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Ag-Sb bearing minerals from the Kongsberg Silver Deposit, Buskerud, Norway

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Introduction

The historical silver mines at Kongsberg, Norway, were operative more or less continuously from 1623 to 1958. The mines are world-famous for spectacular samples of wire silver exhibited in numerous mineralogical museums around the world. Minerals reported from the deposit include native elements (Ag, Au, As, Cu, S, C), sulphides, sulphosalts, selenides, arsenides, carbonates, sulphates, arsenates and halides, in addition to a range of silicate minerals (Neumann 1944, Johnsen 1986, 1987, Bancroft *et al.* 2001). Knowledge of the compositional variations of native silver and other minerals from the deposit is limited as little data acquired by modern analytical techniques e.g. electron microprobe has been published so far. The present paper gives a first modern documentation of the compositional variations of Ag-Sb bearing minerals from the silver deposit.

Geological setting

The silver mines occur in an about 30 km long and 10 km wide area (Fig. 1) within the Kongsberg Terrane belonging to the Sveconorwegian orogenic belt in S. Norway (Bingen *et al.* 2008). The host rocks of the mines are dominated by Proterozoic (≈ 1.6 Ga) quartz-plagioclase-biotite gneisses, mica and chlorite schists, amphibolites and granitic gneisses (Bugge 1917, Jacobsen and Heier 1978, Starmer 1985). Presence of *fahlbands* (Fig. 1), i.e. north-south striking subvertical zones enriched in sulphides, predominantly pyrite and pyrrhotite (e.g. Bugge 1917, Gammon 1966), is typical for the area. The two largest fahlbands, which occur in the central mine area, are called Overberget and Underberget. The fahlbands are cross-cut by nearly vertical E-W trending mafic dikes and quartz and calcite veins. K-Ar whole rock data from the mafic dikes suggest that they are Permian (270 - 276 Ma) and related to the Oslo Rift. Field relationships indicate that the emplacement of the mafic dikes occurred close in time with the formation of the quartz and calcite veins (Ihlen *et al.* 1984). In the early days workers in the mine became aware that the native silver mineralizations occur exclusively at the intersections between the calcite veins (subvertical, running E-W) and the sulphide-enriched *fahlbands* (e.g. Bancroft *et al.* 2001).

Field observations suggest that the quartz veins, which carry sulphides of iron, copper, zinc and lead, are older than the calcite veins (Neumann 1944). Neumann (1944) reported two types of calcite veins, one silver-bearing and one silver-free. The latter veins are thicker and more extensive than the silver-bearing ones. In addition to calcite, the silver-free veins carry fluorite, sphalerite and galena. Neumann (1944) referred to the silver-bearing veins as “*calcite – nickel-cobalt-arsenide – native silver veins*”, and described them as very narrow, varying in width from a few mm, rarely up to 0.5 m,

with an average thickness of 5 to 10 cm. He mentioned, however, that the silver-bearing calcite veins in places can be as big as an ordinary sitting-room.

