1-3-5 Genetic Model of the Noril'sk Deposits

Many genetic models of the Noril'sk deposits are presented. There are several models such as the "single-magma-input model" in which ore genesis is considered as the process in a single magma chamber, the "multiple-magma-input model" in which multi-stage magma injections into magma chamber are assumed, and the "lava-conduit model" in which intrusion itself is considered as conduit through which magma ascends. In this report, we explain the "multiple-magma-input model" by Fedorenko (1994). In this model, immiscible sulfide melts accumulate in the process of multiple magma injections, and in this point this model has something in common with the "lava-conduit model" by Naldrett (1992). The Genetic model of Fedorenko (1994) is illustrated in Fig. II-1-3-14 and Fig. II-1-3-15.

(1) Evolution of the Parental Magmas to the Noril'sk Deposits

a) After the eruption of the Tk lava, the magma remained in the magma chamber underwent fractional crystallization and crustal contamination to form the parental magma to the Nd_1 and Nd_2 lavas. When this magma reached sulfur saturation, immiscible sulfide melts were separated from the silicate magma and precipitated at the bottom of the magma chamber. As a result, chalcophile elements depleted parental magmas to the Nd_1 and Nd_2 lavas were formed.

b) After the eruptions of the Nd1 and Nd2 lavas, the magma remained in the magma chamber mixed with mantle-derived fresh magma to form the parental magmas to the Nd3 and Mr1 lavas. During this magma reaction, crustal contamination and segregation of immiscible sulfide melts continued.

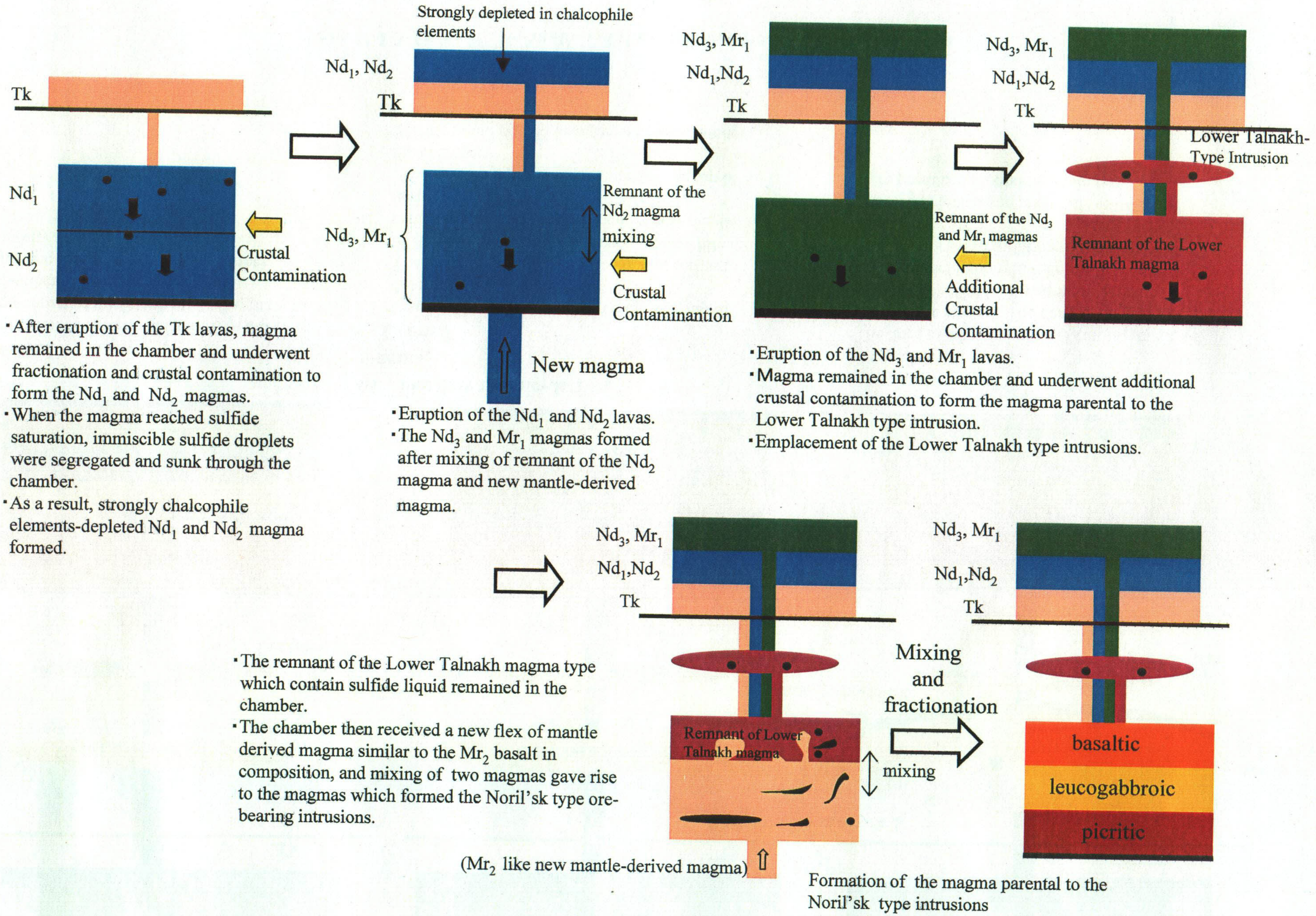
c) After the eruptions of the Nd3 and Mr1 lavas, the magma remained in the magma chamber underwent additional crustal contamination and sulfide segregation to form the parental magma to the Lower Talnakh type intrusions. This magma intruded into the shallow level of crust, and weakly mineralized the Lower Talnakh type intrusions were formed.

d) The remnant of the Lower Talnakh magma, containing sulfide disseminations, mixed with a new mantle-derived fresh magma similar to the Mr2 lava in chemical composition in the magma chamber. As a result, the parental magmas to the Noril'sk type ore-bearing intrusions were formed.

e) Above parental magmas underwent fractional crystallization and zoned magma chamber which differentiated from picritic to basaltic was formed.

