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Temporal and spatial distribution of magmatic Cr-(PGE), Ni-Cu-(PGE), and Fe-Ti-(V) deposits in the Bird River–Uchi–Oxford-Stull–La Grande Rivière–Eastmain domains: a new metallogenic province within the Superior Craton

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ABSTRACT

Chromium and Fe-Ti-(V) mineralization in ultramafic-mafic intrusions is known to occur in several areas of the Superior Province, but was considered to be of marginal significance until the discovery of world-class Cr deposits and potentially significant Fe-Ti-(V) mineralization in the McFaulds Lake greenstone belt ("Ring of Fire") of northern Ontario. Cr-(PGE), Ni-Cu-(PGE), and Fe-Ti-(V) deposits/occurrences in the northern part of the Superior Province occur predominantly within Meso to Neoarchean supracrustal successions along the margins and within the interiors of the Bird River–Uchi–Oxford-Stull–La Grande Rivière–Eastmain domains (i.e. BUOGE domains). These domains define a new metallogenic province within the Superior Province characterized by the presence of major Cr-(PGE) with Ni-Cu-(PGE) and Fe-Ti-(V) metal associations that appear to be fundamentally different from other parts of the Craton, such as the Abitibi greenstone belt or the apparently relatively unmineralized North Caribou core, Island Lake, and Goudalie domains. Despite the fact that only the Cr-(PGE) deposits and Ni-Cu-(PGE) deposits (Eagle's Nest) in the McFaulds Lake greenstone belt appear to be potentially economic, the presence of a significant amount of Cr-(PGE) mineralization across the BUOGE domains highlights the prospectivity of these regions of the Superior Province.

INTRODUCTION

The Superior Province is a well-endowed metallogenic province that contains a variety of mineral deposits, including VMS, lode Au, magmatic Fe-Ni-Cu-(PGE) sulphide, Cr-(PGE), and Fe-Ti-V deposits, and rare-metal deposits. The metallogenic history of the Superior Province has generated interest from the scientific community and exploration for decades. The first attempts to systematically subdivide the Superior Province into metallogenic domains were done in the early 1960s (Lang, 1961). Card and Poulsen (1998a,b) produced an extensive review of the mineral deposits occurring in the Superior Province and proposed seventeen mineral belts across the Superior Province to explain the distribution of these deposits. More recently, an overview of the spatial and the temporal distribution of the mineral deposits in the Superior Province has been conducted by Percival (2007).

The discoveries of world-class Cr-(PGE) deposits, a major Ni-Cu-(PGE) deposit, and numerous significant Fe-Ti-(V) occurrences in the McFaulds Lake greenstone belt (MLGB; also known as "Ring of Fire") of northern Ontario have greatly renewed interest in orthomagmatic mineralization associated with mafic-ultramafic intrusions in the Superior Province. Mafic-ultramafic intrusions and ultramafic volcanic rocks are widespread throughout the Superior Province, but their association with significant Cr-(PGE), Ni-Cu-(PGE), and Fe-Ti-(V) mineralization is not evenly distributed across the craton.

In this study we have focussed primarily on the distribution of the orthomagmatic Cr-(PGE), Ni-Cu-

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(PGE), and Fe-Ti-(V) deposits and to a lesser extent, the significant occurrences. The aim of this contribution is to propose a new Cr-(PGE) metallogenic province (defined as an area characterized by a particular assemblage of mineral deposits, or by one or more characteristic types of mineralization). A metallogenic province may have had more than one episode of mineralization: Jackson, 1997) that also contains Ni-Cu-(PGE) and Fe-Ti-(V) metal associations within the Superior Province based on currently available information and interpretations of the various terrane and domain boundaries within the Superior Province. This study is a part of the High-Magnesium Ultramafic to Mafic Systems subproject under the Targeted Geoscience Initiative 4 of the Geological Survey of Canada (GSC) conducted in collaboration with the Ontario Geological Survey (OGS), the Manitoba Geological Survey (MGS), the ministère de l'Énergie et des Ressources naturelles (MERN: Quebec), several universities across the country, and the mineral industry.

SUPERIOR PROVINCE

The Superior Province is the largest coherent Archean craton in the world, with exceptional mineral endowment reflected in the presence of numerous world-class Au and volcanogenic massive sulphide (VMS) deposits, and significant Ni-Cu-(PGE) deposits (e.g. Poulsen et al., 1992; Card and Poulsen, 1998a,b).

Early investigations of the Superior Province recognized a limited number of subprovinces based on general lithological characteristics and regional structural styles (e.g. Douglas, 1973; Card and Ciesielski, 1986). Subsequently, more detailed lithological and geochronological data were used in an attempt to subdivide the former Sachigo subprovince into terranes (e.g. Thurston et al., 1991) and the western Superior Province was further subdivided into superterranes and terranes by Stott (1997). The eastern Superior Province was subdivided into lithotectonic elements with distinct compositional, mineralogical, and geochronological attributes and aeromagnetic character by Percival et al. (1992). Since then, considerable efforts by the MGS, OGS, MERN, and GSC have been devoted to identifying stratigraphically and tectonically distinct terranes and domains across the Superior Province using high-resolution geochronological, structural, stratigraphic, geochemical, geophysical, and tectonic data that progressively led to a revised tectonic map of terrane and domain boundaries of the Superior Province, which were proposed by Stott et al. (2010) and subsequently revised by Percival et al. (2012).

There is no attempt to describe the overall geology of the Superior Province in this contribution; only a summary of specific relevant aspects are included. The reader is referred to Percival et al. (2012) for a more thorough review of the geology and tectonic evolution of the Superior Province.

