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**GEOLOGICAL SURVEY OF CANADA
OPEN FILE 6578**

**Geochemistry of 44 Ni-Cu-platinum group element deposits
in the contact, footwall, offset, and breccia belt environments,
Sudbury mining district, Canada**

D.E. Ames, C.E.G. Farrow, I.R. Jonasson, E.F. Pattison, and J.P. Golightly

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2014

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GEOCHEMISTRY OF 44 Ni-Cu-PLATINUM GROUP ELEMENT DEPOSITS IN THE CONTACT, FOOTWALL, OFFSET, AND BRECCIA BELT ENVIRONMENTS, SUDBURY MINING DISTRICT, CANADA

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BACKGROUND

In the late 1990s, it was known that many platinum group elements (PGE) bond with various trace elements (e.g. Se, Te, Bi, As, Sn, Pb, and Hg) to form platinum group minerals (PGM), (Cabri, 2002); however, the concentrations of these trace elements in Ni-Cu-PGE ores were not known. Few trace element studies of Ni-Cu ores have been undertaken (Jonasson et al., 1987) and those that have, analyzed the full suite of PGEs in world-class Ni-Cu-PGE ores only in the absence of the trace elements that constitute the ore minerals, which emphasizes the bulk precious metal content (e.g. Naldrett et al., 1999). With the advent of laser ablation ICP-MS (Jackson et al., 1992), several studies investigated the trace element composition of individual sulphide minerals in Ni-Cu ores; however, only a few, of the more than 87 base and precious metal ore deposits in the Sudbury district, were investigated (Dare et al., 2010a,b; 2011; Beaudin, 2011; Warren et al., 2013; MacMillan, 2014).

The geochemical and mineralogical composition of a vast array of ore deposit types found in the Sudbury mining district have been studied using the collection of rock samples that are housed at the Geological Survey of Canada, in Ottawa (Fig. 1). In 1999, field collection of Ni-Cu-PGE mineralization throughout the Sudbury Structure was initiated by the primary author, following an initial assessment and sampling of the GSC's mineral deposit collection and the National Mineral Collection. A suite of more than 600 rock samples was assembled comprising the field collection of the first author, a subset of ore samples collected by former GSC geologists (Fig. 2b), and a unique Inco display collection, which had been specifically collected to represent the individual ore deposit types from 10 Inco mines that operated from 1960 through the 1980s, (Fig. 2, 3). In 2005, the suite of samples for this study was completed with the collection of both high-sulphide and low-sulphide PGE samples from PGE and precious metal-rich deposits that formed in a footwall environment, which was a new exploration target for the Sudbury camp.

This study was funded by the Geological Survey of Canada's Targeted Geoscience Initiatives (2000–pre-

sent) and is an exceptional mineral district ore collection and geochemical database, which is available in the public domain as a source for the mining industry, further research, and training.

INTRODUCTION

The 1.85 Ga Sudbury Structure is host to over 87 present and past-producing deposits (Fig. 1; Ames et al., 2005, 2006, 2008). Primary metal production in the Sudbury mining district is nickel (for which Sudbury is a global producer), copper, and cobalt; however, companion and precious metals (e.g. platinum, palladium, gold, silver) have become the prime target of district exploration, particularly since the millennium (2000–2014).

The district's enormous Ni-Co, Cu-Pt-Pd-Au-Ag resources are spatially associated with the Sudbury Igneous Complex (SIC), a 60 x 30 km elliptical body that represents the eroded and folded remnant of a much larger sub-horizontal impact melt sheet in one of the Earth's largest and oldest preserved impact structures. The SIC straddles the boundary between the Archean Superior Province deeply exhumed basement rocks of the North Range (and east), and the Paleoproterozoic Southern Province intracratonic rift and platformal sequence, which contains numerous mafic Proterozoic dyke swarms, of the South Range. The ore deposits are located proximal to the base of the SIC in different environments that define them. These include the following deposit types (1) *contact deposits*, which are hosted in depressions in the lower contact of the SIC; (2) *offset deposits*, which are hosted in radial and concentrically distributed dykes and structures; and (3) *footwall deposits*, which are hosted in impact brecciated rocks in the country rocks below the SIC (Morrison et al., 1994). In the footwall environment, the deposits are further subdivided into “sharp-walled vein” and “low sulphide” disseminated mineralization (Farrow et al., 2005). The newly identified footwall environment has triggered a wealth of footwall mineralization studies to characterize and identify mineralogical or compositional vectors to the elusive hydrothermal-magmatic footwall Cu-PGE mineralization (Kjarsgaard and Ames, 2010; Tuba et al., 2010;

