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Geochemical assessment of the metallogenic potential of Proterozoic LIPs of Canada

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ABSTRACT

The lithogeochemistry of eight Proterozoic Large Igneous Provinces (LIPs) within Canada has been studied to determine the Ni–Cu–PGE prospectivity of these major magmatic events. Three of the LIPs, the 1.87 Ga Chukotat, 1.27 Ga Mackenzie and the 2.49–2.45 Ga Matachewan LIPs, are associated with known magmatic Ni–Cu–PGE sulphide mineralisation. Four of the other LIPs, the 1.14 Ga Abitibi, 0.59 Ga Grenville, ~1.25 Ga Seal Lake and 1.24 Ga Sudbury (distinct from the Sudbury impact event) LIPs, have no known Ni–Cu–PGE mineralisation. The 0.72 Ga Franklin LIP may be associated with the coeval and mineralised Dovyren intrusion in southern Siberia (in a Rodinia reconstruction); in addition, several Franklin-related Ni–Cu–PGE prospects are known within northern Canada.

The mineralised LIPs are characterised by basalts with Ti/V ratios below 50, Gd/Yb ratios close to primitive mantle values and variable La/Sm ratios. The magmas that formed these LIP magmas assimilated significant amounts of crustal material and both chalcophile depleted and undepleted magmas were present during these magmatic events. This indicates that the magmas that formed these LIPs were fertile and S-undersaturated when they left the mantle and subsequently underwent an S-saturation event, forming immiscible magmatic sulphides. The close relationship between chalcophile element depletion and crustal contamination suggests that S-saturation was caused by assimilation of crustal material, most likely by assimilation of crustal sulphides. The magmatic sulphides produced during this event were presumably segregated from magma and deposited in cogenetic mafic–ultramafic sills and intrusives associated with these LIPs.

The Grenville and part of the Franklin LIPs have similar magma source characteristics to those with known Ni–Cu–PGE mineralisation. However, although magmas from both LIPs were fertile and assimilated crustal material, the Grenville LIP did not undergo an S-saturation event prior to emplacement. During the Franklin LIP event, chalcophile-element undepleted fertile magmas may have become S-saturated by assimilation of crustal material, most likely crustal sulphides. Identification of the timing and location of this S-saturation event may be a useful guide during exploration for Ni–Cu–PGE mineralisation. The Abitibi, Sudbury and Seal Lake LIPs are dominated by alkali basalts and are characterised by high Gd/Yb ratios, a wide range in La/Sm ratios and Ti/V ratios higher than 50. This suggests that the melting that formed the magmas associated with these LIPs occurred at depths of >90 km, and potentially involved melting of enriched mantle sources. All samples from the Abitibi, Seal Lake and Sudbury LIPs are chalcophile element depleted, suggesting that these magmas left residual sulphide within the mantle during melting, and indicating that these LIPs are probably not prospective hosts for Ni–Cu–PGE sulphide mineralisation.

1. Introduction

The association between mafic–ultramafic Large Igneous Provinces (LIPs) and magmatic Ni–Cu–PGE mineralisation is well established (e.g., Begg et al., 2010; Borisenko et al., 2006; Eckstrand and Hulbert, 2007; Naldrett, 1997, 1999, 2010; Pirajno, 2000; Schissel and Smail, 2001). However, in comparison to the Phanerozoic LIP record, the Proterozoic LIP record is poorly understood in terms of the processes that operated during LIP formation, the potential for LIPs to host hitherto unknown Ni–Cu–PGE mineralisation, and the lithogeochemical techniques and signatures that can differentiate between barren and prospective LIPs (e.g., Ernst, 2007; Zhang et al., 2008).

