*New Frontiers in Research on Magmatic NiS-PGE Mineralisation*
*Centre for Global Metallogeny, University of Western Australia*
*February 2003*
*P129-136*

# The Pechenga Ore Deposits: Russia

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## Discovery and resources

In 1912, Russian geological and geographical expeditions found Ni-bearing rocks in the Pechenga region (Gorbunov, 1968). In 1921, an extensive study of the area by Finnish geologists resulted in the discovery of economically interesting Ni-Cu sulphide ore. Magmatic sulphide mineralisation is found in association with ~ 1970 Ma gabbro-wehrlite intrusions and genetically related ferropicrite flows (Melezhik and Sokolov, 1996). The total estimated resource for the Pechenga camp is 392 mt at 1.2 % Ni and 0.9 % Cu yielding 4.7 mt Ni metal and 3.5 mt Cu metal (Rajavuori, 2001). Annual production is ~ 35 kt Ni metal (Strishkov, 1989) and current reserves should enable mining operations to continue for another 40 to 50 years (Chadwick, 1992).

## Regional geology

The early Proterozoic Pechenga-Pasvik Greenstone Belt is located in the northwestern corner of the Kola Peninsula (Figure1). This belt is part of the 1000 km long, discontinuously developed, early Proterozoic Polmak-Opukasjarvi-Pasvik-Pechenga-Imandra/ Varzuga-Ust'Ponoy Greenstone Belt that traverses the northeastern part of the Fennoscandian Shield. Initial formation occurred in the easternmost part of the Kola Peninsula as the Imandra/Varzuga and Ust'Ponoy intracontinental rifts between two Archaean blocks, prior to the appearance of 2505+/-1.6 Ma layered gabbro-norite intrusions. The rifts and associated volcano-sedimentary basins, subsequently migrated towards the northwest. The early stages of the Pasvik-Pechenga rift zone coincided with uplift and partial erosion of the layered gabbro-norite intrusions (Melezhik and Sturt, 1994).

Structurally, the Pechenga rift comprises the North and South Pechenga Groups that are separated by the major, longitudinal and at times synvolcanic Poritash Fault Zone. The North Pechenga Group (NPG) forms a southeast to southwest dipping ($30^o$ to $60^o$), asymmetric synclinorium with a length of 70 km and a maximum width of 30 km. Remarkable features of the sequence are its great thickness (>8 km), long-lasting volcanism for almost 400 Ma, and the cyclic repetition of volcanic and sedimentary rocks. The rocks have undergone metamorphism from prehnite-pumpellyite or greenschist facies in the central part of the belt to amphibolite facies towards the peripheral zones. The NPG is further subdivided into three tectonic blocks termed the Western, Central and Eastern Rift Grabens (Melezhik, 1996). All of the commercial Pechenga Ni-Cu sulphide deposits are found within the Western Rift Graben (Green and Melezhik, 1999).

## Stratigraphy of the North Pechenga Group (NPG)

The NPG rests discordantly on Archaean basement and comprises four major sedimentary-volcanic cycles each separated by an unconformity generally marked by palaeoweathering. This group is further subdivided into eight formations, the Neverskrukk, Ahmlahti Volcanic, Kuetsjarvi, Kolasjoki and Pilgujarvi Sedimentary and Volcanic Formations.

### *The Neverskrukk Formation*

The Neverskrukk is the basal formation of the NPG and comprises a basal sequence of immature closely packed, poorly sorted framework conglomerates. Boulders and pebbles are generally locally derived Archaean plagioclase granites, plagioclase-microcline granites, gneisses and amphibolites.