(2) Formation of the Noril'sk Deposits

The Noril'sk type ore-bearing intrusions were formed by intrusive activities from the above



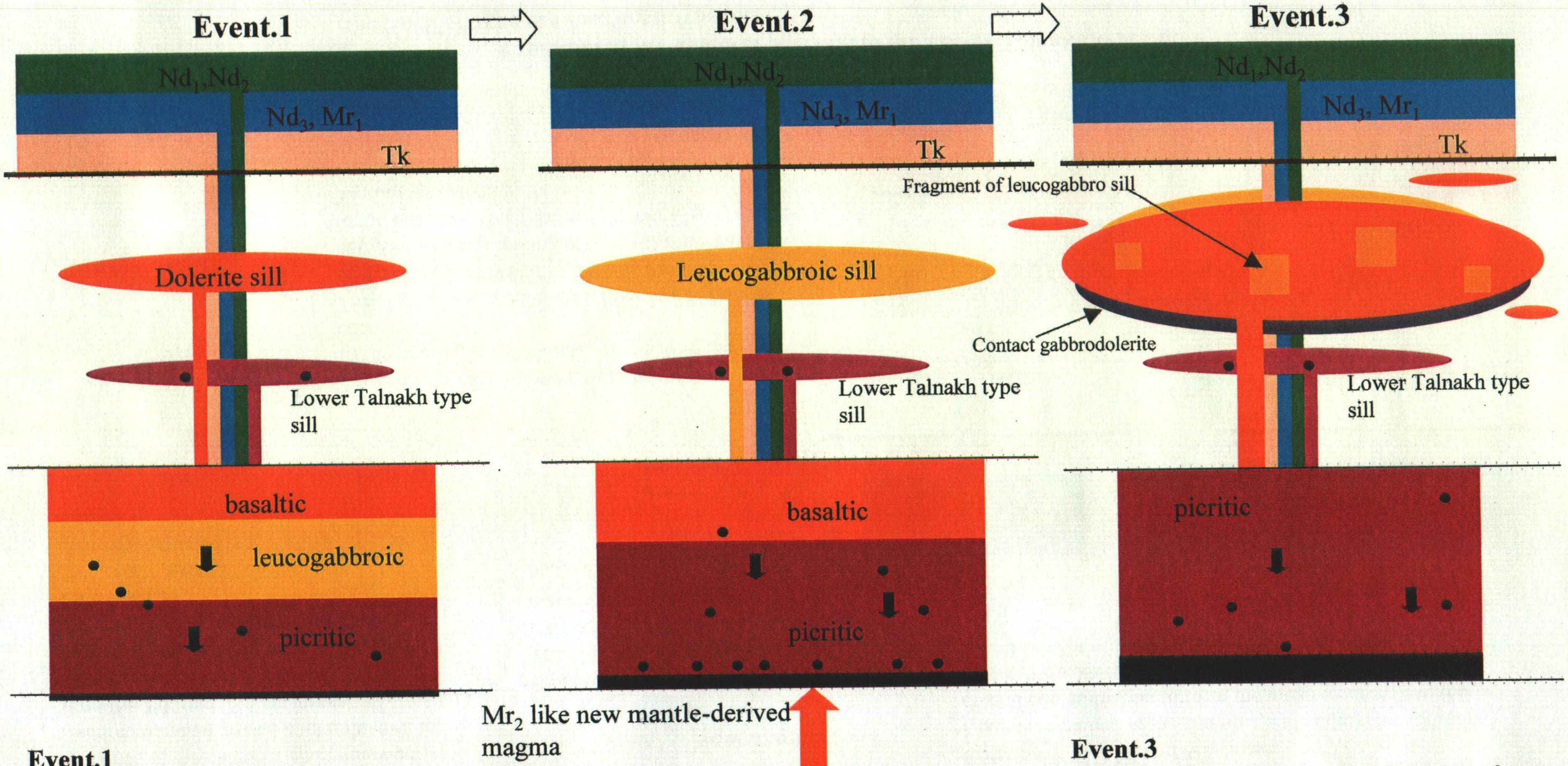
- After eruption of the Tk lavas, magma remained in the chamber and underwent fractionation and crustal contamination to form the Nd$_1$ and Nd$_2$ magmas.
- When the magma reached sulfide saturation, immiscible sulfide droplets were segregated and sunk through the chamber.
- As a result, strongly chalcophile elements-depleted Nd$_1$ and Nd$_2$ magma formed.

- Eruption of the Nd$_1$ and Nd$_2$ lavas.
- The Nd$_3$ and Mr$_1$ magmas formed after mixing of remnant of the Nd$_2$ magma and new mantle-derived magma.

- Eruption of the Nd$_3$ and Mr$_1$ lavas.
- Magma remained in the chamber and underwent additional crustal contamination to form the magma parental to the Lower Talnakh type intrusion.
- Emplacement of the Lower Talnakh type intrusions.

- The remnant of the Lower Talnakh magma type which contain sulfide liquid remained in the chamber.
- The chamber then received a new flex of mantle derived magma similar to the Mr$_2$ basalt in composition, and mixing of two magmas gave rise to the magmas which formed the Noril'sk type ore-bearing intrusions.

Fig. II-1-3-14 **Evolution of the magmas parental to the Lower Talnakh type and the Noril'sk type ore-bearing intrusions**



Event.1

- Intrusion of basaltic magma from the upper part of the intermediate magma chamber to form the dolerite sill.
- In some intrusive systems, no further activity took place.