The North Caribou Terrane (NCT) is the largest reworked Mesoarchean to Neoarchean crustal block of the western Superior Province. The NCT consists of a central core (North Caribou core) composed of granitoid rocks from the Berens River plutonic complex (2.75 to 2.71 Ga) with remnants of Mesoarchean tonalitic and supracrustal rocks (3.0–2.8 Ga). The North Caribou Terrane is flanked by the Island Lake (ILD) and the Oxford-Stull domains (OSD) to the north and by the Uchi domain (UD) to the south (Fig. 1; Stott et al., 2010; Percival et al., 2012). The ILD consists of older Mesoarchean (2.9–2.85 Ga) with subordinate Neoarchean (2.74 Ga) supracrustal assemblages that appear to have incorporated variable components of older ca. 3.0 Ga crustal sources (e.g. Parks et al., 2014). The OSD, which includes the MLGB, consists largely of Neoarchean volcano-plutonic rocks (2.88–2.73 Ga) with a more juvenile character and it is distinguished from the Island Lake and the Uchi domains by the lack of pre-3.0 Ga supracrustal rocks (e.g. Percival et al., 2012). The UD records more than 300 Ma of tectonostratigraphic evolution and contains several greenstone belts and plutonic complexes that record multiple episodes of rifting, arc-magmatism, deformation, and associated sedimentation from ca. 3.0 to 2.7 Ga (Percival et al., 2006, 2012). Re-examination of the aeromagnetic data of the western Superior Province in Ontario within the OSD and UD led Stott (2008a,b, 2009) to propose that these domains merge under the James Bay Lowland Paleozoic cover on either side of the North Caribou core. Furthermore, it has also been proposed that the OSD and the UD probably extend eastward, along strike with the La Grande Rivière and the Eastmain domains, and could have formed a single domain across the James Bay area (Stott et al., 2010).

Within the Superior Province, another region of interest is the Bird River area located between the English River basin (ERB) and the Winnipeg River terrane (WRT) in southeast Manitoba (Fig. 1). The Bird River greenstone belt and its eastern equivalent, the Separation greenstone belt in Ontario, extend for 150 km from Lac du Bonnet (Manitoba) in the west to Separation Lake (Ontario) in the east and consist of a series of metavolcanic and metasedimentary rocks (Blackburn and Young, 2000; Gilbert et al., 2008). Assignment of the Bird River-Separation Lake greenstone belt to a lithotectonic entity is still under debate and it may be included as part of the Winnipeg River terrane, English River basin, or Uchi domain. Initially, based on its distinct character compared with the surrounding WRT and ERB, Card and Ciesielski (1986) elevated the Bird River-Separation greenstone belt to a

