GEOSCIENCE FRONTIERS 2(3) (2011) 375—384

available at www.sciencedirect.com
China University of Geosciences (Beijing)
GEOSCIENCE FRONTIERS
journal homepage: www.elsevier.com/locate/gsf

ORIGINAL ARTICLE

Magmatic Ni-Cu-(PGE) deposits in magma plumbing systems: Features, formation and exploration

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Received 30 September 2010; accepted 15 January 2011
Available online 25 May 2011

KEYWORDS
Magmatic Ni-Cu sulfide deposit;
Magma conduit;
Sulfide immiscibility;
Tectonic extension;
China

Abstract The three most crucial factors for the formation of large and super-large magmatic sulfide deposits are: (1) a large volume of mantle-derived mafic-ultramafic magmas that participated in the formation of the deposits; (2) fractional crystallization and crustal contamination, particularly the input of sulfur from crustal rocks, resulting in sulfide immiscibility and segregation; and (3) the timing of sulfide concentration in the intrusion. The super-large magmatic Ni-Cu sulfide deposits around the world have been found in small mafic-ultramafic intrusions, except for the Sudbury deposit. Studies in the past decade indicated that the intrusions hosting large and super-large magmatic sulfide deposits occur in magma conduits, such as those in China, including Jinchuan (Gansu), Yangliuping (Sichuan), Kalatongke (Xinjiang), and Hongqiling (Jilin). Magma conduits as open magma systems provide a perfect environment for extensive concentration of immiscible sulfide melts, which have been found to occur along deep regional faults. The origin of many mantle-derived magmas is closely associated with mantle plumes, intracontinental rifts, or post-collisional extension. Although it has been confirmed that sulfide immiscibility results from crustal contamination, grades of sulfide ores are also related to the nature of the parental magmas, the ratio between silicate magma and immiscible sulfide melt, the reaction between the sulfide melts and newly injected silicate magmas, and fractionation of the sulfide melt. The field relationships of the ore-bearing intrusion and the sulfide ore body are controlled by the geological features of the wall rocks. In this paper, we attempt to demonstrate the general characteristics, formation mechanism,

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Peer-review under responsibility of China University of Geosciences (Beijing).
doi:10.1016/j.gsf.2011.05.005

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tectonic settings, and indicators of magmatic sulfide deposits occurring in magmatic conduits which would provide guidelines for further exploration.

1. Introduction

Magmatic sulfide deposits host ∼40% and >99% of the global resources of nickel (Ni) and platinum-group elements (PGE) and ∼3% of copper (Cu) and provide 60% Ni and >99% PGE to the world market. According to their geological and geochemical characteristics, magmatic sulfide deposits can be broadly divided into two major groups: rich in sulfides (sulfide >5%, generally 20%–90%) and sulfide poor (sulfide <5%) (Table 1). The former can be further divided into Ni-Cu-PGE and Ni-Cu-(Co) deposits. As shown in Table 1, world-class super-large magmatic Ni-Cu-(PGE) deposits with Ni grade higher than 1 wt.% are hosted in intrusions associated with basaltic, picritic, or troctolitic magmas and at the base of komatiite flows, whereas the super-large sulfide-poor PGE deposits occur in large layered intrusions, although a few small sulfide-poor PGE mineralizations, such as the Jinbaoshan and Zhubu intrusions in the Emeishan Large Igneous Province (ELIP) (Tao et al., 2007; Song et al., 2008), occur within magma conduits.

Since 1883, several Ni-Cu-PGE deposits have been discovered at the base of the Sudbury layered intrusion, Canada, which has assigned this deposit the status of the first super-large magmatic Ni-Cu-PGE deposit in the world. The total metal reserves of Ni, Cu, and PGE in the Sudbury deposit are 1978 million tonnes, 1780 million tonnes, and 1933 tonnes, respectively (Table 1). In the following decades, using the Sudbury model, geologists tried to find other magmatic Ni-Cu-PGE deposits in large layered intrusions around the world, such as the Bushveld and Great Dyke in Africa, Duluth and Stillwater in North America, and Skaergaard in Greenland. However, what they found in these areas were stratiform sulfide-poor PGE deposits (Table 1). In contrast, several super-large Ni-Cu-(PGE) deposits rich in sulfides were discovered in small mafic-ultramafic intrusions, such as the Jinchuan Ni-Cu-(PGE) deposit (Gansu Province, China), the Noril'sk Ni-Cu-PGE and Pechenga Ni-Cu-(PGE) deposits (Russia), the Voisey's Bay Ni-Cu-Co deposit (Canada), and the Uitkomst Ni-Cu deposit (South Africa) (Table 1) (Naldrett et al., 1995; Naldrett, 1997, 2004; Li et al., 2000). As mentioned above, some important magmatic Ni-Cu deposits were found at the bases of komatiite flows (Table 1). Many studies have indicated that the Sudbury intrusion is a most unusual exception and is associated with crustal melting in response to a meteorite impact. Extensive studies have also revealed that economically important magmatic Ni-Cu-(PGE) sulfide deposits tend to occur in magma conduit systems, rather than in large layered intrusions (Li et al., 2001; Maier et al., 2001). Thus, in the past 20 years, exploration targets moved from large layered intrusions to magma conduit systems. This led to the discovery of the Voisey's Bay Ni-Cu-Co deposit during 1993–1997, and remains as the only finding of a super-large magmatic sulfide deposit in the past 40 years. The research and exploration activities over the past 10 years have yielded a better picture on the formation mechanism of the magmatic sulfide deposits within magma conduit system.

In this paper, we focus on the general characteristics, formation mechanism and tectonic settings, as well as the indicators of the magmatic sulfide deposits occurring in magmatic conduits.

2. Salient characteristics

Since the discovery of the Jinchuan, Limahe (Sichuan Province), and Hongqiling (Jilin Province) Ni-Cu-(PGE) deposits during the 1950s to 1960s, several magmatic sulfide deposits related to magma conduit systems have been found in China, such as the Kalatongke and Huangshan Ni-Cu deposit (Xinjiang), and the Yangliuping Ni-Cu-PGE deposit (Sichuan Province) (Sixth Geological Unit, 1984; Tang, 1990; Wang and Zhao, 1991; Tang and Li, 1995; Song et al., 2003, 2008; Tao et al., 2008; Song et al., 2009).

These discoveries offered good prospects for the exploration of magmatic sulfide deposits in China. Here we focus on the

Table 1 Characteristics of different types of magmatic sulfide deposits and the major super-large deposits around the world (from Naldrett (2004)).

Deposit type	Origin	Deposit	Metal reserve (@ average grade)		
			Ni (Mt @ wt%)	Cu (Mt @ wt%)	PGE (t @ g/t)
Ni-Cu-(PGE) deposit rich in sulfides	Intrusion related to meteorite impact	Sudbury (Canada)	1978@1.2	1780@1.08	1933@1.17
	Magma conduit	Noril'sk (Russia)	2320@1.77	4673@3.57	12,438@9.5
		Pechenga (Russia)	400@1.18	215@0.63	107@0.32
		Jinchuan (China)	545@1.06	389@0.75	135@0.26
		Voisey's Bay (Canada)	217@1.59	116@0.85	26@0.19
	Base of komatiite flow	Thompson (Canada)	349@2.32	24@0.16	124@0.83
		Kambalda (Australia)	194@2.9	14@0.21	75@1.13
Sulfide-poor PGE deposit	Large layered intrusion	Bushveld (South Africa)	1500@0.04–0.41	688@0.02–0.2	65,473@4.1–6.2
		Great Dyke (Zimbabwe)	540@0.21	360@0.14	13,946@5.42
		Stillwater (America)	1.5@0.05	0.7@0.02	804@24.9

following questions: (1) what are the main features of magmatic Ni-Cu-PGE deposits associated with magma conduit systems; (2) why super-large deposits formed in small intrusions on the magma plumbing system; (3) what are the predominant factors controlling Ni, Cu and PGE grades of sulfide ores; (4) what are the ideal tectonic settings of these deposits; and (5) what are the important indicators for the deposits.

Below we consider the main features of sulfide-rich Ni-Cu-(PGE) deposits associated with a magma conduit system, comparing the Ni-Cu-(PGE) deposits formed at the base of the Sudbury intrusion and komatiite flows.

2.1. Ore-bearing intrusions are generally small and highly mineralized

Sulfide-rich Ni-Cu-(PGE) deposits associated with magma conduit systems are hosted in relatively small intrusions, but the sulfide ore bodies often occupy large proportions of the intrusion. For example, the Jinchuan ultramafic intrusion is only 6.3 km long and 20–527 m wide with an outcrop area of ~ 1.34 km^2, whereas the three giant ore bodies fill $\sim 43\%$ of the intrusion (Tang and Li, 1995). The outcrop of the Y_1 intrusion at Kalatongke is only ~ 0.1 km^2, and the Ni-Cu sulfide ore body occupies $\sim 60\%$ of it (Wang and Zhao, 1991). In the Hongqiling area, intrusion No.7 is almost completely sulfide mineralized (Qin, 1995). The largest Ni-Cu-PGE deposit in the world is hosted in the Kharaelakh, Talnakh, and Noril'sk mafic-ultramafic sills at Noril'sk, Russia; the thicknesses of these intrusions are less than 300 m (Zen'ko, 1994; Zen'ko and Czamanske, 1994).

2.2. Ore-bearing intrusions in sill-like, lens or irregular shapes distributed along regional deep faults

All magma plumbing systems are located near regional deep faults, through which the mantle-derived magma moved up into the magma conduit system where sulfide segregation occurred. The original shapes of the ore-bearing intrusions largely depend on the shape and dimension of the secondary fractures in the wall rocks along the regional deep fault. The fractures in sub-horizontal unfolded sedimentary strata may extend to a greater distance than in metamorphic rocks because high-grade metamorphic rocks have higher strengths than the sedimentary strata and may be folded. Thus, the magma chambers emplaced in sub-horizontal sedimentary strata should have had a larger extension than those intruded into metamorphic rocks. Examples include more than 20 intrusions occurring in three areas: Talnakh, Noril'sk and Imangda, along the Noril'sk-Kharaelakh fault in the Noril'sk region (Fig. 1). These sill-like intrusions, emplaced into unfolded Devonian–Lower Permian horizontal sedimentary strata, have large variable lengths, up to 15–20 km long and 2 km wide, and low thicknesses up to 350 m (Fig. 2) (Naldrett et al., 1995; Naldrett, 1997; Arndt et al., 2005). Regional geological, petrological, mineralogical, and geochemical studies have indicated that these intrusions are linked with the magma plumbing system of the mantle plume related to Upper Permian continental flood basalt (Siberian Traps) (Naldrett et al., 1995; Lightfoot and Hawkesworth, 1997; Naldrett, 1997).

In contrast, the intrusions emplaced in folded metamorphic rocks generally have small dimensions and are of lens- or irregular shape. Some of the best examples of such intrusions include the Jinchan intrusion (China) and the Voisey's Bay intrusion (Canada). In the Longshoushan Terrane, Gansu Province, most of

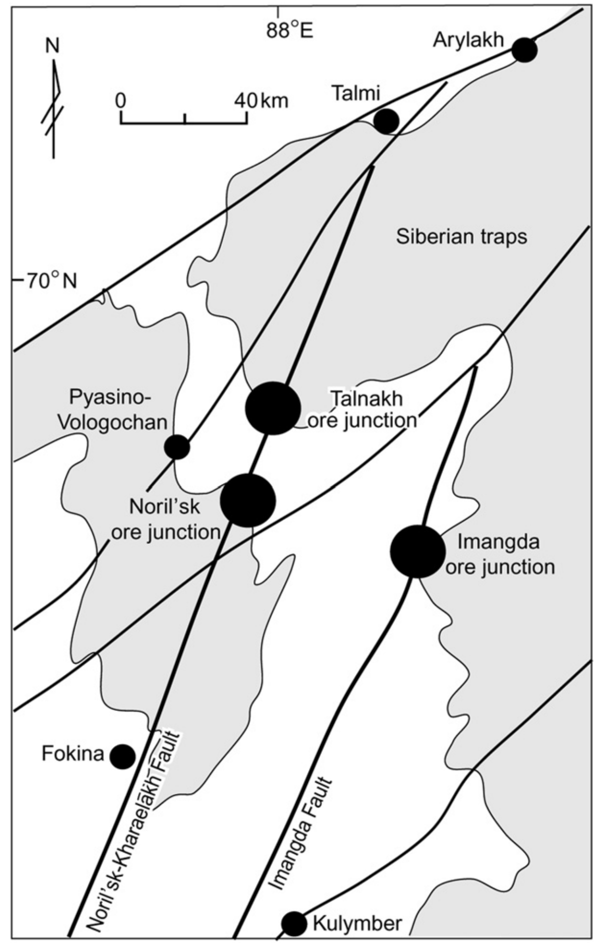

Figure 1 Distribution of the magmatic Ni-Cu-PGE sulfide deposits in the Noril'sk-Talnakh district, Siberia, Russia (after Naldrett, 2004).

the mafic-ultramafic intrusions emplaced in Proterozoic metamorphic rocks are small and lens-shaped. Only a few intrusions, such as Jinchuan and Zhangbutai, are up to 2–4 km long (Tang and Li, 1995). Recent lithological and geochemical study shows that the segments on the two sides of the fault F_{16-1} belong to two originally separate intrusions at Jinchuan (Fig. 3). These two intrusions have thicknessup to 500 m with a lateral extent of less than 4 km (Fig. 3A) (Tang et al., 2009), much less than the lengths of the sill-like intrusions in the Noril'sk area. Although Segment II has concentric lithologic distribution, the normal fractionation sequence of the Upper unit of Segments I and III, comprising dunite, lherzolite and pyroxenite from the base to the top, indicates that the intrusions at Jinchuan were initially sub-horizontal (Fig. 3B). Extensive movement of the regional thrust fault F_1 toward the northeast made the Jinchuan intrusions steeply dipping to the southwest (De Waal et al., 2004; Song et al., 2009; Tang et al., 2009). In the Labrador area of eastern Canada, the Voisey's Bay intrusion comprises a series of small lens-shaped intrusions between two troctolite intrusions within Neoproterozoic metamorphic rocks. The Ni-Cu-Co ore bodies occur as lens-shaped bodies where the magma conduit widened out and the magma flow slowed down (Li et al., 2000).

In the ELIP, several magmatic sulfide-deposit hosting intrusions are emplaced in different wall rocks. The intrusions emplacing in Paleozoic strata are sill-like with large extension and small thickness. For instance, in the Yangliuping area in the

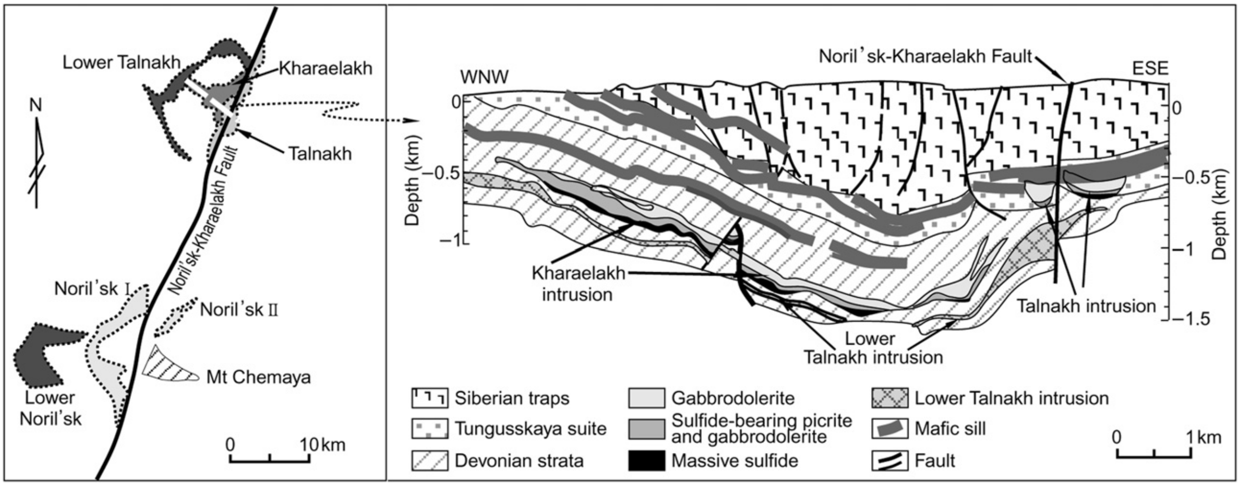

Figure 2 Distribution and field relationships of the three largest intrusions containing Ni-Cu-PGE sulfides in the Noril'sk-Talnakh district, Siberia, Russia (after Naldrett, 2004).

northern ELIP, the sill-like sulfide-bearing intrusions, including Yangliuping, Zhengziyanwou, Xiezuoping, and Daqiangyanwou, are emplaced into unfolded Devonian limestone along beddings with lengths of 1–3 km and thicknesses of less than 300 m (Fig. 4A) (Song et al., 2003; Song et al., 2004; Tao et al., 2007; Song et al., 2008). The regional metamorphism of the wall rocks and intrusions in the Yangliuping area occurred after the formation of the intrusions. The Jinbaoshan sill containing a PGE deposit in Yunnan Province is also emplaced in non-metamorphosed and unfolded Devonian dolomite (Fig. 4C). In contrast, as shown in Fig. 4B, the funnel-shaped Limahe intrusion hosting magmatic Ni-Cu ore bodies is emplaced within Proterozoic metamorphic rocks (Song et al., 2008; Tao et al., 2008).

2.3. Ore bodies at the base and entry of intrusion and widened portion of magma conduit

Because the density of sulfide liquid is higher than that of silicate liquid, the segregated sulfide droplets tend to settle down to the lower parts of the magma chamber. In particular, when sulfide immiscibility and segregation occurred relatively earlier than the crystallization of the silicates, the sulfide droplets could be concentrated at the base of the magma chamber to form massive or semi-massive ores. In contrast, if sulfide segregation and silicate crystallization occurred at the same time, they would settle down together and form disseminated sulfide ores.

In a horizontal magma conduit, the settled sulfides could form large and continuous ore layers at the bases of the magma chamber, such as the ore-bearing intrusions in the Noril'sk area (Fig. 2) and in the Yangliuping area, Sichuan (Fig. 4). However, in a magma conduit with a complicated shape within metamorphic rocks, the sulfides concentrate in those places where the conduit became widened and flat, or at the entry of a new magma chamber, such as in the case of the Voisey's Bay deposit (Li et al., 2000; Naldrett, 1997). Sometimes, the sulfide-silicate mushes could move under structural compression to form new ore bodies of unusual shape and lithologic distribution. For instance, the Jinchuan No. 1 ore body is situated at the centre of Segment II (Fig. 3) (Song and Li, 2009) and the massive sulfides of the Limahe deposit are located at the lower margin of the mafic-ultramafic intrusion (Fig. 4C) (Song et al., 2008; Tao et al., 2008).

2.4. Genetic links between ore-bearing and sulfide-poor intrusions and PGE depleted extrusive rocks

Ore-bearing and sulfide-poor intrusions and extrusive rocks on the same magma plumbing system could have been derived from the same upper mantle source and thus have a closely genetic relationship. Many studies have indicated that continental flood basalts contain not only information on the origin and evolution of the mantle-derived magma and also clues of the formation of the magmatic sulfide deposit beneath the intrusion. Genetic links between the Ni-Cu-PGE mineralization in the ore-bearing sills and consistent Ni, Cu and PGE depletion of some suites of the Noril'sk Siberian Traps have been attested by recent studies (Naldrett, 2004). Similarly, the formation of the Ni-Cu-PGE deposits resulted in the PGE depletion of the Middle Unit of the Emeishan continental flood basalts at Yangliuping (Song et al., 2003, 2006).

However, it is sometimes difficult to find extrusive rocks related to magmatic sulfide ore-bearing intrusions because of the strong erosion that occurs during regional uplift. For example, the Emeishan continental flood basalts in the central zone of the ELIP related to the formation of the ore-bearing intrusions (e.g. Limahe, Qingkuangshan and others) have been eroded mostly during Mesozoic–Cenozoic uplift (Song et al., 2008). No Proterozoic extrusive rock srelated to the Jinchuan Ni-Cu-(PGE) deposit have been found in the Longshoushan Terrane until now.

3. Why super-large deposits can be formed in small intrusions in magma conduit systems

Abundant sulfide is concentrated in a relatively small intrusion basically because of the unusual geological characteristics of the magma conduit system as discussed below.

3.1. Volume of magma involved in formation of deposit in magma conduit systems

The Noril'sk Ni-Cu-PGE deposit contains 23 million tonnes Ni and ∼12,438 tonnes PGE, but the total volume of these ore-bearing intrusions is only 3.5 km^3. S-unsaturated basaltic magmas derived from the upper mantle commonly contain ∼300 ppm Ni.

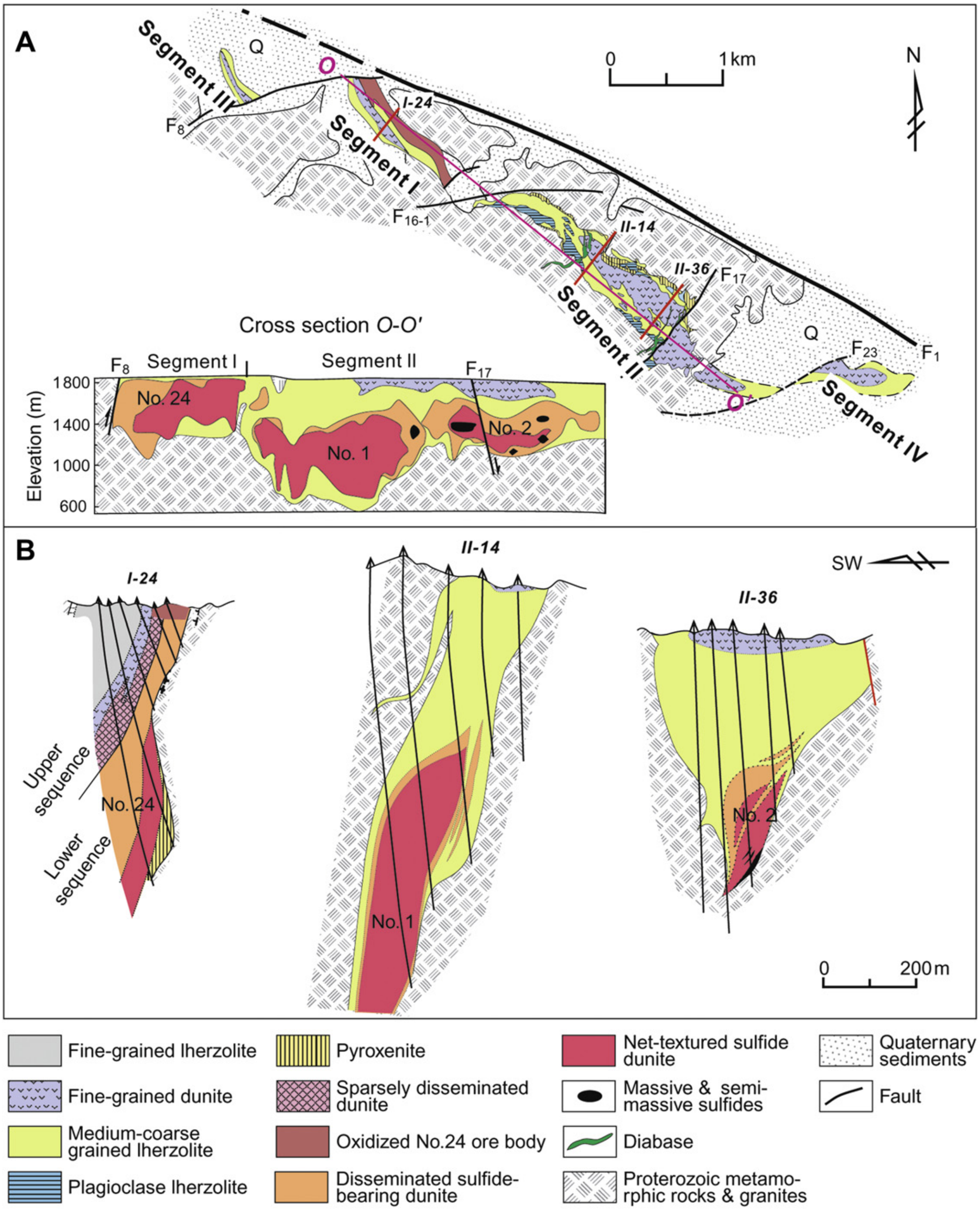

Figure 3 Simplified geological map (A) and main exploration sections (B) of the Jinchuan ultramafic intrusion and hosted Ni-Cu-(PGE) sulfide deposit (modified after Sixth Geological Unit, 1984; Song et al., 2009). I-24 is the exploration line 24 of Segment I, II-14 and II-36 are the exploration lines 14 and 36 of Segment II, respectively.

Thus, concentration of abundant Ni and PGE in the Noril'sk intrusions indicates that as much as 1000 km^3 basaltic magma was involved in the formation of the deposit (Naldrett, 2004). The volume of the Jinchuan intrusions is only $\sim$1 km^3, with the reserve is $\sim$5.45 million tonnes Ni implying that about 300 km^3 basaltic magma passed through the magma conduit system. These mass-balance calculations indicate that an ore-forming magma conduit must be an open system. When new pulses of magma-bearing sulfide droplets entered the magma conduit, those droplets settled down, and at the same time, the overlying sulfide-poor and PGE depleted magma was squeezed out and ascended to a higher level to form a new intrusion or erupted to form lava. This mechanism makes the magma conduit the perfect space for a magmatic sulfide deposit. However, why the sulfide deposition and concentration occurs in only few magma chambers is still unclear.

3.2. Main factors controlling sulfide liquid immiscibility

The mantle-derived magmas having potential to form Ni-Cu-PGE deposits must have been produced by relatively high degrees of partial melting and S-undersaturation whereas, PGE remained at

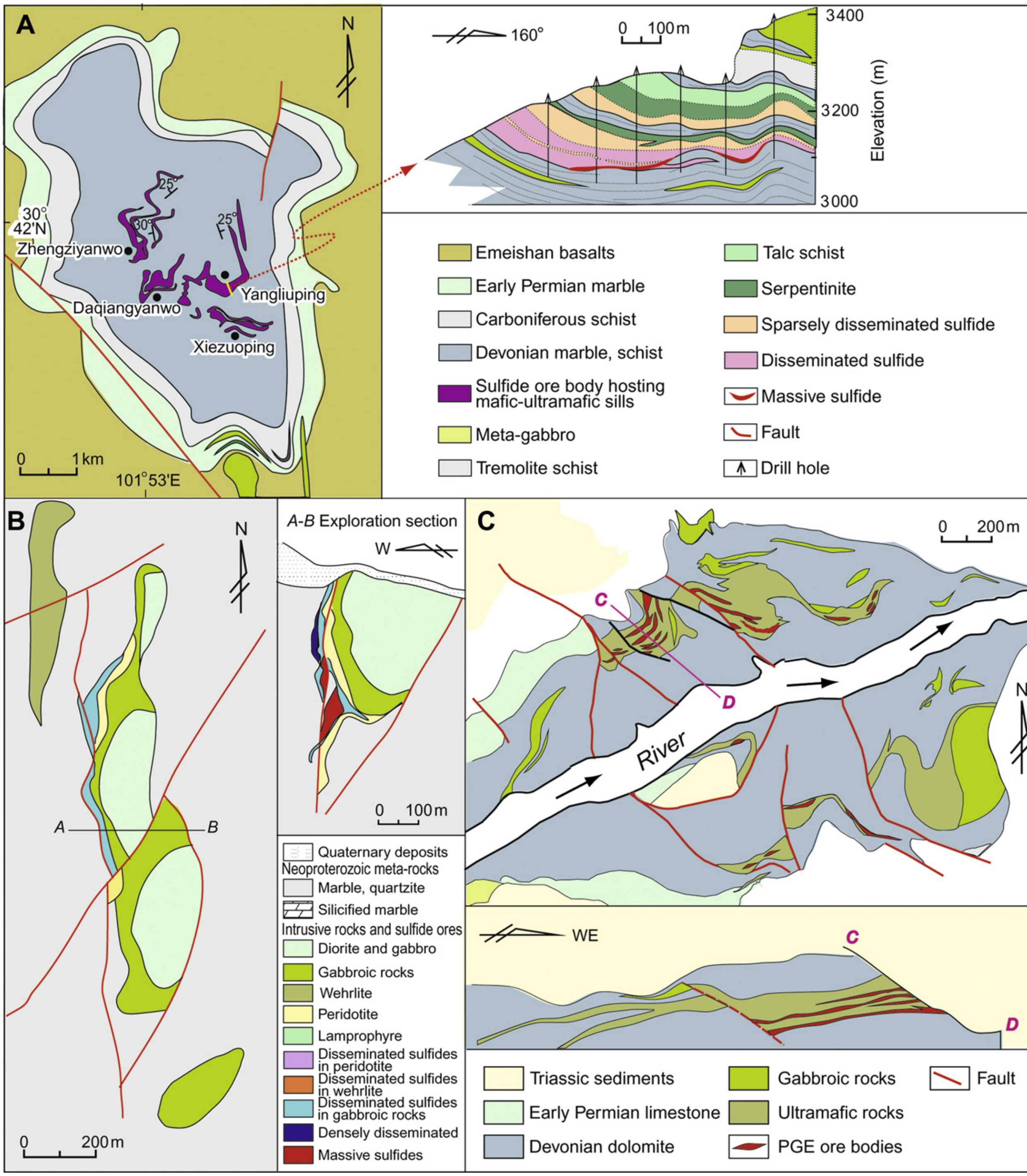

Figure 4 Geological map and cross sections of the typical magmatic sulfide deposits in the Emeishan Large Igneous Province (after Song et al., 2008). A: Geological map of the Yangliuping area and cross section of the Yangliuping sill hosting Ni-Cu-PGE sulfide ore bodies; B: The Limahe complex hosting Ni-Cu sulfide deposit and vertical section across the complex; C: The Jinbaoshan mafic-ultramafic sill hosting PGE sulfide ore bodies.

the mantle source with sulfides during low degrees of partial melting, which produced S-saturated and PGE-poor magmas. Thus, S-saturated primary magmas have the potential to form Ni-Cu deposits rather than a Ni-Cu-PGE deposit. Experimental studies have indicated that S solubility of mafic magma decreases with decrease in temperature and of FeO and TiO_2 in the magma, and increase with decreasing pressure (Haughton et al., 1974; Shima and Naldrett, 1975; Buchanan and Nolan, 1979; Wendlandt, 1982; Mavrogenes and O'Neill, 1999). Therefore, sulfide immiscibility does not occur during adiabatic ascent from the mantle because of the decrease of pressure. In contrast, an S-saturated magma could become S-undersaturated when the magma rises to a shallower level. Thus, input of sulfur and SiO_2 and Al_2O_3 during crustal contamination is a key factor to trigger the mantle-derived basaltic magma reaching S-saturation. The formation of magmatic sulfide deposits found around the world until now is clearly related to crustal contamination. However, the magmas generated from metasomatized mantle might have had high S solubility because of high oxygen fugacity. Sulfide immiscibility and segregation could be triggered by deoxidization when the magma encountered sediments containing carbon or organic materials, and input of sulfur might then be unnecessary.

One of the intriguing questions is whether sulfide immiscibility, segregation and concentration occur in the same magma chamber or in different magma chambers in a magma plumbing system. If these processes occurred in the same magma chamber, input of adequate sulfur from the wall rocks was needed, or sulfur solubility must have been extensively lowered by means of input of a large amount of SiO_2 and Al_2O_3 during contamination. However, the wall rocks of some ore-bearing intrusions have too low sulfur contents to provide enough sulfur to trigger sulfide immiscibility. For instance, the sulfur contents of wall rocks of the Jinchuan intrusion are less than 100 ppm, much lower than the saturation solubility of mafic magmas (~1000 ppm). Thus, it is clear that sulfide immiscibility must have occurred in another magma chamber at Jinchuan (Ripley et al., 2005). Similarly, the wall rocks of the Yangliuping and Limahe intrusions are also not rich in sulfur. The sulfur of the sulfides of the Voisey's Bay Ni-Cu-Co deposit was also not derived from the wall rocks of the intrusion (Naldrett, 2004). Although input of a large amount of SiO_2 and Al_2O_3 by wall rock contamination could decrease sulfur solubility of the mafic magmas and trigger sulfide segregation, extensive contamination also resulted in decrease of temperature and crystallization of silicate minerals. The sulfide droplets and silicate minerals would settle down together and form disseminated ores, which would be uneconomic. Moreover, if sulfide segregation occurs after crystallization of olivine, the sulfides would have very low Ni grades and also be uneconomic.

Thus, a more convincing interpretation is that the mantle-derived magma reaches S-saturation when they pass through sulfur-rich sedimentary rocks in the crust before crystallization of olivine or at the same temperature as the liquidus of olivine. The sulfide droplets would then settle down and concentrate to form ore bodies when the sulfide-bearing magma entered a magma conduit system. Previous studies (Li et al., 2001; Ripley et al., 2005; Song et al., 2009) indicated that sulfide immiscibility of the Voisey's Bay and Jinchuan deposits occurred at deep levels before the respective magmas entered the ore-bearing intrusions.

4. Main factors affecting Ni, Cu and PGE grades

Several factors affect the Ni, Cu and PGE grades of the sulfides of the magmatic sulfide deposits, the most important of which include: concentration of these elements of the parental silicate magma, degree of sulfide segregation, reaction between the sulfide droplets and new pulses of mafic magma, and fractionation of the sulfide liquids.

4.1. Nature of primary silicate magma

Concentrations of Ni, Cu and PGE of the mantle-derived magma depend not only on the degree of partial melting and nature of the mantle source, but also on magmatic evolution, such as fractional crystallization and particularly sulfide separation. For a certain mantle source, the concentrations of Ni, Cu and PGE of the primary magmas are decided by the degree of partial melting. Komatiitic and picritic magmas produced by high degrees of partial melting have high PGE concentrations and high Ni/Cu ratios. In contrast, the mid-ocean ridge basalts (MORB) generated by a low degree of partial melting of the upper mantle are PGE depleted in general. Fractional crystallization under S-undersaturation can cause a slight increase of Pd concentration of the basaltic magmas and decrease of IPGE (Os, Ir, Ru) concentrations. Once S-saturation is reached, the basaltic magmas will become PGE depleted once a small amount of sulfide is separated, but the Ni and Cu concentration of the magma changes little. Concentrations of Ni, Cu and PGE of the sulfide liquid are positively correlated with the concentrations of these elements in the parental magma if the sulfide liquid does not experience fractional crystallization. Thus, the compositions of disseminated sulfide ore are useful for investigation of the nature of the parental magma, from which the sulfide separated. Song et al. (2009) estimated that the Cu/Pd ratios of the parental magma of the Jinchuan intrusion are 2×10^4 to 9×10^6 according to the Cu/Pd ratios of the disseminated sulfide ores. Their calculation indicated that ratios are much higher than that of the primitive mantle (~7000–10000), indicating that the Jinchuan sulfides were separated from the PGE-depleted basaltic magma because of prior weak sulfide segregation.

4.2. Degree of sulfide segregation

The degree of sulfide segregation can be defined by the ratio of silicate melt/sulfide liquid (R factor). For a certain magma, the larger the R factor, the smaller the amount of sulfide segregated from the parental silicate magma and higher Ni, Cu and PGE concentrations of the sulfide liquid are expected, whereas a low R factor implies low Ni, Cu and PGE concentrations of the sulfide liquid. Because partition coefficients of PGE between the sulfide liquid and the silicate melt ($D^{Sul/Sil}$) are as high as 10^4–10^5 (superscript "Sul" means sulfide liquid, "Sil" means silicate melt), much higher than those of Ni and Cu (10^2–10^3), the effect of the R factor on the PGE concentration of the sulfide liquid is more obvious than on the Ni and Cu concentrations when the R factor is larger than 1000. The PGE concentrations of the sulfide liquids may be elevated by reaction with new pulses of S-undersaturated and PGE-undepleted magmas. The very high PGE grades of the Noril'sk deposits are attributed to the reaction between the sulfide liquid and new pulses of magma (Naldrett, 2004).

4.3. Fractionation of sulfide liquid

Nickel and IPGE having partition coefficients ($D^{Mss/Sul}$) between monosulfide solid-solution and sulfide liquid are larger than 1 (superscript "Mss" means monosulfide solid solution, "Sul" means sulfide liquid), whereas the partition coefficients ($D^{Mss/Sul}$) of Cu and PPGE (Pt, Pd, Rh) are less than 1. Thus, fractional crystallization of the monosulfide solid-solution will result in differentiation between Ni and Cu and between IPGE and PPGE. Copper and PPGE will be concentrated in the residual sulfide liquid during fractional crystallization of monosulfide solid-solution. Differentiation between IPGE and PPGE is very common in massive and semi-massive (net-textured) sulfide ores, and is unusual in disseminated sulfide, in which the sulfide liquid droplets are separated from each other by the silicate melt. Differentiation between the IPGE and PPGE has been found not only in the massive and semi-massive sulfide ores of the Noril'sk and Jinchuan deposits, but also in the magmatic sulfide deposits in the ELIP.

5. Tectonic setting of deposits

S-undersaturated primary basaltic magmas generally contain ~300 ppm Ni and ~10–20 ppb Pt and Pd. The formation of large economic magmatic sulfide deposits required the involvement of a large volume of basaltic magma, and a continuous supply of such magma is pivotal for the formation of large and rich ore bodies. On the other hand, crustal contamination is always a key factor in the formation of magmatic sulfide deposits. Thus, the perfect tectonic settings for large and super-large deposit are a large igneous province and a rift zone in a continental plate, where a large amount of basaltic magma is generated by extensive upwelling of the upper mantle.

5.1. Large igneous province

A large igneous province comprises of flood basalts covering a large area and associated intrusions resulting from a mantle plume. Mantle plumes come up probably from the boundary between the lower mantle and the core (e.g., Maruyama et al., 2007; Santosh, 2010) and thus have very high temperatures (up to 1500 °C). An upwelling mantle plume results in extensive high-temperature partial melting of the asthenosphere, lithosphere as well as the plume itself producing a large amount of S-undersaturated basaltic magma in a short time (1–2 Ma). Basaltic magma produced by a mantle plume provides enough material for the formation of a large Ni-Cu-(PGE) sulfide deposit, a V-Ti-Fe oxide deposit, and a chromite deposit. The formation of the magmatic sulfide deposits in magma conduit systems, such as the Noril'sk Ni-Cu-PGE deposit, Voisey's Bay Ni-Cu-Co deposit, and the magmatic sulfide deposits at the bases of komatiite flow, and the PGE deposits in large layered intrusions, such as the Bushveld intrusion and Great Dyke, are closely related to mantle plumes (Naldrett et al., 1995; Lightfoot and Hawkesworth, 1997; Naldrett, 1997, 2004; Li et al., 2000; Arndt et al., 2005; Li et al., 2005; Song et al., 2006; Song and Li, 2009). Recent studies indicated that the magmatic sulfide deposits and V-Ti-Fe oxide deposits in the ELIP resulted from the activity of a Permian mantle plume (Song et al., 2003; Song et al., 2006; Wang et al., 2006; Tao et al., 2007; Song et al., 2008; Tao et al., 2008).

Although the presence of a mantle plume satisfies some important conditions for the formation of a large magmatic sulfide deposit, these deposits have been discovered in only a few large igneous provinces. Thus, with the exception of a continuous supply of a large amount of magma, crustal contamination, particularly input of enough sulfur from the sedimentary rocks in a certain magma plumbing system is also a very important precondition for the formation of a large magmatic sulfide deposit. This is why no magmatic sulfide deposits have been found in a large igneous province within an oceanic plate (such as the Ontong Java LIP in the Pacific Ocean). This is probably because the oceanic crust cannot provide sulfur to trigger sulfide immiscibility of the basaltic magma.

5.2. Rift zone

Extension and thinning of continental lithosphere can cause extensive partial melting of the upper mantle and create a good background for the formation of a magmatic sulfide deposit. Several tectonic processes can cause continental lithosphere extension and rifting, such as mantle plume, upwelling of the asthenosphere, and post-collisional extension. Extension and thinning of continental lithosphere not only result in upwelling of the upper mantle, but also induce extensive decompression melting of the upper mantle under relatively low temperature and produce a large amount of basaltic magma. Deep faults permit mantle-derived magmas to ascend rapidly to a shallow magma chamber or to erupt to the surface. Thus, most of the large magmatic sulfide deposits (except for Sudbury) occur in rift zones and are distributed along regional deep faults. As indicated above, the Noril'sk Ni-Cu-PGE deposits are located along the large Noril'sk-Kharaelakh and Imangda faults, which were formed during regional extension because of the upwelling of a mantle plume. The magmatic sulfide deposits in the ELIP are also situated along some deep faults. Tang and Li (1995) proposed that the Jinchuan deposit was formed in a Proterozoic rift zone at a continental margin and Li et al. (2005) suggested that the rifting was related to a Neoproterozoic mantle plume.

In general, an intracontinental rift experiences incipience, maturity and opening of the oceanic basin stages. In the incipient stage, a series of large mafic-ultramafic intrusion form along linear regional deep faults. A triple junction forms in the mature stage and many intrusions and lavas are formed because of more extensive magmatism. An ocean basin opens at the late stage of the rift and magmatism becomes weak. Naldrett (2004) proposed that the Great Dyke and Voisey's Bay deposits are the results of incipient rifting, the Noril'sk deposit was formed during the mature stage of a rift, and the Jinchuan and Pechenga deposits are associated with magmatism of the late stage.

In fact, post-collisional extension of the lithosphere may cause upwelling of the asthenosphere, although rifts may not be formed in such an environment. Upwelling of the asthenosphere may induce partial melting of the overlying metasomatized mantle and produce mafic magmas. This situation is similar to the incipient stage of a rift zone and some mafic-ultramafic intrusions are formed when the mafic magma ascends to the crust. Studies have indicated that the magmatic Ni-Cu deposits at Kalatongke and the Huangshan-Jingerquan zone formed in a post-collisional tectonic setting related to partial melting of metasomatized mantle sources (Song et al., 2009; Zhang et al., 2009).

6. Implications for exploration

Some of the important questions to be resolved in the exploration for ore deposits are: (1) how to evaluate the potential to discover new deposits in a target area; (2) how to estimate the possible type of deposit; and (3) how to define significant indicators for possible deposits. These aspects are briefly considered below.

6.1. Evaluation of mineralization potential of an exploration target area

The foregoing discussions indicate that intracontinental extension zones, particularly rift zones resulting from upwelling of mantle plumes are potential targets for the exploration of magmatic sulfide deposits. Because the mantle-derived magmas in different tectonic settings offer different potential for the formation of magmatic sulfide deposits, estimating the tectonic setting of the magmatism through studies on the regional geology and geochemistry of the volcanic rocks is important for evaluating the exploration potential of the target region. The formation of large and super-large deposits needs a large volume of sulfide-bearing basaltic magma passing through a certain magma conduit and leaving the sulfide in the same magma chamber. This implies that such large and super-large deposits must be closely related to a magma plumbing system, which is a regional pathway for the basaltic magma and intrusions distributed along regional deep faults that comprise the most important exploration targets. Therefore, it is very important to accurately determine the tectonic framework and the relationships between the origin and evolution of the basaltic magma and the regional geological events as well as the link between the distribution of ore-bearing intrusions and regional deep faults. Also needed is an evaluation of the structural deformation and original field relationship of the ore-bearing intrusion and magma conduit system.

The magmatic sulfide ore bodies are generally located at the base or along the margins of the ore-bearing intrusions and thus the ore bodies are usually concealed. Platinum-group element depletion of the outcrops of the intrusion and Ni depletion of olivine crystals imply a potential to find ore bodies in the lower parts of the intrusion. If there is only PGE mineralization in the deep level of the intrusion, the upper part of the intrusion will only show PGE depletion and will have not Ni and Cu depletion or Ni depletion of olivine.

A thick thermal contact metamorphic zone of a small intrusion implies that such an intrusion was a magma conduit that accommodated a large amount of magma passing through the conduit. If some units of the basalt sequence show extensive Ni, Cu and PGE depletion, it is possible that economic magmatic sulfide mineralization occurs in some of the comagmatic intrusions in the area.

6.2. Exploration indicators and program

In summary, the important indicators of magmatic sulfide mineralization include: (1) PGE depletion and Ni and Cu depletion of the comagmatic intrusive and extrusive rocks; (2) Ni depletion of olivine; (3) extension tectonic settings, particularly intrusion distribution along regional deep fault; (4) thick thermal contact metamorphic zone around the intrusion; (5) strong magnetic anomalies associated with the intrusion. Recognition of these characteristics will aid further exploration of this type of magmatic sulfide deposits.

Future exploration strategies should take into account: (1) evaluation of the tectonic framework of the magmatism and the potential of forming a magmatic sulfide deposit; (2) estimation of the type of mineralization by checking depletion of Ni, Cu and PGE of the comagmatic intrusive and extrusive rocks and Ni depletion of olivine; (3) pertinent geophysical investigations; and (4) planning of the drill holes in the target area based on the geochemical and geophysical anomalies.

Acknowledgements

This study is supported by 973 Program (2007CB411408) and National Natural Science Foundation of China (NSFC) projects (40730420 and 40973038) and grant from Chinese Academy of Sciences (KZCX2-YW-Q04). The authors also thank Dr. Susan Turner (Brisbane) for improving the English.

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