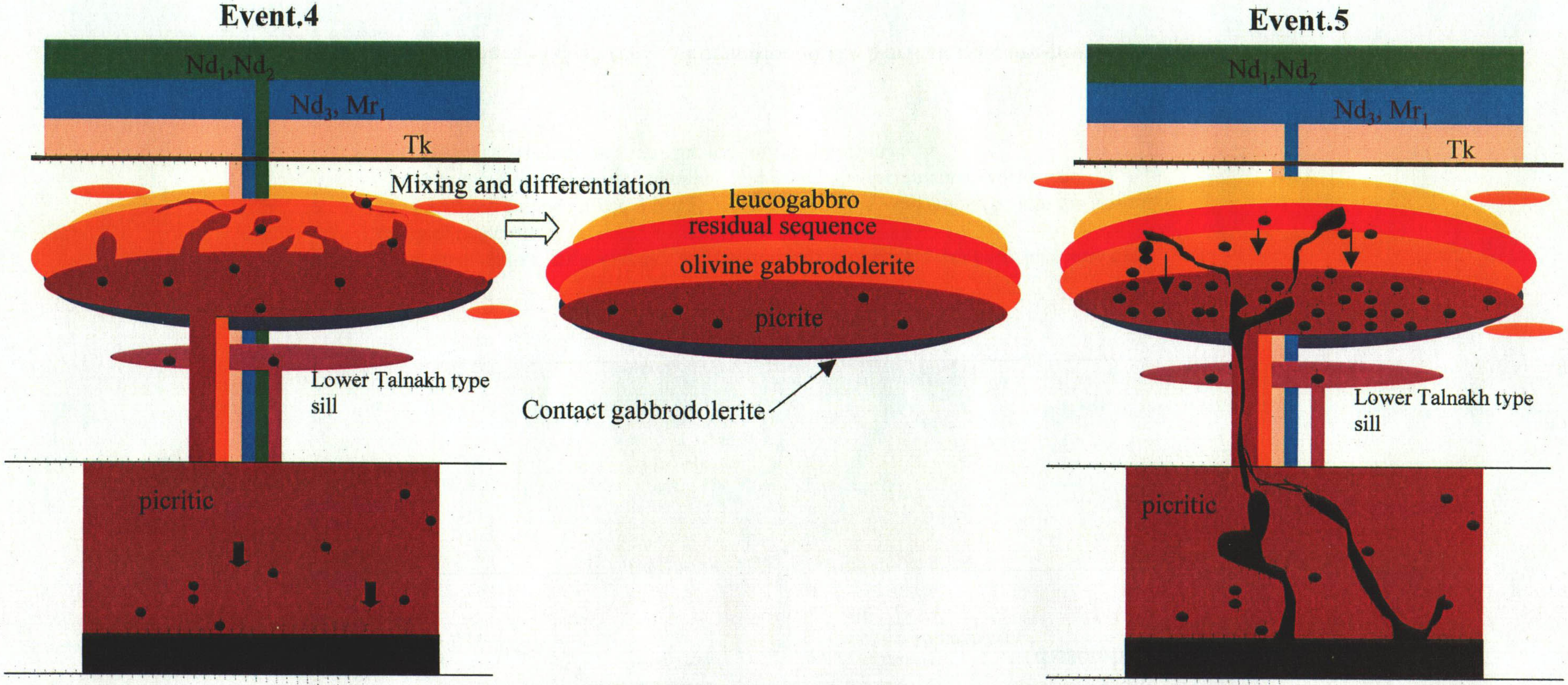
Event.2

- Leucogabbroic magma entered the still-liquid dolerite sill.
- The leucogabbro sill solidified before formation of the main body of the intrusion, meanwhile the chamber was being replenished by new mantle derived Mr_2 like magma.
- New basaltic layer was developed at the top of the chamber.
- Sulfide liquid pooled lowermost in the chamber.

Event.3

- The third event was a second emplacement of the basaltic magma. The composition of the magma(7-8wt%MgO) was represented by the basal contact gabbrodolerite.
- This event caused inflation of the elongated area.
- Numerous lenses and short sills of dolerite were produced around the main body.

Fig. II-1-3-15 (a) Formation of the Noril'sk type ore-bearing intrusion



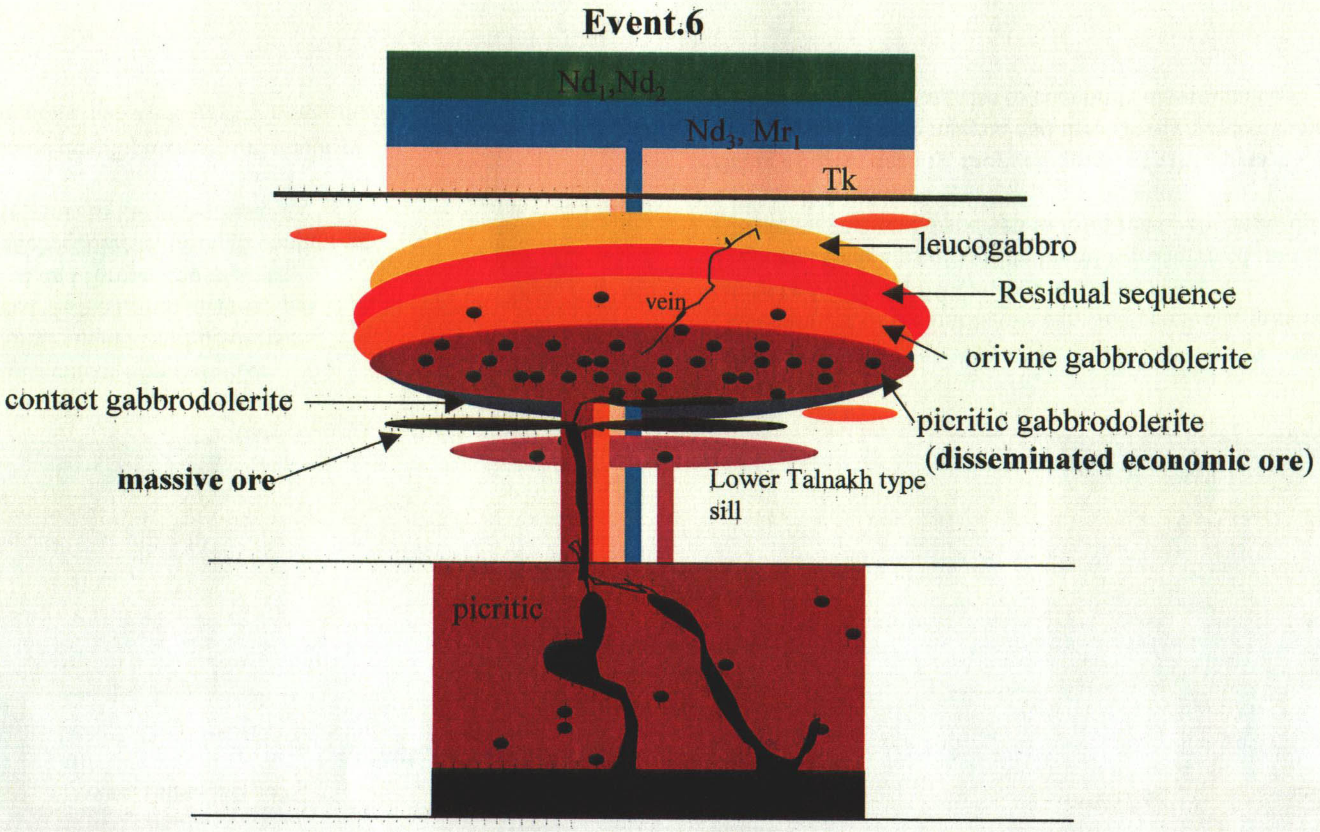
Event.4

- The forth event was emplacement of picrite-like magma carrying small, disseminated sulfide droplets.
- The picritic magma mixed with basaltic magma, and this mixture differentiated and formed the regular sequence from picritic gabbrodolerite, through containing decreasing amounts of olivine, to the upper residual sequence.
- The fourth event terminated development of the majority of the Noril'sk type intrusions that were weakly mineralized.