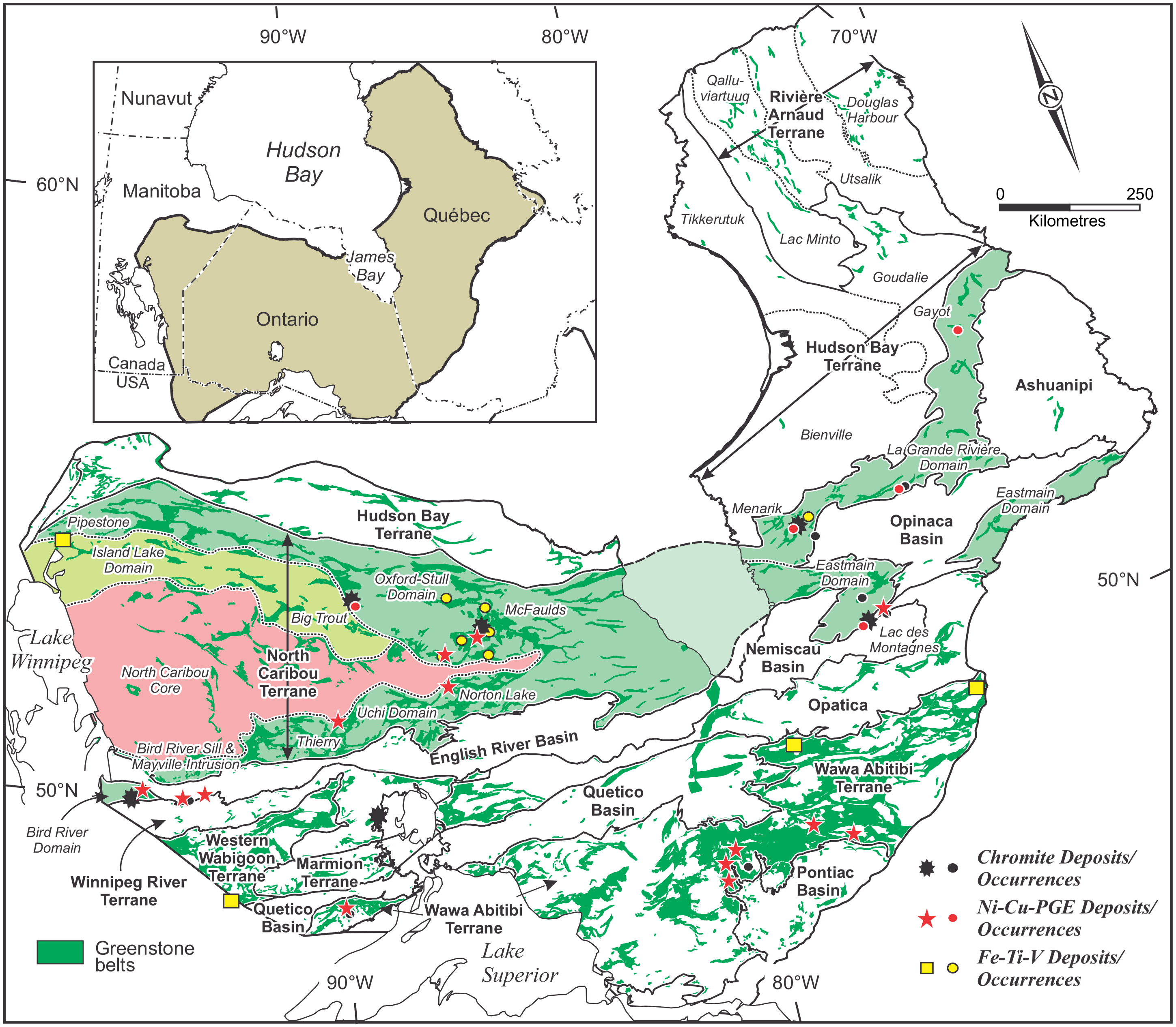

Figure 1. Schematic geological map showing the main Archean Cr-(PGE), Ni-Cu-(PGE), and Fe-Ti-(V) deposits/occurrences within the Superior Province. Terrane and domain boundaries are modified from Stott et al. (2010) and Percival et al. (2012).

subprovince, referred to as the Bird River subprovince (BRS). More recently, Stott et al. (2010) and Percival et al. (2012) have incorporated the BRS into the Winnipeg River terrane. However, recent geological mapping by the MGS in the Bird River greenstone belt and the Rice lake greenstone belt (Uchi domain), located just across the English River basin, has revealed some similarities between these two belts on either side of the English River basin (Anderson, 2005; Gilbert et al., 2008). Early supracrustal assemblages in the Uchi domain have no counterpart in the BRS; however, a possible correlation may be made amongst the younger supracrustal assemblages (Gilbert et al., 2008; Anderson, 2014; Gilbert and Kremer, 2014). Subsequent orogenic sediments in the two belts are interpreted to be correlative (Gilbert et al., 2008; Gilbert and Kremer, 2014) and also stratigraphically equivalent to the epiclastic rocks and metamorphic derivatives of the English River basin, which lies between the Uchi domain and the Bird River subprovince (e.g. Hrabi and Cruden, 2006).

The Uchi–Oxford-Stull-La Grande Rivière–Eastmain domains exhibit similar geochronological, stratigraphic, structural, and tectonic characteristics suggesting that they may represent a similar regional tectonic environment along the margins of the NCT (Stott et al., 2010). These approximately east-west-trending domains appear to have been a favourable region for the emplacement of mafic-ultramafic magmas with significant orthomagmatic mineralization. However, a remaining question is how the Bird River subprovince fits into this picture and further investigation is needed to resolve this issue. In the light of recent geological mapping, many similarities appear to exist between the Bird River and the Rice Lake greenstone belts; therefore it could be postulated that the Bird River subprovince may have a tectonostratigraphic history more similar to the Uchi domain rather than to the Winnipeg River terrane. If this is correct, the Bird River subprovince could be a domain that belongs to the southern margin of the NCT and part of the Uchi–Oxford-Stull-La Grande Rivière–Eastmain domains. These domains have previously been referred to as the BUOGE "superdomain" (Houlé et al., 2013a,b), however, because of uncertainty regarding the Bird River domain, it should be referred to instead as the BUOGE domains (i.e. B: Bird River, U: Uchi, O: Oxford-Stull, G: La Grande Rivière, E: Eastmain) that comprise a broad grouping of domains that appear to share a similar evolution and tectonic history a rather than a strict lithotectonic entity (Fig. 1).

RESULTS

Mafic to ultramafic intrusions occur throughout the BUOGE domains and span a wide range of ages from 2.88 to 2.70 Ga (Table 1; see Houlé et al., 2015a). The vast majority of known Archean Cr-(PGE) deposits and occurrences across the Superior Province have been discovered within Meso- to Neoarchean supracrustal successions along the margins and within the cores of these domains (Fig. 1). Known Archean Ni-Cu-(PGE) deposits occur predominantly within the Wawa-Abitibi terrane, however, the BUOGE domains contain numerous deposits of this type and in some cases the deposits are spatially associated with and/or occur within the same intrusions that hosts Cr-(PGE) deposits (Fig. 1). It is difficult to make generalizations regarding the distribution of the Fe-Ti-(V) deposits, as almost all of them occur within different terranes/domains (e.g. Pipestone deposit in the Island Lake domain – NCT; Bad Vermillion deposit in the western Wabigoon terrane; Rivière Bell and Lac Doré deposits in the Wawa-Abitibi terrane) (Fig. 1). However, numerous Fe-Ti-(V) occurrences, especially in the MLGB, were recently discovered in the vicinity of Cr-(PGE) deposits (Metsaranta et al., 2015). In the course of this study, three main regions across the BUOGE domains, including 1) Bird River greenstone belt (Manitoba), 2) McFaulds Lake greenstone belt (Ontario), and 3) the La Grande Rivière and Eastmain domains, were investigated and are briefly described below.

Bird River Greenstone Belt, Bird River Domain

The Bird River greenstone belt (BRGB) in southeastern Manitoba contains numerous Neoarchean mafic-ultramafic intrusions that host significant Ni-Cu-(PGE) and Cr-(PGE) deposits and occurrences. Nine main intrusions (Table 1) occur over a strike length of 75 km laterally and 20 km across on each side of the Maskwa Lake Batholith.

The internal stratigraphic variations of these intrusions can be characterized by two end members: 1) well layered differentiated mafic-ultramafic intrusions containing variable ultramafic components but preponderant mafic parts (e.g. National-Ledin, Chrome, Page, Maskwa, Bird Lake, Euclid Lake), and 2) poorly layered mafic-dominated intrusions without distinct ultramafic components (e.g. Coppermine, New Manitoba, and Mayville intrusions). The very well layered Chrome mafic-ultramafic intrusion in the Bird River Sill is the type example of the former. It contains a thin lower ultramafic zone composed of dunite and peridotite with lesser chromitite layers overlain by a thicker upper mafic zone composed of gabbro, leucogabbro, and anorthositic gabbro with lesser trondhjemite layers. The less-stratified Mayville intrusion is the type example of the latter. It contains a lower heterolithic intrusive breccia zone with sporadic mafic to ultramafic horizons along the basal contact, overlain by

Table 1. Cr-(PGE), Ni-Cu-(PGE), and Fe-Ti-(V) deposits and main mineral occurrences in the Superior Province with compiled and preliminary age constraints from this study.

