Recent advances in structural geology, lithogeochemistry and exploration for VHMS deposits, Kristineberg area, Skellefte District, Sweden

Nils F Jansson, Tobias Hermansson, Mac Fjellerad Persson, Alexandra Berglund, Annika Kruuna
Boliden Mines, Exploration Department

Pietari Skyttä
University of Helsinki

Kai Bachmann, Jens Gutzmer
TU Bergakademie Freiberg

Reia Chmielowski, Pär Weihed
Luleå University of Technology

Abstract. Kristineberg is the largest mine and VHMS deposit in the Palaeoproterozoic Skellefte District, Sweden. The deposit was discovered in 1918, and it has been mined since 1941. Besides the Kristineberg deposit, several other VHMS deposits have been mined in the Kristineberg area. Despite the long history of mining, significant advances are still being made in terms of exploration and understanding the geological framework of the ore bodies. A key to this success has been persistence in exploration and a combination of local and regional scale geological, geophysical and geochemical surveys. Holistic industry-university collaborative research projects have furthermore played an important role in bringing together geologists and geophysicists from different disciplines to tackle the large-scale geological framework. Among other things, these projects have resulted in the first structural geological 3D model of the Kristineberg area, better age constraints on the formation of the deposits, a regional alteration map as well as ongoing work to model alteration in 3D. This contribution summarizes the results of these investigations and recent exploration.

Keywords. Kristineberg, Skellefte District, VHMS, 3D modelling, Exploration

1 Introduction

Kristineberg is the largest mine in the Palaeoproterozoic Skellefte District, Northern Sweden. The deposit was discovered during an electromagnetic survey in 1918, yet production did not start until 1941. Until present, c. 27.8 Mt ore has been produced from more than 10 lenses in the VHMS deposit, on average grading 3.74 % Zn, 1.04 % Cu, 1.4 g/t Au, 39 g/t Ag and 0.24 % Pb. Successful near-mine exploration is the key to the mine’s longevity, and continues to add new reserves. The current proven and probable reserve totals 4.65 Mt.

Besides the Kristineberg mine, the Kristineberg area also hosts several other, abandoned mines such as the Rävldmyran mine (7.18 Mt mined 1950-1991), the Rävlden mine (1.56 Mt mined 1941-1988), the Kimheden mine (0.13 Mt mined 1967-1969 and 1974-1975) and the Hornträskviken mine (0.64 Mt mined 1981-1991). These mines are currently of interest for the field exploration in the area (Fig. 1).

The Kristineberg deposit is hosted by the 1.89-1.88 Ga Skellefte group metavolcanic rocks (SG). The

![Figure 1. Regional geological map of the Kristineberg area. Inset shows the position of the Skellefte District in Fennoscandia. Modified after Årebäck et al. 2005, Barrett et al. 2005 and Skyttä et al. 2012.](image)
volcanic rocks are towards the west overlain by the predominantly metasedimentary 1.88-1.87 Ga Vargfors group (VG). Whereas Kimheden occupies a similar stratigraphic level as Kristineberg, the other VHMS deposits occur close to the SG-VG contact (Fig. 1). The host stratigraphy is folded around gently to moderately WSW-plunging fold hinges. Axial surfaces are generally steeply-moderately S-dipping, and commonly sub-parallel to c. E-W trending high-strain zones. The ore lenses commonly have complex and variable geometries, ranging from sheet-like, moderately-steeply S-dipping lenses to more elongate, gently W plunging.

Following a review of mineral exploration in the Skellefte district carried out by Boliden in 2007, the Kristineberg area was defined as a top priority target, resulting in increased exploration activity and discoveries of new mineralization. A key to successful exploration has been the combination of local-scale exploration methodology, such as down-hole EM surveys, alteration mapping and deposit-scale lithogeochemical surveys, with regional scale geological, geochemical and geophysical surveys. The latter have in the last years been carried out as collaborations between Boliden and universities such as Luleå University of Technology (LTU), Uppsala University and TU Bergakademie Freiberg. Among other things, these projects have resulted in the first structural geological 3D model of the Kristineberg area, a regional alteration map as well as ongoing work to model alteration in 3D. This contribution summarizes the results of these investigations and recent exploration.

