3D geochemical modelling of hydrothermal alteration related to 1.89 Ga VHMS-type deposits, Kristineberg area, Skellefte District, Sweden

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Abstract. A 3D geochemical model of the Kristineberg area of the Skellefte District, Sweden, is currently under construction, utilizing data from more than 1600 regionally distributed whole-rock lithogeochemical samples. The model will improve our understanding of the formation the VHMS deposits in this area. The model is built by mapping geochemical variations in 3D, and using this as a basis for modelling hydrothermal alteration in the unsampled portions of the rock column. A better understanding of the geometry, intensity, vectors of transport, and zonation of the hydrothermal zones in 3D will aid deep exploration for massive sulphide deposits in the Kristineberg area, and may potentially lead to new discoveries.

Keywords. 3D geochemical model, Skellefte district, VHMS, hydrothermal alteration, mass balance, fluid flow

1 Introduction:

The Palaeoproterozoic Skellefte mining district, northern Sweden (Figure 1), is one of the most important mining regions in Europe, containing more than 85 pyritic Zn-Cu-Au-Ag massive sulphide deposits (Kathol and Weihed 2005). Despite a long history of mining, exploration, and research, it is only in recent years that the detailed, regional 3D structure of the district is starting to be understood. This understanding has come about due to the construction of advanced 3D geological models (produced under the banners of the VINNOVA project "4D modelling of the Skellefte District" and the PROMINE project) developed in collaboration between geologist and geophysicists from Boliden Mineral AB, Luleå University of Technology, and Uppsala University.

However, these models have focused on regional structure and tectonic evolution, while the geometry, size and distribution of the hydrothermal alteration zones associated with the mineral deposits have not yet been studied in 3D. The goal of this research project is to develop a 3D geochemical model for one the most important areas in the district; the Kristineberg area, which hosts the currently mined 26.5 Mt Kristineberg volcanic-hosted massive sulphide (VHMS) deposit (Fig. 1).

This study is the first to apply a 3D approach to the lithogeochemistry of a significant mining area in Sweden. Indeed, very little has been done worldwide in interpreting hydrothermal alteration systems in VHMS districts in 3D, primarily due to a lack of high quality geochemical whole-rock analyses obtained from sufficient drill holes to provide good regional cover.

The project is undertaken in collaboration between Luleå University of Technology and Boliden Mineral AB. It aims at better understanding the regional 3D geometry, size and zonation of the hydrothermal system, which envelopes metamorphosed and deformed VHMS deposits. It furthermore aims at understanding the chemical changes involved in hydrothermal alteration, the intensities thereof, the path and flow directions of mineralizing hydrothermal fluids, and the mass changes in whole rock composition resulting from hydrothermal alteration. The project carries on from previous two dimensional (surface maps, cross-sections) studies, which addressed the chemical changes in the rock units caused by the hydrothermal alteration related to mineralization in the Kristineberg area (e.g. Barrett et al. 2005; Schlatter 2007; Bachmann 2010).

In addition to improving our understanding of ore formation in the Skellefte district, the model will directly assist exploration in the Kristineberg area. The methodology and approach can furthermore be applied to other mature mining districts around the world.

2 Geological background

The Kristineberg area covers around 120 km^2 (Figure 1). The main unit outcropping in this region is the Skellefte Group, a thick sequence of Proterozoic (1.9 Ga) greenschist to amphiboilite facies felsic- to intermediate submarine metavolcanic rocks (Figure 1). These are overlain by the dominantly metasedimentary Vargfors Group, which contains metamorphosed, fine-grained turbiditic sedimentary rocks, graphitic phyllites, conglomerates and mafic-intermediate volcanics (Weihed 2010). These units are interpreted to have formed via accretionary processes in a volcanic arc setting. Massive sulphide deposits occur both within the Skellefte Group and close to the contact with the Vargfors group (Fig. 1)

All of the samples analysed for this project come from low-medium grade metamorphosed volcanic and volcano-sedimentary units within the Skellefte Group; these samples have also undergone variable degrees of hydrothermal alteration related to mineralization.