Terrane	Greenstone Belt	Intrusive Suite	Intrusions/Volcanics	Age (Ma)	Cr-PGE	Ni-Cu-PGE	Fe-Ti-V	Examples
North Caribou terrane								
Island Lake domain								
	CLGB		Pipestone	A 2760 [1] CA			X	**Pipestone**
Oxford-Stull domain								
	BTSGB		Big Trout Lake	- ND	X	X		**Big Trout Lake**
	MLGB	Ring of Fire intrusive suite						
		2733–2734 Ma	Ultramafic-dominated subsuite					
			Black Thor intrusive complex	A 2734 CA	X	X		**Black Thor, Big Daddy, Black Label, Black Creek**
			Double Eagle intrusive complex	- ND	X	X		**Eagle's Nest; Blackbird, Black Horse**
			Mafic-dominated "ferrogabroic" subsuite					
			Butler West	- NZ			X	**Butler West**
			Butler East	- ND			X	**Butler East**
			Thunderbird	A 2734 CA			X	**Thunderbird**
			Big Mac	A 2734 CA			X	
			Croal Lake	A 2733 CA			X	
			Highbank-Fishtrap intrusive complex					
			Highbank	A 2810			X	*Highbank Fe-Ti-(V)*
			Fishtrap	A 2810 CA				
Uchi domain								
	RLGB		Garner Lake intrusive complex	B 2871 [2] CA				
	PLGB		Thierry	- ND		X		**Thierry**
			July Falls	A 2749 [3] CA				
	MFHGB		Norton Lake	- ND		X		**Norton Lake**
			Oxtoby Lake	A 2717 CA				
			Wabassi intrusive complex					
			Max	A		X		
			Wabassi Main	A 2727 CA			X	*Wabassi Fe-Ti-(V)*
La Grande Rivière domain								
	YGB		Menarik	A 2750 CA	X	X		**Menarik;** *4930N-1; 3700N-1;*
			Lac Ultra	ND				**Menarik**
			Baie Chapus	A 2802 IA			X	*Baie Chapus*
	LGKGB		Lac Guyer komatiite	B 2820 [4] CA				
	VMGB		Gayot Lake komatiite	B [5] CA		X		
Eastmain domain								
	BEGB		Lac Fed	B 2739 [6] CA	X			*Sledgehammer, Dominic*
			Komo formation komatiite	B 2703 [6] CA				
	NGB		Lac des Montagnes	A 2802 CA		X		**Lac des Montagnes**
			Levack	- ND	X	X		**Nisk-1**
Winnipeg River terrane								
Bird River domain								
	BRGB		Synvolcanic gabbro (Northern MORB fm)	A 2745 CA				
		Bird River intrusive suite						
		2742–2744 Ma	National-Ledin	- ND	X			
			Chrome	A 2743 [7] CA	X			**Chrome**
			Page	- ND	X	X		**Page; Page**
			Maskwa	- ND	X	X		**Maskwa; Dumbarton**
			Bird Lake	A 2743 CA		X		**Bird Lake**
			Euclid Lake	A 2744 CA	X	X		**Euclid Lake**
			Coppermine	A 2742 CA	X	X		
			New Manitoba	A 2743 CA		X		**New Manitoba**
			Eileen	- NZ				
			Mayville	A 2743 CA	X	X		**M2**

[1]Corkery et al., 1992; [2]Davis, 1994 and Anderson, 2013; [3]Young et al., 2006; [4]Goutier et al., 2002; [5]David et al., 2009; [6]Moukhsil et al., 2007; [7]Scoates and Scoates, 2013

A = direct age constraint, B = indirect age contraint obtained via a dated crosscutting dykes or subjacent host volcanic rocks; CA = crystallization age; IA = inheritance age; ND = not dated; NZ = not zircon found

Greenstone belt (GB): BRGB = Bird River; BTSLGB = Big Trou Lake–Swan Lake; CLGB = Cross Lake; LGB = Eastmain; LGKGB = Lac Guyer-Keyano; MFHGB = Miminiska–Fort Hope; MLGB = McFaulds Lake; NGB = Nemaska; PLGB = Pickle Lake; VMGB = Venus-Moyer; YGB = Yasinski

Deposits: Black = Chromite deposits; **Red** = Ni-Cu-PGE deposits; **Blue** = Fe-Ti-V = Deposits; *italic* are significant occurrences a thick mafic zone composed of leucogabbro and megacrystic anorthosite.

Despite their compositional and internal stratigraphic variations, BRGB intrusions are interpreted to have been generated during a single large mafic-ultramafic magmatic event (Houlé et al., 2013c), referred to as the Bird River intrusive suite, emplaced between 2744 and 2742 Ma (Table 1). The footwall of these intrusions, at least within the main part of the BRGB, has been dated during the course of this study and yielded a U-Pb crystallization age of 2745 Ma for a synvolcanic gabbro that occurred within the Northern MORB formation near the Maskwa mine (Table 1). These intrusions also generated significant basal (e.g. Maskwa: Chrome), contact-style Ni-Cu-(PGE) mineralization (e.g. M2: Mayville intrusion), as well as Cr mineralization (e.g. Chrome, Page, Euclid) higher up in the stratigraphy, near the contact between the ultramafic and mafic zones.

