

Sulfide chemistry and trace element department at the metamorphosed Lappberget Zn-Pb-Ag-(Cu-Au) ore body, Sweden: Implications for Mineral Processing

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Abstract. The 58 Mt Lappberget Zn-Pb-Ag-(Cu-Au) ore body represents one of the largest and most significant polymetallic base metal sulfide deposits in Sweden. The complex mineralogical characteristics of the ore body pose particularly tough challenges for successful production forecast because of the mixed Zn-Pb-Cu base metals, the complex association of the beneficial Ag and Au, and the presence of influential elements such as Sb, Mn and Mg. Thus, a detailed mineralogical characterization study was conducted, focusing on the department of trace and minor elements (including credit and penalty elements). Mineral chemistry data derived from electron microprobe and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) analyses reveal the complexity in the composition and associations of the ore minerals, consisting of textural and chemical varieties of sphalerite, galena, chalcopyrite, iron sulfides, antimonides and sulfosalts. Recrystallization, re-mobilization and re-concentration of sulfide minerals, compositional banding, and ductile and brittle deformation textures (i.e. deformation twins on sphalerite, brecciation, bent cleavage planes, etc.) are observed throughout the deposit. The mineralogical and textural complexity and heterogeneity of the sulfide ore are reflected in the variability in grades and recovery from the processing plant.

1 Introduction

Located approximately 180 km northwest of Stockholm, the Lappberget ore body is part of Boliden Mineral AB's Garpenberg mine, Sweden's oldest still-operating mine. Recent research has shown that mining operation started as far back as 375 BCE (Bindler et al. 2017) and it has developed into one of the country's largest base metal mines. The mine targets several sulfide ore bodies distributed along the northwestern limb of the Garpenberg syncline (Figure 1). The ore bodies are commonly located in upright structural domes. Lappberget is the largest ore body in the mine with a combined mineral resource and ore reserve of 58 Mt at 3.42% Zn, 1.68% Pb, 0.06% Cu, 70 g/t Ag and 0.41 g/t Au (Högnäs 2018). It is hosted by intensely altered and metamorphosed felsic volcanic rocks and former limestone that are overlain by less altered metavolcanic rocks. Mineralization formed at c.1.89 Ga, prior to ductile deformation and metamorphism during the Svecokarelian orogeny (Jansson and Allen 2011). Allen et al. (1996) suggested that the mineralization was

formed as a subsea-floor stratabound replacement-type deposit (SVALS-type), associated with a major caldera-forming volcanic event. The metamorphic grade is estimated at lower amphibolite facies with a peak metamorphic temperature of 550°C at pressures below 3.5 kbar (Vivallo 1985). The metamorphic overprint has made it uncertain whether calc-silicates in the ores formed during metamorphism (cf. metamorphosed VMS) or in conjunction with ore formation as in metasomatic skarn deposits (cf. Jansson and Allen 2011).

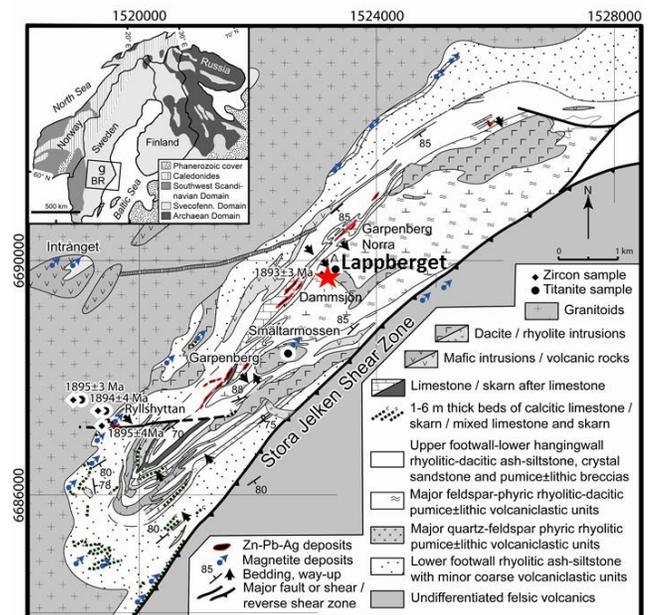


Figure 1. Regional geological map of the Garpenberg area with inset showing the location of the Bergslagen (BR) region where Garpenberg (g) is located (Jansson and Allen 2011b). Ages refer to dated metamorphic rocks intrusions presented in Jansson and Allen (2011a). Grid is Swedish National Grid RT90.

