetism in magnetic minerals. TRM is associated with magmatic and high-grade metamorphic rocks. TRM is the remanence obtained for ferrimagnetic mineral-bearing rocks when it is above the Curie temperature under the influence of a magnetic field (Schön, 2004).

3. Method

Laboratory petrophysical measurements were conducted on 51 drill core samples from the Lovisa mine, each segment has a length between 3-11 centimetres and were collected from six different boreholes with a total length of 177 meters. The selected segments were collected where a distinct difference in lithology could be observed after the core had been moistured for easier identification. The variation in the lithology and how it varies along the borehole is of interest when correlating lithology with petrophysics. The rock segments were sampled when a significant change appeared in texture, color, grain size, hardness and mineralogy. A sample number was provided to each sample (the drill hole and depth) and they were photographed if later visual analysis is needed in the correlation process. The samples physical properties were measured with three different computerized instruments described below in chapter “Petrophysics laboratory methods” and include: natural remanent magnetization, density and magnetic susceptibility.

3.1. Lithology correlation

The method used for lithology interpretation of the petrophysical data collected from drill cores was described by Uppsala University and uses direct determination. This method applies a compositional methodology based on density and to types of magnetism. The first step of the interpretation process was to get the data converted to logs that showed how the different properties varied with depth. The second step was to analyse the three logs and the levels where a simultaneous change occurred in order to determine were the lithology changed and the number of main lithologies present in each drill core. The third step was to do a literature study regarding the lithologies in the Lovisa area, the geological processes that have affected the rocks and also the depositional environment of the rocks. The third step limit the number of possible lithologies that could match the petrophysical data. The fourth step was to find literature data on density, magnetic volume susceptibility and natural remanent magnetization properties for different rock types. The fifth and final step was to correlate the physical properties acquired from the measurements with literature data on rocks with the same physical properties that guided the lithological interpretation of the drill cores and compare these with the logged lithologies at Lovisa (appendix 1).
3.2. Petrophysic laboratory methods
The instruments used for magnetic measurements consist of a susceptibility bridge that is powered by a DSP lock-in amplifier and an oscillator amplifier as well as the remanence meter tube which is connected to the magnetometer system. The measurements were conducted at the Geological Survey of Sweden and the setup is developed by the Geological Survey of Finland.

3.2.1. A&D weighing FX-3200
The density measurements were done using a model A&D weighing FX-3200 scale with a readability of 0.01g that was connected to a computer. The method uses the principle of Archimedes to determine the density of each sample. The loss in weight of a body immersed in liquid is equal to the weight of the liquid displaced by the body and in this case water was used as the liquid. The device had two scales. One scale measures the $W_{\text{air}}$ and the other scale measure $W_{\text{liq}}$ of the body (figure 4). During the calibration of the instrument the temperature of the water was measured and logged into the computer and the weight of the water was calculated. The samples volume was calculated by the computer using the body weight in air and the body weight in water. The density was calculated with the equation $W_{\text{air}}/(W_{\text{liq}}-W_{\text{water}})$ (Parasnis, 1971).

3.2.2 Susceptibility bridge
The susceptibility bridge measures the magnetic volume susceptibility (figure 4). The instrument produces a magnetizing field by a current carrying-solenoid or a flat coil, and a balanced coaxial pick-up coil detects the induced magnetisation. When the sample is inserted in the instrument, the coil system alters the inductive balance which produces an out of balance signal in the pick-up coil that is proportional the total volume susceptibility. The AC-bridge uses a peak magnetic field with a strength of 0.1 mT with a frequency of 1 to 10 kHz. The AC-bridge was calibrated with iron and bismuth samples. The first and last measurements and also between each sample measured, were done without a sample. Between each blank measurement the sample is inserted and measured, thereafter the susceptibility was calculated (Thompson & Oldfield, 1986).
3.2.3 Remanence meter
The remanence meter apparatus consists of two components (figure 5), the tube and the magnetometer system with sensor probe model B that is connected to the tube. The samples were measured at six different orientations in the tube, which uses alternating field demagnetization to reveal the natural remanent magnetization. The tube creates a decaying alternating magnetic field that affects the sample. The external direct magnetic field will remove the remanent magnetization coercivity that is lower than the peak intensity of the applied alternating field. The decaying alternating field generates an amplitude of every half-cycle applied that is smaller than the previous half-cycle. Within each half-cycle the mobile domains within the sample with lower remanent magnetization coercivity smaller than the peak will be align in the field. After multiple half-cycles the numbers of domains in positive and negative directions will be the same along the axis of demagnetization. After each half-cycle the percentage of domains that have a greater coercivity compared to the peak will increase. After several half-cycles of applied alternating fields, the net of remanent field within the sample will be zero and the NRM will be revealed.

