

The spatial variation of mineralogy in the vanadiferous magnetite deposit of the Lac Doré Complex (Chibougamau, Québec) and its implications on the chemical purity of magnetite concentrates

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Abstract. The incorporation of contaminating elements in vanadiferous magnetite concentrates produced from layered intrusions can lead to expensive complications during vanadium extraction and purification processes. These contaminants may be contained in magnetites, as well as in gangue minerals attached to magnetites after the ore was comminuted. To better understand the flow of contaminating elements incorporated into magnetite concentrates, this project investigates the implications of textural and chemical features of mineralogy on the metallurgical behavior of vanadium ores produced from the Lac Doré Complex in Chibougamau (Québec). *In situ* quantitative mineralogical analysis will be combined with laboratory-scale comminution and magnetic separation tests to develop a framework for a geometallurgical model aiming to improve the process leading to the production of high-purity magnetite concentrates. Results from our preliminary petrographic study reveal that magnetite is preferentially associated with ilmenite, ferrochlorite and ferropargasite in response to magmatic and metamorphic processes. As the mineral abundance, attachments and composition vary greatly in the cumulate pile due to changes in rock type and metamorphic conditions, the chemical constancy of magnetite concentrates will inevitably be affected.

1 Introduction

Vanadium extraction from titanomagnetites by roasting or smelting is very sensitive to the presence of contaminating elements (e.g., Si, Ca and transition metals such as Cr and Mn), which either consume reactants, form refractory phases, or concentrate in the end-product. Consequently, a good knowledge of the distribution of these chemical contaminants in rocks and a good understanding of ore behavior during comminution and mineral separation processes are critical to optimise the extraction of vanadium. Geometallurgy, an emerging approach within the mining industry, aims to integrate geological and metallurgical data to develop predictive models for the

improvement of ore processing (e.g., Lamberg 2011). Knowingly, a geometallurgical modeling proves to be an efficient tool to optimize the extraction processes of vanadium produced from heterogeneous titanomagnetite deposits.

VanadiumCorp Resources Inc. plans to extract the vanadium contained in the structure of magnetites from its Lac Doré property (South limb of the Lac Doré Complex, Québec, Canada) to produce a high-purity vanadium electrolyte (99.99%) for the industry of vanadium flow redox batteries. However, due to the presence of contaminating elements in gangue minerals (e.g., ilmenite and silicates such as ferrochlorite and ferropargasite), as well as in magnetites themselves (by diadochic substitution), the extraction process of vanadium may require expensive purification steps. Therefore, obtaining magnetite concentrates with the lowest possible amount of contaminating elements must be optimized for the metallurgical process.

The objective is to assess the implications of textural and chemical variations on the purity of magnetite concentrates produced from a 122-metre-long transect line chosen to represent the stratigraphy of the East deposit (Lac Doré property). A detailed mapping of this transect was carried out in the summer of 2016 (Fig. 1). Two main problems will be investigated to develop a framework for a geometallurgical model: (1) the implication of textural variations on magnetite liberation during comminution processes; and (2) the implication of mineral composition and its variations on the incorporation rate of contaminating elements in vanadiferous magnetite concentrates. Given that the project is in its early stages, this short paper only includes preliminary results that encompass some textural features for magnetitites and magnetite-bearing anorthositic rocks sampled along the studied transect.

