Ore Geology Reviews 82 (2017) 285–308

Contents lists available at ScienceDirect

Ore Geology Reviews

journal homepage: www.elsevier.com/locate/oregeo

Genesis of the Zinkgruvan stratiform Zn-Pb-Ag deposit and associated dolomite-hosted Cu ore, Bergslagen, Sweden

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ARTICLE INFO

Article history:
Received 26 February 2016
Received in revised form 5 December 2016
Accepted 6 December 2016
Available online 10 December 2016

Keywords:
Broken Hill-type deposits
SEDEX
VMS
Bergslagen
Zinkgruvan

ABSTRACT

Zinkgruvan, a major stratiform Zn-Pb-Ag deposit in the Paleoproterozoic Bergslagen region, south-central Sweden, was overprinted by polyphase ductile deformation and high-grade metamorphism (including partial melting of the host succession) during the 1.9–1.8 Ga Svecokarelian orogeny. This complex history of post-ore modification has made classification of the deposit difficult. General consensus exists on a syngenetic-exhalative origin, yet the deposit has been variably classified as a volcanogenic massive sulfide (VMS) deposit, a sediment-hosted Zn (SEDEX) deposit, and a Broken Hill-type (BHT) deposit. Since 2010, stratabound, cobaltiferous and nickeliferous Cu ore, comprising schlieren and impregnations of Cu, Co and Ni sulfide minerals in dolomitic marble, is mined from the stratigraphic footwall to the stratiform Zn-Pb-Ag ore. This ore type has not been fully integrated into any of the existing genetic models. Based on a combination of 1) widespread hematite-staining and oxidizing conditions ($Fe_2O_3 > FeO$) in the stratigraphic footwall, 2) presence of graphite and reducing conditions ($Fe_2O_3 < FeO$) in the ore horizon and hangingwall and 3) intense K-feldspar alteration and lack of feldspar-destructive alteration in the stratigraphic footwall, we suggest that both the stratiform Zn-Pb-Ag and the dolomite-hosted Cu ore can be attributed to the ascent and discharge of an oxidized, saline brine at near neutral pH. Interaction of this brine with organic matter below the seafloor, especially within limestone, formed stratabound, disseminated Cu ore, and exhalation of the brine into a reduced environment on the sea floor produced a brine pool from which the regionally extensive (>5 km) Zn-Pb-Ag ore was precipitated.

Both ore types are characterized by significant spread in $\delta^{34}S$, with the sulfur in the Cu ore and associate marble-hosted Zn mineralization on average being somewhat heavier ($\delta^{34}S = -4.7$ to +10.5‰, average 3.9‰) than that in the stratiform Zn-Pb-Ag ore ($\delta^{34}S = -6$ to +17‰, average 2.0‰). The ranges in $\delta^{34}S$ are significantly larger than those observed in syn-volcanic massive sulfide deposits in Bergslagen, for which simple magmatic/volcanic sulfur sources have been invoked. Mixing of magmatic-volcanic sulfur leached from underlying volcanic rocks and sulfur sourced from abiotic or bacterial sulfate reduction in a mixing zone at the seafloor could explain the range observed at Zinkgruvan.

A distinct discontinuity in the stratigraphy, at which key stratigraphic units stop abruptly, is interpreted as a syn-sedimentary fault. Metal zonation in the stratiform ore (decreasing Zn/Pb from distal to proximal) and the spatial distribution of Cu mineralization in underlying dolomitic marble suggest that this fault was a major feeder to the mineralization. Our interpretation of ore-forming fluid composition and a dominant redox trap rather than a pH and/or temperature trap differs from most VMS models, with Selwyn-type SEDEX models, and most BHT models. Zinkgruvan has similarities to both McArthur-type SEDEX deposits and sediment-hosted Cu deposits in terms of the inferred ore fluid chemistry, yet the basinal setting has more similarities to BHT and felsic-bimodal VMS districts. We speculate that besides an oxidized footwall stratigraphy, regionally extensive banded iron formations and limestone horizons in the Bergslagen stratigraphy may have aided in buffering ore-forming brines to oxidized, near-neutral conditions. In terms of fluid chemistry, Zinkgruvan could comprise one of the oldest known manifestations of Zn and Cu ore-forming systems involving oxidized near-neutral brines following oxygenation of the Earth's atmosphere.

