

Advances in the understanding of Canadian Ni-Cu-PGE and Cr ore systems – Examples from the Midcontinent Rift, the Circum-Superior Belt, the Archean Superior Province, and Cordilleran Alaskan-type intrusions

Preface

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INTRODUCTION

The present volume comprises a collection of nine papers summarizing research undertaken as part of the Geological Survey of Canada's Targeted Geoscience Initiative, Phase 5 (TGI-5). This 5-year thematic research program on Canadian ore systems ran from April 2015 to March 2020 with the broad aims of advancing the understanding of Canadian ore deposits and their broader ore system contexts, developing methods to help detect buried ore deposits, and providing public geoscience to increase the effectiveness of mineral exploration in both "brown fields" and "green fields" settings. The research program was designed around the concept of "ore systems" (e.g. Hronsky and Groves, 2008; Bleeker et al., 2014), i.e. the broader set of processes and their spatial-temporal context, and pre-history, that culminate in the formation and preservation of economic mineral deposits, often in clusters at the scale of a mining camp or at the larger scale of a mining district or geological province.

Implicit in this more holistic approach to ore deposit research, initially modelled on the system-scale approach typical of modern oil and gas exploration ("petroleum systems", see Wyborn et al., 1994), is the concept that individual constituents that make up an ore deposit are generally derived from dispersed sources, then transported by some medium, and finally precipitated and concentrated to ore levels at some depositional site, and under a highly specific set of circumstances (Fig. 1). The ore system approach thus involves the entire "process chain" from ultimate source reservoirs, such as the lower crust ("sources"), and transport pathways ("conduits"), to final depositional sites ("traps"). It also is cognizant of the post-depositional processes that play important roles in long-term preservation (e.g. sedimentary and/or tec-

tonic burial), without which few ancient orebodies would be preserved.

For practical reasons, the thematic research of TGI-5 was organized into five major ore systems (orthomagmatic systems, gold systems, volcanic and sedimentary systems, porphyry-related systems, and uranium ore systems). This volume presents results from the orthomagmatic ore system that focused on Ni-Cu-PGE and Cr deposits. Some studies included here involved a detailed look at the Fe-Ti oxides associated with these deposits.

Of the nine individual contributions to this volume, eight were funded directly by the TGI-5 program and led by researchers from the Geological Survey of Canada (GSC). The final contribution to the present volume, on mineralized "Alaskan-type" intrusions (Irvine, 1974) in the Canadian Cordillera, was funded in part by the research grants component of the TGI-5 program—competitive grants that are awarded to selected researchers external to the GSC.

SYNOPSIS OF INDIVIDUAL CONTRIBUTIONS

The nine papers in this volume present research results on orthomagmatic ore systems across time and from across Canada, from Archean systems in the various subprovinces of the Superior craton, to komatiite-hosted magmatic sulphide deposits of the Paleoproterozoic "Circum-Superior Belt" on the margins of this craton, to the younger Proterozoic rift system of the ca. 1.1 Ga Midcontinent Rift, and finally the much younger Alaskan-type intrusions associated with Phanerozoic orogenic settings in the Canadian Cordillera (Fig. 2). For a complete list of peer-reviewed journal papers, government reports, and student theses stemming from the Orthomagmatic Ni-Cu-