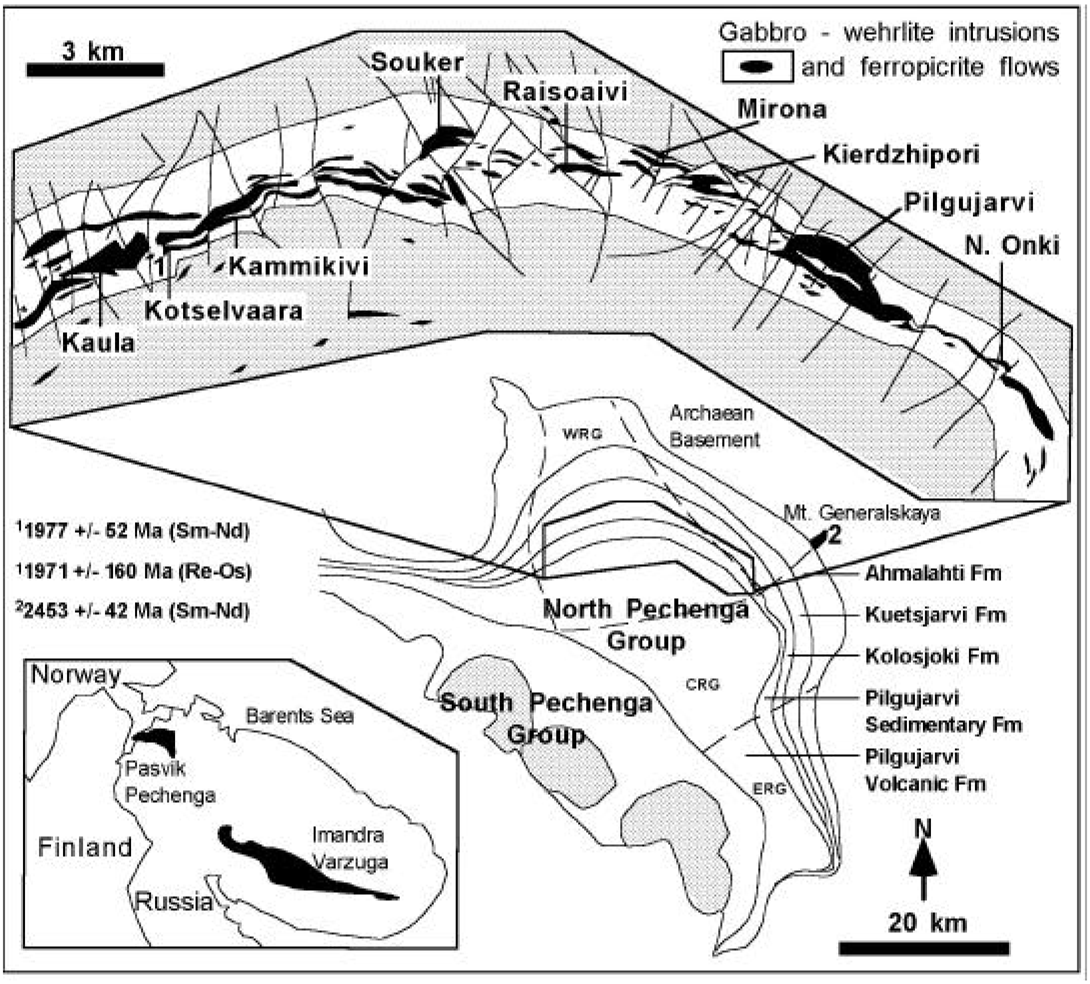

*Figure 1. Generalised geology of the Pechenga region highlighting the distribution of ferropicrite flows and associated gabbro-wehrlite intrusions of the Pilgujarvi Sedimentary Formation.*

In the vicinity of Mt. Generalskaya the formation includes clasts of gabbro-norite derived from the underlying layered intrusion. This intrusion is dated at 2453+/-42 Ma (Bakushkin et al. 1990) and constrains the lower age limit of the Neversukk formation and the NPG.

### *The Ahmalahti Volcanic Formation*

This formation has a gradational contact with the underlying sedimentary formation and comprises sub-aerial amygloidal basalts, basaltic andesites and andesitic dacites. The upper part of the formation is dominated by amygloidal sub-alkaline andesites with subordinate picritic lapilli tuff and thin lenses of volcaniclastic greywacke sandstones. An exposed eruptive centre in the middle of the formation contains xenoliths of granite, granite-gneiss and amphibolite fragments indicating the rift was underlain by continental crust. Andesitic dacites have been dated and yield an age of 2330+/-38 Ma (Balashov et al. 1991).

### *The Kuetsjarvi Sedimentary and Volcanic Formations*

Weathered basalts of the Ahmalahti Volcanic Formation are overlain by sediments of the Kuetsjarvi Sedimentary Formation that include quartzitic gritstones, red-coloured dolostones, doloarenites, dololutites, stromatolitic dolostones and subordinate sedimentary dolomite breccia with tuff matrix.