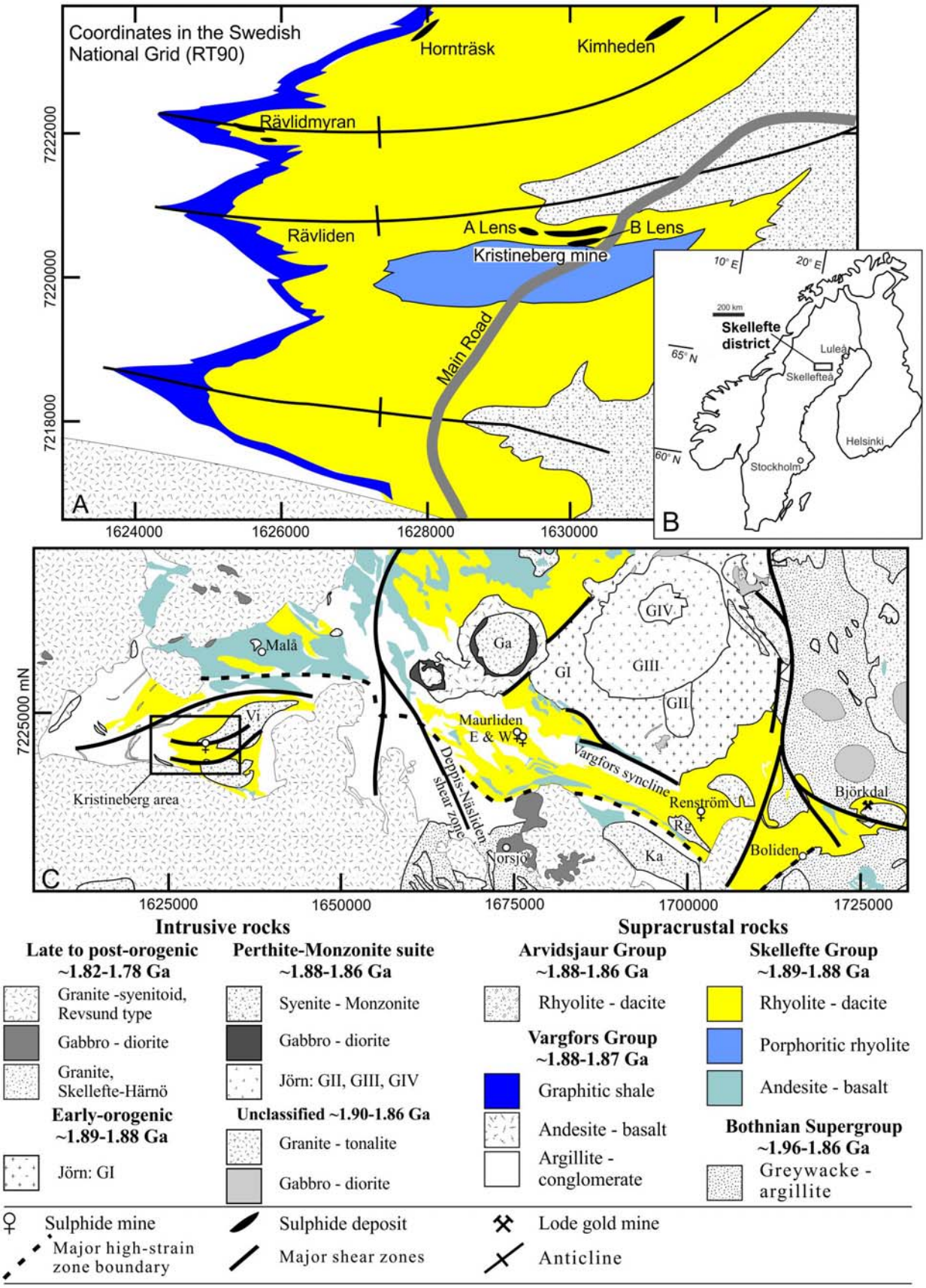


Figure 1. A: General geology of the Kristineberg area, Skellefte district, Sweden (modified after Barrett et al, 2005). **B:** Location of the Skellefte District within Scandinavia. **C:** General geology of the Skellefte district. Intrusions: Vi = Viterliden, Ga = Gallejaur, Rg = Rengård, Ka = Karsträsk, GI, GII, GIII, GIV = Jörn type intrusions, phases I-IV. Geology after Kathol et al. (2005) and Bergman Weihed (2001).

3 Processing lithogeochemical data

The Kristineberg area has been chosen, in part, based on the availability of a pre-existing data set (containing 1569 lithogeochemical analyses from 82 drill holes) and numerous additional drill holes in the area from which to select additional samples. As of January 2013 an additional 167 new lithogeochemical samples have been collected and analysed from 10 drill holes in the Kristineberg area specifically for this project and additional sampling is in progress.

Lithogeochemical analysis has been conducted in several labs, but primarily by ACME in Vancouver, Canada, using fusion ICP-AES for major and certain trace elements, fusion ICP-MS for REE and other trace elements, and an aqua regia digestion for the metals.

In addition to the whole-rock lithogeochemical analysis, over 100 representative samples have also been chosen for petrographic analysis in thin section. Most samples exhibit intense alteration; the most common alteration minerals include sericite, chlorite, pyrite, and potassium feldspar, all of which are accompanied by Na-depletion (Figure 2).