Figure 5. Remanence meter apparatus.
4. Result

4.1. Borehole:1501

![Graph showing density, magnetic volume susceptibility, and natural remanent magnetization properties from three different samples displayed over an interval of eight meters from borehole 1501.](image)

**Figure 6.** Density, magnetic volume susceptibility and natural remanent magnetization properties from three different samples displayed over an interval of eight meters from borehole 1501.
4.2. Borehole: 1502

**Figure 7.** Density, magnetic volume susceptibility and natural remanent magnetization properties from 13 different samples displayed over an interval of 58.6 meters from borehole 1502.
4.3. Borehole: 1503

**Figure 8.** Density, magnetic volume susceptibility and natural remanent magnetization properties from nine different samples displayed over an interval of 33.64 meters from borehole 1503.
4.4. Borehole:1504

Figure 9. Density, magnetic volume susceptibility and natural remanent magnetization properties from six different samples displayed over an interval of 17.97 meters from borehole 1504.
4.5. Borehole: 1505

[Diagram showing density, magnetic volume susceptibility, and natural remanent magnetization properties from eight different samples displayed over an interval of 73.12 meters from borehole 1505.]

**Figure 10.** Density, magnetic volume susceptibility and natural remanent magnetization properties from eight different samples displayed over an interval of 73.12 meters from borehole 1505.
4.6. Borehole: 1506

Figure 11. Density, magnetic volume susceptibility and natural remanent magnetization properties from nine different samples displayed over an interval of 78.17 meters from borehole 1506.
4.7. Log data analysis

Based on the petrophysical measurements (appendix 2) and literature data on variation in lithologies the host-rock to the ore in the Lovisa mine shows that the cores 1501-1506 (figure 6-11) consist of six different rock types. The different physical rock properties in drill core 1501 (figure 6) change at the same place in the core. The magnetic volume susceptibility and NRM increase with higher density and decreases with lower density.

The core from borehole 1502 (figure 7), which is measured over a greater length, have more distinct and greater variations of physical rock properties. The larger variations between all physical parameters indicate that there are more rock types present in the core. At the first glimpse it seems that the three different physical parameters increases and decreases at the same place in the drill core 1502 but examination of the figure, reveals that the change is almost at the same place and this is also observed in drill cores 1503 - 1506. In drill core 1502 (figure 7), a decrease in density generally coincide with an increase of magnetic volume susceptibility and NRM.

In drill core 1503, (figure 8) the first 4.29 meters show a trend where an increase in density leads to an increase in both magnetic susceptibility and NMR. Between 195.479 - 204.820 meter shows another feature, where an increase in density coincides with an increase in magnetic volume susceptibility but a decrease in NRM. Drill core 1504 (figure 9) has a trend between 179.970 - 190.129 meters, where the density and magnetic volume susceptibility decreases whereas the NRM increases. Between 192.84 - 197.64 meters an increase in density leads to an increase in magnetic susceptibility and NMR.

Between 142.420 - 157.090 meters in drill core 1505 (figure 10) show a pattern where a decrease in density and magnetic susceptibility coincides with an increase in NMR, and between 160.670-206.250 meters the pattern is that an increase in density coincides with an increase in magnetic susceptibility but a decrease in NMR. Drill core 1506 (figure 11) shows a trend between the first 2.61 meters, where an increase in density leads to a decrease in magnetic susceptibility and NMR. Between 175.75 - 179.02 meters an increase in density leads to an increase in magnetic susceptibility but a decrease in NMR and between 199.4 - 250.1 an increase in density results in a decrease in magnetic susceptibility and an increase in NMR.
4.8. Lithology: Borehole 1501

