Geochemistry of Ultramafic-mafic Units Related to Fe-, Cu-, and Au Deposits in the Gällivare Region, Northern Norrbotten, Sweden

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Abstract. Geochemical investigations were carried out in the Gällivare area as a part of a larger project aiming to understand the crustal architecture of the region in 3D. Major igneous suites such as the Dundret and Vassaravaara intrusions with additional smaller mafic intrusions have been identified as key localities and investigated. Results indicate two distinct rock units. The first suite is assigned to ultramafic-mafic layered intrusions with a calc-alkaline to a more tholeiitic composition belonging to the Dundret and Vassaravaara intrusions. The second suite is mainly of mafic to intermediate composition with a clear ophitic texture. This paper investigate the source and origin of the key rock suites, playing a major role on the evolution of the Gällivare region, a region which is characterized by porphyry Cu, IOCG, and AIO deposits including some of Europe's top producing Fe and Cu-Au-Ag (-Mo) mines.

Keywords. Geochemistry, layered intrusion, 3D-modelling, IOCG

1 Introduction

The northern Norrbotten region in Sweden is regarded as Europe's top Fe- Cu ±Au mining province hosting more than 241 known mineralized occurrences (SGU 1998). It includes some world class deposits such as the underground Fe mines of Kiirunavaara and Malmberget operated by LKAB and the Cu-Au-Ag (-Mo) open pit mine Aitik, operated by Boliden Mineral AB. Additionally, 17 minor Fe and Cu-Au occurrences within the Gällivare area make this region a hot topic for IOCG discussions.

The deposits are hosted within volcanic and volcano-sedimentary successions intruded by multiple generations of intrusive suites and exposed to at least two deformational events with an intense late hydrothermal overprint (Bergman et al. 2001, Wanhainen et al. 2012). Previous research in the area has mainly focused on mine scale investigations with limited regional data for interpreting major geologic events leading to formation of these ore deposits.

The current project aims at understanding the geologic evolution and the 3D crustal architecture of the Gällivare area and surroundings from regional to semi-regional and local scale. It includes geochemical and geochronological investigations that cover the major ultra-mafic, mafic to intermediate igneous suites on a semi-regional scale and their relation to major geological structures. This study focuses on the geochemical characteristics of igneous suites related to ore formation in the Gällivare region.

2 Regional geology

Bedrock in the Gällivare area comprises volcanic, volcaniclastic and volcano-sedimentary rocks formed in a volcanic arc environment related to the subduction of Palaeoproterozoic oceanic plate beneath an old Archaean craton at 1.90 Ga (Fig 1; Wanhainen et al. 2006). These rocks were deformed and metamorphosed under amphibolite facies conditions during early and late stages of the Svecofennian orogeny at 1.88 Ga and 1.80 Ga, respectively (Bergman et al. 2001). Igneous suites with tholeiitic to calc-alkaline trends are suggested to range from Palaeoproterozoic to Mesoproterozoic in age (Bergman et al. 2001, Wanhainen et al. 2005). The most topographically prominent intrusive complex is the Dundret mafic layered intrusion (Martinsson 2000). Most of the mineralization in the region, including the Aitik and the Malmberget deposits, are hosted within volcano-sedimentary successions. Intense hydrothermal alteration is common and includes K-feldspar, epidote and magnetite alteration. The Gällivare area is dominated by a NNW-SSE-striking major crustal shear zone, the Nautanen Deformation Zone (NDZ).

3 Sampling and methods

Field work on local and semi-regional scale was conducted during late 2013 and summer 2014, investigating the role of igneous suites and their relation to dominant structures and mineralization. The investigation focused on major plutonic and volcanic rocks, such as the Dundret layered intrusive complex and the Vassaravaara intrusion. Additionally, minor mafic to intermediate suites from the eastern part of the NDZ and from the Aitik mine were investigated (Fig 1). In total more than 1000 structural and lithological outcrop observations were performed. 334 outcrop samples were collected, of which 34 samples belonging to ultramafic-mafic and intermediate suites were analysed for major and trace elements. The analysis were performed at ALS Chemex laboratories, Canada, using inductive coupled plasma mass spectrometry (ICP-MS) for major elements and inductive coupled plasma atomic emission spectrometry (ICP-AES) for trace elements.