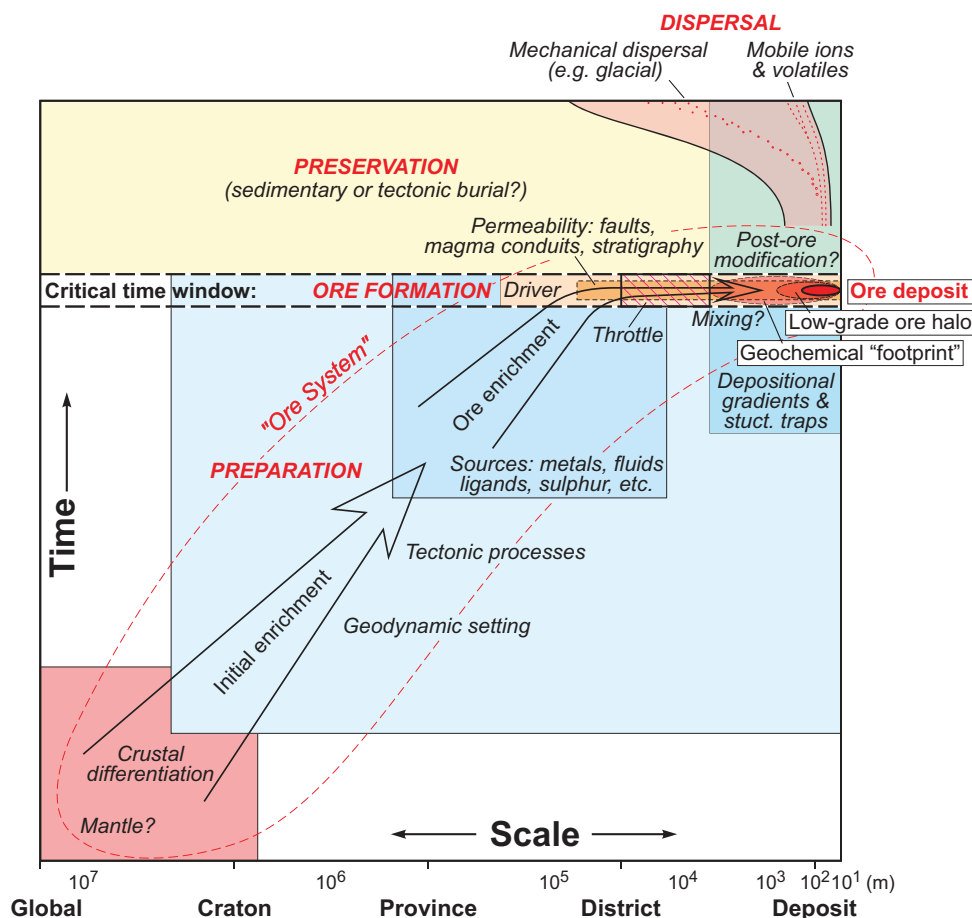


Figure 1. Diagram of geological time versus spatial scale illustrating the concept of complex mineral systems culminating in an economic ore deposit (small red ellipse along the right axis). The existence of an ore deposit accessible to mining typically involves initial preparatory processes (e.g. metal enrichment in the lower crust), a number of critically linked ore-formation processes (often with specific tectonic drivers, and typically operating in a narrow time-interval), and finally preservation (e.g. tectonic burial and/or sedimentary burial). These linked processes occur across a vast range of scales. Initially, large-scale geodynamic and tectonic processes concentrate elements of interest into a regional- to district-scale source region, from which they are stripped by hydrothermal fluids or magmas. Faults or other permeable zones (magmatic conduits, stratigraphy?) then focus metal-bearing fluids or magmas into depositional environments where chemical, physical, and/or thermal gradients lead to ore deposition. After passing through the depositional environment, spent fluids disperse into the environment. Many of these processes leave forensic evidence, such as hydrothermal alteration, that can be used to locate mineral deposits and their more extensive geochemical “footprints”. Post-depositional dispersal of ore constituents or “pathfinder” elements, whether by chemical or mechanical means, may again enlarge the scale of the exploration target. (from Bleeker et al., 2014; modified after <http://www.ga.gov.au/minerals/projects/current-projects/mineral-systems-of-australia.html#>)¹.

PGE-Cr Ore Systems Project under TGI-5, the reader is referred to the Appendix at the end of this volume.

The ca. 1.1 Ga Midcontinent Rift System and its Mineralized Intrusions

(1) Starting with the Midcontinent Rift system, **Bleeker et al. (2020)** present an overview of this superbly preserved late Mesoproterozoic rift system thought to be associated with an upwelling mantle plume. A large

and diverse set of intrusions is associated with this rift system, many of which are mineralized. Some of the key mineralized settings are described and new U-Pb ages are presented for several of the key intrusions, placing them in a more refined evolution of the rift system. Mineralized intrusions are not confined to a single magmatic pulse, but distributed through time and associated with each major magmatic pulse, from ca. 1117 to 1092 Ma. Many of the mineralized intrusions show

¹This diagram is designed to illustrate, in particular, the process chain inherent to magmatic and hydrothermal ore systems. It is only partially applicable to some other ore systems, such as, for example, those forming on the seafloor due to selective scavenging of metals and adsorption onto highly condensed organic-rich black muds. The ore system of such deposits (HEBS: highly enriched black shales), involves a continental weathering cycle, delivery of metals to the global oceans, and finally highly specific adsorption processes. In that particular system there is again a lengthy preparatory stage, conduits in the sense of rivers, but no explicit “throttle”.