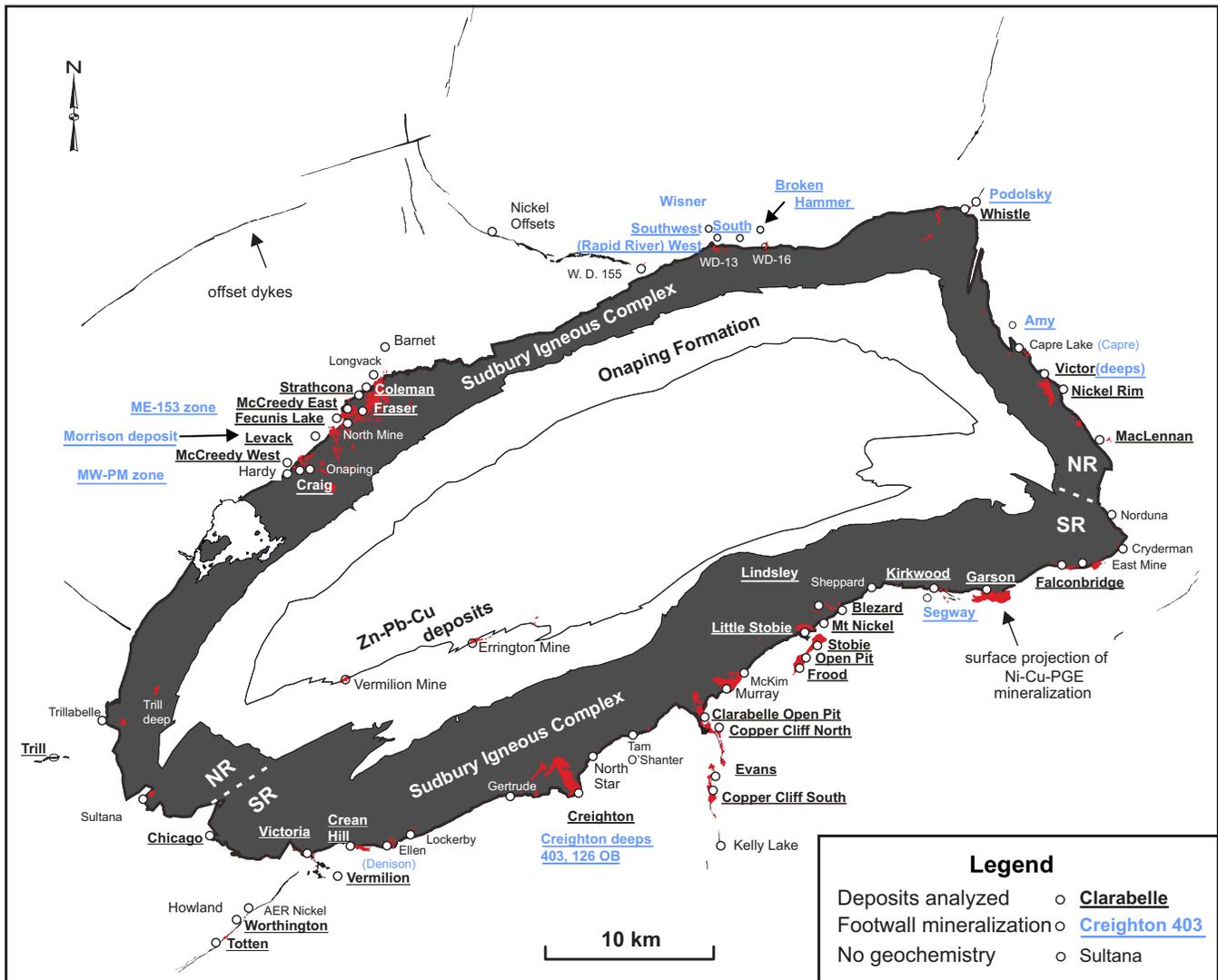


Figure 1. Location map of the Ni-Cu-(PGE) and Cu-(Ni)-PGE deposits in the Sudbury mining district, Ontario, Canada highlighting those for which there are geochemical analyses. The dashed white line delineates the approximate location of the border between the North Range (including East) and South Range nomenclature that is used in the district.

2014; White, 2012; Ames et al., 2013; MacMillan et al., 2013; Dare et al., 2014; MacMillan, 2014).

