Partial melting and melt segregation within the contact aureole of the Sudbury Igneous Complex (Ontario, Canada) and their significance in hydrothermal Cu-Ni-PGE mineralization of the footwall

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Summary of the dissertation

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Introduction

Crystallization of the superheated impact melt sheet within the 1.85 Ga Sudbury impact structure to form the layered sequence of the Sudbury Igneous Complex (SIC) provided the heat source for various processes within its footwall that had a significant effect on the deposition and re-mobilization of world-class Ni-Cu-PGE ores. These include: (1) an assimilation process that consumed several hundred metres of the footwall, and resulted in the formation of the contact Sublayer, one of the main hosts of magmatic Ni-Cu-PGE sulphides (Prevec et al., 2000; Prevec and Cawthorn, 2002), (2) the development of an 1 to 2 km wide contact metamorphic aureole (e.g., Dressler 1984b; Boast & Spray, 2006), (3) the formation of the Footwall Breccia, the other main host of magmatic ore deposits, through a combination of partial melting and thermal recrystallization (e.g., Coats and Snajdr, 1984; Lakomy, 1990; McCormick et al., 2002a), (4) circulation of hydrothermal fluids, which had a great significance in the final distribution of metals especially in the footwall of the SIC (e.g., Farrow and Watkinson, 1992; Li and Naldrett, 1993a; Molnár et al., 1997, 1999, 2001; Hanley et al., 2005).

Although the exact role of hydrothermal fluids in the formation of footwall Cu-Ni-PGE occurrences as much as 2 km away from the SIC/footwall contact is debated and was certainly not the same within different deposits, there is a general agreement that they had a great significance in the remobilization of metals from the primary magmatic ores (e.g., Jago et al., 1994; Watkinson, 1999; Molnár and Watkinson, 2001; Farrow & Lightfoot, 2002; Hanley et al., 2005; Ames & Farrow, 2007). Typical footwall-style ore consists of massive Cu-rich sulphide vein stockworks ("sharp-walled" vein systems) occurring especially in impact brecciated zones of the footwall (Sudbury Breccia). However, recently another type of ore has also been recognized. These "low-sulphide"-systems (Farrow et al., 2005) are exceptionally enriched in Pt, Pd and Au, although consisting only of disseminations, and veinlets of sulphides accompanied by hydrous silicate assemblages and typically having less than 3 modal % sulphide contents.

A few authors reported signs of hydrothermal activity within mineralized parts of the Sublayer and Footwall Breccia, which suggest that remobilization of metals from the contact environment into the deeper footwall may have occurred (Farrow and Watkinson, 1996; McCormick and McDonald, 1999; Molnár et al., 2001; McCormick et al., 2002b). The source of fluids interacting with contact sulphides, as well as those involved in formation of footwall Cu-Ni-PGE occurrences still remains speculative (Marshall et al., 1999). Molnár et al. (2001) described a fluid exsolution process from "footwall granophyre" (FWGR) veins, which represent crystallized partial melts within mineralized Footwall Breccia. They suggested that brines segregating from these melts may have been major components of the hydrothermal system in the footwall of the

SIC, and argued that superimposing hydrothermal events independent from the SIC-driven fluid flow also had some role in later redistribution of metals.

The general aim of this study was to establish the genetic relationship between partial melting and Cu-Ni-PGE mineralizing processes in the contact aureole of the SIC. However, to be able to outline a generalized model explaining these interrelated processes required the investigation of parts of this complex system separately. This means separate parts in a spatial sense (i.e., two environments: the SIC/footwall contact zone and the deeper footwall of the SIC), but also with respect to a variety of processes including partial melting, melt segregation, fluid segregation from crystallizing melts, hydrothermal alteration and deposition of metals.