Event.5

- Development of the intrusions carrying economic mineralization continued with the fifth and sixth events.
- Turbulent fountains of sulfide liquid were injected into the silicate magma and dispersed to form relatively large(up to 3cm) and small droplets.
- Being of great density, they fell quickly to the upper boundary of the dense picritic magma and then slowly descended into the picritic magma, giving rise to economic disseminated minelarization.

Fig. II-1-3-15 (b) **Formation of the Noril'sk type ore-bearing intrusion**



Event.6

- The final, sixth event took place after solidification of the silicate intrusions with their disseminated ores.
- Massive ore bodies formed when sulfide magma pools were emplaced into the lowermost units of the ore-bearing intrusions and underlying metasedimentary rocks, and occasionally, as veins, reaching the roof of the intrusion.

Fig. II-1-3-15 (c)　　Formation of the Noril'sk type ore-bearing intrusion

zoned magma chamber. These activities are divided into six events as shown below(Czamanske et al., 1995).

a) From the upper part of the chamber, basaltic magma intruded into the shallower level and doleritic sills were formed. During this event, precipitation of the immiscible sulfide melts continued in the chamber. Some intrusive systems stopped their growths in this event.
b) The leucogabbroic magma intruded into the doleritic sills which were still in a liquid phase, and gradually solidified. Fresh magma similar to the Mr2 lava in chemical composition was supplied into the chamber from mantle. This magma mixed with the remaining magma. The magma chamber with a layered structure from picritic to basaltic due to fractional crystallization grew again. During this stage, sulfide melts continued to pool at the bottom of the chamber.
c) The third event was a second emplacement of the basaltic magma. The main body of the intrusions were formed by this event. This event caused inflation of the elongated area on the surface. MgO content of this basaltic magma is 7 to 8 wt%, and is thought to be represented by the contact gabbrodolerite that is the chilled margin of the Noril'sk type ore-bearing intrusions. Therefore, this contact gabbrodolerite is considered to have been formed during this event. This magma intruded just below the leucogabbroic sill that had already solidified. Finally doleritic sills including fragments of the leucogabbroic sill were formed. Small scale doleritic sills were formed around the main body. During this event, sulfide melts continued to pool at the bottom of the chamber.
d) The fourth event was the intrusion of the picritic magma from the magma chamber into the main body of the intrusion. This event occurred when the contact gabbrodolerite grew 1 to 2 m in thickness. The picritic magma intruded like a turbulent flow, and reached the uppermost part of the intrusion where it mixed with basaltic magma. This magma conveyed drops of sulfide melt into the intrusion. The mixed magma fractionated to form weakly mineralized layered intrusions. During this stage, sulfide melts continued to pool at the bottom of the chamber.

Many of the intrusive systems stopped their activities at this event and unmineralized or weakly mineralized intrusions were formed. The formation of the economic Noril'sk type ore-bearing intrusion required additional fifth and sixth events. These events were intrusive activities from the sulfide pools developed at the bottom of the chamber.

a) Turbulent fountains of sulfide melt were injected into the silicate magma from the sulfide melt pool formed at the bottom of the chamber. The injected sulfide melt dispersed to form relatively large(up to 3cm) and small droplets. Being of high density of the droplets, they fell quickly to the upper boundary of the dense picritic magma and then slowly descended into the picritic magma, giving rise to economic disseminated mineralization. Through such process, economic disseminated ores were formed in the picritic magma. Irregular distribution of ore grades suggests that these injections occurred repeatedly.

b) The final, sixth event, took place after solidification of the intrusions with disseminated ores. Massive ore bodies were formed when sulfide melt emplaced into the lowermost part of the intrusions and underlying metasedimentary rocks, and occasionally, as veins, reached the roof of the intrusions.

1-3-6 Genetic Model of the Orthomagmatic Sulfide Deposits and Key Factors in the Exploration of the Noril'sk Style Deposits

Lesher and Stone (1996), Keays (1995, 1997), and Brooks et al. (1999) reviewed the requirements for the genesis of the orthomagmatic sulfide ore deposits accompanied by mafic to ultramafic magmas. Based on these papers, the genesis of the orthomagmatic ore deposits and key factors in the exploration of the Noril'sk-style deposit which belongs to these deposits, are discussed.

Keays (1997) presented the following three requirements for the genesis of the economical orthomagmatic sulfide deposits.

- Generation of sulfur undersaturated magma and its transportation to shallow crustal level without reaching sulfur saturation
- Sulfur saturation of the magma and forming immiscible sulfide melt
- Reaction of the immiscible sulfide melt with voluminous silicate magma

(1) Generation of Sulfur Undersaturated Magma and its Intrusion to the Shallow Crustal Level

Since all of the large scale nickel-copper sulfide deposits are enriched in PGE in various degrees, the magma which forms the economic orthomagmatic sulfide ore deposits must be sulfur undersaturated when it generates and must be transported into shallow cruatal level without reaching sulfur saturation, as the first requirement. If the magma is sulfur saturated during magma generation, or saturated when it rises, PGE, which is selectively partitioned into sulfide melt, should be removed from silicate magma with immiscible sulfide melt. Under such conditions, the genesis of ore deposits is impossible. Therefore, existence of sulfur undersaturated magma is the most important requirement for the genesis of the nickel copper sulfide ore deposits. Vogel and Keays (1997) reported that the sulfur undersaturated magmas and sulfur saturated magmas can be discriminated by their Pd-Cu diagram. The sulfur undersaturated magmas are relatively enriched in palladium against copper compared with sulfur saturated magmas.

The magmas that satisfy the above requirement are the high- temperature magnesium-rich magmas generated by sufficient degrees of partial melting of the mantle (Brooks et al., 1999). The magmas that are rich in sulfur, nickel, and PGE are generated by sufficient partial melting of the mantle. On the other hand, the lower temperature magmas generated by lower degrees of partial melting, such as MORB (Mid-Oceanic ridge Basalt), would remain PGE and sulfur in the mantle (Keays, 1997). PGE rich magmas generated by sufficient degrees of partial melting may be geochemically represented by the low-Ti type magma. The magmas must rise to upper crustal level without contaminated by crustal materials. The magmas that satisfy these requirements may not have signs of crustal contamination shown by some geochemical values such as increasing La/Sm and Th/Nb.

