Svartliden gold mine: shear zone and BIF-hosted orogenic gold deposit, Gold Line, northern Sweden

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Abstract The Svartliden gold deposit is found within a metamorphosed volcano-sedimentary sequence within the Bothnian Basin and has been recognized as an orogenic, lode-style gold deposit with strong stratigraphic and structural controls on mineralization. The entire volcano-sedimentary sequence and mineralization have been overprinted by several episodes of deformation including a first episode of tight folding, followed by intense shearing which has divided the geology into discontinuous shear lenses, a second episode of gentle folding, and late-stage brittle deformation. The ore zone is situated at the contact between amphibolite, banded-iron formation (BIF), and meta-sediments. The ore zone is associated with a quartz mylonite which is interpreted to have been created by a fault/shear zone and which served as the main conduit for hydrothermal fluid flow. The BIF acted as a chemical trap for low-salinity, deep-sourced As-Au-bearing fluids. Ore bodies contain massive calc-silicate and silica-rich mineral assemblages and are mineralized with löllingite-arsenopyrite-pyrrhotite. Gold is present in the form of electrum with 18–32 % silver and occurs at the löllingite-arsenopyrite interface. The main phase of hydrothermal alteration and ore formation is considered to be pre- to syn-metamorphic and the peak metamorphic conditions reached lower to mid-amphibolite facies.

Keywords Gold Line, orogenic lode-gold, banded-iron formation, amphibolite facies metamorphism

1 Introduction

The Svartliden gold deposit is located in the Storuman-Lycksele area, ca. 50 km southwest from the well-known Skellefte Distict in northern Sweden. The NW-SE trending anomalous gold belt known as the “Gold Line” is situated in supracrustal rocks of Paleoproterozoic age and hosts a number of gold deposits and occurrences, e.g. Knaften, Fäboliden, Svartliden, Stortjärnhobben, Barsele, and Blaiken (Bark 2008). The Svartliden gold deposit is the only deposit in production in this region, operating since 2005 by open-cut and underground mining methods. By September 2012, the mine had produced 307,286 ounces of gold from 2.38 million tonnes of ore grading 4.42 g/t gold.

2 Regional geology

The prominent Skellefte District hosts a large number of Au-rich massive sulfide deposits, a few low-grade porphyry Cu deposits and a number of gold deposits. It is considered to be a relic of a Palaeoproterozoic volcanic arc which was formed at the margin of an Archaean continental landmass to the north and a sedimentary basin to the south (Allen et al. 1996). In the Early Proterozoic, the Archaean craton rifted with the final break-up at ca. 1.95 Ga, generating a large oceanic basin to the south referred to as the Bothnian Basin (Nironen 1997). The Bothnian Basin mainly consists of a sequence of meta-greywackes and meta-pelites, with a thickness (> 10 km) suggesting formation at a shallow continental margin (Lundqvist 1987), as well as mafic meta-volcanic rocks (Kathol & Weihed 2005). The supracrustal rocks were intruded by S-type granites of the Skellefte-Härnö and Revsund calc-alkaline suite, and to a lesser extent by gabbros, during the Svecokarelian orogeny (1.9 to 1.77 Ga; Claesson & Lundqvist 1995).

The geology of the Storuman-Lycksele ore province is dominated by sedimentary and mafic volcanic rocks of the Bothnian Supergroup metamorphosed to conditions of lower to mid-amphibolite facies, with abundant Svecokarelian granitic plutons (Kathol & Weihed 2005).

3 Geology of the Svartliden deposit

3.1 Geological setting and tectonic evolution

The Svartliden gold deposit is hosted by two major rock types: meta-volcanics and meta-sediments (Fig. 1). The sequence is dominated by meta-sedimentary rocks, which bound and split the meta-volcanics into separate northern and southern units. The meta-sedimentary rocks mostly consist of biotite-rich schists. The northern boundary with the meta-volcanics is marked by a graphite and sulfide-bearing schist. The mineralization occurs at the contact between the northern amphibolite and the middle sediment package and is related to beds and lenses of banded iron formation. The entire Svartliden sequence was intruded by numerous granites dikes and sills of the Skellefte-Harnö suite (Andersson 2012) at 1800 ± 8 Ma (Persson 2011).

The Svartliden deposit has a complex deformational history with several episodes occurring after mineralization and subsequently deforming the ore body. The earliest structure observed in the sequence is likely related to a quartz mylonite, typically located adjacent to the ore zone, generally between the BIF and the amphibolite. While not mineralized, its proximity to mineralization is significant and discussed in the following sections.

Based on thickness changes, observed parasitic folds and the geometry of the ore body, the sequence appears to be tightly folded, with an axial plane roughly parallel to strike, and has created the appearance of multiple lodes. While folds often create fluid traps as observed in the Victoria Gold Fields and elsewhere (Narayanaswami et al. 1960, Schaubs & Wilson 2002, and others), the folding at Svartliden appears to occur post-mineralization based on observed parasitic folds of the ore body as well as the geometry of the lodes which lack prominent saddle reefs.

The most significant deformational event occurred post-folding in the form of intense and widespread shearing that affected the entire sequence. This deformation complicated the geology by creating en echelon shear lenses that are observed from hand specimen to regional scale in most lithologies. The effect is more pronounced in the mineralized zone where rheological contrasts and previous deformation associated with the quartz mylonite are localized. The result is a lack of continuity in the ore body as well as stratigraphy since the shear lenses act as boudins on a local and regional scale. Sulfides are often remobilized along the shear planes that bound those lenses present near the ore zone resulting in locally elevated gold values.

Post-shearing, the deposit was folded once again, albeit rather gently and creating a gentle synform with a fold axis perpendicular to strike. Lastly, brittle faulting cuts the stratigraphy with the greatest offset occurring in the middle of the deposit along a primarily left-lateral strike-slip fault.

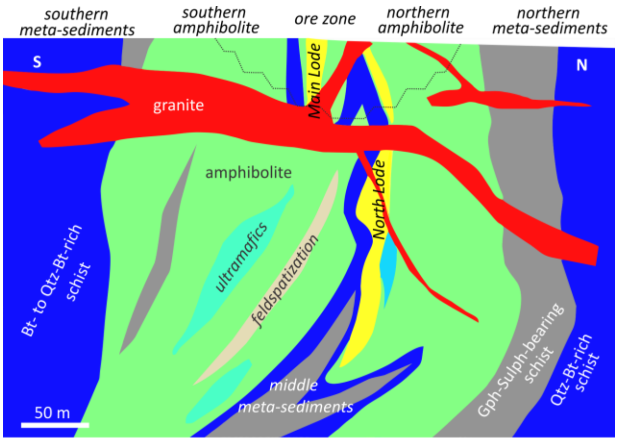

Figure 1 Idealized vertical profile of the Svartliden deposit.

3.2 Petrography of host rocks and their alteration styles

The meta-sedimentary units dominantly consist of biotite-rich schist with variable content of quartz (quartz–rich layers) and rarely andalusite and chlorite alteration. The graphite-sulfide-bearing schists, located on the boundary with the northern meta-volcanic unit, are very fine-grained, dark grey to black rocks which shows elevated magnetic susceptibility (10^{-3} to 10^{-2} SI) as a result of the presence of variable amounts of pyrrhotite(-pyrite) veins and veinlets.

Meta-volcanic rocks of the Svartliden deposit are dominated by amphibolites stratigraphically divided into northern and southern units which differ in extent, thickness and alteration styles. The amphibolites consist of calcic amphiboles, plagioclase, biotite, and accessory titanite and ilmenite. Fine-grained amphibolites are in places hydrothermally recrystallized and are locally intercalated by coarse-grained plagioclase-rich sills and dikes. The southern amphibolite unit also hosts metamorphosed dark green to grey ultramafics which consist of clinopyroxene, basic plagioclase, serpentinized olivine and fine- to coarse-grained magnetite.

Several different alteration styles are hosted by the amphibolite. The most notable style is potassic alteration. Biotitization appears as large recrystallized biotite grains or fine-grained biotite completely replacing amphiboles and is also observed as distinct biotite-rich bands. The southern amphibolite hosts a distinct zone (up to 30m wide) of strong K-rich alteration, pink to reddish in color, with mineral associations of plagioclase (up to 70 vol. %), biotite, clinopyroxene, titanite, hematite, and pyrrhotite (rarely up to 20 vol. %). Calc-silicate alteration of amphibolite appears in the form of distinct veins, hosting diopside-hornblende-garnet-quartz ± wollastonite mineral associations. Those veins often reveal zoning with garnet in the central portion and diopside and eventually quartz at the edges. This alteration style is also observed in the sediments adjacent to the mineralization. Pervasive calc-silicate alteration is present in the ore zone (Fig 2).

The granite dikes and sills are light grey, two-mica leucogranites with variable textures from equigranular to pegmatitic with large K-feldspar phenocrysts, plagioclase, quartz, biotite, occasionally garnet, and are rarely pyrrhotite mineralized.