McFaulds Lake Greenstone Belt, Oxford-Stull Domain

The McFaulds Lake greenstone belt is an extensive (>200 km long), arcuate-shaped, Meso- to Neoarchean greenstone belt occurring in the central part of the Oxford-Stull domain (Ontario), which is characterized by an unusual endowment of mafic to ultramafic intrusive rocks hosting world-class chromite deposits (e.g. Black Thor, Black Label, Big Daddy, Black Horse, Blackbird), a major Ni-Cu-(PGE) deposit (Eagle's Nest), and several Ni-Cu-(PGE) occurrences (e.g. AT-12, SE-Central-NE Breccia Zones), and significant Fe-Ti-(V) mineralization (e.g. Thunderbird, Butler West, Butler East, Big Mac) (Metsaranta et al., 2015).

At least two generations of mafic-ultramafic intrusions (ca. 2810 and 2734–2733 Ma) appear to host these types of mineralization, although the bulk of significant mineralization appears to be associated with Neoarchean intrusions (see Metsaranta et al., 2015). The Neoarchean intrusions, referred to as the Ring of Fire intrusive suite (RoFIS), can be further subdivided into two main magmatic subsuites: an ultramafic-dominated subsuite (e.g. Black Thor: see Carson et al., 2015) and a mafic-dominated "ferrogabbroic" subsuite (e.g. Thunderbird, Butler and Big Mac: see Kuzmich et al., 2015; Sappin et al., 2015). The RoFIS occurs across the entire MLGB and exhibits incredibly consistent U-Pb crystallization ages at 2.73 Ga, suggesting the presence of a large magmatic mafic-ultramafic event in the MLGB (Table 1).

Thus far, Cr-(PGE) and Ni-Cu-(PGE) mineralization appears to occur essentially within the Neoarchean ultramafic-dominated intrusions of the RoFIS, whereas Fe-Ti-(V) mineralization occurs in both Neoarchean and Mesoarchean mafic-dominated intrusions. However, further investigation currently in progress along the southern margin of the Oxford-Stull domain could reveal that some of the mafic to ultramafic intrusions along this domain boundary may also have the potential to host Cr-(PGE) and Ni-Cu-(PGE) mineralization.

La Grande Rivière and Eastmain Domains

The Yasinski and Nemaska greenstone belts within the La Grande Rivière and Eastmain domains (Quebec), respectively, also contain numerous and widespread Mesoarchean and Neoarchean mafic to ultramafic intrusions, many of which host orthomagmatic Cr-(PGE), Ni-Cu-(PGE), and Fe-Ti-(V) mineralization (Houlé et al., 2015b; Table 1).

Chrome mineralization appears to be one of the most abundant and significant styles of the mineralization in these regions and many chromitite occurrences have been identified over the years. The most significant are associated with the Neoarchean Menarik Complex (MC) and the Mesoarchean Lac des Montagnes intrusion (LMI). Preliminary geochronological data has yielded U-Pb ages of 2750 Ma and 2802 Ma for the Menarik Complex and the Lac des Montagnes intrusion, respectively (Table 1). The LMI intrusion is part of a series of east-northeast-trending ultramafic intrusions, referred to as the Lac des Montagnes intrusive suite, occurring in the Nemaska volcano-sedimentary belt at the margin between the Opinaca basin and the Eastmain domain of the North Caribou terrane. Both intrusions have lower ultramafic zones and upper mafic zones, and contain several laterally continuous chromitite seams, ranging from a few centimetres to 3 metres, within their ultramafic zones. Thus, these chromite deposits in the Eeyou Istchee Baie James region are Meso- and Neoarchean, which differs from those of the RoF area where only Neoarchean chromite deposits have been identified so far. Other intrusions (e.g. Nisk, Gayot) have Ni-Cu-(PGE) mineralization near their bases (Houlé et al., 2015b). Although not as significant as the other mineralization styles, Fe-Ti-(V) mineralization also occurs within some ultramafic to mafic intrusions (e.g. baie Chapus Pyroxenite). This mineralization is characterized by an accumulation of magnetite containing abundant ilmenite exsolutions within a massive to semi-massive magnetite horizon near the upper part of the intrusion.

DISCUSSION

Cr-(PGE) Metallogenic Province

Almost all Cr-(PGE) deposits and significant occurrences in the Superior Province occur within the BUOGE domains and range from Neoarchean to Mesoarchean, with the best examples occurring in the