Figure 12. A: Interpreted lithologies with petrophysical data derived from literature. B: Lithology based on log from Lovisa mine. The figure shows the different lithologies extension over drill cores 1501. The extension of the first and last layer of every core is unknown. The symbol shows the location in the drill core where measurements have been conducted. Sources: (Hone et al., 1987; Hunt et al., 1995; Parasnis, 1971; Soltani et al., 2015).
4.9. Lithology: Borehole 1502

**Figure 13.**

- **A:** Interpreted lithologies with petrophysical data derived from literature.
- **B:** Lithology based on log from Lovisa mine. The figure shows the different lithologies extension over drill cores 1502. The extension of the first and last layer of every core is unknown. The symbol shows the location in the drill core where measurements have been conducted. **Sources:** (Hone et al., 1987; Hunt et al., 2013; Parasnis, 1971; Soltani et al., 2015).
4.10. Lithology: Borehole 1503

**Figure 14.** A: Interpreted lithologies with petrophysical data derived from literature. B: Lithology based on log from Lovisa mine. The figure shows the different lithologies extension over drill cores 1503. The extension of the first and last layer of every core is unknown. The symbol shows the location in the drill core where measurements have been conducted. **Sources:** (Hone et al., 1987; Hunt et al., 2013; Parasnis, 1971; Soltani et al., 2015).
4.11. Lithology: Borehole 1504

Figure 15. A: Interpreted lithologies with petrophysical data derived from literature. B: Lithology based on log from Lovisa mine. The figure shows the different lithologies extension over drill cores 1504. The extension of the first and last layer of every core is unknown. The symbol shows the location in the drill core where measurements have been conducted. Sources: (Hone et al., 1987; Hunt et al., 2013; Parasnis, 1971; Soltani et al., 2015).
4.12. Lithology: Borehole 1505

**Figure 16.** A: Interpreted lithologies with petrophysical data derived from literature. B: Lithology based on log from Lovisa mine. The figure shows the different lithologies extension over drill cores 1505. The extension of the first and last layer of every core is unknown. The symbol - shows the location in the drill core where measurements have been conducted. Sources: (Hone et al., 1987; Hunt et al., 2013; Parasnis, 1971; Soltani et al., 2015).
4.13. Lithology: Borehole 1506

Figure 17. A: Interpreted lithologies with petrophysical data derived from literature. B: Lithology based on log from Lovisa mine. The figure shows the different lithologies extension over drill cores 1506. The extension of the first and last layer of every core is unknown. The symbol shows the location in the drill core where measurements have been conducted. Sources: (Hone et al., 1987; Hunt et al., 2013; Parasnis, 1971; Soltani et al., 2015).
4.14. Lithology comparison

Comparing the lithologies in A, from literature data for different lithologies with B, core logs from Lovisa (appendix 1) (figures 12-17), shows that there are some differences. In B (figure 12B – 17B) are there much more units and that is because the core logs describes the interval of the core in a detail. In drill core 1501 sphalerite ore occur at 180 meter (figure 12 B) and it has been correlated with massive rhyolite according to literature data (figure 12 A). At 173.82 meter in drill core 1503, the core logs from Lovisa describe it to be metavolcanic rock (figure 14 B) but have literature data equivalent to calc silicate rock (figure 14A) The felsic volcanic siltstone at 176.45 meter has literature data equivalent to massive rhyolite, the siltstone with skarn at 182.28 meter has literature data equivalent to volcanic sandstone and the breccia at 187.99 meters has data equivalent to dolomite. In drill core 1504 has the felsic volcanic rock (figure 15 B) at 180.02 meter been correlated with the petrophysical literature data that correspond with dolomite (figure 15 A), the sphalerite ore with skarn at 188.81 meters has literature data equivalent to dolomite and the felsic volcanic siltstone with sphalerite at 190.18 meter has data equivalent to dolomite. The felsic volcanic siltstone with sphalerite and galena at 145.65 meter in drill core 1505 have physical properties that correspond with the literature data for dolomite (figure 16 A), the felsic volcanic siltstone at 148.70 meter correspond with volcanic sandstone, the felsic volcanic siltstone with skarn at 156.55 meter correspond with the literature data for dolomite and the felsic volcanic rock at 211.81 meter with volcanic siltstone. In drill core 1506 has the felsic volcanic rock with skarn at 173.60 meters (figure 17 B) been correlated with dolomite (figure 17 A), the felsic volcanic rock at 176.13 meters with felsic volcanic siltstone and the felsic volcanic rock at 201.20 meters with massive rhyolite.
4.15. Histograms

**Figure 18.** Histogram showing the density variations in the Lovisa mine, with data collected from six different boreholes.

