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Structural controls on the primary distribution of mafic–ultramafic intrusions containing Ni–Cu–Co–(PGE) sulfide mineralization in the roots of large igneous provinces

Peter C. Lightfoot [a], Dawn Evans-Lamswood [b]

[a] Vale, Exploration, Highway 17 West, Sudbury, Ontario P0M 1N0, Canada
[b] Vale Newfoundland and Labrador Limited, 10 Fort William Place, Baine Johnston Centre, Suite 700, St. John's, Newfoundland, A1C 1K, Canada

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ABSTRACT

Deposits of Ni–Cu–Co–(PGE) sulfide often occur in association with small differentiated intrusions that reside within local transtensional spaces in strike-slip fault zones. These faults often develop in response to incipient rifting of the crust and the development of large igneous provinces due to far-field stresses generated by plume-induced continental drift. We review the geology of a number of large and small nickel sulfide deposits and the associated intrusions, and show that the geometry of the host intrusion and localization of the mineral zones can be classified into three main groups. Further, we show that the morphology of each is controlled by space created in response to deformation on structures.

One group of intrusions has the plan shape of an asymmetric rhomboid with the long axis sub-parallel to a fault zone, and contacts which have often been structurally modified during and/or after emplacement of the magma. The typical cross section is a downward-closing cone shape with curved walls and often a dyke-like keel at the base. This morphology is found in the Ovoid and Discovery Hill Zones of the Voisey's Bay Deposit (Canada), the Jinchuan, Huangshan, Huangshandong, Hongqiling, Limahe, Qingquanshan, and Jingbulake (Qingbulake) Intrusions in China, and the Eagle and Eagle's Nest deposits in the USA and Canada, respectively.

A second group of deposits is associated with conduits within dyke and sheet-like intrusions; these deposits are often associated with discontinuities in the dyke which were created in response to structural controls during emplacement. Examples include the Discovery Hill Deposit and the Reid Brook Zone of the Voisey's Bay Intrusion, where there are plunging domains of thicker dyke which control the mineralization inside the dyke, and thin discontinuous segments of the dyke which are associated with structurally controlled mineralization in the surrounding country rock gneisses. The Oktyabrysk, Taimyrsk, Komsomolsk, and Gluboky Deposits in the Noril'sk Region of Russia are localized at the base of thicker parts of the Kharaelakh Intrusion which appear to be a conduit that follows synformal features in the country rocks located west of the Noril'sk–Kharaelakh Fault. Other examples of dyke-like bodies with both variation in width and the development of discontinuities are the Copper Cliff and Worthington Offset Dykes which radiate away from the Sudbury Igneous Complex (Canada). The distribution of ore bodies in these Sudbury Offset Dykes is principally controlled by variations in the thickness of the dyke, interpreted to reflect the presence of conduits within the dyke.

A third group of mineralized intrusions located within structural corridors have the geometry of oblate tubes; examples include Kalatongke in China, Northeastern Talnakh and Noril'sk 1 in Russia, Babel–Nebo in Australia, and Nkomati in South Africa. Sometimes these oblate tube-like intrusions form in bridging structures between larger intrusions hosted in the more significant structures. Examples include the Tamarack Intrusion in Minnesota, USA, and the Current Lake Complex in Ontario, Canada, both of which contain magmatic Ni–Cu sulfide mineralization. In all of these deposits, the intrusions appear to be open system magma pathways, and so the term “chonolith” can be applied to describe them as a group. All of these intrusions are characterized by a high ratio of sulfide/silicate; there are 1–3 orders of magnitude more sulfide in the intrusion than the magma contained in the intrusion is capable of dissolving. The formation of these deposits is considered to have taken place in open system magma conduits. It is possible that the metal tenor of the sulfides were upgraded by equilibration of successive batches of silicate magma passing through the conduit, and equilibrating with a stationary pool of magmatic sulfide. At Voisey's Bay there appears little doubt that the sulfides were injected through a conduit dyke into higher level magma chambers. A similar model has been proposed for the formation of the deposits at Jinchuan and Noril'sk–Kharaelakh. Economically significant nickel sulfide deposits that tend to be high in Ni tenor, are often related to the late injection of magma that form distinct parts of the intrusion, and the localization of mineralization tends to be related to changes in the geometry of the magma chamber. Strongly deformed and metamorphosed komatiite-associated deposits (e.g. Pechenga, Thompson, and the Yilgarn komatiite associations)

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appear to be the remains of open system magma conduits which are now represented by segmented and boudinaged ultramafic bodies as a result of more than 4 phases of post-emplacement deformation.
LIP activity at craton margins has long been recognized as a key control on the genesis of magmatic sulfide deposits; we show that the principal regional controls of strike-slip tectonics underpin the local geometry of the intrusions, and we provide an explanation for why so many of the global nickel sulfide ore deposits are associated with intrusions that share common morphologies and characteristics. This model provides a framework for more detailed structural investigations of nickel sulfide deposits, and it is a predictive framework for mineral exploration.

1 . Introduction

The principal geological controls on the formation and localization of magmatic Ni–Cu–Co–platinum group element (PGE) sulfide mineralization have been widely discussed (e.g. Barnes and Lightfoot, 2005; Keays, 1995; Lightfoot, 2007; Naldrett 2004, 2010). It is now generally accepted that the formation of economic concentrations of mineralization requires: 1. A primitive S-undersaturated and metal un-depleted parental magma originating from the mantle; 2. a sulfide saturation event that produced a dense immiscible magmatic sulfide (e.g. Keays and Lightfoot, 2009); 3. enrichment of the sulfides in metals by equilibration of the sulfide magma with a large relative amount of silicate melt; and 4. accumulation and localization of the dense sulfide melt into traps at the margin of the intrusion that contains the mineralization (e.g. Keays, 1995; Lightfoot, 2007; Naldrett 2004, 2010 and references therein). The compositions of these sulfide melts can be modified by processes which fall into two broad groups: 1. Fractional crystallization of the magmatic sulfide to produce a Cu-rich liquid and a monosulfide solid solution (Keays and Crocket, 1970); and 2. modification by post-magmatic processes that remobilize and fractionate the sulfides during deformation, metamorphism, and hydrothermal activity (Farrow and Watkinson, 1997; Lightfoot et al., 2012a,b).

Although much attention has been paid to the petrology and geochemistry of the sulfide-bearing rocks and the magmatic processes responsible for their formation (Barnes and Lightfoot, 2005; Naldrett, 2004, 2010), less attention has been paid to the morphology of the magma chambers and conduits that form the intrusions which contain these sulfides (Ripley and Li, 2011). This paper reports evidence to suggest that mafic–ultramafic intrusions that contain Ni–Cu–Co–(PGE) sulfide mineralization share several key features which make them part of a group, viz: 1. The relative volumes of sulfide to silicate magma in the intrusions is high and the metal content of these sulfides is also very high, thus, these sulfides cannot have formed by in-situ segregation and accumulation from the observed volume of silicate magma contained in the intrusion (e.g. Naldrett et al., 1995); 2. the internal distribution of rock types is complex and includes a range of rock types from ultramafic through mafic as well as local development of magmatic breccias that are typically spatially associated with the sulfide mineralization (e.g. Lightfoot, 2007); 3. the intrusions have morphologies that are controlled by pre-existing and reactivated structures in the crust that guided magma from the mantle to shallower levels (e.g. Lightfoot et al., 2012a); and 4. there is now strong evidence to suggest that sulfides were injected as sulfide- and fragment-laden magmas and possibly sulfide magma into a final resting place (Lightfoot et al., 2012a,b; Tang, 1992, 1993).

This study reports a review of key aspects of a group of Ni–Cu–Co–(PGE) deposits found in China; these include Mesozoic deposits associated with intrusions cutting largely Carboniferous-aged country rocks in the Kangguer Fault Zone of eastern Xinjiang (deposits associated with intrusions at Huangshan, Huangshandong, Hulu, Tulargen, Erhongwa, and Xianshan), the Nalatishan Fault Zone in western Xinjiang (Jingulake), the Fuyun Fault Zone of northern Xinjiang (Kalatongke), the Longshoushan Fault Zone of Gansu Province (Jinchuan), the Huifeihe Fault Zone of Jilin Province (Hongqiling), and the North–South Panxi Region faults in the roots of the Permian-aged Emeishan flood basalts of Yunnan and Sichuan Provinces (Yangliuping, Limahe, Qingquanshan, Baimazhai, Jinbaosan). We show how this model is important in understanding the origin of the deposits at Noril'sk–Talnakh and Voisey's Bay. The global significance is then emphasized with reference to other deposits which also share these features; these include Babel–Nebo Western Australia), Nkomati (South Africa), Eagle, Tamarack, and Current Lake (Mid-continent Rift of Canada and the USA), and Double Eagle (Ontario, Canada). We show how these intrusions are all part of a group of open system magma channels or conduits which have traditionally been termed chonoliths (e.g. Naldrett et al., 1995), and we show how these intrusions develop in localized open space created by cross-linking structures within major strike-slip fault zones towards the margins of cratonic bodies. We propose that the entire class of deposits form in a direct response to the plumbing system in structural zones where magma migration is controlled by a process of tectonic pumping which transfers both sulfide and crystal-laden magmas through open system passageways. The geological setting in which these systems were developed relates to supercontinent break-up, and large igneous province (LIP) magmatism at cratonic margins (e.g. Begg et al., 2010).

2 . Geology of the Chinese nickel deposits

The distribution of nickel sulfide deposits in China is summarized in Fig. 1, where the size of the symbol is proportional to the original Ni content of the deposit (modified after Tang, 1992). The deposits range in age from Phanerozoic to Mesozoic and although the tectonic setting tends to be associated with the cratonic margin, some of the deposits link to large igneous province events whereas others occur in structural corridors within late orogenic belts (e.g. Zhou et al., 2002). The Jinchuan Intrusion and deposits are part of the Neoproterozoic Rodinian plume event (Pirajno, 2012; Fig. 1). The intrusions associated with the early Permian Tarim LIP include those hosting the deposits of the Kangguer Fault Zone in the Huangshan-Jing'erquan area (Figs. 1 and 2A). The Panxi faults in the roots of the Emeishan LIP contain a number of deposits like Limahe and Yangliuping (Pirajno, 2012). Some mineralized intrusions pre-date the Early Permian LIP by up to 200 Ma; an example is the Jingbulake Intrusion in the Nalatishan Fault Zone in the Western Tian Shan area. Intrusions developed in structures cutting the Central Asian Orogenic Belt appear to belong to a Mesozoic igneous event as recorded by the 217 Ma age of the Hongqiling Intrusion (Wu et al., 2004). A summary of relevant geological features of each of the deposits is given in Table 1.

2.1. The Huangshan-Jing'erquan Belt intrusions and nickel deposits of the Kangguer Fault Zone, eastern Xinjiang

The Huangshan-Jing'erquan Belt contains the second largest combined resource of nickel sulfide in China (Mao et al., 2008). The majority of the deposits occur along the Kangguer strike-slip fault system in the eastern segment of the Tian Shan Belt of the Central Asian Orogen. Fig. 2A shows the geology of northwestern China, and highlights the distribution of the deposits in the context of regional strike-slip faults identified by Cunningham and Mann (2007) based on the digital elevation model for the region and structural work referenced in these papers.