The first part of our work was to outline the significance of hydrothermal fluids in the formation of footwall Cu-Ni-PGE occurrences. Among these deposits, the "low-sulphide"-style systems have been recognized only recently (Farrow et al., 2005) and detailed descriptions of these extremely high PGE-grade mineralized zones are scarce. Thus, a detailed study was initiated of two recently discovered footwall Cu-Ni-PGE occurrences in Wisner Township of the North Range, where such mineralization was not known before. With data from the "low-sulphide"-style South zone occurrence and the "hybrid" (both "low-sulphide"- and "sharp-walled" vein-style parts) Broken Hammer zone the understanding of the footwall mineralizing processes evolved. The main questions to be answered were:

1. What are the differences and similarities of the mineralogy, mineral chemistry and bulk rock metal geochemistry of certain mineralization styles of footwall deposits?
2. What was the role of hydrothermal fluids in the formation of "sharp-walled vein"-type and "low-sulphide" deposits?
3. What kind and how many generations of fluids were involved in the hydrothermal process?

In the second part of our study the aim was to understand the partial melting processes within the contact aureole of the SIC, which were proposed to be important fluid sources of the magmatic hydrothermal system of this environment (Molnár et al., 2001). We selected mapping and sampling areas in various parts of the North and East Ranges, but not the South Range, because there the contact aureole was affected by several phases of deformation and metamorphism. As there were no earlier geologic studies focusing on these melting processes (only thermal modelling of SIC-related assimilation and partial melting was performed), first we had to investigate and answer a variety of questions regarding this topic:

1. What were the conditions of partial melting and how did they change spatially?
2. Where and to what depth did partial melting occur below the SIC and how did the degree of melting change with distance from the contact?

3. How significant was the melting process volumetrically?
4. Which rock types were affected by melting?
5. What are the similarities and differences of crystallized partial melts in the various occurrences of the contact and footwall environments?

In the final part the aim was to connect these two topics and to reveal evidences for or against the genetic link proposed by Molnár et al. (2001). Examples highlighting different aspects of their possible genetic relationship were provided:

1. What is the temporal and causal relationship of the partial melting and hydrothermal processes in the contact environment?
2. Is there a spatial association of the two processes within the footwall?

Methods

Mapping and sampling was carried out in the field seasons of 2005 to 2009 on properties mostly owned by Wallbridge Mining Company Ltd. and partly by Xstrata Nickel (Windy Lake, Foy and Wisner in the North Range, Skynner and Frost in the East Range, and Creighton in the South Range of the Sudbury structure). Detailed geologic and alteration mapping, as well as mapping of partial melting features was performed on trenched and high-pressure washed outcrops ("trenches") at a scale of 1:50 and 1:75 in the Wisner South, Southwest and Broken Hammer zones, as well as the Frost Amy Lake zone. Field mapping in the scale of 1:2000 was also completed in many areas and supplemented by logging and sampling of diamond drill cores deepened within the same locations.

Bulk rock geochemical analyses of grab samples and half-core samples were carried out for major elements, as well as 50 base metals and trace elements (including Pt, Pd and Au) by ALS Chemex Ltd. (Vancouver, Canada). Six element PGE (Pt, Pd, Ir, Os, Ru, Rh) concentrations were determined at Labtium Oy (Espoo, Finland). Fluid inclusion microthermometric analyzes were performed on a Chaixmeca-type and a Linkam THM 600 apparatus at the Department of Mineralogy (Eötvös University). Titanium concentrations in quartz for thermometry purposes were analyzed with Laser ablation ICP-MS method at the laboratory of the Hungarian Academy of Sciences, Institute for Isotopes (Budapest, Hungary) using a double-focusing magnetic sector ICP mass spectrometer (ELEMENT2) equipped with a New Wave UP-213 laser ablation system.

Most of the mineral chemical data was acquired using a Camebax MBX electron microprobe by wavelength dispersive analysis at Carleton University (Ottawa, Canada). Further analyzes were carried out using the Jeol SEM 6310 scanning electron microscope with a wavelength and energy dispersive system at the Karl-Franzens University (Graz, Austria).

Summary

(1) Several Cu-Ni-PGE mineralization styles could be distinguished within the Broken Hammer and South zones of the Wisner area in the North Range of the SIC. Although massive sulphide veins account for the major part of the ore, sulphide-poor assemblages (patches, disseminations, silicate-quartz-rich vein stockworks) may have similarly high precious metal contents, and are very significant in understanding the mineralization processes involved in ore formation. As all the mineralization is hosted by sulphide-poor assemblages in the South zone, this occurrence can be classified as a "low-sulphide", PGE-rich system. Although such assemblages are also important carriers of metals at the Broken Hammer zone, as large part of the ore are hosted by "sharp-walled" massive sulphide veins (like the "Big Boy" vein), this occurrence may be regarded as a "hybrid" system.

