Petrogenesis of massive sulphides from the Lac-des-Iles palladium ore deposits, Western Ontario, Canada

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Abstract. Previously characterised as a sulphide-poor Pd ore deposit, massive sulphides have recently been discovered in Lac-des-Iles. The massive sulphides occur across the different lithological units and show variable degrees of alteration. The least altered samples comprise a typical magmatic assemblage of pyrrhotite, pentlandite and chalcopyrite. Chalcopyrite-rich samples are found at the edges of the pyrrhotite/pentlandite-rich pods. Base metal and platinum-group element (PGE) compositions indicate that as a whole they represent a frozen sulphide liquid, different from the one that formed the sulphide-poor samples, that was injected along structural features. The altered samples are rich in pyrite and magnetite. Molecular proportions of base metals and S/Se ratios are the same for the altered and unaltered samples indicating that neither S nor Fe has been remobilized from the system. We propose instead that oxidation was responsible for the observed changes in mineralogy. This alteration event appears not to have affected the PGE content.

Keywords. Massive sulphides, structural control, Lac-des-Iles Pd ore deposits

1 Introduction

The Archean Lac-des-Iles (LDI) Complex, western Ontario, is Canada's only primary platinum-group elements (PGE) producer and the world's fourth largest palladium (Pd) producer. In contrast to most PGE ore deposits which occur either as strataform PGE-rich layers within large layered intrusions (e.g. Bushveld and Stillwater) or as PGE-rich Ni-Cu sulphides at the base of mafic intrusions (e.g. Norils'k and Sudbury), the LDI mineralization occurs as sulphides and platinum-group minerals (PGM) disseminated in a small mafic intrusion of chaotic lithologies (i.e. magmatic breccias and varitextured gabbronorites). The mineralization is characterized by extreme and variable Pd-enrichment highlighted by unusually high Pd/Pt ratios. Studies by Hinchey et al. (2005), Barnes and Gomwe (2011), and Djon and Barnes (2012), suggest that both PGE collection by a magmatic sulphide liquid followed by Pd-remobilization by later magmas or fluids have contributed in the ore formation. However, the contribution of each process is poorly understood, and relatively little is known about how the Pd-enrichment was achieved.

The LDI complex has been previously characterized as sulphide poor (i.e. < 3%). However massive sulphides have recently been discovered, which raises the question of the processes involved in their formation. Three possible origins may be considered: a)

the sulphides are monosulphide solid solution (MSS) cumulates and the fractionated liquid has migrated away to form the disseminated sulphides; b) the sulphides represent a frozen sulphide liquid; c) the sulphides precipitated from late-magmatic aqueous fluids.

In the current study we document new data on the geology, petrography/mineralogy, and whole rock geochemistry of the newly discovered massive sulphides from the LDI complex in order to consider their origin.

2 Geology of LDI and location of massive sulphides

The LDI Complex consists of three mafic to ultramafic intrusions emplaced into gneissic tonalites and granodiorites, which are in turn intruded by various granitoids. The Mine Block Intrusion is the central intrusion of the complex and is the only one that hosts Pd-deposits (i.e. Roby and Offset zones). The Mine Block Intrusion is concentrically zoned in both composition and texture. Compositions range mainly from leuco- to melano-gabbros and gabbronorites, including a magnetite-rich gabbro. Magmatic breccias occur in the Roby zone but have not been observed at depth. Varitextured gabbros form a rim around the gabbroic and gabbronoritic units. Most of the rocks regardless their texture or degree of alteration, have similar compositions (Barnes and Gomwe 2011). The shape of the intrusion suggests an elongation along a SW-NE trend.