The samples are grouped using ratios of immobile element ratios to help differentiate between different pre-alteration rock types (MacLean and Barrett 1993). Once the protoliths have been determined it is possible to identify the "least altered" examples of each group. Despite the pervasive intense hydrothermal overprint in this region there are sufficient "least altered" samples available to provide the requisite baseline for mass balance calculations (MacLean 1990). It is these mass balance calculations which provide the framework for the model.

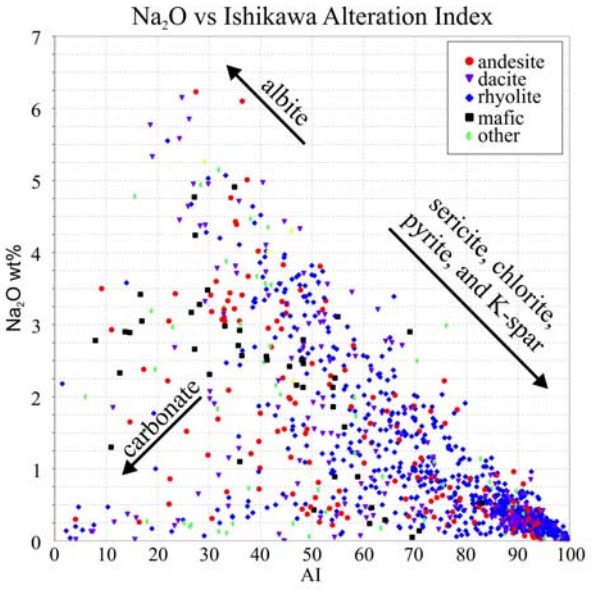


Figure 2. Comparison of the Alteration Index (Ishikawa et al. 1976) with the Na_2O content of the samples. AI = [100 (K_2O + MgO)]/(K_2O + MgO + Na_2O + CaO) Note that, in general, the more intense the alteration the more depleted the sample is in Na_2O.

4 Preliminary results: Building a 3D model

The 3D model is developed using the LeapfrogGeo modelling software, which permits a 3D display of geochemical data using polyharmonic Radial Basis Functions (Carr et al. 2001) to create smooth surfaces from scattered data points, such as isolated samples collected from drill holes. As a result of this technique, the program also facilitates the interpolation of likely concentrations of elements between the existing data points, which is necessary for building a 3D model.

The geochemical data will be bounded and constrained using the 3D structural model generated for this region (Bauer et al. 2011; Skyttä 2012), in order to ensure that the interpreted geometries of the alteration zones are plausible. In addition results from the petrographic analysis of selected thin sections will permit linking the 3D geochemical model to specific alteration mineral assemblage zones.

The first step in building the model involves simple viewing of the geochemical data in 3D. Figure 3 shows the locations of the sample analyses with colours indicating the rock type, and the size of the spot is determined by the Alteration Index (Ishikawa et al. 1976). This region is heavily altered, and more than 90% of the samples have an AI greater than 40. However, Figure 3 clearly shows that the most intense alteration is concentrated along certain drill holes, which are located near the mine itself. The few isolated samples on the centre left of the figure which also display high AI values (94 to 96) are indicative of a region which should be targeted for additional sample acquisition in order to build a more accurate model.

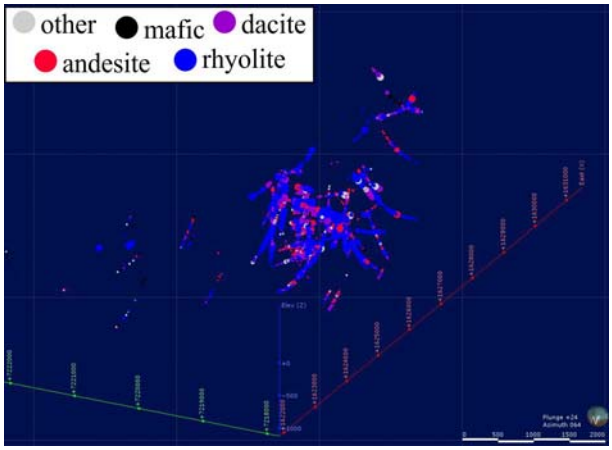
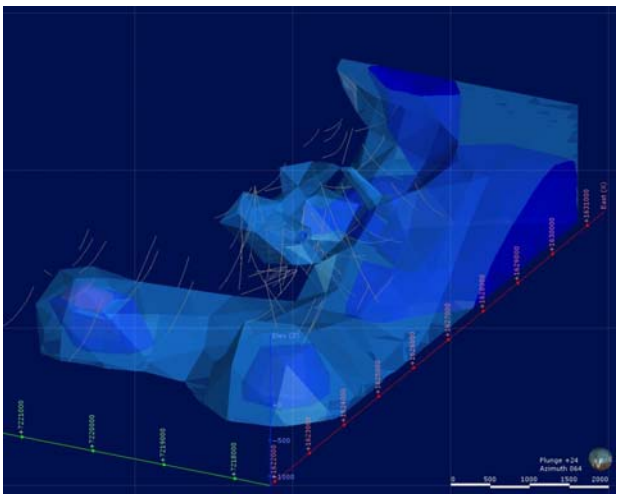