**Figure 19.** Histogram showing the magnetic volume susceptibility variations in the Lovisa mine, with data collected from six different boreholes.
5. Discussion

5.1. Lithology interpretation

The histograms (figures 14 and 15) illustrate that there is a wide variation of physical properties of the rocks in the area and that there are several different lithologies in the cores. The densities are generally in the range between 2610 and 2850 kg/m³, which is the density range of metamorphic rocks. The magnetic volume susceptibility is also in the general range of metamorphic rocks (Hunt et al., 2013).

Each specific rock type in the stratigraphy has a very wide range in density, natural remanent magnetization and magnetic volume susceptibility.

According to the literature data on petrophysical properties for different lithologies, the following rock types are present in the measured drill cores: volcanic siltstone, volcanic sandstone, rhyolite, skarn, calc silicate and dolomite, which all have been metamorphosed.

Volcanic siltstone has natural remanent magnetization range of 6-193 J, rhyolite 32-225 J, volcanic sandstone 22-149 J, dolomite 40-440 J, calc silicate rock 41-133 J and the skarn has a range of 4-134 J. The general density variations for the interpreted rocks are as follows: siltstone 2625-2670 kg/m³, rhyolite 2700-2760 kg/m³, volcanic sandstone 2421-2490 kg/m³, dolomite 2790-2800 kg/m³, skarn 3300-3320 kg/m³, volcanic sandstone 2550-2578 kg/m³ and the calc silicate rock around 3000 kg/m³. The magnetic volume susceptibility also has a wide range were the volcanic siltstone has a range between 34-297 SI, rhyolite 133-428 SI, volcanic sandstone 62-225 SI, dolomite 316-806 SI, calc silicate rock 144-527 SI and the skarn 1625-12299 SI (Hone et al., 1987; Hunt et al., 2013; Parasnis, 1971; Soltani et al., 2015). This wide ranges of the density and magnetic properties within each rock at Lovisa is related to the presence of ore minerals or porphyroblasts. The magnetic properties of a rock are usually caused by a very small fraction of the total composition of the rock (Schön, 2004). It is therefore likely that this wide range in the samples is related to a small fraction of skarn minerals and/or magnetite. Since skarn minerals and magnetite are common in the Lovisa cores it is possible that the samples with higher NRM and magnetic volume susceptibility have higher content of these minerals and the samples with the lower range have less content of ferrimagnetic minerals. The log description (Appendix 1), shows that sphalerite and galena is present not only in the ore zone but also in various concentrations throughout the host-rock nearby.

Another possibility for the wide range of magnetic properties within the rocks at Lovisa, is the variation of different grain size and grain shapes distributed within each sample. Albeit the volcanic siltstone and volcanic sandstone have a specific and small grain size fraction, it still has a small range and the grain size can vary. Stephenson et al. (2007) stated that a rock with smaller grains of magnetic minerals has a lower magnetic volume susceptibility than a rock with same proportion of magnetic minerals but whose grains are larger. This could also be a reason for the observed variations in the siltstone and sandstone as well for the other rock units.
The samples with higher values might contain larger grains of magnetic minerals than those with lower values.

The lithology interpretation based on petrophysical properties has been compared to the core logs and with Lovisa mine maps (figure 3) (appendix 1). Borehole 1501 cross cut a pyritic rhyolitic silt-sandstone (figure 3) and the lithology based on petrophysics and literature data give almost the same result as they fall within the range of volcanic siltstone, massive rhyolite and volcanic sandstone (figure 12). Borehole 1502 (figure 3) transect a rhyolite silt-sandstone with local thin mass flow deposits from 138-154 meter and between 188-197 meter there is a Fe oxide/skarn unit and grey rhyolitic silt-sandstone (figure 13). The petrophysical data between 138-154 meter overlap with literature data for siltstone followed by rhyolite, siltstone, dolomite, rhyolite, calc silicate rock, rhyolite and finally a unit of siltstone (figure 12). The location of boreholes 1503-1506, are not shown in the map (figure 3) but they crosscut the ore at 30 meters. After comparing the petrophysical results from boreholes 1501 and 1502 with the geological cross section at Lovisa (figure 3), it seems that the result and literature data reasonably matches the lithology.