The ore body is currently being mined and processed to produce four different concentrates: Zn, Pb, Cu and a gravimetric concentrate. The complex mineralogical characteristics of the ore body pose particularly tough challenges for successful production forecast because of the mixed Zn-Pb-Cu base metals, the complex association of the beneficial Ag and Au, and the presence of influential elements such as Sb, Mn and Mg. There are few studies addressing the sulfide ores from Garpenberg, and the existing accounts mainly focus on other aspects of the deposits (e.g. Allen et al. 1996; Vivallo 1985). Currently, there is no published literature on the

metallurgical assessment of the Lappberget ore body. Thus, this study aims to provide a detailed mineralogical characterization of the Lappberget sulfide ore body, focusing on the deportment of trace and minor elements (including credit and penalty elements). The result will provide constraints in identifying the metallurgical behavior of the ore during flotation, which can help a) improve the grade and recovery of the processing plant and b) determine its possible environmental impact.

2 Methodology

Drill core samples were collected from various sections of the ore body. Petrographic investigations were carried out on thin sections, using optical light microscopy and scanning electron microscopy (SEM). Sputter-coating with carbon was undertaken for all SEM and electron probe microanalyses (EPMA). Mineral chemistry data were derived for twenty-five thin sections on a CAMECA SX100 electron microprobe at the Geological Survey of Finland equipped with five wavelength-dispersion spectrometers (TAP, 2 LLIF, PET and LPET). All the sulfide analyses were determined using an accelerating voltage of 20 kV with a probe current and beam diameter of 40 nA and 1 micrometer, respectively. Natural minerals and metals were used as reference standards.

Quantitative trace element composition of sulfides was derived using a New Wave Research (NWR193) laser-ablation system coupled to an iCAP-Q quadrupole inductively coupled plasma mass spectrometer (LA-ICPMS, Thermo Scientific) at Luleå University of Technology. Spot sizes of 50 μm and 25 μm were used with a laser repetition rate of 5 Hz and a total acquisition time of 85 s (15 s background measurement, 30 s sample ablation and 40 s delay). The following isotope suites were analyzed: ^{34}S , ^{49}Ti , ^{51}V , ^{53}Cr , ^{55}Mn , ^{57}Fe , ^{59}Co , ^{60}Ni , ^{65}Cu , ^{66}Zn , ^{69}Ga , ^{73}Ge , ^{75}As , ^{77}Se , ^{95}Mo , ^{107}Ag , ^{111}Cd , ^{115}In , ^{118}Sn , ^{121}Sb , ^{125}Te , ^{182}W , ^{193}Ir , ^{197}Au , ^{202}Hg , ^{205}Tl , ^{208}Pb and ^{209}Bi , with a total sweep time of 0.840 s. ^{66}Zn was used as the sphalerite internal standard, ^{208}Pb for galena and ^{57}Fe for the other sulfides. Data reduction was done using the IOLITE software package (Paton et al. 2011).

3 Ore mineralogy and texture

The Lappberget ore body contains sphalerite, galena, pyrite, pyrrhotite, chalcopyrite and magnetite as the main sulfide and oxide components. Trace amounts (generally <0.1 wt%) of tetrahedrite-tennantite ((Cu,Fe) $_{12}$ (Sb,As) $_4$ S $_{13}$), bournonite (PbCuSbS $_3$), freibergite ((Ag,Cu,Fe) $_{12}$ (Sb,As) $_4$ S $_{13}$), boulangerite (Pb $_5$ Sb $_4$ S $_{11}$), jamesonite (Pb $_4$ FeSb $_6$ S $_{14}$), dyscrasite (Ag $_3$ Sb), gudmundite (FeSbS) and arsenopyrite (FeAsS) are also present. Rarer minerals present are cubanite (CuFe $_2$ S $_3$), troilite (FeS), native antimony, native silver, allargentum (Ag $_{1-x}$ Sb $_x$), nisbite (NiSb $_2$), ilmenite (FeTiO $_3$), gahnite (ZnAl $_2$ O $_4$), and native arsenic. Sphalerite, pyrite and galena occur in all massive sulfide ores but in varying proportions. Magnetite is only abundant in the uppermost and easternmost portion of the ore body (Jansson 2011).