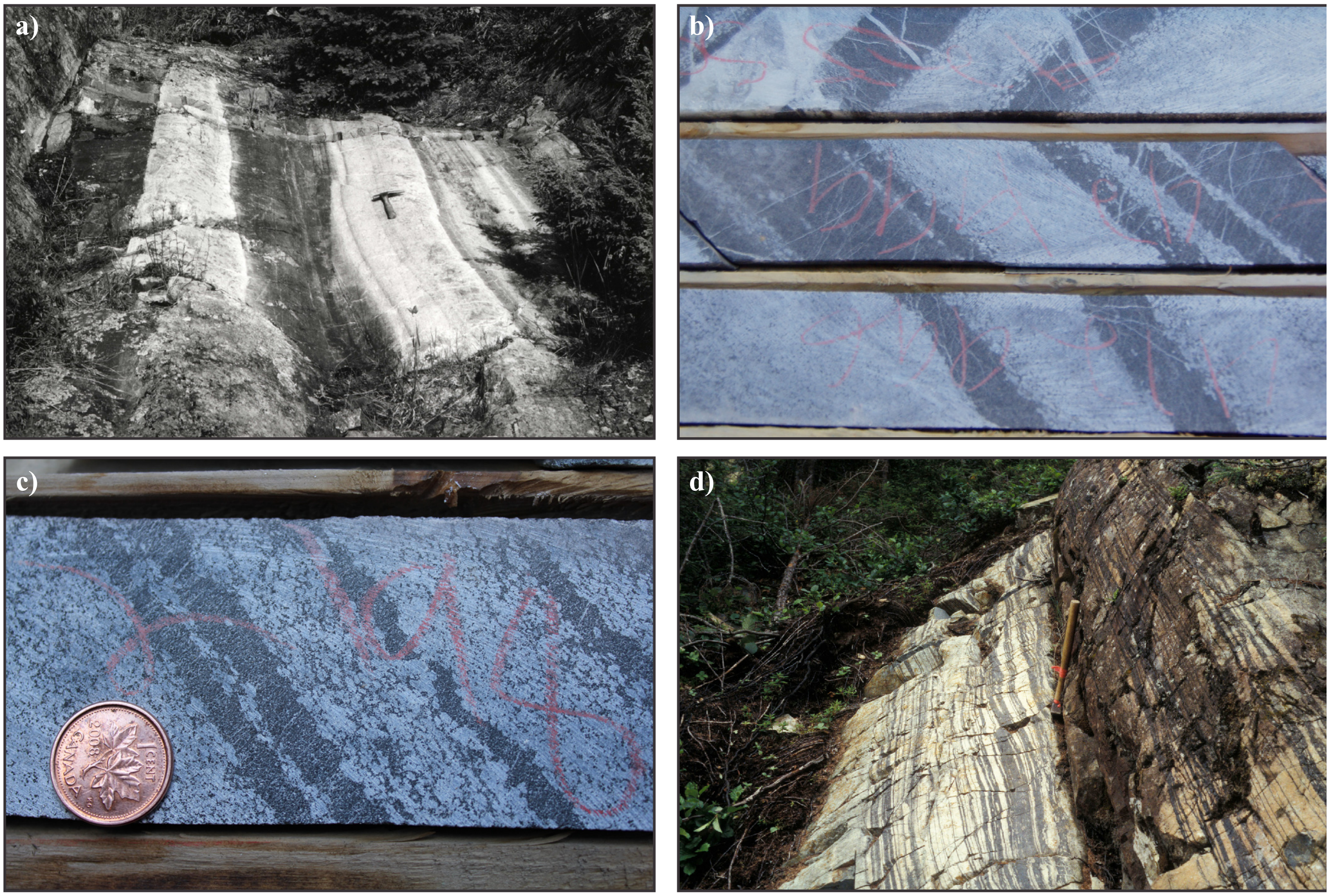

Figure 2. Typical Cr-(PGE) mineralization associated with mafic and ultramafic intrusions in the Bird River–Uchi–Oxford-Stull–La Grande Rivière–Eastmain (BUOGE) domains. **a)** Chromitite layers in the Bird River Sill, southeast Manitoba (after Williamson, 1990). Hammer is 30 cm long. **b)** Chromitite layers at the Black Thor deposit in the Ring of Fire Intrusive Complex, northern Ontario. Diameter of the core is 4.5 cm. **c)** Chromitite layers at the Blackbird deposit in the Ring of Fire Intrusive Complex, northern Ontario. Coin is 1.8 cm in diameter. **d)** Chromitite layers in the Menarik Complex, James Bay area, Quebec. Hammer is 38 cm long.

Bird River (e.g. Chrome - Bird River Sill; Fig. 2a), Oxford-Stull (e.g. Black Thor and Blackbird - Ring of Fire Intrusive Complex; Fig. 2b and 2c, respectively), and La Grande Rivière (e.g. Menarik; Fig. 2d) domains (Table 1). Chromium-(PGE) mineralization is virtually absent in the remainder of the Superior Province except for domains that belong to the North Caribou terrane and for the Bird River domain.

Nickel-Cu-(PGE) deposits are abundant in the Wawa-Abitibi terrane (Houlé and Lesher, 2011) and Bird River domain, but are less abundant in the Uchi, La Grande Rivière, and Eastmain domains, and essentially absent in the remainder of the Superior Province. Nickel-Cu-(PGE) deposits occur across the BUOGE domains and range from Neoarchean to Mesoarchean, with the best examples occurring within the Bird River (e.g. Maskwa – Bird River Sill; Fig. 3a), Uchi (e.g. Norton Lake), Oxford-Stull (e.g. Eagle's Nest - Ring of Fire intrusive suite; Fig. 3b and 3c), Eastmain (e.g. Nisk-1), and La Grande Rivière (e.g. Gayot; Fig. 3d) domains (Table 1).

Iron-Ti-(V) deposits are less abundant and most occur within the southern part of the Superior Province in the Wawa-Abitibi (e.g. Rivière Bell and Lac Doré complexes) and in the western Wabigoon terranes (e.g. Bad Vermillion complex). Another major Fe-Ti-(V) deposit, the Pipestone deposit, is located near the northern margin of the Island Lake domain and the Oxford-Stull domain. Quite significant Fe-Ti-(V) prospects have been discovered recently in the MLGB; but resource estimates have not yet been conducted (Kuzmich et al., 2015; Sappin et al., 2015). A small Fe-Ti-(V) occurrence is also hosted within the baie Chapus Pyroxenite in the La Grande Rivière domain in Quebec (Houlé et al., 2015b).

The overall distribution of the chromite deposits, (essentially restricted to the BUOGE domains) appears to define a craton-scale Cr-PGE metallogenic province within the Superior Province that contains at least two episode of Cr-(PGE) mineralization. The older episode is Mesoarchean age (ca. 2802 Ma; Table 1) that appears, so far, to be restricted to the southern part of

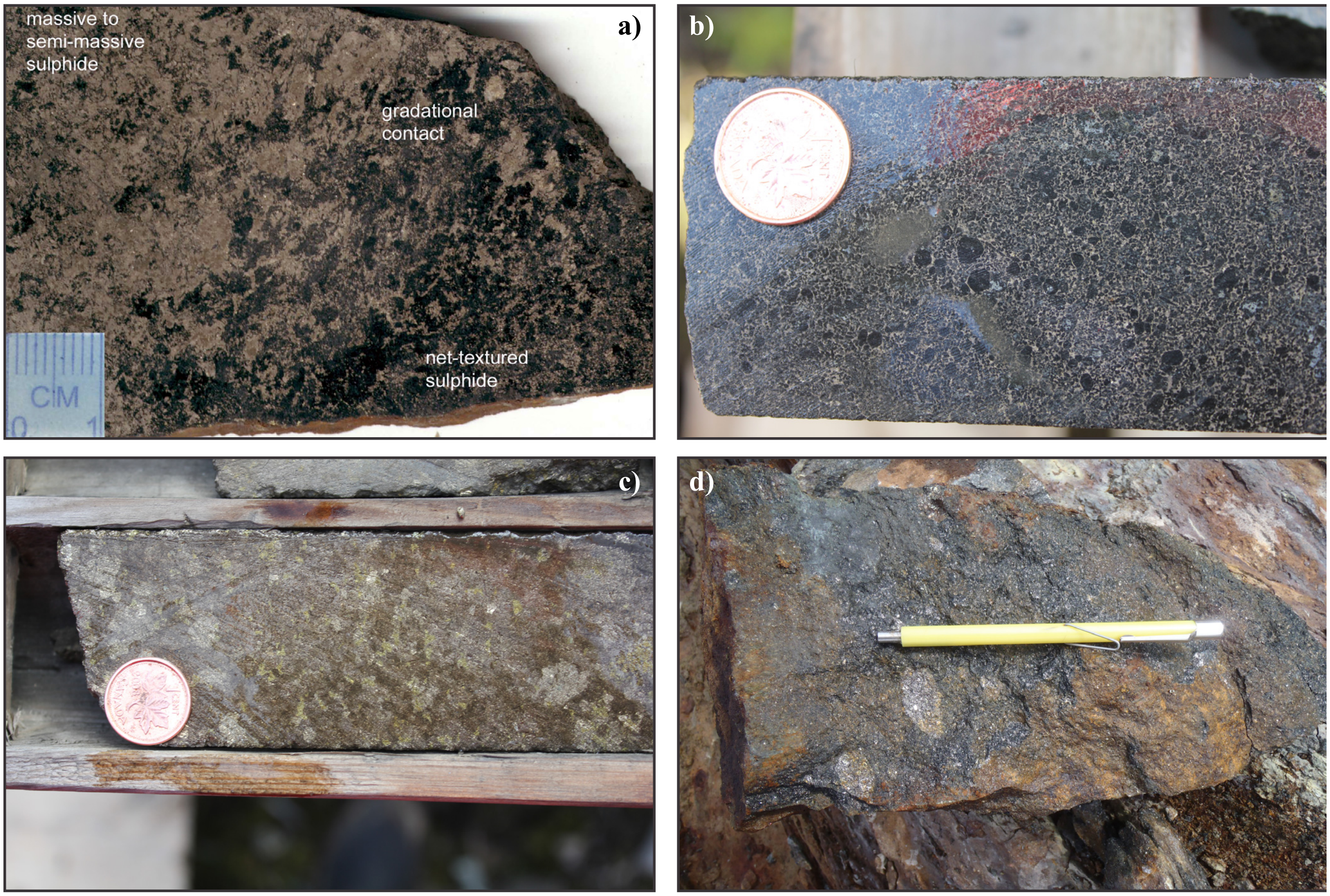

Figure 3. Typical Ni-Cu-(PGE) mineralization associated with mafic and ultramafic intrusions in the Bird River–Uchi–Oxford-Stull–La Grande Rivière–Eastmain (BUOGE) domains. **a)** Gradational contact between semi-massive sulphide and net-textured sulphide at the Maskwa deposit, Bird River Sill, Manitoba (after Stansell, 2006). **b)** Net-textured sulphide at Eagle's Nest in the Ring of Fire Intrusive Complex, Ontario. Coin is 1.8 cm in diameter. **c)** Massive sulphide at Eagle's Nest in the Ring of Fire Intrusive Complex, Ontario. Coin is 1.8 cm in diameter. **d)** Peridotite with disseminated sulphides containing centimetre-scale blebs of massive sulphides from the L occurrence in the Gayot area (courtesy of Mines Virginia). Magnetic pen is 12.3 cm.

the Eastmain domain whereas the second episode is the most significant one, spatially widespread throughout the BUOGE domains (e.g. Bird River, McFaulds Lake, Menarik) and Neoarchean age (ca. 2750–2734 Ma). In contrast to Cr-(PGE) mineralization, Ni-Cu-(PGE) and Fe-Ti-(V) deposits do not show the same spatial restriction with the BUOGE domains. However, within the BUOGE domains, Ni-Cu-(PGE) mineralization is associated with the same ultramafic-dominated intrusive bodies as Cr-(PGE) mineralization and Fe-Ti-(V) occurrences are contained within mafic-dominated intrusions in close vicinity to Cr-bearing intrusions, indicating a strong association of all these metals/mineralization styles. The connection between Cr-(PGE) and Ni-Cu-(PGE) deposits is that both styles of mineralization are formed in dynamic magma conduits.

Potential Remnant of Large Igneous Provinces

The defining features of Large Igneous Provinces (LIPs) include (Bryan and Ernst, 2008; Ernst and Jowitt, 2014) a minimum extrusive/intrusive volume exceeding 0.1 Mkm^3, a minimum areal extent of 0.1 Mkm^2, a short duration of magmatism of less than 50 Ma (but typically less than 10–15 Ma and in many cases a few Ma or less), multiple pulses of magmatism (LIPs with more than 20 Ma age spans typically contain multiple shorter pulses ranging from 1 to 5 Ma), and finally that the magmatism occurred in an intraplate tectonic setting.