Data was collected for this regional study of Canada’s world-class Ni (Cu-PGE) Sudbury mineralization to characterize the geological, geochemical, and mineralogical traits of the various Sudbury ore types, and to understand the processes that control the trace elements that constitute platinum group, ore, and accessory minerals and assess their relevance to issues of genesis, metallurgy, and exploitation of resources. The major and trace element geochemical database included with this release is accompanied by rock slab photographs of each of the samples in the database of Ni-Cu-PGE, sulphide, and low-sulphide ores and some host rocks from the Sudbury mining district (Fig. 1; Appendices A and B). A companion publication of the mineral chemistry microprobe results for ores from 39 Sudbury-district mineral deposits will be published in a

subsequent Geological Survey of Canada Open File report (Ames et al., 2014). Preliminary mineralogical results have also been published in Ames et al. (2007), Kjarsgaard and Ames (2010), and Ames and Kjarsgaard (2013).

METHODS

The analyses of the Sudbury district ore samples that were collected for this study was, undertaken by the Geological Survey of Canada (GSC) - Ottawa analytical laboratories between 1998 and 2007. After which time, the mandate of the laboratories changed focus and routine geochemical analysis was terminated. All samples were analyzed for each element using the same techniques in the same laboratory. Most elements in the sulphide ores were analyzed in the GSC laboratories (Ottawa) with the exception of As, Se, Au, Pt, Pd, which was analyzed by Activation laboratories,

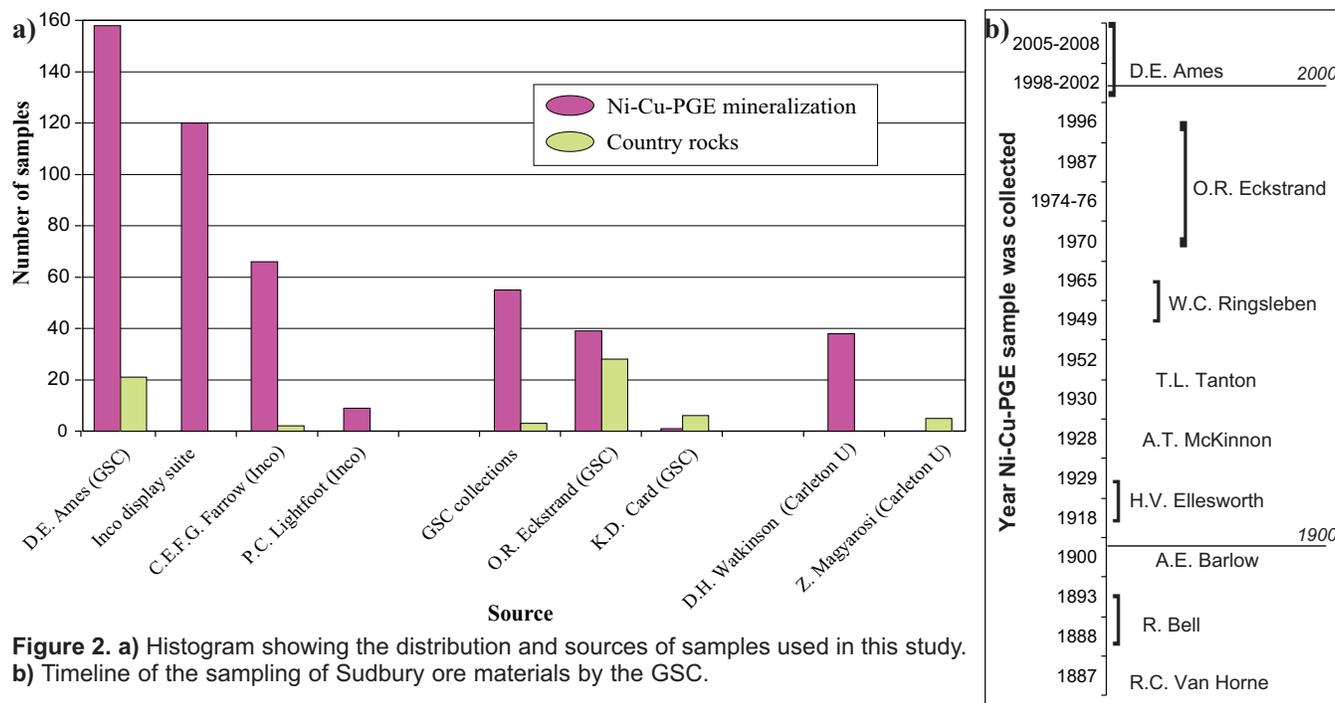


Figure 2. a) Histogram showing the distribution and sources of samples used in this study. b) Timeline of the sampling of Sudbury ore materials by the GSC.