A number of important Ni–Cu–PGE camps and deposits are associated with LIPs, the most important of which is the world-class magmatic Ni–Cu–PGE sulphide mineralisation at Noril'sk–Talnakh, associated with the end-Permian Siberian Trap LIP (Arndt et al., 2003; Hawkesworth et al., 1995; Lightfoot and Keays, 2005; Naldrett et al., 1992). Numerous other LIP-related magmatic Ni–Cu–PGE sulphide deposits have also been discovered, including Ni–Cu–PGE mineralisation associated with the Permian Emeishan LIP (e.g., Borisenko et al., 2006), mineralisation at the Duluth Complex associated with the 1115–1085 Ma Keweenawan LIP (e.g., Miller and Ripley, 1996), and

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the world-class Jinchuan Ni–Cu–PGE deposit on the Alashan block and potentially associated with the Guibei LIP event of the South China block (e.g., Ernst, 2007; Li et al., 2005; Pirajno et al., 2009; but also cf. Li and Ripley, 2011, who prefer a link with the North China Craton). In each case, a number of key characteristics present within the associated LIP have been positively linked with the genesis of Ni–Cu–PGE mineralisation. These key characteristics include, amongst others, the presence of large volumes of fertile chalcophile element-undepleted magmas (e.g., Naldrett, 2004; Zhang et al., 2008) and chalcophile element depletion associated with crustal contamination and the assimilation of crustal sulphur and the segregation of immiscible magmatic sulphides (e.g., the Nadezhdinsky Formation of the Siberian Trap LIP; Lightfoot and Keays, 2005). In comparison, LIPs with no magmatic Ni–Cu–PGE sulphide mineralisation lack one or more of these characteristics. For example, the barren Deccan Trap LIP did not assimilate significant crustal sulphur via crustal contamination, did not reach sulphur saturation, and therefore did not develop Ni–Cu–PGE sulphide mineralisation (Keays and Lightfoot, 2010).

Another perspective on the controls on Ni–Cu–PGE prospectivity is presented by Zhang et al. (2008), who compiled geochemical data from 10 major LIPs, the Deccan, Kerguelen, Ontong Java, Parana, Ferrar, Karoo, Emeishan, Siberian, Midcontinent (Keweenawan) and Bushveld LIPs, to determine possible geochemical signatures favourable for Ni–Cu–PGE mineralisation. They focussed mainly on the source characteristics of magmas, concluding that, although all LIP parental magmas were generated from deep-seated mantle plumes, there are differences between those associated with known Ni–Cu–PGE mineralisation and those without. LIPs associated with Ni–Cu–PGE mineralisation contain primitive melts with high MgO and Ni and low Al_2O_3 and Na_2O concentrations that were enriched in incompatible elements. These primitive melts also have isotopic signatures that vary between depleted plume and EMI-type mantle compositions, suggesting that interaction between plume magmas and ancient cratonic lithospheric mantle may significantly contribute to the formation of Ni–Cu–PGE magmatic sulphide deposits (Zhang et al., 2008). In contrast, barren LIPs have fewer high-MgO magmas and have isotopic compositions that vary between plume and EMII type mantle, suggesting either involvement of deep recycled crustal material in the mantle source region for these LIPs or crustal contamination, but little interaction with old lithospheric mantle (Zhang et al., 2008). However, although this approach assessed the fertility of individual LIPs, little attention was paid to processes other than the initial fertility of a magma.

Four key factors need to be determined before the Ni–Cu–PGE prospectivity of a LIP can be identified: (1) are the magmas that formed the LIPs fertile (cf. Zhang et al., 2008); (2) what processes control the formation of Ni–Cu–PGE mineralisation in LIPs and what geochemical signatures do these processes have; (3) when and where does sulphur saturation occur in an individual LIP and how can this be identified and (4) what techniques are effective in discriminating between barren and prospective LIPs and between different segments of a LIP. To address these points, here we present initial interpretations of whole-rock geochemistry from a number of LIPs within Canada, using the database of Ernst and Buchan (2010): the 1.14 Ga Abitibi, 1.87 Ga Chukotat, 0.72 Ga Franklin, 0.59 Ga Grenville, 1.27 Ga Mackenzie, 2.49–2.45 Ga Matachewan, ~1.25 Ga Seal Lake and 1.24 Ga Sudbury LIPs (Fig. 1).