The erroneous lithologies based on petrophysical literature data compared to drill core logs is partly a result of heterogeneity in the rocks composition (appendix 1-2). The presence of higher density layers or minerals within a lighter rock results in a rock type that mimic another rock. With measurements of a samples density, magnetic susceptibility and NRM it is impossible to determine these rather discrete variations in the rocks composition. The most obvious example is the dolomite correlation (figure 14-17 B) with 70 meters in total as dolomite, which is not present in any of the drill cores. Dolomite has generally been correlated with layers of skarn and galena. Because both skarn and layers with significant galena have high density, magnetic susceptibility and NRM, the presence of these minerals in a rock mimics dolomite that also have these petrophysical properties.

These petrophysical properties of rocks vary widely for the three measured physical properties and therefore a classification based solely on petrophysical data is inadequate.

The drill core lithologies derived from correlation with petrophysical data is more detailed but based on rather few measurements than the stratigraphy presented in Jansson et al. (2018) (figure 3) but not as detailed as the core logs (appendix 1). When geology is visualized in a cross section or on a map, it need to be generalised because the geology is often very complex and can change composition and texture within centimetres or less especially in zones which have been affected by hydrothermal alternation (appendix 1).

The reason for the crude rock names for the lithologies based on petrophysical data is related to the types presented in the literature, where only a very general classification of the different rocks and their physical properties is shown. The units in the drill cores are often heterogeneous (appendix 1 and 2), and contain other significant minerals or rock layers than typical rock units like banding, - lamination, - impregnations. There is no literature data that present this kind of heterogeneity and
this likely to be the most significant factor for the erroneous interpreted lithologies based on petrophysical data only.

5.2. Methods and limitations
An aspect that affects the detail level of the results is the interval between the measured samples that is approximately one sample every 1 to 6 meters. A consequence of the time limitation for the petrophysical measurements at SGU, is that only a restricted number of samples could be measured. The consequence is that important lithologies present in the drill cores have been missed and results in to extensive lithologies in some cases (figure 12-17) (appendix 1). Parts of the drill cores were not available especially from 1505 and 1506. This implies that a single unit extends over 46 meters in 1505 and 50 meters in 1506 (figures 10, 11 and 13) even though no samples have been collected and measured in these intervals.

To obtain meaningful results from petrophysical measurements, on a single or a few petrophysical properties, the sample measured needs to be homogeneous. Most samples measured here were in general relatively homogeneous according to visual determinations but some samples were not. Several samples also contain minerals that are not part of the major composition of the lithology (appendix 1 and 2), like quartz veins and porphyroblasts. For heterogeneous samples, density and magnetic properties values obtained from the petrophysic measurements might mimic a completely different rock that lead an incorrect interpretation of the lithology. This is probably the reason for the limited number of literature data that shows physical properties for specific lithologies (Hunt et al., 2013), and instead present properties for a general rock classification (i.e. igneous, sedimentary and metamorphic).

When interpretations of the lithologies are done based petrophysical characteristics, the physical properties measured are usually Gamma ray, sonic and PEF (Cannon, 2016), probably because the variation of these properties are much smaller for a specific rock than the properties measured in the Lovisa cores and possibly a more correct lithology interpretation would have been obtained if also these properties were measured. The reason for the fairly correct correlation with lithology and density, magnetic susceptibility and NMR is because of the rather adequate data in the literature. As described, the physical properties can vary significantly for a specific rock (appendix 2), and the literature data show the same range for density, magnetic susceptibility and NMR for several rock types and without the knowledge of the specific lithology (i.e. drill core logs), the suggested rock type derived from literature data would be inaccurate.
6. Conclusions

Based on the petrophysical properties the lithology of the host-rock to the ore at the Lovisa mine consists of volcanic siltstone, volcanic sandstone, massive rhyolite, calc-silicate rocks, skarn and dolomite. The log from Lovisa mine show that the host-rock also consists of sphalerite, volcanic rock, siltstone, galena-bearing units, massive rhyolite, skarn, breccia, meta-mafic rock, pegmatite, calcite-quartz veins, jaspelite, magnetite, ball ore, conglomerate and rocks with epidote, sericite and cordierite. To use only density, NMR and magnetic susceptibility data for lithological interpretation only works reasonable well if there is a good knowledge about the rocks present in the area and also a good understanding about the geologic processes that have affected them.