(Ancaster) (Table 1, Appendix B2). The major elements analysed in the GSC labs (TiO_2 to P_2O_5 , Ni, and Cu: % levels) were determined by XRF with an ICP-ES finish following initial fusion with Li tetraborate/tetraborate flux, and dissolution in nitric acid. A separate aliquot of each sample was used to determine SiO_2 to a precision of 0.1% or better. Wet chemical methods and a Leco furnace were used to analyze for $\text{CO}_2(\text{t})$, S(t), F, Cl, and loss on ignition (LOI). Care was taken to ensure all minerals were completely absorbed into the solution: especially magnetite, ilmenite, rutile, telluride, cassiterite, and native metals. Minor, trace, and lanthanide elements examined in the GSC labs were determined following dissolution in a nitric, perchloric, hydrofluoric acid mixture, and fusion of the residues with lithium metaborate was taken up in hydrochloric acid. Combined solutions were analysed by ICP-ES/MS.

Other key elements in the ores, such as Au, Ir, As, Br, Hg, and Se, were analyzed by Activation Laboratories using INAA methods (Au + 34 1D enhanced package) Pt, Pd, and Au were analyzed by nickel sulphide fire assay followed by ICP-MS procedures. Some elements were analyzed by multiple methods and labs, which served as a cross laboratory check for many analyses.

The polished slab of each sample was photographed and is presented in Appendix A, allowing for firsthand textural observation. The photographs and hand-sample descriptions of mineralization from the North Range are presented in Appendix A1 and the South Range ores in Appendix A2. The database of the ore

sample geochemistry and sample locations (NAD 27) is provided in Appendix B.

RESULTS

Sudbury Ni-Cu-PGE Geochemistry

The regional compositional variation of Sudbury mineralization was investigated through integrated geochemistry and mineralogy of 44 Ni-Cu-PGE deposits and a few Cu-PGE deposits and occurrences (Fig. 1)

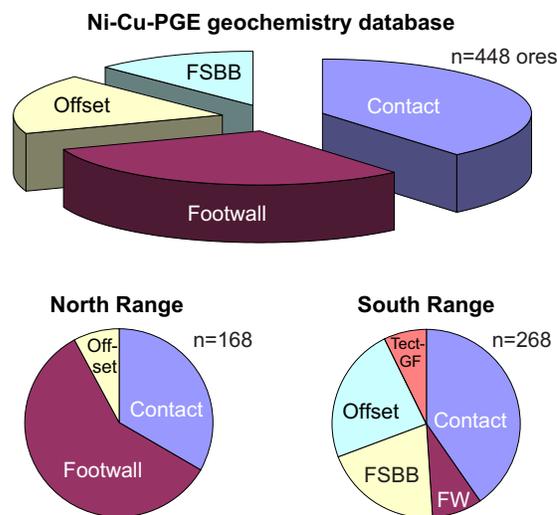


Figure 3. Pie diagrams showing the relative distribution of Sudbury Ni-Cu-PGE samples from the various deposit settings for (a) the entire mining district, (b) the North Range, and (c) the South Range. Abbreviations: FSBB - Froid-Stobie breccia belt; FW- footwall; Tect (FG) - tectonically modified deposits, Falconbridge and Garson ores. For further detail, see the databases in appendices A and B.

Table 1. List of methodologies, limit of detection, and analytical laboratories used in this study.