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http://dx.doi.org/10.1016/j.oregeorev.2016.12.004
0169-1368/

1. Introduction

Stratabound and stratiform Zn-Pb-Ag deposits occur in folded and metamorphosed supracrustal inliers enclosed by plutonic rocks in the Bergslagen mining district of south central Sweden. The deposits range from small showings to world class deposits, such as the Garpenberg stratabound Zn-Pb-Ag-(Cu-Au) and Zinkgruvan stratiform Zn-Pb-Ag-(Cu) deposits, which are the two largest sulfide deposits in the region. These two deposits were historically regarded as belonging to distinct deposit types, termed 'Falun type' and 'Åmmeberg type' respectively by Magnusson (1950). Both were regarded as epigenetic but related to different types of granitoid magmatism (e.g., Geijer, 1917; Magnusson, 1953).

Subsequent work re-interpreted most sulfide deposits in Bergslagen as products of syn-genetic exhalative processes related to volcanism, prior to deformation and metamorphism, whereby the distinction and genetic link to granitoids became largely obsolete (e.g.; Lagerblad and Gorbatschev, 1985; Vivallo, 1985; Hedström et al., 1989). A two-fold division was however re-instated by Allen et al. (1996), who, based on regional facies analysis and study of the ore host successions, distinguished: 1) stratiform, ash-siltstone hosted (SAS) Zn-Pb-Ag-(Cu) sea-floor deposits, such as Zinkgruvan and 2) stratabound, volcanic-associated marble- and skarn-hosted (SVALS) Zn-Pb-Ag-(Cu-Au) replacement deposits, such as Garpenberg and Sala (Fig. 1). This division was consistent with the results of Sundblad (1994), who demonstrated that the historic end-members show contrasting Pb isotope trends.

During the last two decades, genetic models for the Garpenberg deposit have involved: 1) metamorphosed volcanogenic massive sulfide (VMS) (e.g., Vivallo, 1985), 2) metamorphosed subsea-floor replacement deposits with similarities to VMS (Allen et al., 1996), 3) metasomatic skarn (e.g., Zetterqvist and Christofferson, 1996), or 4) combinations of these (Allen et al., 2003; Jansson, 2011). The main obstacle to classification is a strong overprint by polyphase ductile deformation, amphibolite facies metamorphism and sulfide remobilization, leading to an uncertainty regarding the timing of formation of ore versus skarn host minerals. Notwithstanding these complications, the deposit is demonstrably coeval with a large submarine volcanic system, in which sulfides formed by subsea-floor replacement of a stromatolitic limestone that was deposited during a pause in volcanism (Allen et al., 2003).

At Zinkgruvan, general consensus has been reached regarding a syngenetic-exhalative origin. Yet, controversy still exists on whether the deposit should be regarded as a VMS deposit (Billström, 1991), Broken Hill-type (BHT) deposit (e.g., Plimer, 1988; Beeson, 1990; Parr and Plimer, 1993; Allen et al., 1996; Walters, 1996; Gunn, 2002), SEDEX deposit (Hellingwerf, 1996), or a VMS-SEDEX hybrid (Hedström et al., 1989). This controversy may impact on exploration strategy, as the nature of ore-forming fluids, trapping mechanism and the footprint of the hydrothermal systems differ fundamentally among SEDEX, BHT, and VMS deposits (e.g., Cooke et al., 2000). A currently mined, dolomite-hosted, Cu deposit has furthermore not been fully integrated into any of the genetic models, although Hedström et al. (1989) suggested that it occupies a feeder to the stratiform mineralization.