The more plastic sulfide minerals (i.e. galena,

chalcopyrite, sphalerite, pyrrhotite) display ductile deformation textures, interstitial overgrowth, annealing with triple junctions, and locally occur as inclusions in garnet and quartz. In contrast, the more rigid sulfide minerals (i.e. pyrite, arsenopyrite, tetrahedrite) exhibit cataclastic textures with gaps filled with plastic sulfide minerals, rounded grains, late euhedral open-space fill, and intergrowth and overgrowth textures (Figure 2). Tetrahedrite generally occurs as myrmekitic exsolutions in galena. Troilite only occurs as an exsolution in pyrrhotite, whereas cubanite is commonly present as exsolution lamellae in chalcopyrite but may also occur as individual grains. Silver minerals (i.e. dyscrasite, allargentum) are typically associated with the presence of tetrahedrite, Ag-rich chalcopyrite, cubanite, and alabandite.

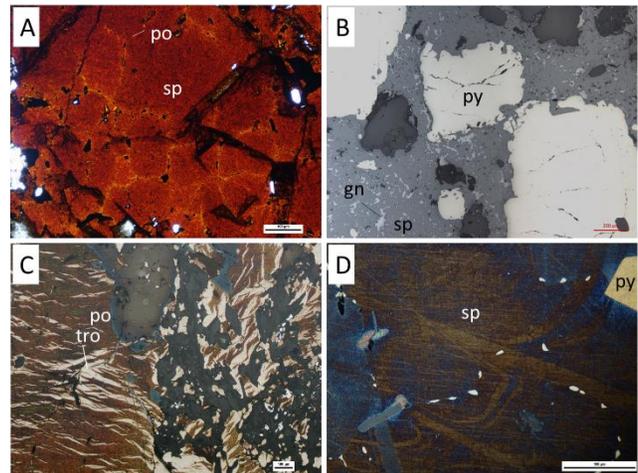


Figure 2. Photomicrographs of different sulfide textures. (A) annealed sphalerite grains showing triple junctions and pyrrhotite inclusions along boundaries (LPB1617-91.02, plain transmitted light), (B) tectonoclastic rotation and rounding of pyrite in sphalerite-galena matrix (LPB1101-246.03, reflected light), (C) coarse flame texture resulting from low temperature exsolution of troilite in pyrrhotite, which has undergone brecciation; sample etched with NaClO (LPB1103-198.32, reflected light), and (D) deformation twins in sphalerite; sample etched with NaClO (LPB3458-178.06, reflected light). Abbreviations: gn–galena, po–pyrrhotite, py–pyrite, sp–sphalerite, and tro – troilite.

3.1 Mineral chemistry of sulfide minerals

Sphalerite is the main Zn mineral in the Lappberget ore body and occurs in massive sulfide lenses, veins and disseminations. It commonly contains pyrrhotite or chalcopyrite inclusions. Results from this study show varying concentration of Zn, Fe and Mn (Figure 3), allowing four sphalerite populations to be identified: 1) Zn-rich (Fe- and Mn-poor), 2) Fe-rich, 3) Mn-rich and 4) Fe- and Mn-bearing. Zn-rich sphalerite contains elevated amounts of Cd, In, Co and Sb but lower Ga and Ge as compared to the other sphalerite populations.

Galena, the main Pb mineral in Lappberget, generally occurs with sphalerite. It exhibits a plastic behavior, typically occurring as an interstitial phase between sphalerite and, less commonly, pyrrhotite and chalcopyrite. Mineral chemical analyses of galena reveal varying concentration of Ag, Sb and more rarely As in the

crystal lattice. Galena may contain 0.01 – 0.24 wt% Sb, 0.01-1 wt% As and 0.10-0.20 wt% Ag. The high Sb and As content coincide with the presence of neighboring gudmundite and arsenopyrite, respectively.