The volcanic formation has a gradational contact with the underlying rocks of the sedimentary formation. The lower part of the formation consists of sub-aerial, amygloidal, magnetite and haematite-bearing hawaiites, trachybasalt, trachyandesite, and mugearite with subordinate picrite. This part of the formation is dated at 2214+/-54 Ma (Balashov et al. 1994). In the Western Rift Graben the lower part of the formation is separated from the upper part of the formation by a thin, volcaniclastic conglomerate to siltstone horizon capped by pillow basalt or columnar jointed basalts. Amygloidal sub-alkaline basalts, alkaline basalts and mugearites dominate the upper part of the formation.

### *The Kolasjoki Sedimentary and Volcanic Formations*

The lower and middle part of the sedimentary formation consists of red arkosic gritstones, red haematite-rich arkosic gritstones, sandstones and sand and gritstones with quartz amygdules. This is overlain by red coloured Ba and Mn-enriched dolomites that are intercalated with and, in eastern Pechenga dominated by jasper. The uppermost part of the formation comprises basaltic and picritic tuffs along with carbon and sulphur bearing siltstones.

Tholeiitic basalts with subordinate Fe and Ti-rich picrites dominate the volcanic formation. Numerous massive and columnar jointed gabbro sills intrude the volcanic succession. A 50 m to 150 m thick carbon and sulphur bearing shale unit separates the volcanic pile into the Upper and Lower Basalt Members. The tholeiitic basalts are dated at 2114+/-52 Ma (Balashov et al. 1991).

### *The Pilgujarvi Sedimentary (Productive Horizon) and Volcanic Formations*

The sedimentary formation consists of three members: A, B and the ‘Upper’ or Lammas Member. Member A: consists of sulphur and carbon-bearing laminated sandstones, siltstones and subordinate conglomerate lenses. Member B: is dominated by black, highly carbonaceous, sulphide-bearing greywackes and Bouma cycle rythmites that are interbedded with basaltic tuffs. The Lammas Member includes ferropicritic tuffs and tuffites with pyrite and carbonate nodules. An alluvial fan within this member has pebbles and boulders of probable Archaean provenance.

The formation attains a maximum thickness of 1000 m in the Western and Eastern Rift Grabens and is host to economically significant magmatic sulphide bearing gabbro-wehrlite intrusions and ferropicrite flow dated at 1970+/-52 Ma (Hanski, 1992).

The volcanic formation has a gradational contact with the sedimentary formation and is dominated by pillowed and massive tholeiitic basalt, flow breccias and tuffs along with subordinate ferropicritic and acid volcanic rocks. Numerous gabbro and gabbro-dolerite sills intrude the volcanic succession particularly in the Western and Central Rift Grabens.

## Intrusions, flows and mineralisation

More than 226 differentiated mafic-ultramafic intrusions and flows have been identified. Of these, 25 contain economic mineralisation, a further 68 contain sub-economic mineralisation and the remaining 113 are described as barren (Zak et al. 1982).

### *Ferropicrite flows*

The ferropicritic volcanics occur as massive flows, pillow lavas, tuffs and layered differentiated flows up to 50 m thick. Differentiated flows display well-developed spinifex textures and vertical zonation similar to those found in differentiated komatiite flows. The uppermost part of the flows consists of a chilled margin, a spinifex zone, and a zone with fine-grained acicular pyroxenes and globules. Both olivine and clinopyroxene spinifex rocks occur in the upper parts of the flows.

The lower parts of the flows consist of olivine +/- chromite cumulates overlain by thin pyroxene cumulates. Primary magmatic kaersutite is present as overgrowths on spinifex pyroxenes or as groundmass needles (Hanski and Smolkin, 1995). Ferropicrite related explosion breccias are found in the vicinity of Kaula and to the south of Kierdzhipori. A 3.2 m thick differentiated ferropicrite flow within the Lammas Member hosts 0.45 m of massive ore overlain by 1 m of disseminated mineralisation (Green and Melezhik, 1999).

Geochemically the ferropicrite liquids are characterised by high MgO ~ 17 wt%, FeO ~ 16 wt% and $TiO_2$ ~ 2.5 wt%. Moreover, rare-earth element concentrations are high and extremely fractionated with La/Yb typically > 10. These geochemical features indicate the parental magmas were derived from a Fe and incompatible element enriched mantle source. Calculated $T_{DM}$Nd model ages for the Lammas flow, Shuljarvi pillow lava and Kaula spinifex zone range from 2300 Ma to 2500 Ma and indicate the likely time of enrichment of the mantle source region.