(2) Both occurrences host a wide variety of PGM, as well as associated silver and trace metal minerals. The assemblages revealed from these zones include minerals typical to footwall deposits (e.g., merenskyite, moncheite, michenerite, hessite etc.), minerals found only in a few Sudbury deposits (e.g., clausthalite, sopcheite, naumannite, bohdanowiczite) and very rare minerals that have not been described earlier from Sudbury (temagamite) or were only described recently and are known only from a couple of localities around the world (malyshevite, lisiguangite). There are several mineralogical questions that would be interesting to follow up: for example, a solid solution of lisiguangite and malyshevite is suggested by our microprobe data, but has never been described earlier; silver minerals found at South zone include compositions, which do not appear to correspond to known minerals ($Ag_2Pd_2Te_3$?, Ag_4TeSe?, $AgPdTe_2$?).

(3) Statistical investigation of metal distribution patterns revealed important trends and differences between the mineralization styles and the two zones. As indicated by increasing Cu/(Cu+Ni) with increasing S content, "low-sulphide" assemblages may contain significant Ni as well as Cu, but massive sulphide veins contain only negligible amounts of Ni. The Pt/(Pt+Pd) ratios decrease with increasing S; "low-sulphide" ore has roughly similar Pt and Pd contents, whereas sulphide veins have much higher concentrations of Pd than Pt (Pt/(Pt+Pd = 0.2). Overall, precious metal (Pt, Pd, Au) and Ag concentrations recalculated to 100% sulphides (tenors) decrease by one or two orders of magnitude for all metals from the disseminated to the massive sulphides highlighting how metal-rich the "low-sulphide" assemblages are. The distribution patterns of base- and precious metals are not consistent with simple models of magmatic sulphide segregation-fractionation.

(4) The combination of field, petrographic and laboratory studies suggest that "low-sulphide" assemblages were formed by high temperature (~ 400-500°C), high salinity (30-40 NaCl equiv. wt.%) fluids of a magmatic-hydrothermal system driven by the heat of the cooling SIC. There is much evidence that these fluids were also present and possibly played an important role during the deposition of massive sulphide veins. Silicate-quartz-(sulphide) veins were precipitated from a similar, but lower temperature fluid (300-400°C) in a later stage of the same system. These results indicate that hydrothermal fluid flow driven by the cooling SIC was not locally restricted (e.g., in the Onaping-Levack area) but also was present and related to Cu-Ni-PGE deposition in other zones of the footwall along the North Range.

(5) Large and small scale mapping of footwall granophyres in numerous localities along the North and East Ranges of the Sudbury structure showed that partial melting due to cooling of the impact melt sheet was widespread within the contact aureole of the SIC. Melting occurred up to 500 metres below the Sublayer. However, the degree of partial melting does not decrease gradually away from the contact, but appears to have been localized, especially to SDBX zones. Outside this distance however, footwall granophyres do not exist even in the Sudbury brecciated zones. These results confirm thermal modelling by Prevec and Cawthorn (2002).

(6) Melting of mafic rocks in the Windy Lake and Frost areas suggests that temperatures in the contact aureole may have reached 850 to 900°C up to 200 m from the contact. It is possible, however, that such high temperatures were only attained in some embayment structures in which a thickened melt sheet could transmit more heat into the footwall. In other areas (e.g., Wisner localities), temperatures reached only about 750°C, mafic rocks did not undergo partial melting and melting of felsic rocks required water-saturated conditions. Thus actual fluid saturation of rocks defined localization of melting processes. Zones of SDBX probably contained pore fluids derived from local footwall rocks at or after brecciation and were therefore more water-rich than unbrecciated granites and gneisses. They also acted as conduits for SIC-related fluids (Rousell et al., 2003), thus fluid flow along breccia zones may also have been important in promoting partial melting.

(7) The difference in partial melting temperature and the contribution of melts derived from various protoliths is responsible for the textural, mineralogical and compositional differences among footwall granophyres. While the bulk rock composition of Wisner samples is in accordance with partial melting of only felsic LGC and CB units, data of footwall granophyres at Frost indicates also significant contribution from the melting of gabbroic rocks.