The sulphide-rich samples occur as small pods and lenses (8 to 65 cm thick), ranging from densely disseminated (~10% sulphides) to massive sulphides (~90% sulphides). These pods are found in different units and at different stratigraphic levels within the intrusion (Figs. 1 and 2). Despite being present in host rocks that formed at different stages of magma differentiation the sulphide-rich samples have similar textural, petrographical and mineralogical characteristics. The semi-massive sulphides host rounded silicate inclusions and exhibit brecciated textures. All these observations suggest that the sulphides have been injected across the stratigraphy of the intrusion implying that they were in a liquid state. The geological setting thus suggests that the sulphides were emplaced along some structural feature and either represent an immiscible sulphide liquid, or have precipitated from late-magmatic fluids.
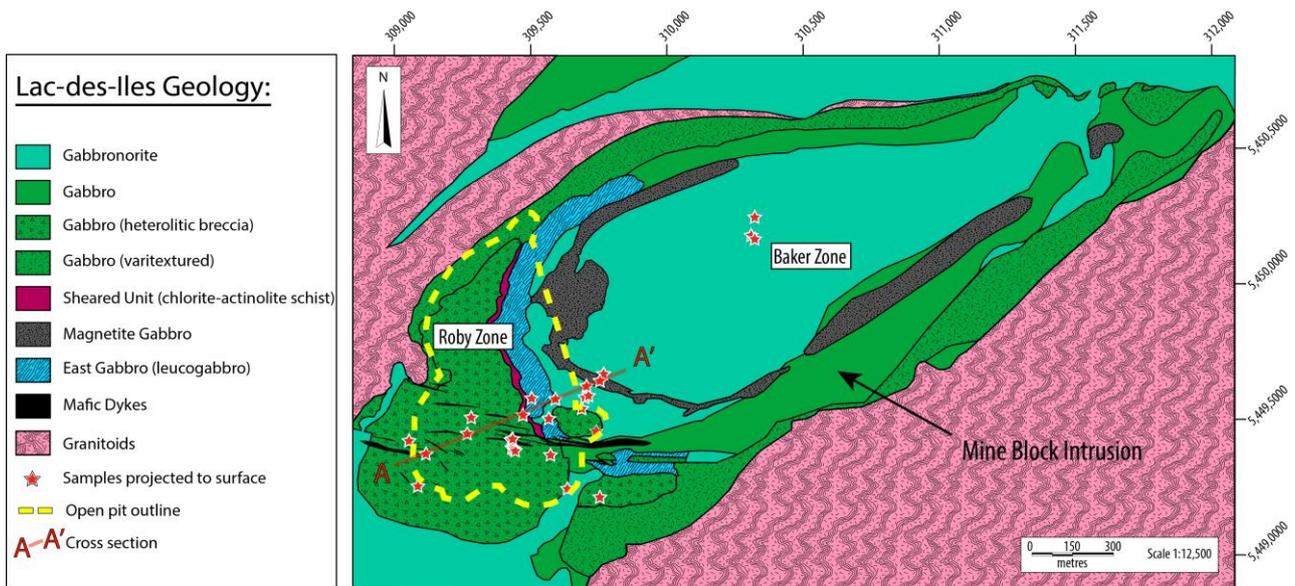
Figure 1. Simplified geological map of the Mine Block Intrusion of the Lac-des-Iles Complex with location of the sulphide-rich samples (Modified from North American Palladium). Note that the samples are projected to surface and form a SW-NE trend. The samples are hosted in the different lithological units.
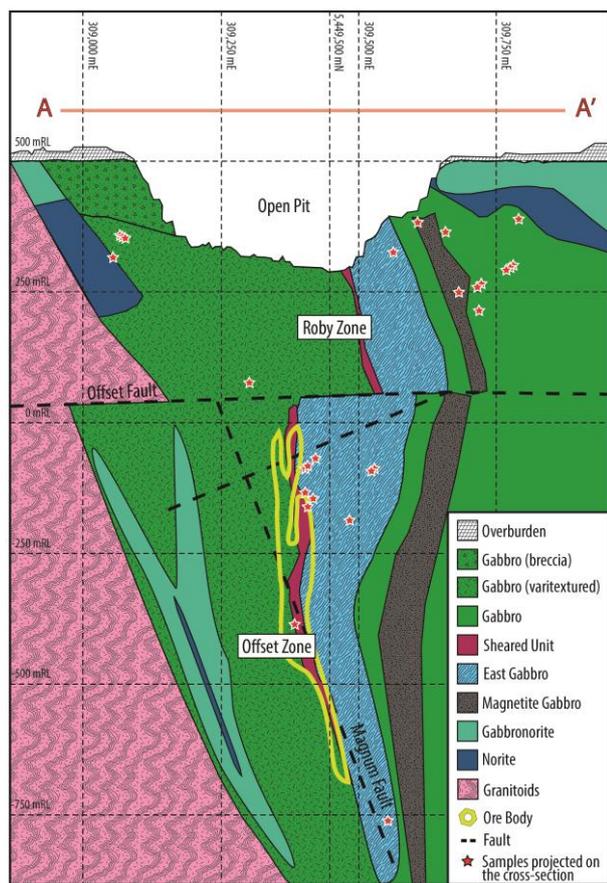