| | Unit | Method.Lab | D.L. |
|---------------------------------|------|------------|------|
| SiO ₂ | % | xrf.gsc | 0.40 |
| TiO ₂ | % | xrf.gsc | 0.05 |
| Al ₂ O ₃ | % | xrf.gsc | 0.10 |
| Fe ₂ O _{3T} | % | xrf.gsc | 0.10 |
| MnO | % | xrf.gsc | 0.02 |
| MgO | % | xrf.gsc | 0.10 |
| CaO | % | xrf.gsc | 0.10 |
| Na ₂ O | % | xrf.gsc | 0.10 |
| K ₂ O | % | xrf.gsc | 0.05 |
| H ₂ O _T | % | chm.gsc | 0.10 |
| CO _{2T} | % | chm.gsc | 0.20 |
| P ₂ O ₅ | % | xrf.gsc | 0.02 |
| S _T | % | chm.gsc | 0.02 |
| Ag | ppm | icp.gsc | 0.50 |
| As | ppm | inaa.act | 0.5 |
| Au | ppb | inaa.act | 2 |
| Ba | ppm | icp.gsc | 20 |
| Be | ppm | icp.gsc | 0.5 |
| Bi | ppm | icp.gsc | 0.2 |
| Br | ppm | inaa.act | 0.5 |
| Cd | ppm | icp.gsc | 0.2 |
| Co | ppm | icp.gsc | 5 |
| Cr | ppm | icp.gsc | 10 |
| Cs | ppm | icp.gsc | 0.02 |
| Cl | ppm | IC.gsc | 100 |
| Cu | ppm | icp.gsc | 10 |
| F | ppm | IC.gsc | 50 |
| Ga | ppm | icp.gsc | 0.1 |
| Hf | ppm | icp.gsc | 0.05 |
| Hg | ppm | inaa.act | 1 |
| In | ppm | icp.gsc | 0.05 |
| Ir | ppb | inaa.act | 5 |
| Mo | ppm | icp.gsc | 0.20 |
| Nb | ppm | icp.gsc | 0.2 |
| Ni | ppm | icp.gsc | 10 |
| Pb | ppm | icp.gsc | 1 |
| Pd | ppb | FA-icp.act | 0.1 |
| Pt | ppb | FA-icp.act | 0.1 |
| Rb | ppm | icp.gsc | 0.05 |
| Sb | ppm | icp.gsc | 0.2 |
| Sc | ppm | icp.gsc | 0.5 |
| Se | ppm | inaa.act | 3.0 |
| Sn | ppm | icp.gsc | 0.5 |
| Sr | ppm | icp.gsc | 10 |
| Ta | ppm | icp.gsc | 0.05 |
| Te | ppm | icp.gsc | 0.2 |
| Th | ppm | icp.gsc | 0.02 |
| Tl | ppm | icp.gsc | 0.02 |
| U | ppm | icp.gsc | 0.02 |
| V | ppm | icp.gsc | 5 |
| Y | ppm | icp.gsc | 0.1 |
| Zn | ppm | icp.gsc | 5 |
| Zr | ppm | icp.gsc | 0.5 |

Notes:

act - Activation Laboratories, Ancaster, ON
 blank - concentration not determined (no value)
 D.L. - detection limit
 gsc - Geological Survey of Canada -Ottawa, pre-2007
 XRF - fused disc

(Ames et al., 2010; Kjarsgaard and Ames, 2010). More than 600 samples of sulphide-rich and sulphide-poor mineralization were collected and analyzed, and is representative of ores in contact, offset, footwall, and the Frood-Stobie breccia belt ore environments (Fig. 3). The Sudbury database contains the extensive geochemical analyses of 451 mineralized samples, comprising whole rock, rare earth, and trace element geochemistry (Appendix B). Trace elements analyzed include S, Sb, Sn, Mo, Bi, Te, Co, Se, Au, Ir, Pt, Pd, Au, Ag, Ni, Cu, Hg, In, Zn, Cd, Pb, and As (Ames et al., 2010). The

data are presented according to geographic location in the mining district (i.e. North or South Range), mine name (i.e. Morrison), and ore environment or type (contact, low-/high-sulphide footwall, offset).

Country Rock Geochemistry

The trace element composition of potential source rocks for the Ni-Cu-PGE ore system was determined for 150 samples from the meteorite impact “target” rocks of the Sudbury impact structure. These samples included Paleoproterozoic, Huronian supracrustal metasedimentary and metavolcanic rocks, mafic and felsic intrusions, dyke swarms, and the Archean Levack gneiss. First-order provinciality of certain elements to geographical and geological location were evident due to differences in host rocks and environment, and from north (Levack Gneiss Complex/Cartier granite) to south (Huronian volcano-sedimentary sequence and Nipissing diabase) (Ames and Farrow, 2007; Ames et al., 2010).

Sudbury Igneous Complex Geochemistry

In the McCreedy East and Levack mine areas, the lower units of the SIC that contained disseminated sulphides were also analyzed (n=15: Appendix B).

SUMMARY

This publication serves as a baseline for the composition of the Ni-Cu-PGE ores of the world-class Sudbury mining district and provides data for important applications that have yet to be realized. Characterization of the geochemistry of individual deposits or orebodies within a deposit in this geochemical database may be useful for mining companies that routinely analyze blended mill feed without firsthand knowledge of the specific attributes of individual orebodies, ore types, individual mines, or geographical regions. Elemental trace element associations that have been identified in a mining camp provide a compositional record of mined-out orebodies and may provide the foundation databases for future mining, education, and exploration.

ACKNOWLEDGEMENTS

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