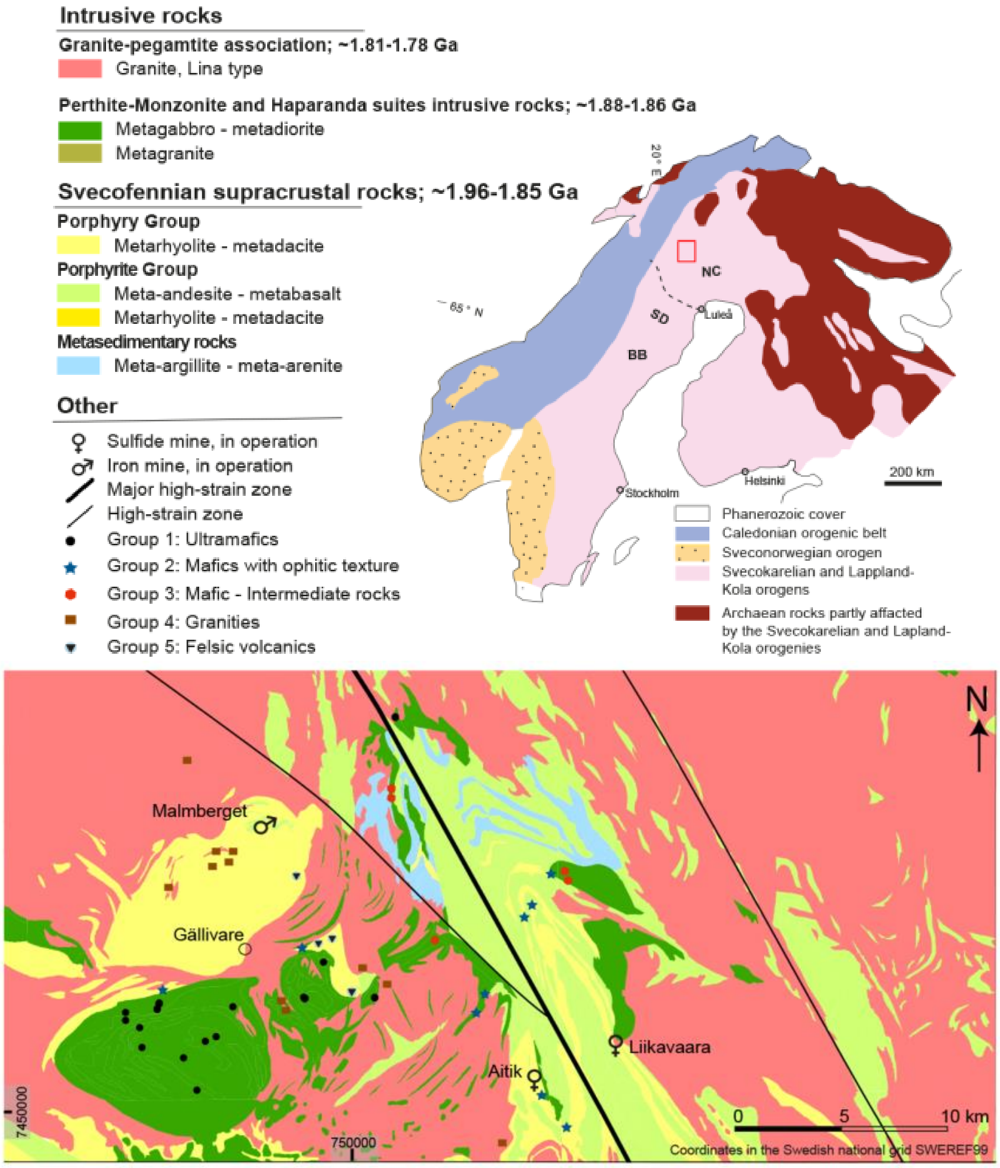

Figure 1. Inset map: Generalized geological map of the Fennoscandian shield. Geological domains: NC=Norrbotten Craton, SD= Skellefte District, BB=Bothnian Basin. Dashed line marks the boundary between rocks with Archaean and Proterozoic Nd-signatures (Mellqvist et al. 1999). Map modified from Koisten et al. (2001). Main map: geological overview map of the Gällivare area and Dundret to the west of NDZ (Nautanen Deformation zone). The Map is modified from the Geological Survey of Sweden (SGU).

3.1 Geochemical classification and trends

For rock classification and monitoring magmatic affinities, immobile trace elements such as high field strength elements (HFSE) and rare earth elements (REEs) have been used. Since these elements are less sensitive to alteration and hydrothermal overprints, they serve as an important tool in pinpointing the source and tectonic setting of many rocks subjected to intense alteration. Data plotted on the diagram modified by Pearce (1996), after Winchester and Floyd (1977), using ratio of immobile trace elements Zr/TiO2 vs Nb/Y show a subalkaline affinity for all samples (Fig 2). Original work by Winchester and Floyd (1977) showed that Zr/TiO2 and Nb/Y ratios are both indices of alkalinity but only Zr/TiO2 ratios represent differentiation index. Thus plotting ratios of immobile element pairs such as Zr/TiO2 vs Nb/Y, both distinguishes between magma affinities and rock types (Winchester and Floyd 1977). However, the graph is limited in distinguishing between products of tholeiitic and calk-alkaline suits. Additionally, fresh volcanic samples were used as basis for plotting more altered and metamorphosed rocks.