The above discussion is about the nature of magmas. In order to give rise to PGE rich fertile magmas, mantle itself may have to be fertile. As mentioned in chapter II: 1-2, mantle peridotite and recycled oceanic crust are thought to be the origin of flood basalt magmas. The former is rich in chalcophile elements, but the latter is thought to be poor in chalcophile elements. Therefore, if we consider mantle peridotite as a original material, qualitatively, generated magma would be rich in chalcophile elements. However, in case the oceanic crust, the hybrid magma that includes considerable amount of mantle peridotite must be considered.

(2) Sulfur Saturation of the Silicate Magma and Forming Immiscible Sulfide Melt

The above mentioned sulfur undersaturated magmas need to contaminate crustal materials in the magma chamber when these are transported to subvolcanic level. The solubility of sulfur in silicate magma decreases due to this assimilation. When the magma is saturated in sulfur, immiscible sulfide melt begins to be segregated from the silicate magma. At this time, copper, nickel, PGE are distributed into the sulfide melt and segregated from the silicate magma. Therefore, the silicate magma becomes markedly poor in these elements. This mechanism may trigger to generate orthomagmatic sulfide ore deposits.

As for the mechanism for the sulfur saturation of the silicate magma, assimilation of crustal materials rich in sulfur (the Noril'sk deposit, the Kambalda deposit), and mixing with a second magma that is already saturated in sulfur (Merensky reef) are presented (Keays, 1997). Beside these ideas, Campbell et al. (1983) argued that magma that is already very close to sulfur saturation can be brought to sulfur saturation through mixing with a second magma that is also close to sulfur saturation. There is a discord of opinion regarding the necessity of the existence of sulfur in crustal materials which contaminate. In case of the Noril'sk ore deposit, many authors have attributed the significantly heavy sulfur isotope signature of the ores to assimilation of sedimentary sulfur. However, Lightfoot and Hawkesworth (1997) have argued that sulfur saturation occurred due to an increase of approximately 5 wt% in the SiO_2 content of the sulfur undersaturated magma, brought about by assimilation of 20-25% crustal contamination. However, regarding the sulfur saturation process of the komatiitic magmas, Keays (1995) have argued that contaminate must contain appreciable quantities of sulfur in order the magmas to be saturated in sulfur. Although the discussion is not settled with respect to this point, in order to assimilate appreciable quantities of crustal materials, high temperature magma is desirable. Therefore, the existence of picritic magma may be important.

(3) Reaction of the Immiscible Sulfide Melt with Voluminous Silicate Magma

The immiscible sulfide melt can be generated by above process. But this process is not enough to generate economic ore deposits. In order to generate economic ore deposits, the sulfide melt should react with voluminous silicate magma rich in chalcophile elements. If the sulfide melt contacts the silicate magma with equilibrium, chalcophile elements are overwhelmingly distributed into sulfide melt. With regard to mafic to ultramafic magmas, experimentally determined partition coefficients for chalcophile elements between sulfide melt and the silicate melt ($D^{sulfide/silicate}$) are as follows; Co: 30, Ni: 100 to 200, Cu: 600 to 1,000, PGE: 10^4 to 10^5. Therefore, concentration of these elements into sulfide melt occurs in order of PGE>>Cu>Ni> Co>>1. Furthermore, the larger the mass of silicate melt reacts with sulfide melt(R-factor) is, the more sulfide melt accumulates.

Where does this reaction occur effectively? In order the immiscible sulfide melt to react with voluminous silicate magma, the geological settings where voluminous silicate magmas are supplied must be required. Such requirement may be satisfied in a center of magmatic activity where crustal suture exists. Therefore, in the center of magmatic activity, if the economic magmatic sulfide ore exists, voluminous silicate magmas which are depleted in chalcophile elements due to reaction with sulfide melt may be expected to exist. The existence of such depleted magma may be an indicator of sulfide mineralization in the underground.

The following is the discussion concerning whether the Noril'sk deposits satisfy above requirements or not.

According to the genetic model of the Noril'sk deposits, the magma which trigged genesis of the deposits is the magma of the Tk lava (Fig. II-1-3-14). Brügmann et al. (1993) showed that the Tk lava had high concentrations of Pt and Pd which range 9-13ppb, increasing with decreasing MgO content. Since the lava is low-Ti type, the lava might have originated with fertile magma derived by relatively higher degree of partial melting of mantle. The Nd_1 and Nd_2 lavas that erupted following the Tk lava are depleted in Pt and Pd. The lavas indicate the evidence of crustal contamination and sulfide segregation. But the Mr and Mk lavas erupted following the Nd_1 and Nd_2 lavas recover Pt and Pd concentrations, ranging 2-9 ppb. Therefore the magmas generated the Noril'sk deposits are thought to be PGE rich fertile one derived from higher degree of partial melting.

Fig. II-1-3-16 to Fig. II-1-3-19 illustrate the variation of Cu, Au, Pd, and Pt with Ni for the Tk, Nd, Mk, and Mr lavas. In these elements, only Ni is compatible to olivine, and strongly distributed into olivine during the fractional crystallization of mafic to ultramafic magmas. Therefore, the Ni content in the residual liquid decreases according to the progress of fractional crystallization. However Cu, Au, and PGE behave as incompatible elements and increase in residual liquid according to the progress of fractionation in the sulfur undersaturated magmas. Whereas in the sulfur saturated magmas, they are strongly distributed into immiscible sulfide melt and the magmas should be markedly depleted in these elements due to sulfide segregation. By these figures, we can recognize that, Cu, Au, Pd, and Pt gradually increase until Ni content reaches to 100 ppm by fractional crystallization. But when Ni content decreases less than 100 ppm, these elements begin to decrease rapidly. This may mean that the magma of the Tk lava reached sulfur saturation when Ni content reached to 100 ppm by fractionation of olivine, and removed immiscible sulfide melt. In the above four elements, the removal of Pd and Pt are remarkable. The reason is that Pd and Pt are distributed more strongly into sulfide melt than Cu and Au. Keays (1995) described that Pd content in a silicate magma decreases from 10 ppb to 2ppb if the magma separates only 0.01 % of immiscible sulfide under the assumption of the partition coefficient $D^{sulfide/silicate}$ of 35,000 and R-factor of 10,000.