### *Gabbro-wehrlite intrusions*

The gabbro-wehrlite intrusions commonly range in thickness from 5 m to 250 m, except for the 466 m thick Pilgujarvi intrusion with strike lengths ranging from 100 m to 6500 m (Zak, 1982). The differentiated intrusions are primarily composed of an olivine cumulate at the base passing upwards through a generally thin clinopyroxenite unit to a gabbroic upper part. Quartz gabbro and or potassium-feldspar bearing essexite represent the most differentiated upper parts of the largest intrusions. Upper and lower chilled margins associated with the Pilgujarvi intrusion are heterogeneous and contain xenoliths of country rock and injections of quartz diorite and pyroxenites (Smolkin, 1997).

The crystallisation sequence of the cumulus minerals is generally Cr-spinel, olivine ($Fo_{84}$ to $Fo_{78}$), clinopyroxene, titanomagnetie and plagioclase. Primary magmatic kaersutite and Ti-bearing phlogopite are common intercumulus minerals throughout the intrusions. Typically the ultramafic rocks are variably altered to serpentinites and dolomite-magnesite-serpentine-talc rocks with preservation of original textures and some primary minerals.

The olivine cumulates from the lower parts of the gabbro-wehrlite intrusions have MgO contents that range from ~34 wt% to ~ 28 wt%. In contrast the upper gabbroic portions of the intrusions have MgO contents that range from ~ 10 wt% to ~ 2 wt%. Both the gabbros and olivine cumulates are relatively enriched in Ti and Fe. Moreover, they are enriched in the light rare-earth elements and have strongly fractionated patterns with La/Sm typically ~ 14. These geochemical features are consistent with the formation of the intrusions from a ferropicrite parental melt. Moreover, this assertion is further supported by analyses of lower chilled margins that are geochemically indistinguishable from analyses of the ferropicrite flows (Hanski, 1992).

### *Mineralisation*

Mineralised bodies are found at all stratigraphic levels within the Pilgujarvi Sedimentary Formation (Figure 1). In the west, the Kaula, Kotselvaara, Kammikivi and West Ortoaivi deposits occur at the highest stratigraphic level within the Lammas Member. These deposits are characterised by mainly high-grade massive ores. In the central and eastern parts the deposits are located in both Member A (East Ortoaivi, North Souker and Mirona) and Member B (Raisoaivi and Souker). The giant Pilgujarvi ore system (Sputnik, Kierdzhipori, Sverny and Zhadanov) intrudes both Member A and B. Four main ore types are recognised: massive, brecciated massive, disseminated and Cu-rich black shale-hosted stringer ores (Gorbunov, 1968). Typical grades in 100% sulphides are ~ 8 % Ni, ~ 1.8 % Cu and ~ 1 ppm Pt+Pd (c.f. Brugmann et al. 2000). In detail the grade distribution is highly variable both between deposits and also between massive and disseminated ores within a given deposit. These features represent a combination of variable R-factor, sulphide fractionation and subsequent structural, metamorphic and metasomatic overprinting (Brugmann et al. 2000).

Sulphur and Re-Os isotope data are crucial to understanding the mode of formation of these deposits. In the west, ores from Kaula, Kotselvaara and Kammikivi yield $\delta^{34}S_{cdt}$ values that typically range from –2 $^{0}/_{00}$ to +4 $^{0}/_{00}$ (mode +2 $^{0}/_{00}$) and radiogenic $\gamma Os_{(1970\ Ma)}$ values that range from +60 to +250 (Hanski, 1992; Walker et al. 1997). In contrast, ores from the Pilgujarvi intrusion to the east yield $\delta^{34}S_{cdt}$ values that range from 0 $^{0}/_{00}$ to +8 $^{0}/_{00}$ (mode +6 $^{0}/_{00}$). Selected Re-Os data define a five point Re-Os isochron for an age of 1971+/-160 Ma and a radiogenic initial $\gamma Os$ value of +45. In both the east and the west, sulphur isotope data closely match the sulphide components from locally available sediments. Moreover, the heterogeneity of both the sulphur and Re-Os isotope data is inconsistent with contamination and homogenisation at depth. The variability in the osmium isotopic composition of the ores is ascribed to a combination of the heterogeneity of local sediments and variation in R-factor. