An updated genetic model for metamorphosed and deformed, c. 1.89 Ga magnesian Zn-Pb-Ag skarn deposits, Sala area, Bergslagen, Sweden

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Abstract. This contribution presents an updated view on the genesis of stratabound Zn-Pb-Ag mineralization in the Sala area, Bergslagen, Sweden. Integrated legacy and new geological, geochemical and geophysical data reveal that the deposits are hosted by a complex array of magnesian skarn-altered zones in dolomitic marble. These mineralized zones parallel early faults and metavolcanic interbeds in the host marble, and converge downwards in the stratigraphy adjacent to a 1.89 Ga calc-alkaline granite-granodiorite batholith. Prograde alteration involved formation of early barren ferroan diopside- and forsterite-bearing skams. Mineralization is mainly associated with subsequent alteration to tremolite, chlorite, serpentine, magnetite and calcite. The hydrous associations overlap mineralogically with assemblages formed during subsequent greenschist facies regional metamorphism between 1.87 Ga and 1.8 Ga. However, ferroan diopside and forsterite are unique to the alteration system, and indicate mineralization in conjunction with an early, high T, metasomatic alteration event at 1.89 Ga. The Sala deposits can be classified as Zn skarn deposits, albeit atypical in the magnesian nature of the skarns and the lack of minerals with essential Mn. The Fe and Mn content in magnesian silicates and carbonates is however sufficient to induce clear enrichment haloes of these elements around the deposits. The magnesian nature of the skams probably reflect formation in a shallow marine continental backarc tectonic setting, and an importance of seawater in early pre-skarn alteration stages, such as dolomitization.

1 Introduction

The Sala area is one of the classic mining areas in the Bergslagen mining district of southern Sweden. Several stratabound polymetallic sulphide deposits are hosted by dolomitized and hydrothermally altered stromatolitic limestone, including the c. 5 Mt Sala Zn-Pb-Ag deposit; Sweden’s most historically important silver mine. The marble unit has also been mined for calcite and dolomite, and high quality dolomite for industrial applications is still mined at Tistbrottet directly west of Sala mine (Fig. 1).

The Sala deposit belongs to a sub-type of stratabound marble- and skarn-hosted deposits in Bergslagen. Current understanding based on field evidence and cross-cutting relationships suggest these deposits formed in an early, sub-seafloor setting at c. 1.89 Ga, when submarine strata were buried and intruded by porphyritic rocks and granitoids. The deposits have many mineralogical and textural similarities to metasomatic skarn deposits (e.g. Allen et al. 2003; Jansson and Allen 2015). However, an overprint by regional metamorphism and deformation during the Svecofennian orogeny at 1.87-1.80 Ga complicate ore genetic interpretation, in particular the distinction between early ore-related silicates and silicates formed during the regional metamorphic overprint. Analogous to classic discussions on the genesis of Broken Hill-type deposits, metamorphism has induced uncertainty on whether minerals such as diopside and garnet formed metasomatically in conjunction with ore formation, or later when lower temperature alteration assemblages were metamorphosed.

The Sala area is particularly favorable for addressing this problem, since the metamorphic grade only reached upper greenschist facies, as opposed to amphibolite or granulite facies elsewhere in Bergslagen. Furthermore, the area contains some of the most texturally well-preserved rocks in the region. This contribution presents an updated genetic model based on a recent drill core logging and mapping campaign complemented by microscopy and analysis of numerous samples for whole-rock lithogeochemistry and mineral chemistry.