Fig. II-1-3-20 is the plot of above 4 lavas on Cu-Pd diagram by Vogel and Keays (1997). The Tk lavas which triggered the Noril'sk deposits are plotted in the field of sulfur undersaturated magmas. The Nd lavas generated by crustal contamination from the Tk lavas are plotted in the field of sulfur saturated magmas, indicating sulfide segregation. The Mr and Mk lavas erupted after the Nd lavas recover Pd content and are plotted again in the field of sulfur undersaturated magmas. Therefore, the Noril'sk deposits satisfy the first requirements (Generation of sulfur undersaturated magma and its transportation to shallow crustal level without reaching sulfur saturation) by the existence of the TK lava, and the second requirement (Sulfur saturation of the magma and forming immiscible sulfide melt) by the existence of the Nd lava.

The third requirement is also satisfied by the existence of the large volume of the Nd lava that is distributed around the center of the mineralization area of Noril'sk. The distribution of the Noril'sk deposits is controlled by the Noril'sk - Kharaelakh fault that is thought to be crustal suture which reaches mantle, and thick Nd lava distributes on and around this fault and the mineralized area of Noril'sk. This means that the Noril'sk deposits may exist in a eruption center of the Siberian flood basalts. Voluminous silicate magmas which originated the Nd lava might have ascended to upper crustal magma chamber through the suture zone such as the Noril'sk - Kharaelakh fault. In a magma chamber, these magmas might have reacted with

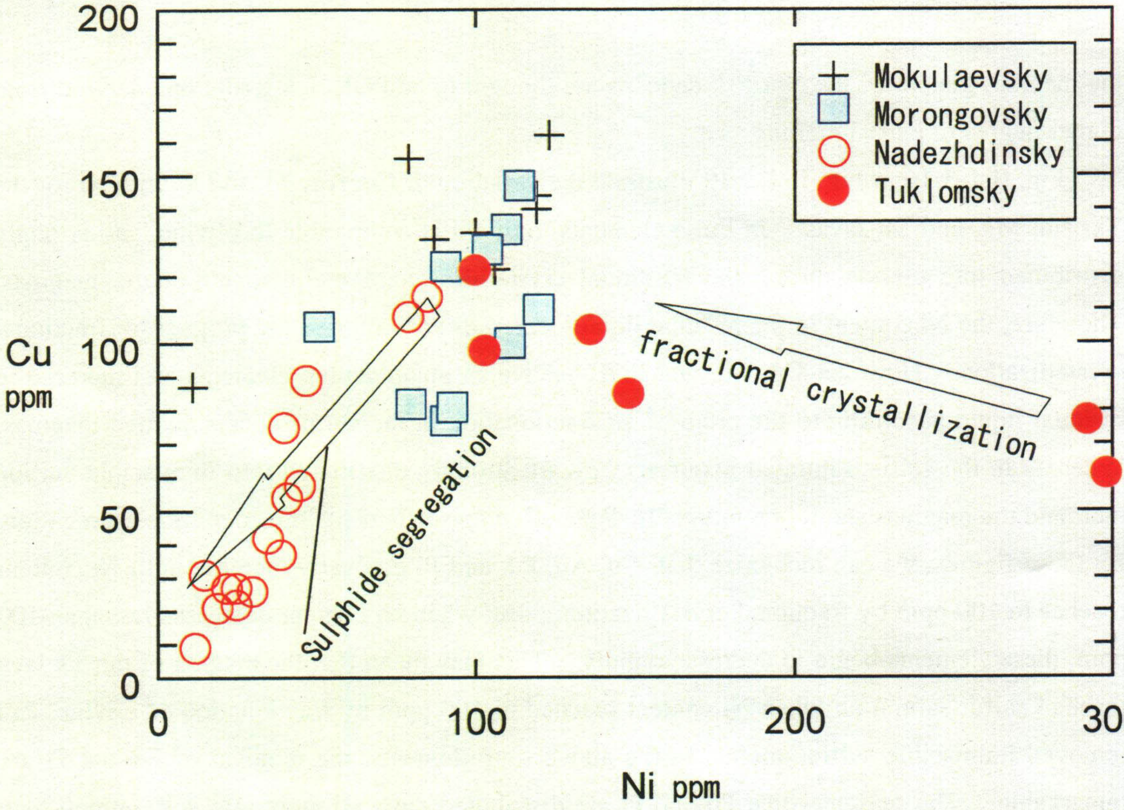


Fig. II-1-3-16 **Ni-Cu correlation in lavas from the Noril'sk region**
Data from Brugmann et al.(1993)