2 Structural geology

2.1 3D and 4D modelling of the Kristineberg area

The first regional 3D model of the Kristineberg area was developed during a recent multidisciplinary research project funded by VINNOVA (e.g. Dehghannejad et al. 2012; Skyttä et al. 2010; 2011) (Fig. 2). This was part of a larger project, aiming at developing robust 4D-models of the crustal evolution of the entire Skellefte district. The models incorporated data from field mapping, drill holes, mines, geochronology (Skyttä et al. 2011), reflection seisms (Dehghannejad et al. 2012), electromagnetics (Garcia-Juanatey 2012), locally detailed by IP and resistivity studies (Tavakoli 2012) and AMS studies (Skyttä et al. 2010).

A major outcome was the recognition of transpressional strain and coeval magmatic events across the district (Skyttä et al., 2011), indicating that the whole district was subjected to the same tectonic events at around 1.89-1.80 Ga (Weihed et al. 2002; Skyttä et al. 2012). The new model for the regional structural evolution could explain why the NE-SW to E-W trending Kristineberg area structures deviate from the WNW-ESE structural grain of the central Skellefte district (Bauer et al. 2011). This was interpreted to reflect the localisation of the Kristineberg area at the lateral termination of a significant transpressional high-strain zone, transecting much of the central district. East of Kristineberg, the zone splays into several branches and defines zones of coaxial and non-coaxial deformation resulting in increasingly complex structure, including significant variations in the plunge of the large antiformal structure where Kristineberg is located.

Reflection seismic results in the vicinity of the Kristineberg deposit indicated that the most pronounced reflectors are sub-horizontal and occur at around 2 km depth below the surface, whereas at higher level the reflectors are less distinct and less continuous (Dehghannejad et al. 2010; 2012). The seismic data is in agreement with ore lens geometries and geological sections interpreted from drill holes, which show coincidence between seismic discontinuities and high-strain zones. The high-strain zones caused transposition of the primary strata and individual ore lense into moderately- to steeply-dipping orientations (Årebäck et al. 2005), and earlier, probably also controlled the localization of the deposits during mineralization.

Coupling between the kinematic evolution of the high-strain zones and the deposit geometries show that
the most significant tectonic transposition is due to reverse movements along the S-dipping high-strain zones (Årebäck et al. 2005). However, overprinting dextral strike-slip shearing and localized sub-horizontal tectonic flow at deep crustal levels, as observed from the Viterliden intrusion stratigraphically below the ore-hosting volcanic rocks (Fig. 1), is inferred to locally have caused transposition at the ore-lens scale (Skyttä et al. 2010).

2.2 Mine-scale investigations

Pervasive overprint by strong-intense hydrothermal alteration and medium-grade metamorphism precludes the possibility of detailed stratigraphic analysis in the Kristineberg mine (Årebäck et al. 2005). Most mineralization is hosted by rocks such as sericite quartzite, andalusite quartzite, chlorite schist and sericite schist, formed by hydrothermal alteration, deformation and metamorphism of originally compositionally distinct, yet now indistinguishable volcanic rocks. The difficulty in distinguishing the various original volcanic rocks has for many years presented a major obstacle to structural analysis. By systematic drill core sampling and immobile element techniques, Barrett et al. (2005) identified several distinct rhyolitic and dacitic-intermediate precursor compositions around the mined ore lenses. These defined a distinct chemostratigraphy which could be used to differentiate between stratigraphic footwall and hanging-wall in the Kristineberg mine. Rock division based on immobile element ratios furthermore provided information on the structural framework of the ore lenses, such as the approximate concordance of the old A and B lenses to original boundaries between compositionally distinct volcanic rocks.

Recent studies have extended this approach to also include currently mined gently west-plunging lenses in the western part of the mine. The results revealed a much more complicated geological picture than inferred in previous surveys, involving significant N-vergent stacking of the altered host stratigraphy along S-dipping high-strain zones (Fig. 3). This is in agreement with the regional structural framework as described above, and provides an explanation for the complex geometry and distribution of ore lenses in the central to western parts of the Kristineberg mine.