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References


**Internet sources**


Appendices

Appendix 1: Descriptive logs (provided by Lovisagruvan AB)

1501  161-169m

155-161.86  Felsic volcanic siltstone
161.86-162.19A  Felsic volcanic siltstone
162.19-163.07A  Sphalerite ore
163.07-163.22A  Sphalerite ore and felsic volcanic siltstone
163.22-164.08A  Sphalerite ore and felsic volcanic siltstone
164.08-164.98A  Felsic volcanic siltstone
164.98-168.40  Felsic volcanic siltstone
168.40-170.30  Felsic volcanic siltstone

1502  137-198m

169.30-179.50  Felsic volcanic rock
172.65-172.85  Fault breccia
179.50-180.30  Felsic volcanic siltstone (with epidote and porphyroblasts)
180.30-181.85  Skarn with magnetite (with felsic volcanic siltstone)
181.85-190.25  Felsic volcanic siltstone
190.25-190.52A  Skarn with felsic volcanic siltstone
190.52-191.74A  Skarn with magnetite
191.74-192.86A  Skarn with magnetite, calcite bands
192.86-193.39A  Magnetite with galena
193.39-193.78A  Skarn with magnetite
193.78-195.80A  Skarn with magnetite
195.80-196.30A  Felsic volcanic siltstone
199.60-199.90  Broken drill core
196.30-201.2  Felsic volcanic rock and skarn

1503  173-208m

170.70-173.82  Felsic volcanic siltstone with skarn
173.82-174.90  Felsic volcanic rock
174.90-175.96A  Felsic volcanic rock
175.96-176.45A  Sphalerite and galena ore (ball ore)
176.45-177.09A  Felsic volcanic siltstone
177.09-177.35A  Sphalerite ore (ball ore in felsic volcanic siltstone)
177.35-177.59A  Fractured quartz with sphalerite and galena
177.59-178.44A  Felsic volcanic siltstone with skarn
178.44-180.83A  Felsic volcanic siltstone
180.83-181.68A  Felsic volcanic siltstone
181.68-182.28A  Sphalerite ore with felsic volcanic siltstone and skarn
182.28-183.32A  Sphalerite ore with felsic volcanic siltstone and skarn
183.32-185.50  Felsic volcanic siltstone with skarn
185.50-189.00  Felsic volcanic siltstone
187.20-187.99  Broken drill core
187.99-188.12  Breccia
188.12-189.00  Broken drill core
189.00-189.30  Metamafic rock
189.30-200.50  Felsic volcanic rock with magnetite
189.60-190.10  Broken drill core
190.10-ff      Broken drill core
190-191.30     Loss of 0.2 meter drill core
191.30-192.80  Loss of 0.4 meter drill core
192.90-193.10  Breccia
193.10-194.14  Breccia (with clay)
195.20-198.30  Loss of 0.3 meter drill core
196.80-198.30  Loss of 0.7 meter drill core
198.30-200.50  Loss of 1.3 meter drill core
200.50-201.05  Felsic volcanic siltstone
201.05-201.23A Mafic metavolcanic rock
201.23-201.98A Felsic volcanic siltstone with sphalerite
201.98-203.53A Felsic volcanic siltstone with skarn
203.53-204.74A Felsic volcanic siltstone with skarn
204.74-205.30A Felsic volcanic siltstone with skarn
205.30-206.23  Felsic volcanic siltstone
206.23-206.75  Felsic volcanic siltstone
206.75-206.95  Felsic volcanic rock
206.95-207.95  Felsic volcanic rock
207.95-221.80  Felsic volcanic siltstone