Figure 3. 3D view from LeapfrogGeo. The size of the sample spots is based on the Ishikawa Alteration Index, not the size of the sample itself. There are 10 size ranges, each containing 10% of the samples. The upper limit of the AI for each range is (rounded to): 40.5, 54.2, 69.0, 81.0,89.1, 92.2, 94.0, 95.4, 96.4, 100.0

The second step in building the model is to interpolate likely values between known data points. Figure 4 shows a rough interpolation based on AI values (Ishikawa et al. 1976). Further model development will result in smoother models which are based upon a

variety of possible indices for alteration and which show



vectors to mass gains and losses of various elements.

Figure 4. 3D view from LeapfrogGeo showing shells of the regions with interpolated similar AI values. Shown are the shells with upper limits (rounded to): 89.1, 92.2, 94.0, 95.4, 96.4, and 100.

Conclusions

One of the main advantages for constructing 3D volumes instead of 2D cross sections is the ability to define volume gains and losses to the full hydrothermal systems. When conducted in 3D, mass-balancing may be used to constrain key features pertinent to ore genetic models, such as net gains or losses of elements within the entire hydrothermal system as well as the source of metals in the deposits. A better understanding of mass changes and better differentiation between the different types of intensely altered samples is furthermore necessary for vectoring towards mineralization in the Kristineberg area, where intensely altered rocks are found several 100 m away from the deposits.

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References

Bachmann K (2010) Chemostratigraphy and alteration in the area of the Kristineberg VHMS deposit, Skellefte district, Sweden. Technicshe Universität Bergakademie Freiberg,

Barrett TJ, MacLean WH, Årebäck H (2005) The Palaeoproterozoic Kristineberg VMS deposit, Skellefte district, northern Sweden. Part II: Chemostratigraphy and alteration. Mineralium Deposita 40 (4):368-395

Bauer TE, Skyttä P, Allen RL, Weihed P (2011) Syn-extensional faulting controlling structural inversion – Insights from the Palaeoproterozoic Vargfors syncline, Skellefte mining district, Sweden. Precambrian Research 191:166-183

Bergman Weihed J (2001) Palaeoproterozoic deformation zones in the Skellefte and the Arvidsjaur areas, northern Sweden. In: Weihed P (ed) Weihed P (ed) Economic Geology Research 1. Sveriges Geologiska Undersökning C 833. pp 46-68

Carr JC, Beatson RK, Cherrie JB, Mitchell TJ, Fright WR, McCallum JE, Evans TR Reconstruction and Representation of 3D Objects with Radial Basis Functions. In: SIGGRAPH Computer Graphics Proceedings, 2001.

Ishikawa Y, Sawaguchi T, Iwaya S, Horiuchi M (1976) Delineation of prospecting targets for Kuroko deposits based on modes of volcanism of underlying dacite and alteration halos. Mining Geology 26:105-117

Kathol B, Weihed P (2005) Description of regional geological and geophysical maps of the Skellefte District and surrounding areas. Geological Survey of Sweden,

Kathol B, Weihed P, Antal Lundin I, Bark G, Bergman W, J., Bergström U, Billström K, Björk L, Claesson L, Daniels J, Eliasson T, Frumerie M, Kero L, Kumpulainen RA, Lundström H, Lundström I, Mellqvist C, Petersson J, Skiöld T, Sträng T, Stølen L-K, Söderman J, Triumf C-A, Wikström A, Wikström T, Årebäck H (2005) Regional geological and geophysical maps of the Skellefte District and surrounding areas. Sveriges geologiska undersökning Ba 57:1.

MacLean W, Barrett T (1993) Lithogeochemical techniques using immobile elements. Journal of Geochemical Exploration 48:109-133

MacLean WH (1990) Mass change calculations in altered rock series. Mineralium Deposita 25 (1):44-49

Schlatter DM (2007) Volcanic Stratigraphy and Hydrothermal Alteration of the Petiknäs South Zn-Pb-Cu-Au-Ag Volcanic-hosted Massive Sulfide Deposit, Sweden. Luleå University of Technology, Luleå

Skyttä P (2012) Crustal evolution of an ore district illustrated – 4D-animation from the Skellefte district, Sweden. Computers & Geosciences 48 (0):157-161. doi:10.1016/j.cageo.2012.05.029

Weihed P (2010) Palaeoproterozoic mineralized volcanic arc systems and tectonic evolution of the Fennoscandian shield: Skellefte District Sweden. GFF 132 (1):83-91