3 Geochemistry

3.1 Kristineberg alteration map

Similar to other VHMS deposits globally, the deposits in the Kristineberg area are surrounded by hydrothermal alteration envelopes that are zoned in terms of alteration intensity, mineralogy and whole-rock composition. One approach to discover new mineralization is to study the extent and zonation of these alteration zones regionally.

Bachmann (2012) compiled all available near-surface lithogeochemical data and conducted complementary sampling in outcrops and drill holes. The aim was to obtain a regional coverage of near-surface lithogeochemical samples that could be used to extend the different chemostratigraphic units of Barrett et al. (2005) and model the variations in alteration intensity and style in the entire Kristineberg area. The data was used to construct surface alteration maps, showing variations in alteration indices such as the Ishikawa Alteration Index (AI; Ishikawa et al. 1976) and Chlorite-Carbonate-Pyrite-Index (CCPI; Large et al. 2001). Among other things, these alteration maps showed that known deposits correlate best with coincidence of high AI and CCPI values.

An ongoing research project aims at extending this approach to depth, to produce the first 3D geochemical model of a mining area in Sweden. The model will be based on lithogeochemical data from the database of Boliden and new drill core samples, and will be constrained by the existing 3D structural model. The project is a joint collaboration between the Luleå University of Technology (LTU) and Boliden. It aims at improving our understanding of the mass changes, geometry and zonation of hydrothermal alteration zones in the Kristineberg area. A benefit of 3D volumes instead of 2D sections is that prospective rock volumes can be constrained in 3D. As a result mineralization at depth can be targeted with improved accuracy.

3.2 Geochronology

By careful selection of samples for SIMS U-Th-Pb zircon dating, Skyttä et al. (2011) constrained the age of the Kristineberg deposit. The youngest sampled phase of the Viterliden intrusion, which contains xenoliths of hydrothermally altered volcanic rocks, was dated at 1889±3 Ma (Fig. 1). A felsic metavolcanic rock in the stratigraphic hanging-wall, inferred to be younger that the Kristineberg sulphide ore, was dated at 1883±6 Ma. These two ages were inferred to constrain a minimum age of the deposit. The 1883±6 Ma age provides a maximum age for the stratigraphically higher Rävliden,
4 Exploration

4.1 Near mine exploration

Recent exploration has been largely focused on the area just west of the mine, a successful strategy resulting in the discovery of several mineralized zones. One of the most important discoveries is the L-zone, which runs roughly parallel to the J-zone (Fig. 3). It was first indicated in a ground EM survey as a geophysical anomaly at depth. In 2004 a westward plunging system of massive sulphide lenses was intersected in drillholes covering a vast horizontal strike.

High-grade parts are typically chlorite schist-hosted, tectonically remobilized and rich in pyrite-sphalerite, although the zone changes character westwards and become more Cu- and Au-dominated. The geological setting of the ore lenses is consistent with that of other ore bodies in the mine, i.e. strongly altered and schistose volcanic rocks that only rarely display primary textures. Geometries vary within the zone due to folding and thrusting, but the general trend is a gentle plunge to the west in accordance with the large scale anticline-syncline structure in which the Kristineberg deposit is located.

Extensive exploration drilling has systematically followed the zone westwards and in 2006 volumes were subsequently added to mineral resources. In 2011, parts of the zone were taken into production.

4.2 Field exploration

The concept of N-vergent stacking in the Kristineberg area has been of importance during the re-appraisal of the potential for new discoveries regionally. A new structural model for the SG-VG contact has allowed more efficient targeting. The precursor to this model was first conceptualized internally by Boliden and a structural consultant (Dave Coller) supplemented by new seismic investigations during the VINNOVA project, and further refined in 3D by Skyttä et al. (2012) (Fig. 2). Successful application and continued refinement of this model has led to the recognition of new targets, which are under investigation.

5 Conclusions

After 72 years of mining, the Kristineberg area is still one of the most productive areas in the Skellefte District. A key to this success has been persistence in exploration and a combination of local and regional scale in-depth geological, geophysical and geochemical surveys. These have increased our knowledge of the structural framework and evolution of the area, the geometry of the mined sulphide lenses, the nature and zonation of hydrothermal alteration. They have furthermore led to the recognition of new prospective areas, which may help to extend the life of this mining area even further.

References