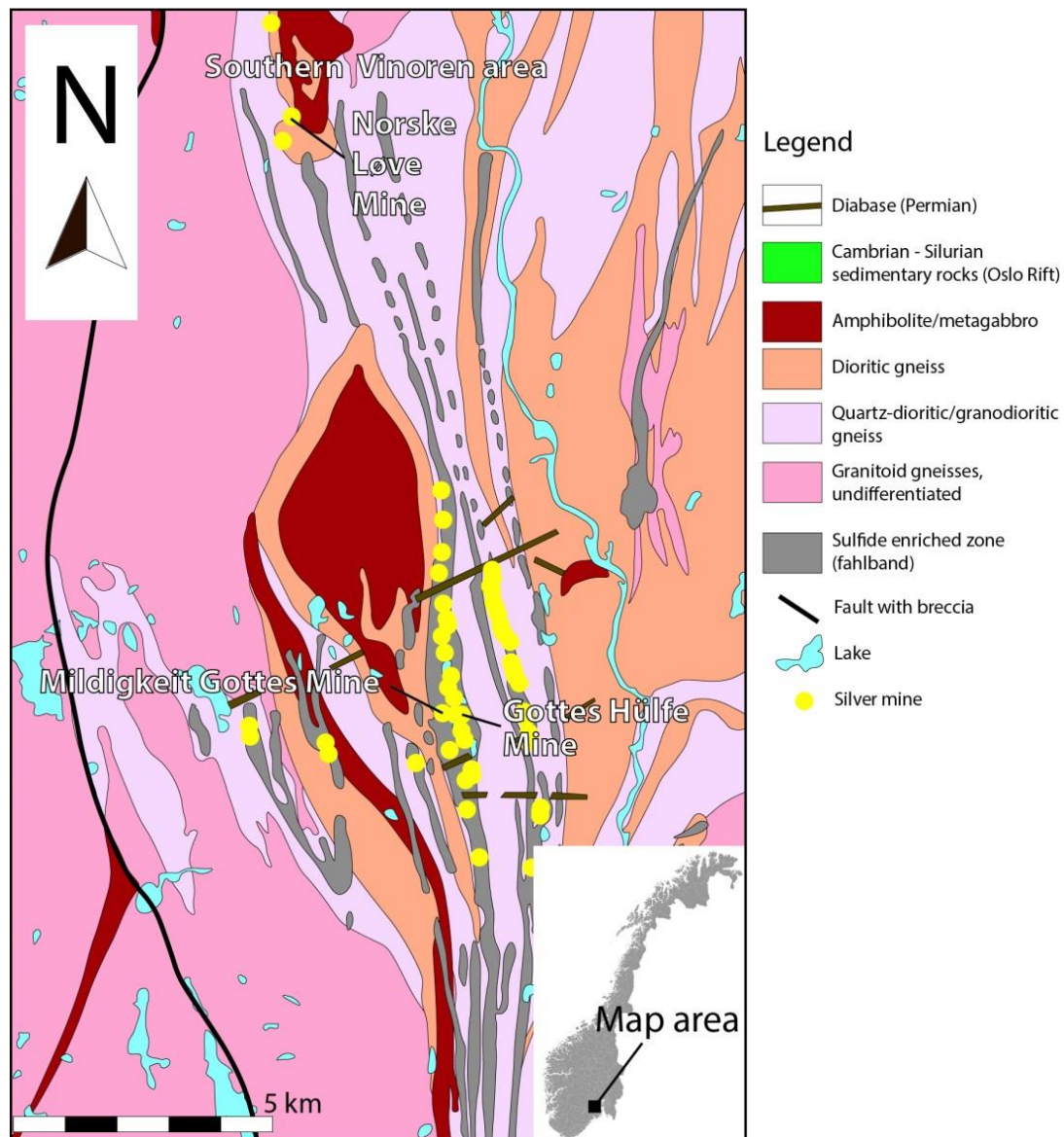


Fig. 1. Geological map of the Kongsberg Silver Deposit.
Modified after Gammon (1966) and Dons and Jorde (1978).

Antimony bearing minerals

Previous work

Neumann (1944) reported the antimony bearing minerals dyscrasite, tetrahedrite, stephanite, polybasite and pyrargyrite from the Kongsberg Silver Deposit (see Table 1 for mineral formulas). He inferred that polybasite and tetrahedrite formed at an early stage prior to native silver, while pyrargyrite and stephanite formed during replacement of native silver. However, Neumann (1944) did not make any conclusion concerning the age relationship between native silver and dyscrasite.