1504  179-198m

178.40-179.16A Felsic volcanic rock
179.16-180.20A Felsic volcanic rock
180.02-180.92A Felsic volcanic rock
180.92-181.08A Felsic volcanic rock
181.08-182.24A Sphalerite ore (ball ore)
182.24-182.40A Sphalerite ore (with felsic volcanic siltstone)
182.40-182.52A Felsic volcanic rock with sphalerite
182.52-183.04A Felsic volcanic rock
183.04-185.28  Felsic volcanic rock
185.28-186.95A Felsic volcanic siltstone with sphalerite
186.95-188.53A Felsic volcanic siltstone with sphalerite
188.53-188.81A Sphalerite ore (with skarn)
188.81-189.29A Sphalerite ore (with skarn)
189.29-190.18A Felsic volcanic siltstone
190.18-190.70A Felsic volcanic siltstone with sphalerite
190.70-192.07A Felsic volcanic siltstone with sphalerite and skarn
192.07-193.60A Felsic volcanic siltstone with sphalerite and skarn
193.60-194.26A Felsic volcanic siltstone with sphalerite and skarn
194.26-195.19A Felsic volcanic siltstone with sphalerite
195.19-197.75  Felsic volcanic siltstone
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<td>Felsic volcanic siltstone with sphalerite and galena</td>
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<td>146.41-147.26A</td>
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<td>Felsic volcanic siltstone with sphalerite and skarn</td>
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<td>Felsic volcanic siltstone with skarn and epidote</td>
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<td>208.30-210.05A</td>
<td>Magnetite with skarn and galena</td>
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<td>Felsic volcanic rock with skarn</td>
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<td>220.17-221.95A</td>
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169.5-172.3  Felsic volcanic siltstone
172.3-172.9  Loss of 0.2 meter drill core
172.9-173.6  Felsic volcanic siltstone
173.6-174.25  Felsic volcanic rock with skarn
174.25-175.00  Felsic volcanic rock
175.00-175.90A  Felsic volcanic rock
175.90-176.13A  Sphalerite ore with galena
176.13-178.20  Felsic volcanic rock
178.20-178.93A  Felsic volcanic rock with sphalerite
178.93-181.10  Felsic volcanic rock
181.10-184.0  Felsic volcanic rock
184.0-187.25  Felsic volcanic rock
187.25-187.69A  Felsic volcanic rock
187.69-188.20A  Sphalerite ore with galena (ball ore)
188.20-188.88A  Sphalerite ore with galena (ball ore)
188.88-189.26A  Felsic volcanic rock with sphalerite
189.26-189.70A  Felsic volcanic siltstone with galena
189.70-194.86  Felsic volcanic siltstone
194.86-195.52A  Felsic volcanic siltstone
195.52-196.54A  Felsic volcanic siltstone with sphalerite
196.54-196.99A  Felsic volcanic siltstone with skarn and sphalerite
196.99–198.58A  Felsic volcanic siltstone with skarn
198.58-199.22A  Skarn with some sphalerite
199.22-199.85  Felsic volcanic siltstone
199.85–200.05  Felsic volcanic siltstone
200.05-200.18  Felsic volcanic rock
200.18-201.2  Skarn
201.2-202.1  Felsic volcanic rock
202.1-202.5  Skarn
202.5-208.05  Felsic volcanic siltstone
208.05-209.8  Felsic volcanic rock
209.8-217.2  Felsic volcanic rock
213.7-214  Quartz (vein/dyke)
214-ff  Skarn
217.2-218.8  Skarn
218.8-221.2  Felsic volcanic rock with skarn
221.2-224.4  Skarn
224.4-229.9  Felsic volcanic rock with skarn
229.9-233.16  Skarn
233.16-235.4  Felsic volcanic rock with skarn
235.4-250.66  Felsic volcanic rock with skarn and epidote
239  Jaspelite
239.85-240.8  Felsic volcanic rock
242.1-243.4  Breccia
243.4-250.66  Felsic volcanic siltstone
250.66-251.67A  Felsic volcanic rock
251.67-252.05A  Skarn with galena
## Appendix 2: Petrophysical data

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<th>Magnetic susceptibility K(uSI)</th>
<th>Natural remanent magnetization J(mA/m)</th>
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