Figure 2. Idealized cross-section of the Mine Block Intrusion of the Lac-des-Iles complex with projected location of samples from drill cores (Modified from North American Palladium). Note that sulphides sampled from the open pit and from Baker zone are not plotted on the cross-section.

3 Petrography

The ore mineral assemblage is mainly composed of pyrrhotite (Po), pentlandite (Pn), pyrite (Py) and magnetite (Mt) with minor amounts of chalcopyrite (Ccp), ilmenite and discrete PGM up to 100 μm diameter. Most of the PGM are either included in sulphides, or along sulphide-silicate and sulphide-sulphide grain boundaries. Only few of them are included in silicates.

Based on modal proportions, the massive sulphides can be divided into 5 assemblages: i) Po + Pn + minor Py (< 10%) ± Ccp (Fig. 3a). This assemblage exhibits magmatic textures. Pyrrhotite forms large anhedral crystals surrounded by granular polycrystalline veinlets of Pn. Pentlandite also occurs as exsolution flames in Po; ii) Po + Pn + Py (> 10%) ± Ccp (Fig. 3b). This assemblage still shows magmatic texture, but the amount of Py present is too high for an igneous assemblage. Pyrite textures vary from subhedral to anhedral individual grains or polycrystalline aggregates. In some rare cases Py occurs as small veins; iii) Py (>50%) + Po + Pn ± Ccp (Fig. 3c); iv) Mt (>30%) + Py (>10%) + Po + Pn ± Ccp (Fig. 3d); v) Ccp (>50 %) found at the edges of the pods (Fig. 3e). All of the assemblages except v) contains too little Ccp to represent sulphide liquid. Assemblages i) and ii) could represent sulphide cumulates and assemblage v) the fractionated liquid. Assemblages iii) and iv) could be extremely altered sulphide cumulates or they could precipitate from late-magmatic fluids.
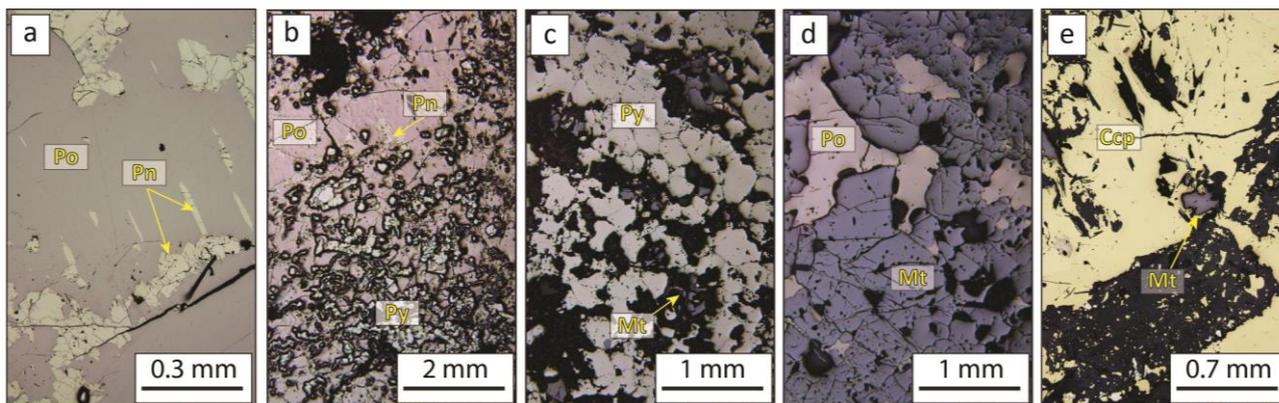
Figure 3. Photomicrographs of the different sulphide assemblages from LDI in reflected light. a) Assemblage i) showing magmatic textures; b) Assemblage ii) where magmatic textures still remain but with considerable amount of Py; c-d) Respectively assemblages iii) and iv) correspond to the most altered samples. Magmatic textures are almost lost and Py and/or Mt are the major phases; e) Assemblage v) where Ccp is the major phase.