Within the plot, two groups can be distinguished; the first group can be addressed to the samples clustered within the basalt field (black points). The second group plot close to the andesite basaltic-andesite field (red points) with a higher Zr-Ti ratio compared to the rocks from group 1. Geochemical data combined with field observations and petrographic studies provide a more robust framework for these groups as follow:

Group 1: Ultramafic rocks

The mineralogy is dominated by plagioclase and olivine, with a generally low abundance of pyroxene. Rock classification based on host mineralogy varies from peridotite, to gabbronorite with a few layers of troctolite. Rhythmic and gradational layering of cumulates can be seen in outcrop scale.

Most of the rocks with ultramafic origin plotting in the basalt field (Fig 2) belong to the Dundret and Vassaravaara intrusive complexes. Additionally, few other rock samples taken in the eastern part of the area exhibit a similar character. Most of the samples seem to be undeformed, except for a few samples located in the vicinity of high strain zones. Following the techniques proposed by MacLean and Barrett (1993) and Barrett (1999), plots of immobile element ratios of Th-Yb and Zr-Y (Fig 3A & B), indicate a tholeiitic to transitional trend for Dundret and Vassaravaara rocks. Zr-Y and La/Yb are regularly used to monitor magmatic affinities. Ratios of Zr-Y are shown to increase from mid ocean ridge type settings towards within-plate due to higher incompatibility of Zr relative to Y during fractionation processes (Pearce 1979). Similar pattern can be observed for La/Yb ratio during fractionation however La can become mobile during certain alteration conditions hence replaced by Th, which is much less effected by aqueous fluids (Pearce 1982, Barrett 1999).

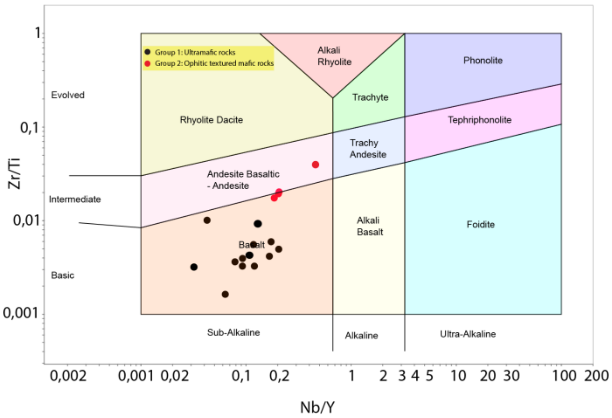

Figure 2: Classification diagram by Pearce (1996), using the immobile element ratio of Zr/Ti vs Nb/Y, which is less sensitive to alteration. Rocks of group 1, Dundret and Vassaravaara in black points plotting within the basalt field. Rocks from group 2, red points plot close to andesite, basaltic-andesite field. Sample east of the NDZ plot entirely within the intermediate field.

Group 2: Mafic rocks with ophitic texture

This rock type is observed in at least four different locations including Aitik, Dundret and east of the NDZ (Fig 1). In the Aitik mine these mafic rocks are emplaced parallel to foliation in volcano-sedimentary units. In other localities they appear as meter to 10 meters wide bodies with dike- and sill-like appearance and chilled margins, indicative of a shallow depth of placements. They comprise a fine- to medium-grained matrix composed of amphiboles and plagioclase with 2-5 mm large plagioclase phenocrysts showing an ophitic texture. These dykes show a transitional to calc-alkaline affinity (Fig 3A and B). The sample taken east of the NDZ plot outside the Th-Yb diagram (Fig 3A), due to a very high Th content.

To further deduce the origin and source of these rocks, a tectonic discrimination diagram for basalts was used (Pearce 2014) plotting ratios of Th/Yb vs Nb/Yb (Fig 4). Th, Nb and Yb behave similarly during petrogenetic processes however subduction related processes will displace Th to higher values relative to Nb (Pearce 1983). Hence higher Th/Yb ratios relative to Nb/Yb ratios are indicative of strong influence by subduction processes (Pearce 1982).

Data strongly suggests a subduction-related setting as the fields of oceanic arcs and continental arcs are occupied by most samples from the two groups. Four samples from the Dundret intrusion including one sample from group 2 plot close to the E-MORB field. Three of the samples are of peridotitic composition and one sample belonging to group 2 is of andesitic-basaltic composition. Samples from the Vassaravaara intrusion together with rocks from the Aitik mine plot within the field overlapping both oceanic arcs and continental arcs.