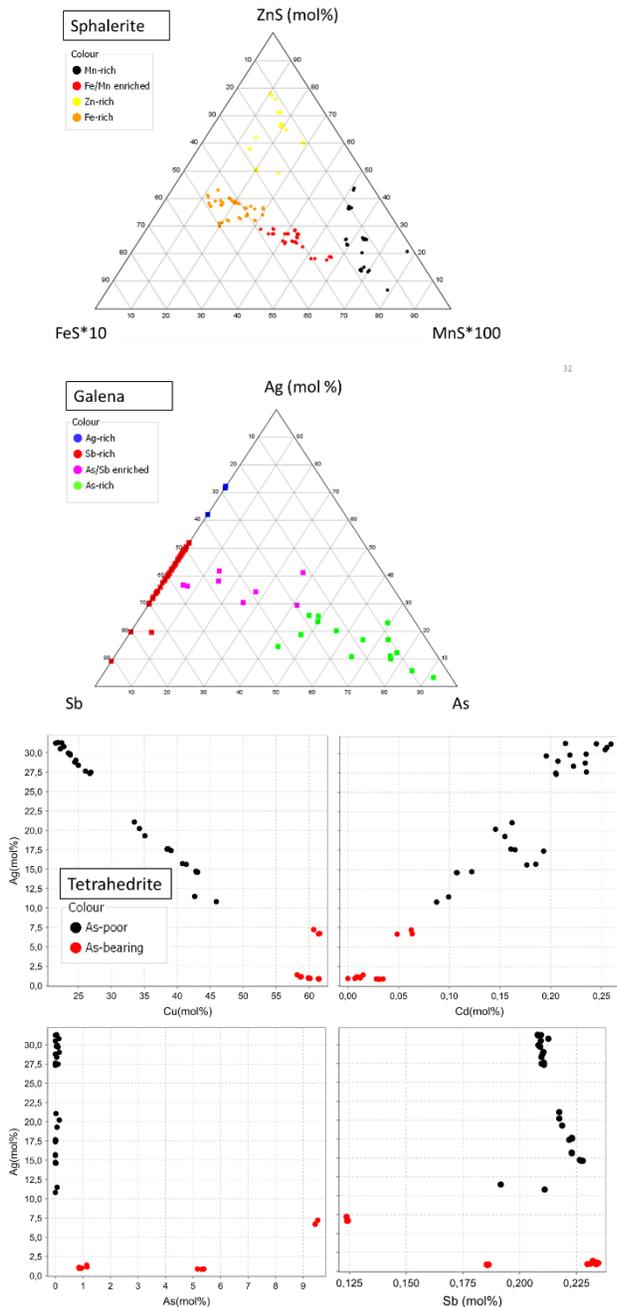


Figure 3. Plotted mineral composition of sphalerite, galena and tetrahedrite based on EPMA data, showing distinct element clusters.

Chalcopyrite is the most abundant Cu mineral in the deposit. It predominately occurs in the lower part of the deposit and is associated with Fe-rich silicates (e.g. biotite). Mineral chemistry of chalcopyrite from EPMA data shows an Ag-rich population of chalcopyrite. However, these results must be interpreted with caution since petrographic analysis shows the presence of tarnished chalcopyrite grains, which according to LA-ICPMS analysis have a thin Ag_2S coating.

Tetrahedrite is the most abundant Ag-bearing mineral in Lappberget and serves as another Cu source. It typically occurs as exsolutions in galena, forming irregular grains 1-100 μm in size. Mineral composition varies considerably in Ag, Cu, Sb and As content (**Error! Reference source not found.3**). Silver shows a strong positive correlation with Cd and a negative correlation with Cu. The presence of As (>0.5 wt%) in tetrahedrite drastically lowers its silver content. Myrmekitic textures containing the assemblage tetrahedrite (secondary) + chalcopryite + sphalerite + gudmundite + arsenopyrite + dyscrasite \pm native antimony \pm alabandite are possibly a result from the breakdown of earlier tetrahedrite grains.