Table 1. Antimony-bearing minerals from the Kongsberg Silver Deposit

Mineral	Formula	Neumann (1944)	This study
Antimonial silver	(Ag,Sb), Sb < 5%		x
Dyscrasite	Ag ₃ Sb	x	x
Allargentum	Ag ₆ Sb		x
Pyrargyrite	Ag ₃ SbS ₃	x	x
Miargyrite	AgSbS ₂		x
Stephanite	Ag ₅ SbS ₄	x	x
Polybasite	[(Ag,Cu) ₆ (Sb,As) ₂ S ₇][Ag ₉ CuS ₄]	x	x
Tetrahedrite	(Cu,Fe) ₁₂ Sb ₄ S ₁₃	x	x

Petrographical observations

For the present study, polished ore samples and thinsections were prepared from 14 samples from the northern and central parts of the silver deposit. Antimony bearing minerals were identified in 7 of the samples. Polybasite was observed in six samples collected from the South Vinoren area and the area around the mines Gottes Hülfe in der Not and Mildigkeit Gottes (Fig. 1). Minerals belonging to the tetrahedrite isotypic series were present in three samples from the same areas. Antimonial silver, dyscrasite, allargentum, pyrargyrite and miargyrite occur in one of the samples from the Norske Løve Mine, South Vinoren, while stephanite occurs in one sample from Mildigkeit Gottes Mine.

The ore minerals show complex textural relationships (Figs. 2 and 3), making the determination of their age relationships difficult. The presence of acanthite, polybasite and chalcopyrite as inclusions in native silver (Fig. 2a) suggest that these minerals formed at an early stage, prior to native silver. However, the occurrence of polybasite in the matrix and occasionally replacing native silver suggests several stages of polybasite formation. The earliest generation of native silver often occurs as sub- to euhedral grains, commonly with a thin rim of a [(Ni,Co,Fe)AsS] polymorph, possibly alloclasite (Fig. 2b). The second generation of native silver envelopes the earliest silver generation with its rims of alloclasite (Fig. 2b). Tetrahedrite shows several types of textural occurrence (Fig. 2b and c). One possible interpretation of the textures in Fig. 2b is that tetrahedrite replaced parts of the first generation of native silver, after formation of the thin rims of alloclasite, but prior to the formation of the second generation of native silver. More work is needed before the age relationships between native silver and the two phases belonging to the tetrahedrite isotypic series shown in Fig. 2c can be established.

Textural relationships between native silver, allargentum, dyscrasite and pyrargyrite (Fig. 3) suggest that allargentum formed as the latest phase during reactions between pyrargyrite and native silver, and dyscrasite and native silver. However, the age relationships between native silver, dyscrasite and pyrargyrite are uncertain. Stephanite replacing native silver was observed in one sample.

Mineral compositions

Chemical analyses of the minerals were performed using the CAMECA SX100 electron microprobe at Masaryk University in Brno, Czech Republic. Compositional variations of dyscrasite, allargentum and antimonial silver are shown in Fig. 4, and compositional variations of phases belonging to the tetrahedrite isotypic series in Fig. 5. Dyscrasite contains 73.9-76.3 wt% Ag, corresponding to 76.2-78.4 atomic % Ag per formula unit (p.f.u.), which is higher than for the ideal formula (Ag₃Sb – 75

atomic % Ag). Allargentum contains 85-86 atomic % Ag p.f.u., which is close to the ideal formula (Ag_6Sb – 85.7 atomic % Ag).

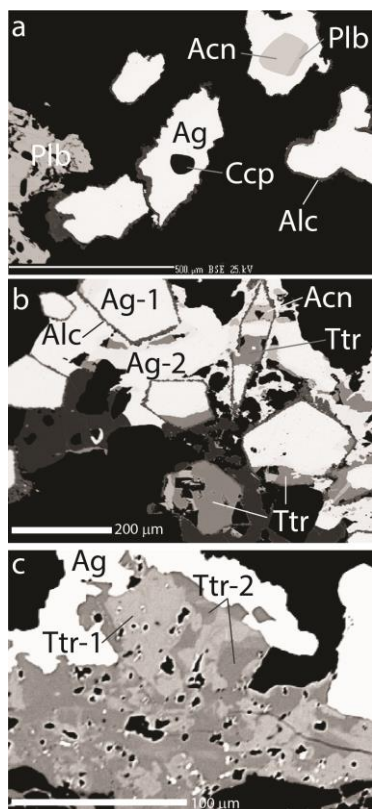


Fig. 2a-c. Back-scattered electron images showing the occurrences of polybasite (Plb), acanthite (Acn), native silver (Ag), chalcopyrite (Ccp), pyrite (Py), pyrargyrite (Pgy), miargyrite (Mgy), dyscrasite (Dsc), tetrahedrite (Ttr), and allargentum or one of its polymorphs (Alc). Note the presence of two compositionally different types of tetrahedrite (Ttr-1 and Ttr-2, indicated by two different shades of grey) in c.