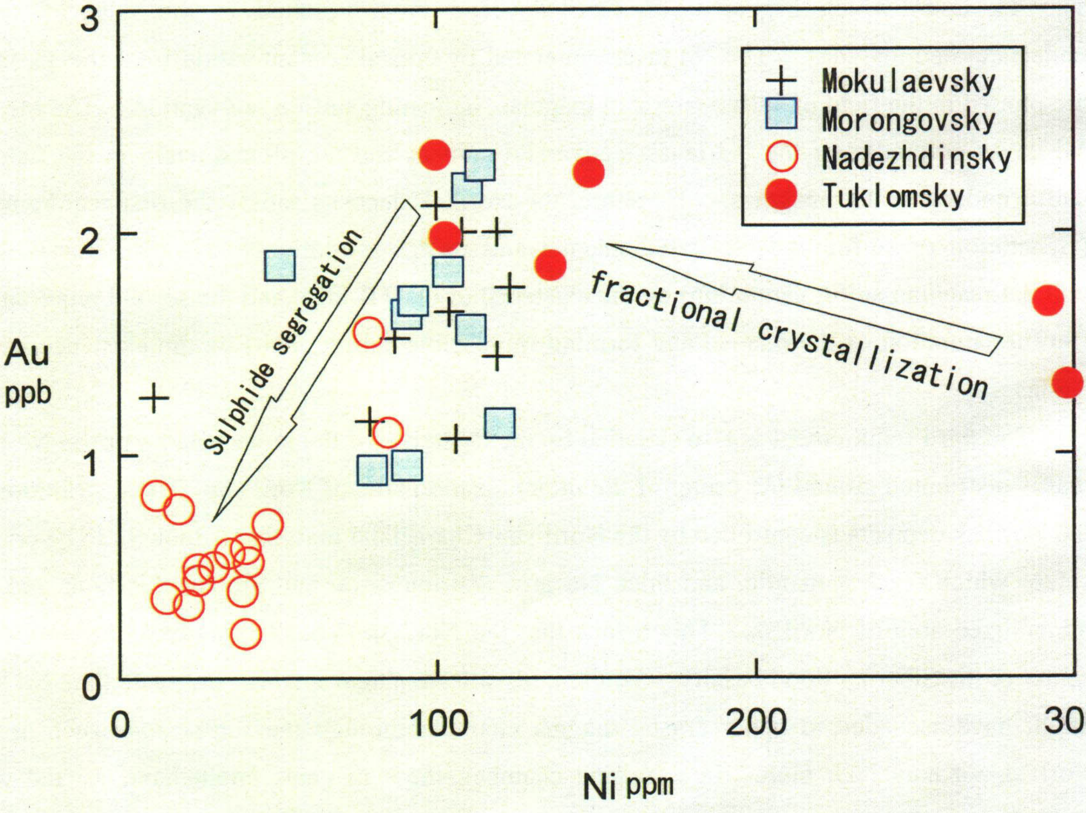


Fig. II-1-3-17 **Ni-Au correlation in lavas from the Noril'sk region**
Data from Brugmann et al.(1993)

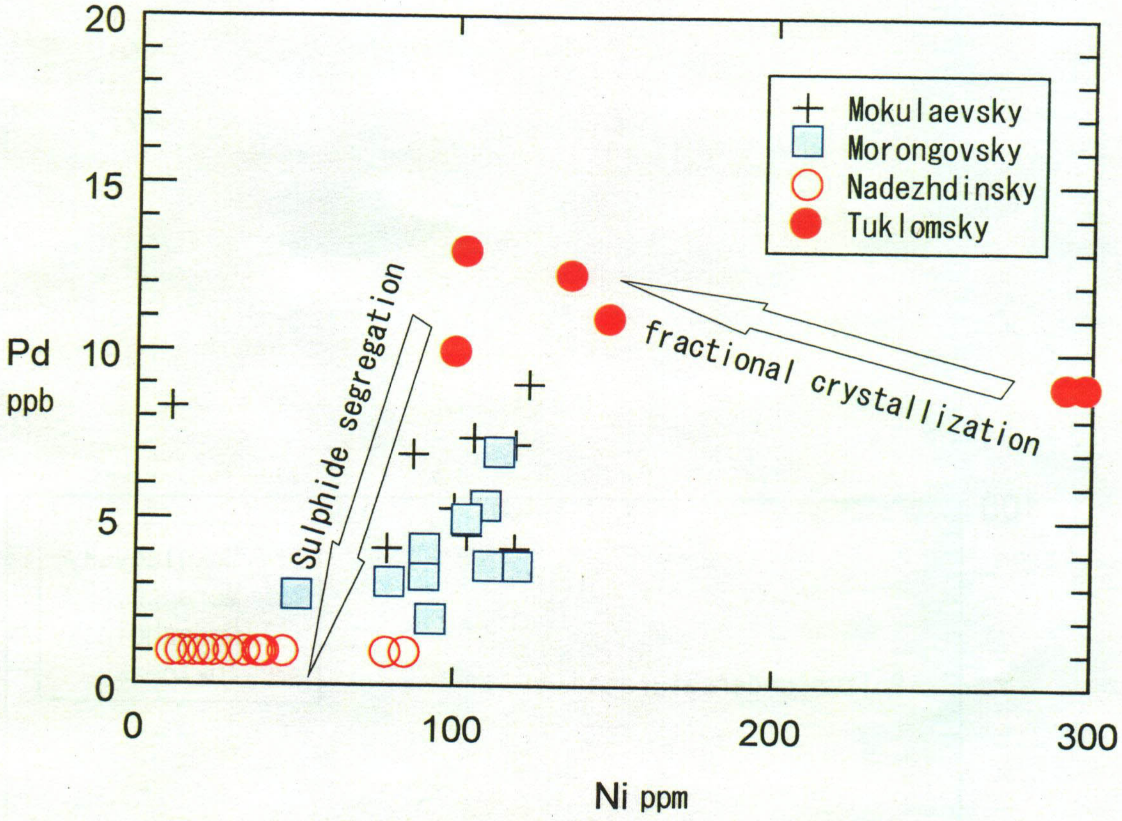


Fig. II-1-3-18 Ni-Pd correlation in lavas from the Noril'sk region
Data from Brugmann et al.(1993)