2 The Sala Area

The Sala area is located in the central part of Bergslagen. It is dominated by c. NW-trending, gently plunging F1 folds that are overprinted by open, NE-trending F2 folds. The eastern part of Fig. 1 is characterized by sigmoidal, parasitic F1 folds whereas the western part is a culmination of F1 folds, interpreted as a F1 synclinorium. The western limb of this synclinorium is truncated by a prominent, WSW-dipping shear zone with inferred dextral and reverse displacement.
Towards the east, the marble unit is truncated by a large calc-alkaline granite-granodiorite batholith; the Sala-Vänge batholith. Ripa et al. (2002) presented two ages of 1891±6 and 1890±6 Ma of magmatic crystallization, overlapping within error with the age of a dated volcaniclastic interbed in the marble. Shearing and granoid emplacement have led to that metavolcanic rocks belonging to the original stratigraphic footwall being only present in the SW part of Figure 1. In terms of original volcanic facies, the footwall can be subdivided into a lower succession of stratified, rhyolitic-dacitic siltstone-sandstone with local volcaniclastic breccia intervals and an upper c. 300 m thick unit of feldspar+quartz-phryic rhyolitic pumice breccia. Deposition of the limestone (now marble) occurred during a lowstand in volcanism during which
growth ofstromatolitic limestone was intermittently interrupted by deposition of resedimented volcaniclastic debris (Allen et al., 2003). A succession of metamorphosed polymict rhylitc volcanic breccia-conglomerate and rhylitic silt-sandstone overlies the marble. The breccia-conglomerate units commonly have erosional lower contacts and locally carry clasts of former limestone. Pumice clasts become more common stratigraphically up-section.

3 The alteration system

The sulphide deposits mainly occur as breccia infill, vein networks and disseminations in skarn-rich dolomitic marble (Fig 2A). Janss (2017) showed that sulphides have locally replaced and mimicked original stromatolitic laminae. The main ore minerals are sphalerite and galena accompanied by pyrrhotite and pyrite. A plethora of Ag-, Sb- and Hg-bearing minerals accompany the base metal sulphides, such as freibergite, silver amalgam, duscarsite, miargyrite, allargentum, pyargyritle gudmunditte, boulangerite and geocronite (Kief et al. 1987).

The gangue minerals are tremolite, calcite, phlogopite, chlorite, serpentine, talc, ferroan diopside, locally barite, magnetite and very rarely grossular-andradite garnet and dravite tourmaline. Dolomitic marble carrying associations of these minerals define c. 200 m wide haloes around most known deposits (Fig. 1). These haloes coincide with weak but consistent whole-rock Fe and Mn enrichments and positive magnetic anomalies imparted by ubiquitous accessory magnetite and pyrrhotite. Using these geochemical and geomagnetic criteria, complex branching geometries are suggested for the alteration system, ranging from discordant to semi-concordant relative to stratigraphy. Janss (2017) showed that this pattern reflects a combination of cross-stratal fluid flow along early faults and fluid flow along the contacts of numerous volcanic interbeds in the limestone precursor. F1 folding transposed these alteration zones with the result that they are now sub-parallel in plan view. The alteration zones converge down-stratigraphy and towards the contact of the Sala-Vänge granodite (Fig.1).

Clinoxyroxene-bearing skarns occupy a central position in the altered zones, including Glagsruran (Fig.1) which is the type-locality of the eponymous ‘salite’; an old term for ferroan diopside. Locally, clinoxyroxene can be seen to have formed as an open-space infilling in zoned vein networks and breccias where it exhibits a bladed habit (Fig 2B). Early clinoxyroxene display complex growth zoning, reflecting variable Fe, Mg and Mn contents (Dper;Hd3;Jhm67;Diss;Hd3;Jhm6c, Fig. 2C).

Moreover in the haloes, forsterite (Fo30Fay54Fos2Fay4) is the main anhydrous skarn mineral; a mineral which hitherto has been neglected at Sala (Fig. 2D). The reason for this is most likely the common alteration of salite and forsterite to hydrous associations of tremolite, serpentine, chlorite, talc, magnetite and calcite (e.g. Fig. 2A), which are now dominant.