3.3 Whole rock geochemistry

The concentration of major and trace elements including rare earth elements (REE) was analyzed by ICP-MS or ICP-AES by ALS Chemex laboratories.

The meta-sedimentary precursors are classified as greywackes or locally Fe-rich shales (Herron 1988) deposited in a turbidite system in a continental island arc tectonic setting, according to Bhatia & Crook 1986.

All amphibolites (46–52 wt. % SiO_2) are characterized by low alkali concentration trends (1.7–2.8 wt. % Na_2O+K_2O) corresponding to tholeiitic basalts (Le Bas et al. 1986). This is confirmed by their Co–Th ratios (Hastie et al. 2007). The bulk REE contents are generally very low (ΣREE<60 ppm) and they exhibit a nearly flat REE pattern with slightly depleted LREE (La_N/Lu_N=0.5–2.5; normalized by the CI-type chondrite after McDonough & Sun, 1995). The immobile elements Ti, Zr, Y, Mn, and P confirm that the amphibolite precursors originated at the ocean floor or an immature island arc setting (Mullen et al. 1983).

The ultramafic rocks are recognized as picrites (16–19 wt. % MgO, and up to 0.7 wt. % Na_2O+K_2O; Kerr & Arndt 2001; and 0.22–0.31 [Al_2O_3] vs. 0.035–0.064 [TiO_2] according to Hanski et al. 2001).

Granites intruding the Svartliden deposit are hydrothermally altered, peraluminous S-type granites (Andersson 2012), and they appear to be syn-collisional orogenic products (Bachellor & Bowden 1985).

3.4 Gold mineralization and the BIF

Gold mineralization is located along the contact between the meta-sediments (hanging wall) and the northern amphibolite (foot wall). Two mineralization forms are distinguished within the lode (ore zone), based on mode and texture of alteration and ore assemblages. First, a quartz- or diopside-dominated arsenopyrite- and pyrrhotite-rich ore typically present south of the banded-iron formation ore (Fig 1).

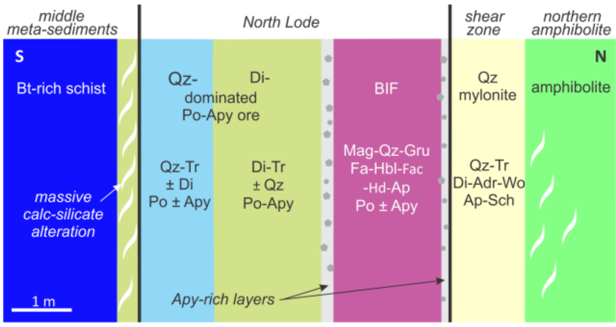

Figure 2 Idealized profile of the ore zone.

Diopside-dominated Apy-Po ore typically contains light green, strong calc-silicate alteration and weak to moderate silicification. It consists mostly of coarse-grained diopside, amphibole, quartz, and gold-bearing pyrrhotite-arsenopyrite-löllingite associations. Sulfides form massive aggregates, bands or veins with fluidal texture. The quartz-rich ore type is dominated by bluish, pervasive silicification with traces of calc-silicate alteration present mostly in the form of diopside-amphibole patches or veins with disseminated pyrrhotite and subordinate amounts of arsenopyrite. Both ore types usually form lodes that range from decimeters to several m´s in thickness, but in places the ore zone can appear up to 40 m wide as a result of structural thickening (folding and shearing). At the contact between the ore types, a thin layer (up to 30 cm) of massive arsenopyrite in a silicified matrix occurs. Gold-bearing arsenopyrite is also disseminated in the adjacent southern amphibolite, but not in economic quantities.

The banded-iron formation is variably deformed and preserved along the strike of ~ 1 km and is usually present as a few decimeters to several meters wide, boudinaged lenses. The least altered BIF samples preserve primary micro-banding of quartz and magnetite, and meso-bands intercalated with grunerite. Additional phases are fayalite, fluoro-apatite, hedenbergite, hornblende, ferro-actinolite, chlorite, and pyrrhotite-arsenopyrite-löllingite with minor chalcopyrite, ilmenite and pyrite. The Svartliden BIF is described as Algoma type (Sciuba, 2013).

The ore zone is bounded towards the foot wall by a barren quartz mylonite with a quartz-diopside-tremolite-wollastonite-andradite assemblage.

Gold is present as electrum grains enclosed in arsenopyrite-löllingite aggregates or in gangue minerals. Electrum composition reveals two generations of formation: when the majority of gold is associated with an arsenopyrite-löllingite association, one can expect 68–71 wt. % Au, whereas single electrum grains associated with quartz or silicates usually contain a higher gold content (74–82 wt. %; Eklund 2007).