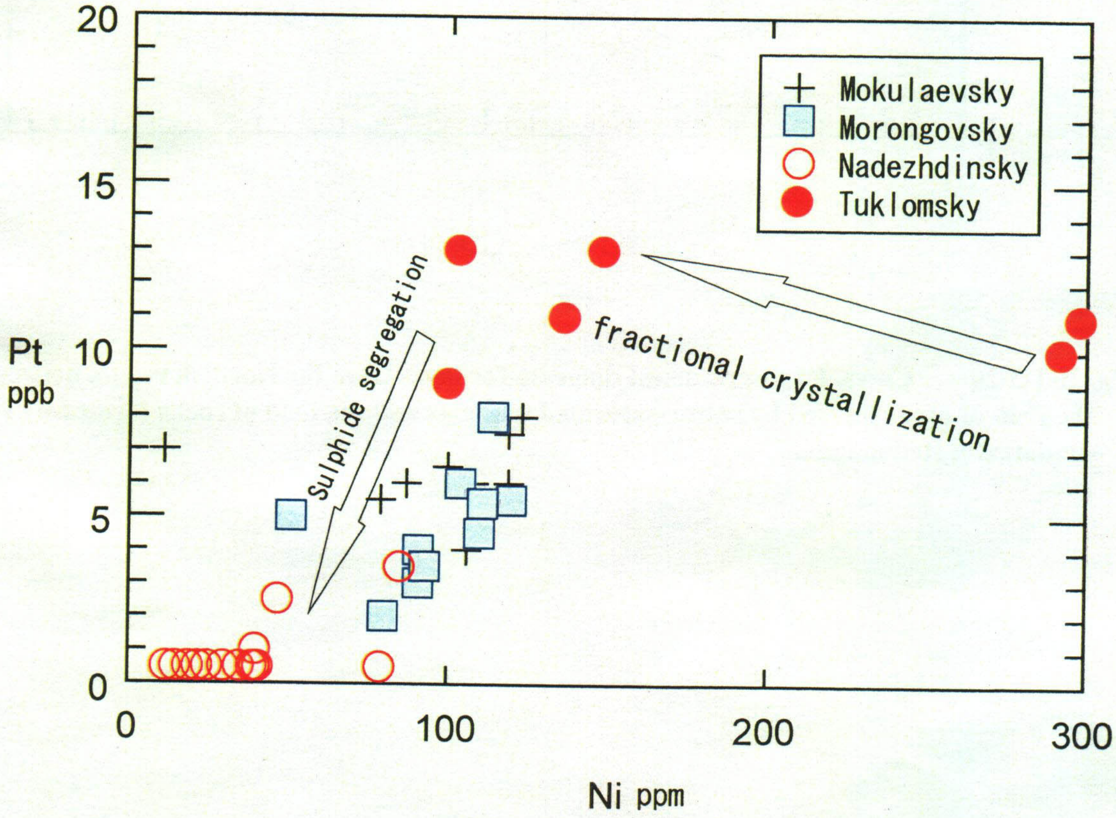


Fig. II-1-3-19 Ni-Pt correlation in lavas from the Noril'sk region
Data from Brugmann et al.(1993)

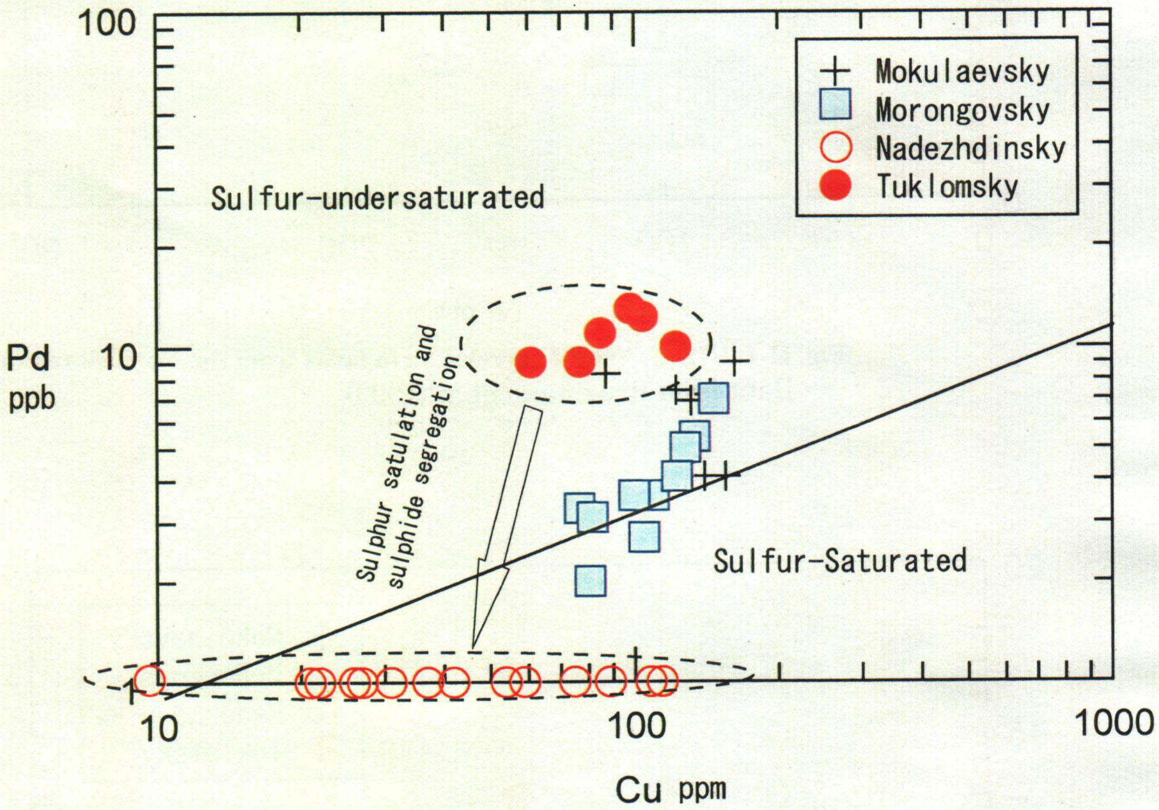


Fig. II-1-3-20 Cu vs. Pd discriminant diagram for lavas from the Noril'sk region between the field of rocks formed by sulfur-saturated magmas and the field of rocks formed by sulfur -undersaturated magmas sulfide melt which had been already formed from the Tk type magmas. As a result, chalcophile elements depleted Nd type magmas were formed. On the other hand, voluminous sulfide melt segregated from the magmas generated the Noril'sk deposits.

The ore generation in a center of magmatic activity in the Noril'sk region may be related to the types of intrusions. There are many types of intrusions in the Noril'sk region, but only the "fully differentiated" intrusions are accompanied by mineralization. The "fully differentiated" intrusions probably mean relatively larger scale ones than the other types, and magma injections into the intrusions must have occurred repeatedly in this type. These repeated magma replenishments into the intrusions may tend to occur in a center of magmatic activity.

As discussed above, the Noril'sk region has all of the theoretically considered requirements for generating the orthomagmatic sulfide deposits associated with mafic to ultramafic magma. Considering the genesis of the Noril'sk style deposits discussed here, it must be required to delineate the promising areas from the huge Parana basin area using the following geological settings as key factors in the exploration. If a area satisfied these geological environments, the immiscible sulfide precipitation and ore generation in the underground would be expected.

a) The existence of low Ti and PGE rich magmas (lavas, intrusions)
b) The existence of magmas showing the signatures of crustal contamination and sulfide segregation associated with above PGE rich magmas (lavas, intrusions)
c) Being a center of the magmatic activity where crustal suture exists. Considering sills as conduits through which magmas of flood basalts ascend (Naldrett et al., 1992), the center of intrusive magmatism may be promising.
d) The existence of picritic magmas (lavas, intrusions). The high temperature picritic magmas have higher potential to assimilate crustal materials to form immiscible sulfide melt. However, the amount of picritic magmas occupies only about 1 % of the total magmas of the Noril'sk region, and the deposits were formed from some of tholeiitic basalt magmas as a result of the crustal contamination (Keays, 1995). Therefore, it is doubtful that picritic magmas are required to generate the Noril'sk style deposits.