Ultramafic to mafic magmatism of various types (e.g. komatiitic, tholeiitic, alkalic) extended over a period of more than 180 Ma within the BUOGE domains, from ca. 2.88 to 2.70 Ga (Table 1). However, four main intervals are recognized to have generated most of the ultramafic to mafic magmatism across these domains: 1) 2.88 to 2.87 Ga, 2) 2.82 to 2.80 Ga, 3) 2.75 to 2.73 Ga, and 4) 2.72 to 2.70 Ga (Fig. 1). In many cases, these age intervals are poorly constrained and might evolve as more precise U-Pb ages are obtained from ultramafic and mafic intrusive rocks. During the course of this study, the focus was placed on the third interval (2.75–2.72 Ga), which includes the intrusive suites of the Bird River in Manitoba (ca. 2744–42 Ma), the Ring of Fire in Ontario (ca. 2734–33 Ma), and several but more localized ultramafic intrusions within the La Grande domain in Quebec (ca. 2750 Ma). Although limited in size (none of these appear to qualify for the areal extent and volume for a LIP), emplacement of large amounts of ultramafic to mafic magmas over a short period of time, especially in the MLGB and the BRGB, locally combined with komatiite-tholeiite successions, suggest that these intrusions might represent remnants of Archean LIPs. It has been suggested by Mungall et al. (2010) and Ernst and Jowitt (2014) that the mafic-ultramafic intrusions in the BRGB and the MLGB could be part of a single plume-related large igneous province. This hypothesis is plausible, despite the fact that the mafic-ultramafic intrusions in the BRGB, MLGB, and the YGB span over 20 Ma. Scoates and Scoates (2013) have proposed a different scenario in which these intrusions are not related. The mafic-ultramafic intrusions, which were formed by at least three magmatic pulses over 20 Ma (2.75–2.73 Ga), are associated with the emplacement of Cr-(PGE) and Ni-Cu-(PGE) deposits and significant Fe-Ti-(V) occurrences across the BUOGE domains. Furthermore, large amounts of subvolcanic-volcanic ultramafic-mafic rocks and inferred large magma fluxes occur at least in some of these areas (see discussion by Carson et al., 2015) favouring for a plume origin. More detailed investigation is warranted but we suggest that these intrusions may represent remnants of an Archean LIPs and rather than being associated with one single plume-related LIP event, they may be the result of multiple and separate large magmatic events that occurred locally within BUOGE domains and were not physically connected but shared similar geological settings that made these regions highly prospective for Cr-(PGE), Ni-Cu-(PGE), and Fe-Ti-(V) mineralization. At this stage, we cannot rule out completely the single-plume hypothesis, but we suggest that our hypothesis better explains the distribution of the Cr-(PGE) mineralization across the BUOGE domains where it may represent a significant metallogenic province within the Superior Craton.

IMPLICATIONS FOR EXPLORATION

Numerous mafic and ultramafic intrusions in the BUOGE domains appear to define an important Cr-(PGE) metallogenic province, which also contains characteristic Ni-Cu-(PGE) and Fe-Ti-(V) associations across the Superior Craton. These domains also appear to be fundamentally different from adjacent terrains, including the Ni-Cu-(PGE) dominated systems in the Abitibi greenstone belt or the apparently relatively unmineralized North Caribou core, Island Lake domain and Goudalie domain with respect to metal endowment (Cr-(PGE) > other areas with orthomagmatic mineralization), magma composition (low-Mg komatiite/high-Mg tholeiite versus high-Mg komatiite/tholeiite), and volcanic-subvolcanic setting (ultramafic intrusions > lava flows versus ultramafic intrusions < lava flows) (Fig. 1).

It is still unclear which factors might be responsible for this distinctive metal endowment, but some critical features appear to be important and may represent efficient metallotects for Cr-(PGE) mineralization (see also Carson et al., 2015), including the presence of 1) a large magmatic event of primitive mantle-derived magmas emplaced over a short duration, 2) significant nearby crustal discontinuities that could have focussed the passage of magma through the crust, and 3) favourable crustal architecture containing potential sulphur (e.g. sulphide-facies iron formation) and oxide reservoirs (e.g. oxide-facies iron formation) for generating the sulphides and chromitites within these ultramafic to mafic magmatic systems.

Thus far, only the Cr-(PGE) deposits (Black Thor, Black Label, Big Daddy, Black Creek, Black Horse, and Blackbird) and Ni-Cu-(PGE) deposits (Eagle's Nest) in the McFaulds Lake greenstone belt appear to be potentially economic. However, significant Cr-(PGE) mineralization occurs within other ultramafic-mafic intrusions across the BUOGE domains (Table 1) and highlights the prospectivity of these regions of the Superior Province. Ongoing and future work aims to establish geological settings and the main defining characteristics of orthomagmatic deposits in many of these areas. This could help to provide better constraints for the genesis of these orthomagmatic deposits and to evaluate the likelihood of discovering additional mineral resources in the BUOGE domains and also in other parts of the Superior Province or throughout the Canadian Shield.

AVAILABLE PRODUCTS

The preliminary results and interpretations of the BUOGE domains, previously referred to as a "super-domain", have been presented at national and international scientific meetings in Winnipeg (Canada: Houlé et al., 2013a) and in Upsala (Sweden: Houlé et al., 2013b), and at the joint assembly of the AGU-GAC-MAC-CGU to be held in Montréal in May 2015. Further forthcoming contributions from this project are planned within each study area (see Bécu et al., 2015; Houlé et al., 2015b; Metsaranta et al., 2015; and Sappin et al., 2015) also in addition to the BUOGE-scale.

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