4 Discussion

Field data from the Dundret and Vassaravaara intrusives and associated units exhibit an ultramafic to mafic layered character with a mixed origin of a tholeiitic (MORB) and a calc-alkaline (continental) affinity. The geochemical character indicates Th enrichment relative to Nb (Fig 4) despite both being equally incompatible. This serves as a particular effective proxy for crustal input (Pearce 2008). The argument is strengthened by the perpendicular to oblique fashion of the samples relative to the MORB-OIB array suggesting crustal input via contamination or deep recycling (Pearce 2008). Dundret, and the Vassaravaara intrusions and the group 2 rocks generally have a lower Zr/Y and Th/Yb ratio (Fig 3A&B), with the exception of 6 samples from the northern and eastern part. This suggest that the northern and eastern part of the Dundret intrusion and Vassaravaara intrusion with associated ultramafic rocks of the eastern part of the Gällivare area were more effected by continental input.

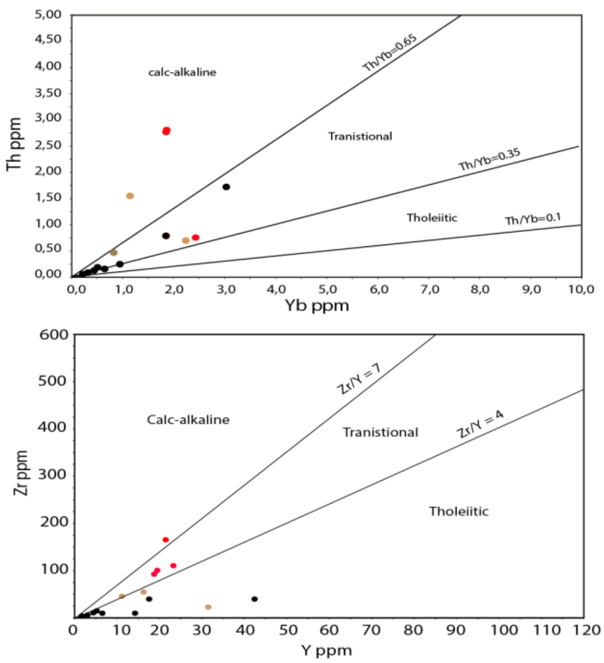

Figure 3: Immobile element plots based on MacLean and Barrett (1993). **A.** Th/Yb plot showing Dundret (black points) and Vassaravaara (brown points) samples plotting mainly in the transitional field with one sample from the eastern part of Vassaravaara plotting in the calc-alkaline field. **B.** Zr/Y plot with Dundret and Vassaravaara samples plotting dominantly in the tholeiitic field. Sample from group 2 (red points) plotting mainly in the transitional field.

These units are suggested to be a post subduction product at 1.87 Ga based on Sm-Nd ages (Öhlander et al. 1993). However, the heterogeneous character and the mixed origin of these rocks are indicative of intra-cratonic or back arc rifting activities generating MORB-type magmas with tholeiitic character subjected to continental contamination upon ascension. Rift-related tholeiitic rocks of Palaeoproterozoic age in northern Norrbotten has been reported by previous researchers (Alapieti and Lahtinen 2002: Martinsson and Perdhal 1995). The role of group 2 rocks, (ophitic-textured mafic rocks) is yet unclear, however continuous mafic activity with island arc basalt (IAB) signature and transitional affinity predating the D_2 deformational event are suggested.

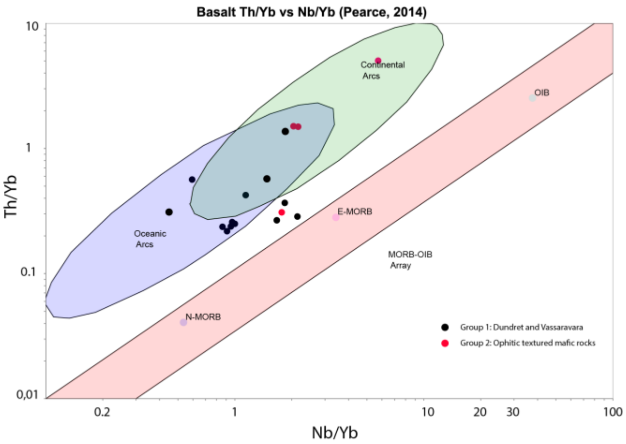

Figure 4: Th/Yb vs Nb/Yb diagram by Pearce (2014). Dispersed pattern shown by rocks belonging to the Dundret and Vassaravaara intrusions (black points). Rocks belonging to group 2, ophitic-textured mafics, exhibit a similar pattern (red points). E-MORB = Enriched Mid Ocean Ridge Basalt, N-MORB = Normal Mid Ocean Ridge Basalt, OIB = Ocean Island Basalt.

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