4 Geochemistry

4.1 Relationship among the assemblages

Based on the behaviour of relatively immobile elements such as Ir and Rh, we do not think that assemblages iii) and iv) represent hydrothermal deposits. These elements fall on a single trend which includes the disseminated sulphides from the mineralized zones and the sulphide-rich assemblages (Fig. 4).
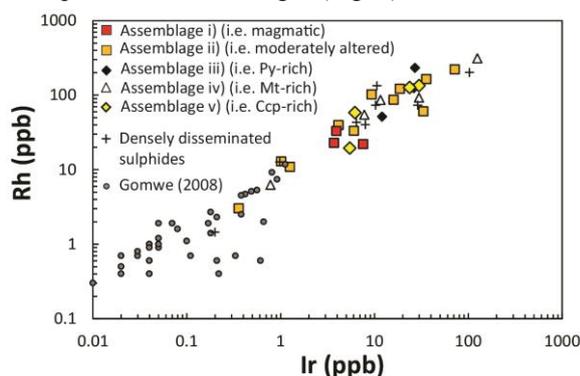

Figure 4. Bivariate plot of whole rock Ir (ppb) versus whole rock Rh (ppb). Values of disseminated sulphides (small circles) from mineralized zones are taken from Gomwe (2008).

Assuming that assemblages ii) to iv) represent altered magmatic sulphides the presence of excess Py and Mt in assemblages ii) to iv) requires either that S has been added or that Fe has been lost from the sulphide assemblage.

In igneous sulphides the molecular proportions of S to Fe + Cu + Ni is approximately 1. Most of the samples including those of assemblage iii) and iv) plot close to the igneous line (Fig. 5). This suggests that for most of the samples, neither S nor Fe has been mobile. The positive correlations between S and Se and S and Ni, combined with S/Se ratios in the mantle range, also suggest that S was not mobile (Fig. 6a,b).
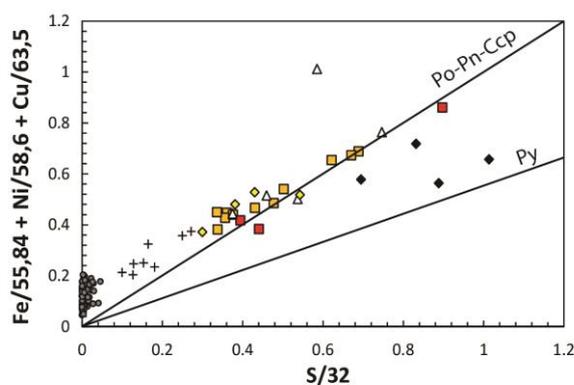

Figure 5. Bivariate plot of molecular proportions of S versus Fe + Ni + Cu. Values of disseminated sulphides (small circles) from mineralized zones are taken from Gomwe (2008).

In order to account for the excess of Py and Mt in assemblages ii) to iv), we suggest that Po was oxidized resulting in the reaction: $Po + O_2 = Py + Mt$. Thus neither Fe nor S was mobile and assemblages i) to iv) represent sulphides which have been partly oxidized during late-magmatic alteration.