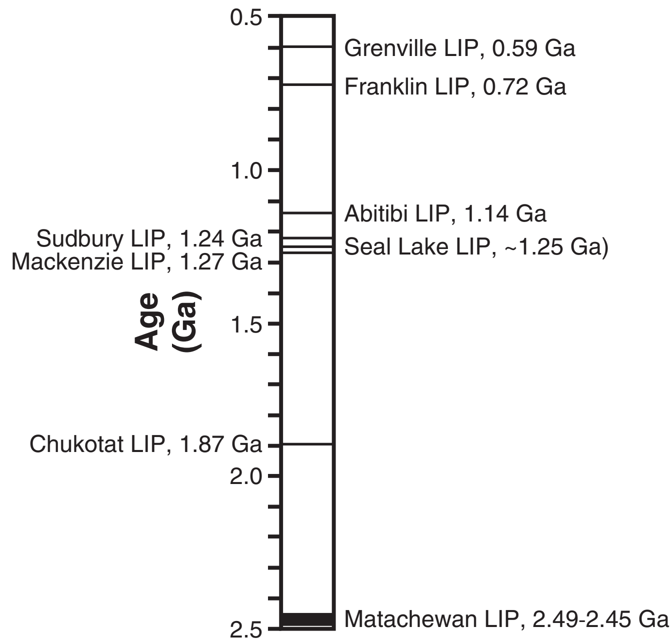

Fig. 1. Temporal distribution of LIP events discussed in this study; thickness of lines denotes relative length of LIP events. Adapted from Ernst and Buchan (2010).

2. Geology of the studied Canadian LIPs

In order to understand the geochemistry of these LIP events, it is first important to understand the general geological settings of these events. The LIPs being considered here formed in differing tectonic settings and times during the geological evolution of Canada. Here, we provide a short description and overview of any known sulphide mineralisation associated with the eight LIPs examined during this study (summarised in Table 1). It is important to note that the Abitibi, Grenville and Sudbury LIPs discussed within this manuscript are not the same as the ca. 2.7 Ga Abitibi greenstone belt, ca. 1.0 Ga magmatism related to the Grenville orogen nor 1.85 Ga magmatism of the Sudbury impact event.

2.1. Geological setting of Proterozoic LIPs of Canada

The oldest event considered here, the ~2445–2490 Ma Matachewan (East Bull Lake) event (Fig. 2), consists most prominently of a radiating dolerite dyke swarm covering an area of about 2.5×10^5 km^2 in the southern and central Superior province, and converging to a focal point on the southeastern margin of the Superior craton (Bates and Halls, 1991; Buchan and Ernst 2004; Ernst and Bleeker 2010; Ernst and Buchan, 1997; Evans and Halls, 2010; Fahrig, 1987; West and Ernst, 1991). Associated volcanic rocks and intrusives of the East Bull Lake Intrusive Suite are distributed near this focal point (e.g., Easton, 2005; James et al., 2002; Vogel et al., 1998) which is interpreted to mark the mantle plume centre responsible for the event. This LIP is related to the rifting and failed breakup of south-eastern Superior from Karelia and other blocks (Bleeker and Ernst, 2006; Ernst and Bleeker, 2010). An initial geochemical assessment of the Matachewan swarm was provided by Phinney and Halls (2001). They suggest that the swarm developed in a two-stage process, whereby the Matachewan magmas fractionated and assimilated crustal material at the base of or within the lower crust. Subsequently these magmas rose and ponded at shallower levels in the crust before undergoing fractionation crystallisation and melt replenishment in shallow magma chambers that acted as feeders for the dyke swarm (Phinney and Halls, 2001).

The 1.87 Ga Chukotat LIP event (Fig. 3) is part of the wider Circum-Superior LIP (Eckstrand and Hulbert, 2007; Ernst and Bell, 2010; Heaman et al., 2009) and is found within the Cape Smith Fold Belt in northern Quebec, an east–west trending early Proterozoic fold and thrust belt separating the southern Archaean Superior province from a group of 'suspect' terranes, the Watts, Spartan and Parent groups, the Kovik antiform and the Narsajuaq arc to the north (Lamothe, 2007). The Cape Smith belt is dominated by three lithological units, the Chukotat Group, Povungnituk Group and the Lac Esker intrusive suite. The Chukotat Group is a sequence of tholeiitic–picritic basalt