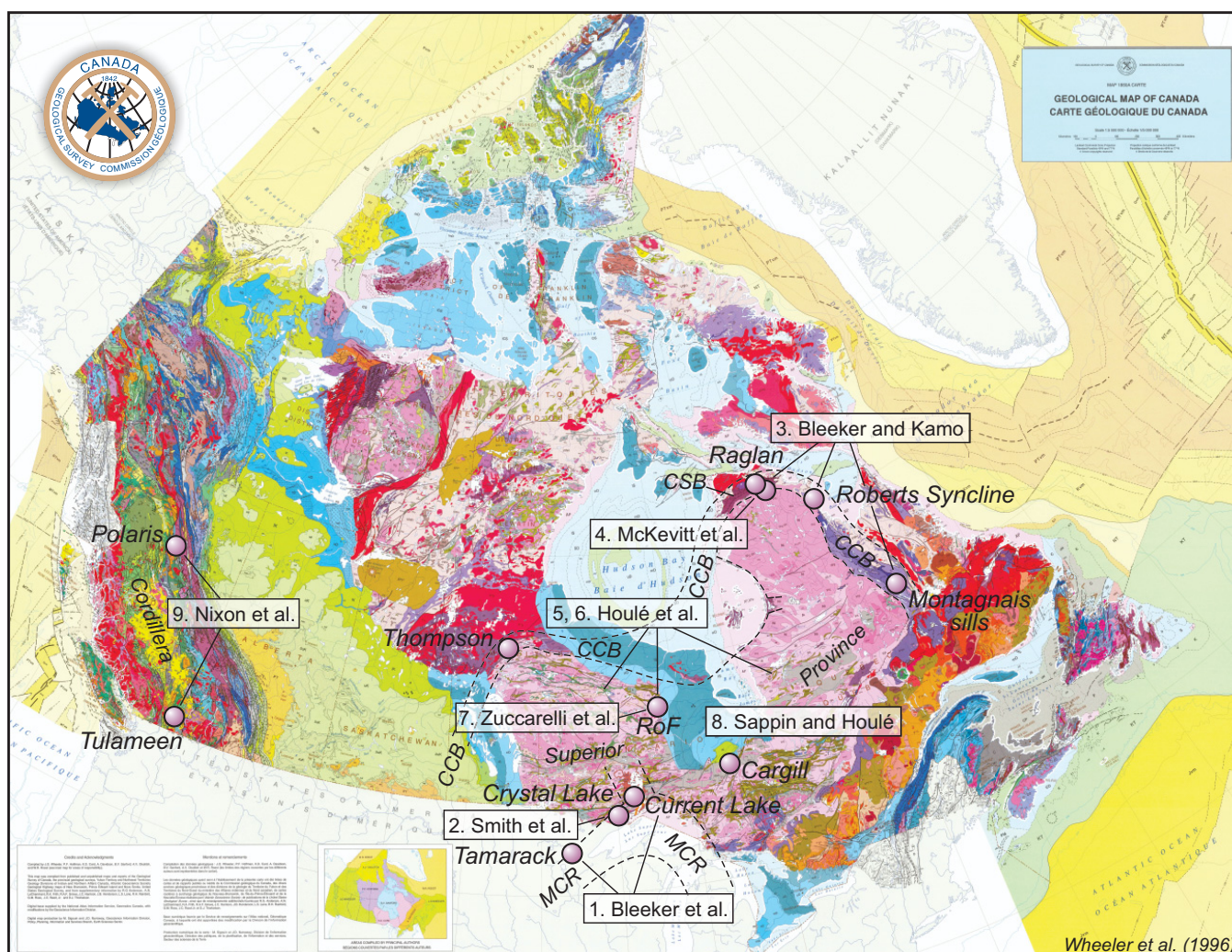


Figure 2. Geological map of Canada (from Wheeler et al., 1996) highlighting the project areas and deposit locations addressed by the present volume. The specific research areas for the nine papers in this volume are indicated. Abbreviations: CCB = the Paleoproterozoic Circum-Superior Belt (southern part of this belt not shown); CSB = Cape Smith Belt; MCR = the ca. 1.1 Ga Midcontinent Rift; RoF = the Ring of Fire area in northern Ontario. New high-precision ages for the Cargill carbonatite, internal to the Superior Province, and the Montagnais sills in the Labrador Trough are part of the Bleeker and Kamo study (2020).

evidence of a dynamic multi-phase intrusive history. This research involved numerous partners from industry, Canadian universities, the Ontario Geological Survey, and scientists from geological survey organizations south of the border.