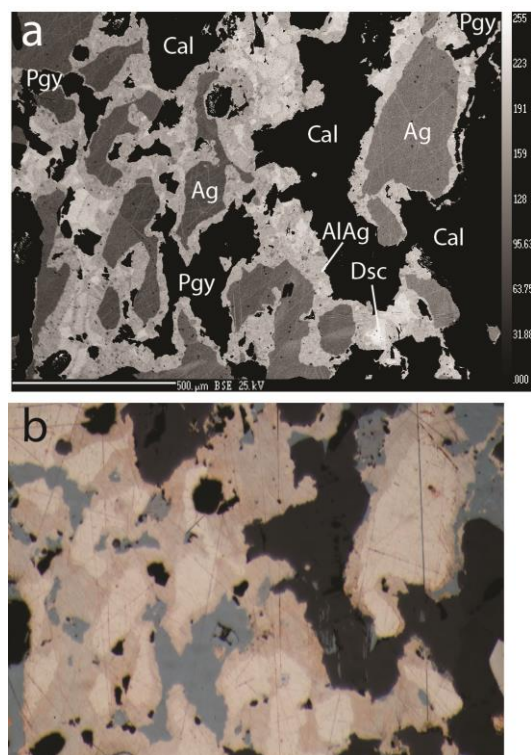


Fig. 3. Back-scattered electron image (a) and reflected light photomicrograph (b) of a sample from the Norske Løve Mine, South Vinoren, showing textural relationships between antimonial silver (Ag), pyrargyrite (Pgy), dyscrasite (Dsc), allargentum (AlAg) and calcite (Cal). The brightness of the mineral phases in a is controlled by the atomic weight of elements constituting the minerals. Colors in b: pyrargyrite = bluish grey, native silver = white, dyscrasite and allargentum = light grey, calcite = black.

Minerals from the deposit belonging to the tetrahedrite isotypic series contain about 2 atoms Fe, 4 atoms Sb and 11.75-13.15 atoms S p.f.u. The high-sulfur grains contains about 3.5 atoms Ag and 6.5 atoms Cu per formula unit, while the low-sulfur grains contain about 6 atoms Ag and 4 atoms Cu per formula unit. Both the S-rich and the S-poor types can be classified as freibergite $[(\text{Ag,Cu})_{10}(\text{Fe,Zn})_2\text{Sb}_4\text{S}_{12-13}]$. Native silver contains up to 2.8 atomic % Sb and can be termed antimonial silver.

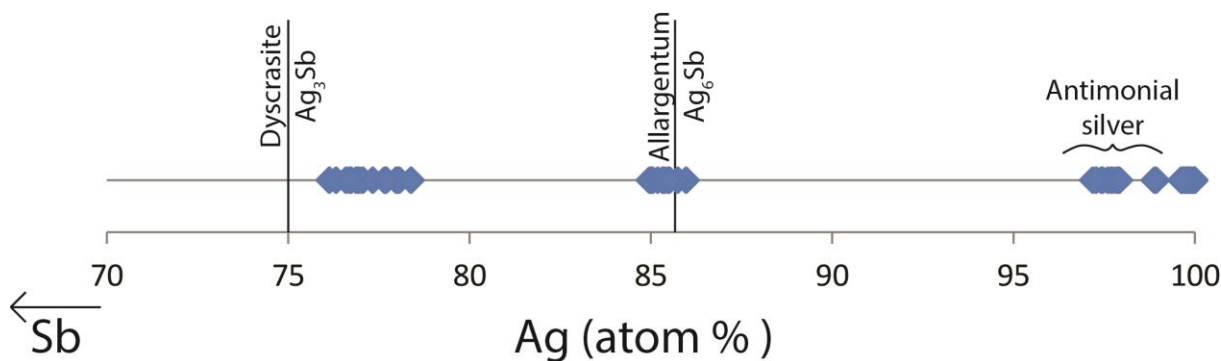


Fig. 4. Binary Sb-Ag diagram showing the compositional variations of dyscrasite, allargentum and native silver (including antimonial silver) from the studied samples.