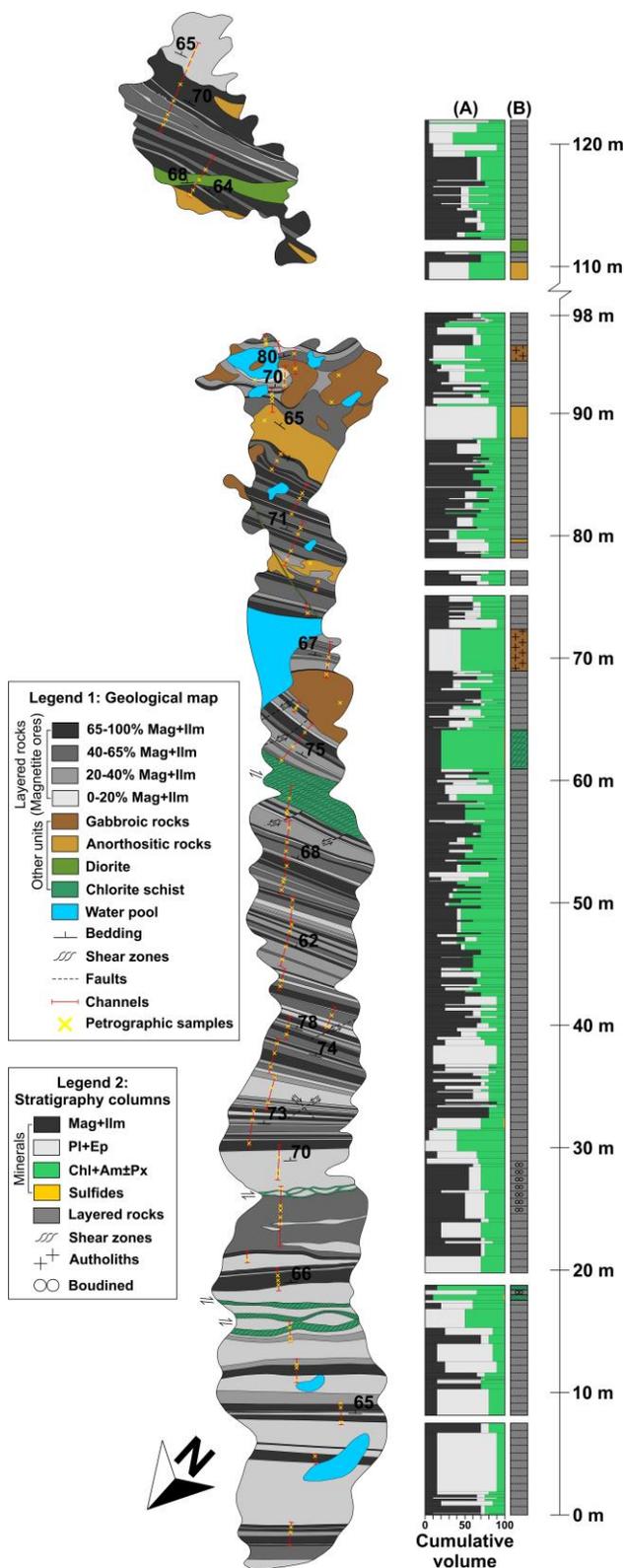


Figure 1. Detailed geological map of the trench 19+50E from the Lac Doré property (VanadiumCorp Resources Inc.). The stratigraphic columns show the estimated modal proportion of minerals (a) and the different types of lithology including layered rocks and non-stratigraphic units (b). Am, amphibole; Chl, chlorite; Ep, epidote; Ilm, ilmenite; Mag, magnetite; Pl, plagioclase; Px, pyroxene.

2 Geological background

The Lac Doré Complex (LDC) is an Archean layered intrusion (2728.3+1.2 / -1.1 Ma; Mortensen 1993) located in the eastern end of the Abitibi greenstone belt in Québec, Canada. Based on the work of Allard (1976) and Daigneault and Allard (1990), the LDC includes from base to top the following stratigraphic levels: (1) the Lower Series; (2) the Layered Series; and (3) the Upper Series. The Layered Series is well known for their vanadium-bearing titanomagnetite deposits, which are mainly represented by a mineralized horizon that extends along the North and South limbs of the LDC (e.g., Allard 1976; Daigneault and Allard 1990; Girard and D'Amours, 2015). The most documented magnetite deposit is in the South limb and consists of an almost continuous mineralized horizon that is typically 60 to 100 metres thick, increasing to more than 200 metres in its most eastern part. According to Girard and D'Amours (2015), the titanomagnetite-rich horizon is steeply dipping to the southeast and extends for 17 km following a NE-SW trend from the Grenville Front toward the southwest. These authors claim that the typical V content of titanomagnetite decreases from 1.47 to 0.86 wt % V₂O₅ towards the top of the Layered Series within the Lac Doré property, while the Ti content increases.

3 Exsolution features

One of the most important problems related to the effects of mineralogy on the purity of vanadiferous magnetite concentrates concerns the presence of fine exsolutions, which are too small to separate from their host magnetite during comminution processes. The systematic incorporation of these exsolutions into the concentrates may result in a significant contamination and a dilution of the V content.

In the Layered Series of the LDC, exsolutions are ubiquitous. The most common features are related to the magnetite-ulvöspinel miscibility gap of which the upper consolute temperature, as determined from various experiments, ranges from about 450 to 600°C (e.g., Price 1981; Lilova et al. 2012). In the studied section, two types of exsolution occurred from the mixing of these two components: (1) ilmenite exsolutions resulting from the oxidation of the ulvöspinel component at temperatures above the solvus of the magnetite-ulvöspinel solid solution; and (2) ilmenite exsolutions resulting from the oxidation of exsolved ulvöspinel. According to Buddington and Lindsley (1964), both types can be referred to as oxy-exsolution.

Oxy-exsolutions in the East deposit exhibit a wide range of textures mainly resulting from the spatial variation of the diffusion rate during cooling. Based on textural evidence, increasing degrees of diffusion result in a systematic textural continuum for both types. Type 1 exsolutions progress from (1) broad trellis- or sandwich-textured lamellae along {111} planes of magnetite (Fig. 2a); through (2) internal granules; to (3) external granules.

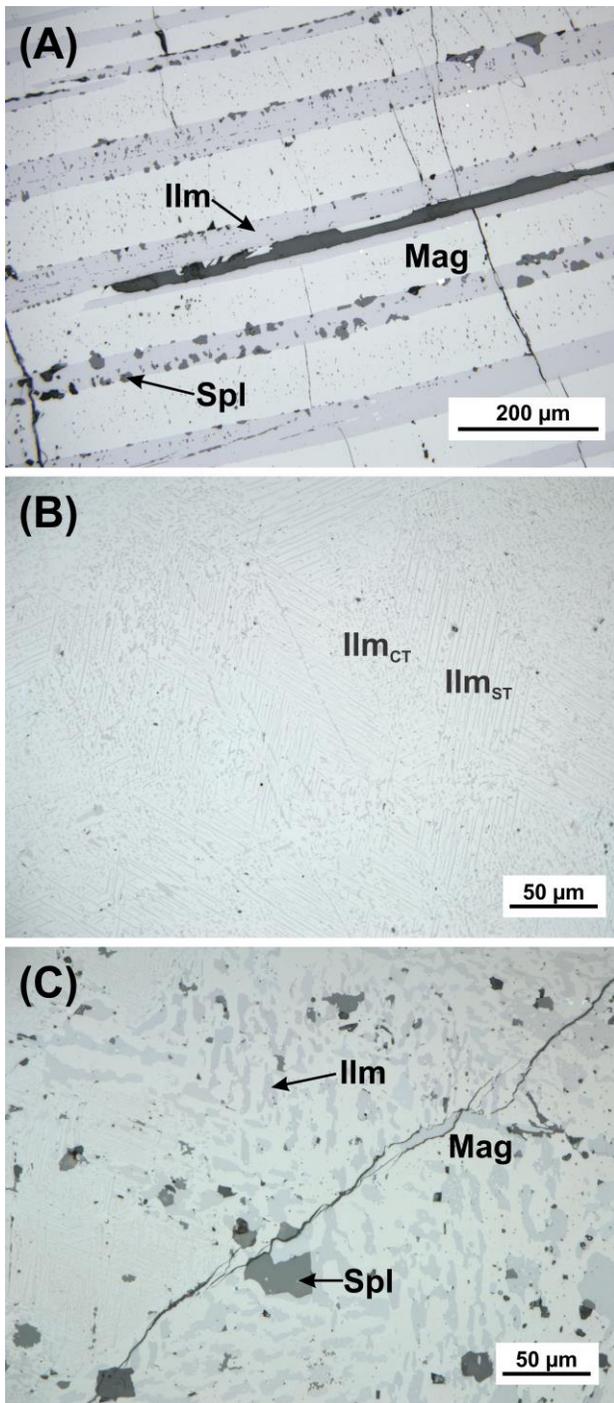


Figure 2. Microphotographs showing some exsolution features in titanomagnetites from the Layered Series of the LDC: (a) broad sandwich-textured lamellae containing small granules of aluminous spinel; (b) contiguous patches of cloth-textured (CT) and sandwich-textured (ST) proto-ilmenite; and (c) pseudo-oriented irregular patches of proto-ilmenite containing very small blebs of magnetite (composite intergrowths). Ilm, ilmenite; Mag, magnetite; Spl, spinel.

On the other hand, type 2 exsolutions [also termed proto-ilmenite by Willemse (1969) and Von Gruenewaldt et al. (1985)] progress from very thin cloth-textured lamellae or

prisms (pseudomorphised ulvöspinel exsolutions; Fig. 2b); through (2) contiguous patches of very thin lamellae forming a second generation of trellis- or sandwich-type texture (Fig. 2b); (3) composite intergrowths (ilmenite \pm magnetite) forming irregular, vermicular or lenticular patches (Fig. 2c); to (4) small external granules. Proto-ilmenite appears to be almost entirely confined in a 30-metre-thick continuous sequence (from 68 to 98 m in Fig. 1). In cases where the proto-ilmenite is dominant, type 1 exsolutions are absent or much less abundant than in the rest of the studied transect.

Aluminous spinels such as those from the hercynite-gahnite solid solution series are also present as exsolution intergrowths in titanomagnetites from the Layered Series. Although their abundance is low compared to ilmenite and varies greatly from one sample to another, they are ubiquitous throughout the transect and occur as very thin discs along {100} planes of magnetite or as very small granules regularly included into broad ilmenite lamellae (Fig. 2a).

4 Silicates and primary ilmenite

Silicates and primary ilmenite (i.e., produced by primary crystallization) in magnetites and magnetite-bearing anorthositic rocks from the Layered Series are also considered as a part of the problem related to the incorporation of contaminating elements in magnetite concentrates. The association of magnetite with a specific mineral may be preferential or not depending on the nature of the mineralogical textures.

The main silicates in the studied transect are those resulting from the metamorphism of rocks at greenschist facies conditions. This includes ferrochlorite, ferropargasite, epidote and albite. The last two are less problematic because they rarely share a common perimeter with magnetite. On the other hand, most of the preferential associations between magnetite and both, ferrochlorite and ferropargasite, can be attributed to the metamorphism of plagioclase, which is responsible for the following features: (1) the presence of kelyphitic rims of ferropargasite resulting from a reaction between magnetite (or ilmenite) and plagioclase with water interaction (in this case the core of plagioclase grains is replaced by a mixture of epidote and albite); (2) the preferential replacement of plagioclase by ferropargasite (\pm epidote) due to sustained water interaction; and (3) the preferential replacement of plagioclase by ferrochlorite (\pm epidote) due to more sustained water interaction. This latter case is peculiar to the magnetites and could be related to the abundance of fractures in magnetites. Magnetite-ferrochlorite association can also be attributed to the replacement of magnetite along fractures and grain margins.

Primary granular ilmenite is ubiquitously associated with magnetite in the Layered Series. This association results from the primary crystallization of both minerals together (or one after the other) as cumulus or intercumulus phases. As suggested by our petrological

observations, the magnetite/ilmenite ratio of magnetites tends to decrease towards the top of the sequence with values ranging from 14.00 to 1.80.

5 Quantitative analysis: a foretaste

Geological data derived from a quantitative mineralogical analysis is the key information to understand ore behavior during mineral processing (comminution, mineral separation and resource extraction). In the course of our study on the East vanadium deposit, we will collect quantitative data sets from *in situ* (on thin sections) analyses of textures and mineral chemistry. The bulk of data will be acquired using the following methods:

(1) *In situ* textural data including, modal mineralogy, exsolution proportion, mineral associations, grain size and contact roughness, will be acquired from colorized backscattered electron (BSE) and energy-dispersive X-ray spectrometry (EDS) images. BSE and EDS images will be obtained using a Zeiss EVO MA scanning electron microscope, and then processed and analysed with the proprietary software ARTSection. Figure 3 shows an example of a colorized BSE image.

(2) *In situ* determination of mineral chemistry will be done by EDS and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Both methods will be used to measure the major, minor and trace element content in minerals such as magnetite, ilmenite, ferropargasite and ferrochlorite.

Combined with laboratory-scale comminution and magnetic separation tests, the *in situ* data will be used to determine the implications of mineralogy on mineral processing in order to develop a framework for a geometallurgical model allowing the improvement of processes leading to the production of magnetite concentrates as pure as possible.

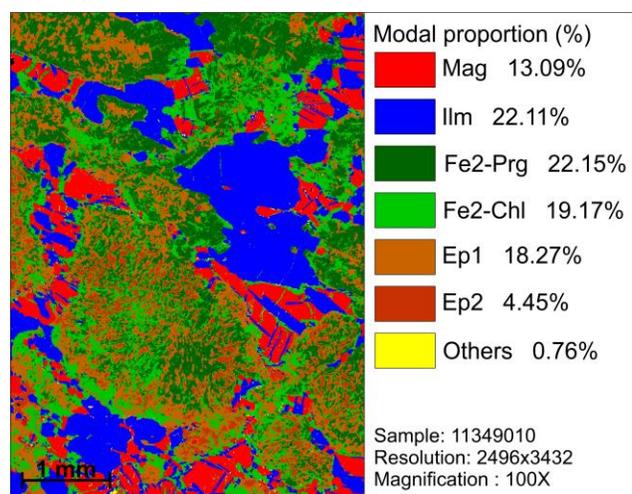


Figure 3. Example of a colorized BSE image showing the modal proportion of minerals. Shades of grey from a mosaic of BSE images have been processed with ARTSection to extract mineralogical parameters. Ep, epidote; Fe2-Chl, ferrochlorite; Fe2-Prg, ferropargasite; Ilm, ilmenite; Mag, magnetite.

6 Concluding remarks

Mineralogical variations in the vanadiferous magnetite deposit of the LDC are expected to affect the purity of magnetite concentrates, and therefore, the efficiency of vanadium extraction processes. One of the main issues related to the effects of mineralogy on mineral processing concerns the eventual control of associated gangue minerals on magnetite liberation, and by extension, on the contamination of magnetite concentrates. As observed during our preliminary petrological study, magnetite in the Layered Series can be associated with (1) ilmenite produced by (i) oxy-exsolution processes or (ii) primary crystallization, (2) ferropargasite and ferrochlorite derived from the metamorphism of plagioclase, and (3) ferrochlorite formed by the replacement of magnetite itself along fractures and grains margins. Each of these associations will be considered as critical features during future work, which will include quantitative mineralogical analyses and laboratory-scale comminution and magnetic separation tests.

Acknowledgements

This work encompasses early stages of the PhD research project of J.-P. A. Valérie Lecomte and Alexandre Néron from IOS Services Géoscientifiques Inc. are thanked for their assistance and advice for BSE image processing and analysis. Annual bursary awarded to the first author to cover living expenses and fees were supported by the Mitacs-Accélération program: grant # IT07474.

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