(2) In a companion paper, **Smith et al. (2020)** focus in on one of the mineralized intrusions, the Crystal Lake intrusive complex ~40 km southwest of Thunder Bay. New high-precision geochronology on multiple phases of this interesting intrusive complex show this intrusion to be ca. 1093 Ma, and thus one of the youngest mineralized intrusions of the Midcontinent Rift. Sulphide mineralization is associated with varietextured “taxitic” gabbros and Smith et al. (2020) draw attention to peculiar spherical sulphide globules with silicate caps—thought to represent former vapour bubbles and attached sulphide globules—that have been described from other mineralized intrusions in recent

years (Barnes et al., 2017). A detailed mineral deportment study of four samples is used to characterize the mineral assemblages and mineral characteristics of the platinum group element and precious metal phases. Modern laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) mapping is used to further characterize compositional details of the various ore minerals and reveals a peculiar microfabric and metal redistribution in some of the sulphides. The authors conclude that sulphur assimilation from country rocks played a critical role in reaching S saturation but that this likely happened prior to final emplacement.

The Paleoproterozoic Circum-Superior Belt and its ca. 1882 Ma Magmatism

(3) Changing focus to the Paleoproterozoic Circum-Superior Belt (Baragar and Scoates, 1981), **Bleeker and Kamo (2020)** review and provide important new

details on the structural and stratigraphic setting of the Cape Smith Belt of northern Quebec. They show that the central part of the belt, hosting the mineralized “Raglan Horizon”, is much less affected by thrust imbrication than previously thought and that the critical stratigraphy is relatively coherent, with the Raglan Horizon being a primary stratigraphic contact. New high-precision geochronology shows that the mineralized peridotite bodies, representing channelized komatiite lava flows, are ca. 1882 Ma, as are differentiated gabbro sills immediately below and above the ore-bearing horizon. This age is identical to that of mineralized komatiites in the Thompson Belt of northern Manitoba and mafic-ultramafic magmatic activity across the Superior craton and around its margins. The authors argue that the overall context appears to be one of mantle plume upwelling and continental breakup rather than one of arc and back-arc processes. The overall scale of this ca. 1882 Ma magmatic event was sufficient to perturb the global ocean-atmosphere system as it is shown that the onset of the major Sokoman iron formation of the Labrador Trough, and broadly correlative iron formations elsewhere along the Circum-Superior Belt, was exactly coeval with the climax of this magmatic event. At Raglan, the authors favour a model of several anastomosing komatiite lava channels that flowed to the north-northeast, rather than a single, giant, meandering lava channel. Finally, the authors show that the Cape Smith stratigraphy can be correlated with that of the northern Labrador Trough.

(4) **McKevitt et al. (2020)** present the initial results of a major compilation of geochemical data from a large number of sources (~18,800 unique whole-rock analyses, with metadata) on mafic-ultramafic volcanic and intrusive rocks of the Cape Smith Belt and neighbouring domains. These data are then used to expand on the geochemical differences and similarities among the major magmatic suites of the Cape Smith Belt, i.e. the Povungnituk Group and the Chukotat Group and their respective subvolcanic intrusive components. In particular, the geochemical data are used to explore the question whether the ultramafic dyke-like system in the southern part of the Cape Smith Belt, mineralized ultramafic occurrences that are known as the “Expo Trend”, could have fed the on-average higher MgO komatiite lava channels of the “Raglan Trend” (i.e. the Raglan Horizon). Both important similarities and differences are identified, and highly incompatible trace element ratios show continuity in data points between the two trends, the main difference being that the mineralized komatiite lavas are more contaminated. Nevertheless, the authors favour an interpretation in which the Expo Trend dykes are not the exact feeders to the Raglan komatiite channels (cf. Bleeker and Kamo, 2020). This conclusion should be tempered, however, with the important

realization that the large feeder dyke systems likely had an extended period of activity and that batches of magma that now fill the dyke system are not the same batches that erupted to the surface and fed the komatiite flows at the peak of the fissure eruptions. Furthermore, no other feeder dyke system has been identified.

The Archean Superior Province and its Mafic and Ultramafic Magmatism

(5) Moving to the Archean Superior Province, **Houlé et al. (2020a)** provide results to date of an on-going compilation of all Mesoarchean to Neoarchean mafic-ultramafic and ultramafic intrusives across this province, as well as all known komatiite occurrences. Regional groupings can be defined, some well known, others emerging or tentative. Using this compilation, the authors also summarize all known magmatic Ni-Cu-PGE, Cr-PGE, and Fe-Ti-V deposits and significant orthomagmatic mineral occurrences across the province. The age distribution of these deposits, to the extent it is known, is presented and discussed, as are the available resource estimates. Finally, the authors speculate on the tectonic and magmatic processes that may have shaped the overall distribution.