3.5 Fluid inclusion study

Fluid inclusions from representative drill core samples and hand specimens from the Svartliden ore zone were studied by microthermometry and Raman microspectrometry (Broman 2010).

Primary aqueous fluid inclusions were found in diopside, actinolite, andradite, quartz and apatite in the ore zone and adjacent quartz mylonites, whereas quartz veins intersecting the ore zone preserve secondary aqueous-, methane- and nitrogen-bearing fluid inclusions. The primary aqueous inclusions consist of a low to moderately saline fluid with 2.4–8.5 wt. %. NaCl eq. The homogenization temperature, uncorrected for pressure, is 300 ± 50°C for inclusions found in calc-silicate minerals and apatite. Secondary inclusions trapped in quartz reveal salinities lower than 7 wt. % NaCl eq. and a homogenization temperature of 155–233°C.

3.6 Geothermobarometry

A geothermometric study of graphite crystallinity on samples from ore zone was conducted (Broman 2010, and references therein). The peak metamorphic temperature that has affected the Svartliden area, estimated from the graphite geothermometer, is 600°C for the andradite-diopside assemblage in quartz mylonite and around 550°C for the ore-related assemblage. Pressure-temperature (*P-T*) conditions of 554–604°C and 3.5–6.4 kbar were calculated to have affected the amphibolites based on a Grt-Bt-Pl-Qz mineral equilibrium (Berglund 2010, and references therein). The peak *P-T* conditions for the least altered BIF sample show a temperature range of 540–600°C which were predicted by thermodynamic modeling using the method of *P-T* Pseudosection (Sciuba, personal communication). Paleo-pressure, linked to the formation of mineralization, was estimated by Broman (2010) using an isochore for a homogenization temperature of ca. 300°C obtained from primary fluid inclusions from the ore zone.

4 Discussion: metamorphic evolution and ore formation

Metamorphic conditions that affected the Svartliden deposit span 540–600°C at estimated pressures of 3–6 kbar. Lower to mid amphibolite facies metamorphic conditions are supported by the presence of the hydrothermal alteration assemblage quartz-diopside-andradite ± wollastonite (Eilu et al. 1999) which is in agreement with regional metamorphic grades of supracrustal lithologies within the Bothian Basin (550–700°C at 3–5 kbar; Lundquist 1990).

The quartz mylonite contains very low concentrations of immobile and incompatible elements, suggesting that the original rock prior to deformation was directly precipitated from aqueous fluids, perhaps in an open extensional structure by localized fluid flow rather than by host-rock emplacement, whereas the ore formation mechanisms have to be further examined. The timing of the mylonitisation relative to ore formation is most likely to be post-mineralization. This steeply dipping fault/shear zone is likely a second order structure splaying off the regional crustal scale "Gold Line" shear zone which acted as a conduit for deeply sourced, low salinity, metamorphic devolatilization fluids. The quartz mylonite is located in a stratigraphic interval of large rheological contrast between the BIF/meta-sediments and an amphibolite body and likely acted as a local conduit for hydrothermal fluid flow. In this scenario the banded-iron formation was a geochemical barrier, whose sulfidation lead to the precipitation of sulfides from aqueous fluid in iron-rich lithologies, thus destabilizing the ligands and resulting in gold precipitation. The sediments would have served as a suitable mechanical trap for mineralizing fluids. Löllingite-gold intergrowths are most likely relics of high-temperature (> 540°C) prograde transformation of gold-bearing arsenopyrite to pyrrhotite-löllingite-Au assemblage (Tomkins & Mavrogenes 2001). A possible origin for the sulfur and arsenic could be the presence of sulfidic-graphitic sediments (Tomkins et al. 2006) in the Bothnian Supergroup. High-grade metamorphism resulted in partial melting of sedimentary precursors and emplacement of syn- to early post-peak metamorphic S-type granite. The granite dikes seem to have intruded along pre-existing structures, in many cases along the same structure as the mineralization. There is strong evidence that this event remobilized gold mineralization based on timing and lithologic relationships between the mineralization and the granite dikes.

5 Conclusions

The Svartliden gold deposit is situated in a volcano-sedimentary sequence of the Paleoproterozoic Bothnian Basin and has undergone regional metamorphic and deformational overprint in lower to mid amphibolite facies during the Svecokarelian orogeny. The deposit is interpreted to be a BIF-hosted orogenic, lode-style gold deposit. The desulfidation of aqueous fluids and precipitation of auriferous mineralization occurred along an Fe-rich geochemical barrier facilitated by local structural complexities.

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