(8) Melt segregation from partially melted rocks with *in situ* melting features occurred in all localities and was promoted by deformation due to crater wall modifications and the ongoing

Penokean orogeny, as well as pre-existing zones of weaknesses in the host rocks (e.g., foliation, shear zones, SDBX veins). While veins and dykes reflect brittle conditions during melt migration, sheared melt pods in SDBX matrix indicate ductile conditions of the matrix during partial melt crystallization.

(9) Exsolution of high salinity fluids at temperatures of ~ 650 to 400°C accompanied the crystallization of partial melts in all localities. Because of the ductile conditions along the contact and proximal footwall environment, there was no large scale migration of melts and fluids in these zones. Significant amounts of external fluids (e.g., formational brines) could not enter the contact environment, partial melts and fluids exsolving from the melts did not leave the closed system. Although individual footwall granophyres appear to be small and insignificant in local scale, the melting process was in fact very widespread and thus important in providing high salinity brines to the hydrothermal system responsible for the redistribution of metals from pre-existing magmatic ores.

(10) In mineralized parts of the Footwall Breccia, interaction of partial melts, exsolved fluids and the pre-existing magmatic Ni-Cu-PGE ores took place. This is evidenced by replacement due to cross-cutting footwall granophyres and pervasive hydrothermal alteration of sulphide ore in Footwall Breccia occurrences at Craig, Windy Lake and Rapid River. As a result of this reaction, metals appear to have been scavenged and carried away from these environments.

(11) A close spatial association of footwall granophyres and "low-sulphide" assemblages at Wisner South and Southwest, as well a Frost Amy Lake zones evidence a coeval existence and a genetic relationship of the partial melting and mineralizing hydrothermal processes. At Frost, the metal-bearing fluids appear to have percolated into the Sudbury brecciated and partially melted zone and mixed with the crystallizing partial melts to form PGE-rich sulphide precipitations within the miarolitic cavities of footwall granophyres. However, the observations from the Wisner South zone indicate a very intriguing process not recognized so far in the Sudbury literature: the coeval migration of partial melts and mineralizing fluids.

(12) Putting results from the Wisner South zone and the contact occurrences into the context of recent knowledge on the cooling history of the SIC, it is suggested that "offshoots" of large volumes of partial melt and metal-enriched fluids from the contact into the footwall environment may have occurred at sudden brittle episodes related to the crater modifications of the Sudbury structure. At these episodes, the melts and fluids that could not migrate due to the ductile conditions of the contact and proximal footwall environment were able to leave this closed system and result in the emplacement of footwall granophyre veins and the precipitation of "low-sulphide" ore. The infiltration of similar mineralizing fluids from the

contact into the footwall occurred in some areas without the migration of partial melts in which cases a spatial association of "low-sulphide" mineralization and FWGR veining is absent (e.g., Frost ALZ). In a similar way, stockworks of rootless FWGR veins have been observed in areas (e.g., Foy footwall) without associated sulphides, which points out that such "offshoots" from the contact were only accompanied by mineralizing fluids, if the contact from which they originated hosted magmatic sulphides that could be remobilized. Emplacement of fractionated sulphide liquids into the footwall may also have occurred during such sudden brittle episodes to form some of the "sharp-walled" vein systems.

(13) It is suggested that the formation of PGE-bearing hydrous silicate-quartz-rich vein stockworks cutting Footwall Breccia and occurring in association to many footwall-style occurrences (like the actinolite-, epidote-, quartz-rich veining at the Broken Hammer zone and the amphibole-epidote-chalcopyrite veins at the Rapid River zone) took place at a later stage, when the contact and proximal footwall environment was already under brittle conditions. The fluids circulating in this system were probably of different sources (including also basinal brines, metamorphic fluids etc.). The formation of some "sharp-walled" vein systems can probably also be put at this late stage of sulphide distribution, which explains why these sulphide veins often crosscut "low-sulphide" mineralization or actinolite veining. The emplacement of "sharp-walled" vein systems probably occurred in multiple phases and by different processes (magmatic vs. hydrothermal), which may explain the controversy regarding their origin.

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