(6) In a second contribution, **Houlé et al. (2020b)** focus in on the so-called “Ring of Fire” area in northern Ontario, one of the most significant emerging mineral deposit regions in Canada, particularly for orthomagmatic chromite deposits, and also Ni-Cu-PGE sulphide deposits. The geology of the Ring of Fire area is briefly reviewed, before focusing in on the 2736–2732 Ma Esker intrusive complex of the arcuate McFaulds Lake greenstone belt (Metsaranta et al., 2015). This now-vertical, southeast-facing, intrusive complex, with a strike-length of ~15 to 20 km, consists of several composite ultramafic to mafic bodies (e.g. Black Thor and Double Eagle intrusions), now partly dismembered by faults, that host the very significant stratiform chromite deposits with chromitite layers up to 80 m thick. The authors argue for a model in which several large blade-shaped dykes intruded upwards and laterally across a footwall of older tonalites, then widened due to magma inflation, and finally coalesced into a differentiated layered complex, with the laterally extensive chromitite layers towards the upper parts of the composite intrusion. This model differs in detail from an earlier model of a single, large, dismembered layered intrusion (Mungall et al., 2010). Finally, the authors discuss their model in which the very significant chromitite layers of this intrusive complex are in part the result of assimilation and incorporation, and the reactive transformation into chromite, of magnetite xenocrysts derived from older iron formations in the footwall; a model that is not without its problems (Brenan et al., 2019, 2020). Pros and cons are discussed.

(7) **Zuccarelli et al. (2020)** present the results of a petrographic and sulphide textural study of Ni-Cu-PGE mineralized samples from the Eagle's Nest deposit, McFaulds Lake greenstone belt, in the Ring of Fire area of northern Ontario. The Eagle's Nest deposit is hosted by an ultramafic dyke-like body that is part of the ca. 2730 Ma Esker intrusive complex (Metsaranta et al., 2015). This study of 200 representative core samples helped to define the distribution of different ore types along the subvertical western margin of the conduit-like body. The relatively new technique of "high-resolution desktop microbeam scanning energy-dispersive X-ray fluorescence spectrometry" (μ XRF), employing a $\sim 40\ \mu\text{m}$ X-ray beam, was then applied to a subset of polished core specimens to map the detailed compositional and textural features that are not easily visible by standard macroscopic and microscopic observation. The imaging technique also highlighted the presence of various inclusions (xenoliths) in some of the ore types, including chromitite, gabbro, and barren country rock clasts, supporting a dynamic evolution of the conduit-like body with multiple pulses of magma injection.

(8) **Sappin and Houlé (2020)** report on an investigation of minor and trace element compositions of Fe-Ti oxides from eleven Archean mafic to ultramafic intrusions from across parts of the Superior Province, specifically the Wawa-Abitibi subprovince and the Bird River-Uchi-Oxford-Stull-La Grande Rivière-Eastmain ("BUOGE") superdomain. Magnetite compositions depend on many factors, ranging from parental magma compositions and processes during crystal fractionation (e.g. what are the co-crystallizing phases) and the oxygen fugacity of the magma, to the history and degree of post-crystallization exsolution processes and redistribution of elements during metamorphism. Nevertheless, it may serve as a useful petrogenetic indicator and fractionation index. The authors collected both electron microprobe data and laser ablation data on their samples and compare the results of each approach. Finally, they evaluate their results in the context of previously established discrimination diagrams and discuss the implications of their work.

Mineralized Alaskan-type Intrusions in the Canadian Cordillera

(9) In the final contribution to this volume, **Nixon et al. (2020)** present new data and observations on a number of Mesozoic "Alaskan-type" ultramafic-mafic intrusions in the accreted arc terranes of the Canadian Cordillera, specifically the Tulameen and Polaris composite intrusions. New high-precision U-Pb age data of ca. 204–205 Ma are presented for two distinct phases of the Tulameen intrusion, ages that fall within a 6 Myr time interval during which the most important por-

phyry Cu-Au deposits in British Columbia were emplaced. The overall setting and internal structure of both intrusions are described in detail, as are details of sulphide mineralization. Traditionally these intrusions were better known for their chromitites and associated PGE mineralization and derived placer deposits (e.g. Cabri et al., 1973; Nixon et al., 1990). An interesting aspect of both intrusions is the complex relationships among ultramafic cumulate rocks and the associated chromitite occurrences, clearly indicating a dynamic environment where cumulate rocks and chromitites were disrupted and complexly intermingled. Chaotic blocks of chromitite and dunite of various sizes are mixed with clinopyroxenite cumulate rocks. Nixon et al. (2020) note that such relationships have been observed in many other Alaskan-type intrusions and attribute them to remobilization and magmatic avalanches during dynamic recharge of new magma pulses into the base of the intrusions.

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