Sphalerite is locally observed in textural equilibrium with a younger generation of ferroan diopside in veins cross-cutting earlier salite skarns, and cm-sized clinoxyroxene and more rarely garnet (Grx+Adr+Sps) were found in the massive sulphide ore (cf. Sjögren, 1910). However, most sulphide mineralization is associated with hydrous minerals; e.g. sphalerite and tremolite replacing earlier clinoxyroxene (Fig. 2A) or dolomite directly (Fig. 2B). Galena and pyrhotite commonly occur in association with tremolite, serpentine, chlorite and minor magnetite replacing forsterite porphyroblasts (Fig. 2D). The altered dolomite and the magnesian silicates have elevated Fe and Mn, and the associated magnetite carry up to 3.10 wt.% MnO. This is the mineralogical manifestation of aforementioned geochemical and magnetic haloes. However, minerals with essential Mn are lacking at Sala.

Sjögren (1910) found that the ore sulphides have locally perfectly pseudomorphed fibrous tremolite crystals, further highlighting the link between mineralization and retrograde alteration. However, the final stages of retrograde alteration appear to have been barren, except for with respect to amalgams, antimonides and native forms of Ag, Sb and Hg (e.g. Kief et al. 1987). In Sala mine, this is best reflected by transgressive zones of talc, serpentine and chlorite that occupy a central part of the mineralized system, yet are essentially barren. The strong spatial relationship of these zones to ore has led most observers to interpret them as fossil conduits for hydrothermal fluids (e.g. Sjögren 1910, Jansson 2017). Their barren nature most likely reflect focused retrograde alteration by highly reactive, acidic and siliceous fluids that were poor in metals and/or sulphur. The high content of mechanically weak silicates in these zones resulted in ductile shear zones during subsequent deformation. Strain partitioning by these zones may be the reason why relatively well-preserved rocks can be found in the area near the Sala mine and adjacent dolomite mines.

The Sala-Vänge batholith has a sharp contact towards the alteration system, but is itself virtually unaltered. At the Bronäs deposit (Fig. 1), irregular bodies of weakly sericite-altered feldspar+quartz-porphyritic rocks with chilled margins intruded highly altered and mineralized dolomitic marble directly adjacent to sulphide mineralization. These features can be reconciled if emplacement of these intrusions post-dated mineralization, yet occurred along the same structures that originally channeled the mineralizing fluids.

4 Conclusions

Despite the tectonometamorphic overprint, we recognize that intrusive-related, metasomatic processes were involved in the genesis of the polymetallic sulphide mineralization in the Sala area. The common association of sulphides with retrograde minerals is similar to typical metasomatic skarn deposits (e.g. Meinert et al. 2005). Similar to Zn skarns worldwide, the Sala deposits appears to be structurally controlled and
to have formed away from intrusive contacts. On the other hand, the skarn parageneses are more magnesian than in typical Zn skarn deposits, which typically formed in calcitic rocks and where the alteration silicates are more Fe- and Mn-rich. Most likely, these differences reflect the unusual submerged, intra-continental backarc tectonic setting of skarn deposits in Bergslagen. This meant involvement of modified seawater in early, pre-skarn alteration stages, such as dolomitization of original calcitic limestone and hydrothermal alteration of volcanic rocks. Nevertheless, the Sala deposits can be included in the larger family of Zn skarn deposits as defined by e.g. Meinert et al. (2005). The results support other studies elsewhere in Bergslagen (e.g. Jansson and Allen, 2015), concluding that despite the complex regional metamorphic overprint, contact metasomatic processes related to 1.89 Ga intrusions can still be recognized.

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Figure 2. Examples of skarn and mineralization parageneses in the Sala area. A) Breccia-type ore with dolomite marble clasts cemented by sphalite, tremolite and phlogopite. B) Clinopyroxene skarn rod in olivine-porphyrblastic dolomite marble. Clinopyroxene is irregularly replaced by tremolite and sulphides whereas olivine have calcite haloes and are replaced by serpentine, sulphide and magnetite. The lamellated zones consist of fine-grained intergrowths of the hydrous minerals and calcite. C) Batten, pre-sulphide clinopyroxene skarn from Glasgruvan, type-locality of salite. A core of ferroan diopside (light) is overgrown and partly replaced by diopside (dark grey), in turn followed by a rim of younger ferroan diopside. D) Forsterite variably replaced by serpentine and accessory magnetite and pyrrhotite.