Pyrite typically occurs as porphyroblasts in the massive sulfide ore and as disseminations in micaceous and quartzose hydrothermally altered rocks. Grain size varies widely from 100 to 2000 μm and the grains seldom display brittle deformation. LA-ICPMS analysis of pyrite samples shows varying trace element distribution as shown in Figure 4. Generally, inclusion-free pyrite has a low and homogeneous trace element distribution, whereas inclusion-rich pyrite contains elevated Ag, As and Co values.

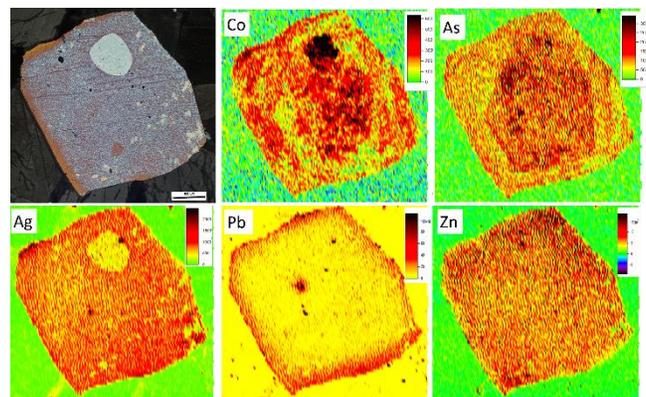


Figure 4 LA-ICPMS trace element mapping of subhedral inclusion-bearing pyrite, which reveals a Co-rich pyrite inclusion (distinguishable in the photomicrograph of the sample etched in NaClO) and an As-rich core (LPB1617-277).

In samples where sphalerite, galena, chalcopryite, and pyrite co-exist, sphalerite is the primary host for Mn, Cd, Ga and Hg. Bismuth is preferentially concentrated in galena whereas Co, Ni and As is preferentially hosted by pyrite. Silver and Sb is highest in chalcopryite followed by galena.

4 Implications for mineral processing

This detailed mineralogical characterization of the Lappberget ore body reveals the complexity in the composition and associations of the ore minerals, including various types of textural and chemical varieties of sphalerite, galena, chalcopryite, iron sulfides, antimonides and sulphosalts. Recrystallization, remobilization and re-concentration of sulfide minerals, annealing of crystals, compositional banding, and ductile and brittle deformation textures (i.e. sphalerite deformation twins on sphalerite, cataclasis, bent cleavage planes, etc.) are observed throughout the

deposit.

The genetic classification of the Lappberget deposit is still unclear since primary textures are highly masked by subsequent metamorphism and deformation. This investigation shows that the formation and modification of the Lappberget sulfide ores occurred at varying physiochemical conditions, giving rise to the heterogeneity of the sulfide minerals. By inference, the resulting sulfide ore varieties are expected to behave differently during flotation. For instance, it is known that varying iron content in sphalerite can have different flotation kinetics (Boulton et al. 2005; Harmer et al. 2008). High Mn and Co content in sphalerite and high Bi and Sb content in galena are deleterious in the pyrometallurgical process (Sinclair 2009, 2005). During the smelting process, high levels of Zn in the copper concentrate and of Cu in the lead concentrate significantly reduce the recovery of copper and lead, respectively (Fountain 2013).

Antimony and As-bearing sulfosalts (e.g., tetrahedrite-tennantite, jamesonite, bournonite, boulangerite) are economically unattractive since Sb and As are highly volatile elements during thermal processes and require additional treatment to prevent hazardous emissions during smelting (Lane et al. 2016). Similarly, the presence of As-bearing minerals, such as arsenopyrite and native arsenic, which reports to the tailings, could pose environmental problems, if not properly managed. On the other hand, high Ag in tetrahedrite, galena and chalcopyrite are economically desirable as long as its effect on the beneficiation route is properly understood.

5 Conclusion

A detailed mineralogical and textural study of the Lappberget ore body highlights the complexity of the sulfide associations in the ore body reflecting a complex geological chain from the initial mineral formation to subsequent recrystallization, remobilization and deformation. The heterogeneity in composition and grain size of the ore minerals can significantly affect flotation performance. For complex ore bodies such as Lappberget, deleterious elements (e.g. As, Sb, Cd, Mn and Hg) should be included in the routine chemical analysis of drill cores to help identify local concentrations.

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