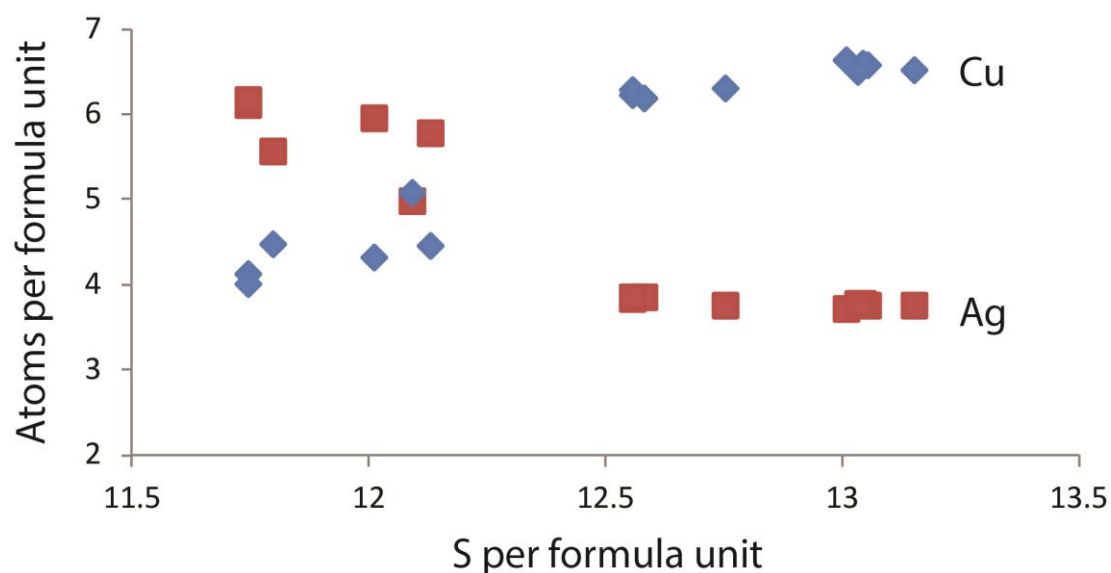


Fig. 5. Cu (blue diamonds) and Ag (red squares) vs. S of minerals belonging to the tetrahedrite isotypic series, showing variations between the approximate compositions $\text{Ag}_{3.5}\text{Cu}_{6.5}\text{Fe}_2\text{Sb}_4\text{S}_{13.15}$ and $\text{Ag}_6\text{Cu}_4\text{Fe}_2\text{Sb}_4\text{S}_{11.75}$.

Discussion and conclusions

Antimony bearing minerals have been identified in 7 of 14 investigated samples from the Kongsberg Silver Deposit, suggesting that antimony is a common trace element at the deposit.

The antimony bearing minerals include native silver (antimonial silver), allargentum, dyscrasite, miargyrite, pyrargyrite, stephanite, polybasite and a mineral belonging to the tetrahedrite isotypic series, which classifies as freibergite.

It is inferred that polybasite formed at an early stage together with acanthite and chalcopyrite, prior to precipitation of native silver. Furthermore, polybasite formed at a late stage, as well as allargentum and stephanite, replacing native silver. Native silver formed during at least two stages, interrupted by a stage of alloclasite formation. The age relationships between native silver, dyscrasite, pyrargyrite, miargyrite and freibergite cannot be determined based on the present data.

The ore mineralogy of the deposit suggests significant fluctuations in the contents of sulfur and arsenic of the ore-forming fluid through time. The observed distribution of antimony-bearing minerals in the studied samples might suggest variations in the Sb-content of the source of the ore-forming fluid as well.

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