In a larger perspective, the distinction between SAS and SVALS deposits has not resolved whether these deposit types constitute different ore facies formed in similar synvolcanic hydrothermal systems (c.f., exhalative versus replacement-type VMS), or whether they constitute products of fundamentally different hydrothermal systems. Allen (2010) suggested that the differences between these end-members were due to several critical features, including temperature, pH, salinity, redox state and S content of the hydrothermal fluid, and whether metal deposition was triggered by (a) mixing with cold (sea)water, (b) encountering a reduced environment with available H_2S, or (c) interaction with a reactive carbonate host rock.

In this contribution, we discuss the genesis of the Cu and Zn-Pb-Ag ores based on a critical review of earlier investigations complemented by a new geological investigation of the ore deposit and new geochemical data, including rare earth elements (REE) for key units of the stratigraphy and sulfur isotope data from the Cu ore. Special emphasis is placed on constraining the timing and controls on ore formation and the nature of the ore-forming fluid.

2. Geological setting and background

Mining at Zinkgruvan was initiated by Vieille Montagne in 1857 and the mine has to date produced 41 million tonnes of ore grading 10.6% Zn, 2.9% Pb and 58 g/t Ag. The current Zn-Pb-Ag mineral resources (including reserves) total 17 million tonnes measured and indicated and 7 million tonnes inferred (Table 1). The mineralization is still open whereby additional resources are expected. Since 2010, 1 Mt of stratabound, dolomite-hosted Cu ore has been mined from a stratigraphically underlying marble unit. The Cu mineral resources (including reserves) are 5 Mt measured and indicated and 0.02 Mt inferred.

Zinkgruvan is situated in the southern part of the Bergslagen lithotectonic unit (BLU) of the Fennoscandian shield (Fig. 1). In the BLU, mainly submarine volcanic and sedimentary rocks deposited at 1.91–1.89 Ga occur as polychronously deformed and metamorphosed inliers enclosed in voluminous plutonic rocks formed during igneous phases at 1.90–1.87, 1.87–1.84, and 1.81–1.78 Ga (Stephens and Andersson, 2015). Polyphase deformation, metamorphism and magmatism reflect various stages of the ca. 1.9–1.8 Ga Svecokarelian orogeny (Stephens et al., 2009). The BLU is bounded to the south and north by WNW-ENE to NW-SE striking shear belts recording dextral transpressive deformation as well as high-grade metamorphism (Fig. 1, Stephens and Andersson, 2015). Regional metamorphism peaked at 750 ± 50 °C and 4–6 kbar in the southern part, where Zinkgruvan is located (Andersson et al., 1992; Stephens et al., 2009; Gunn, 2002).

The principal stratigraphic components in the BLU comprise: 1) a lower metasedimentary succession comprising quartzite, metaturbidite, metagreywacke, meta-arkose, pelite, and migmatite, 2) an overlying greater than 1.5–7.5 km thick succession dominated by juvenile, mainly rhyolitic metavolcanic rocks, and 3) an upper metasedimentary succession of metaturbiditic and locally graphitic mainly pelitic rocks (Allen et al., 1996). The metavolcanic succession comprises a lower section dominated by thick pyroclastic flow deposits and their subaqueous equivalents, deposited during a stage of intense volcanism, and an upper, more stratified, sequence dominated by originally finer-grained silty-sandy reworked volcaniclastic rocks interbedded with stromatolitic limestone units (now marble), deposited during a stage of waning volcanism (Allen et al., 1996). Sub-volcanic intrusions occur throughout the metavolcanic succession. The supracrustal sequence is inferred to have been deposited in a back-arc basin on continental crust (Allen et al., 1996).

The upper part of the volcanic succession hosts the majority of the mineral deposits in the Bergslagen region, including Fe oxide deposits in marble and/or skarn, banded iron formations, stratiform Zn-Pb-Ag-(Cu) deposits, and stratabound marble- and skarn-hosted Zn-Pb-Ag-(Cu-Au) deposits. Zinkgruvan occurs near the top of the better stratified upper part of the metavolcanic succession, at, or just below, the transition to (now migmatized) pelitic and meta-turbiditic rocks. Kumpulainen et al. (1996) termed the metavolcanic unit and the stratigraphically overlying