On a plot of S versus Cu (Fig. 6c) the samples show a good correlation until approximately 5% S. After that the samples plot on either side of the trend, with the Ccp-rich samples above the trend. This could be because the Ccp-rich samples represent the fractionated liquid complimentary to the sulphide cumulate. However this does not appear to be the case because the fractionated liquid should be enriched in Pd and yet the Ccp-rich samples have similar values to the other massive sulphide samples (Fig. 6d). This suggests that the Ccp-rich samples either represent intermediate solid solution cumulates, and the most fractionated liquid has migrated away from the massive sulphide pods. Alternatively Ccp was originally present with Po and Pn in the center of the pods, and has been remobilized to the edges. At present we favour the remobilization because all the massive sulphides have very high Pd/Ir and Pd/Pt ratios (1000-10000; 10-20) which is contrary to the general observation that sulphide cumulates are depleted in Pd.
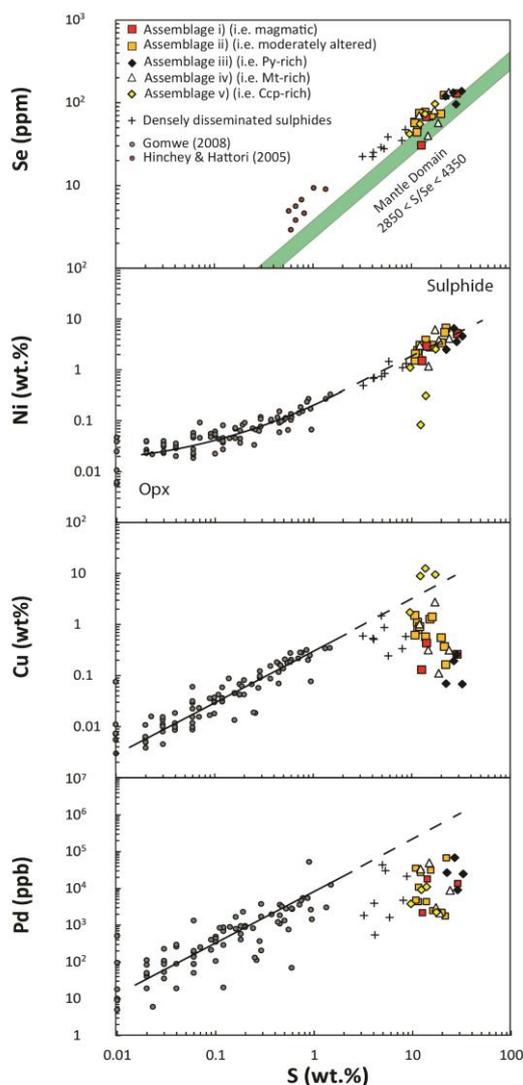
Figure 6. Bivariate plots of whole rock S (wt %) versus whole rock Ni (wt. %), Se (ppm), Cu (wt. %), and Pd (ppb). Values of disseminated sulfides are taken from Gomwe (2008) and Hinchey and Hattori (2005).

4.2 Relationship between massive and disseminated sulphides

If we consider only S, Ni and Se and allow that Cu has been remobilized on the centimeter scale, then it is possible to argue that because the compositions of massive and disseminated sulphides are co-linear, the sulphide component of all the samples represents a sulphide liquid. But when we consider the plot of Pd versus S (Fig. 6d) it is clear that the massive sulphides are depleted in Pd in comparison with the disseminated sulphides. Therefore it cannot be the same liquid.

5 Discussion

Although the position of the sulphides within the complex and their late-magmatic mineralogy could make us think that sulphides might have formed by precipitation from an aqueous fluid circulating through structures within the intrusion, the presence of typical magmatic textures and the geochemical signature of massive sulphides demonstrate their magmatic origin.

Indeed the typical magmatic textures would not have been formed by fluids.

Our model suggests that late in the solidification of the Mine Block intrusion magmatic sulphide liquid was injected from a feeder chamber along structures related to regional crustal movements. Movement along the structures separated the sulphide liquid into pods. The liquid crystallized as Po-Pn-Ccp and PGM.

Deformation or fluid action caused the Ccp to migrate to the edges of the pods and thus forming Ccp-rich and Ccp-poor sulphide assemblages. Oxidation of Po led to the formation of Py and Mt, but does not appear to affect the metal content of the rocks.

6 Conclusions

We propose that: 1) Sulphide liquid accumulated in embayments of a magmatic conduit. 2) This sulphide liquid has been squeezed through dilatencies in consolidated silicate magma and accumulated as massive sulphides across the stratigraphy. 3) The sulphide liquid formed MSS cumulates and a Cu-rich portion. 4) The massive sulphides are not related to the disseminated sulphides as they are poorer in Pd. 5) The primary sulphide assemblage has been altered to Py and Mt by oxidation. 6) This oxidation event did not affect the metal concentrations in the ores; in particular it did not up-grade the Pd because there is no relationship between the sulphide assemblages and the metal contents of the rocks.

Acknowledgements

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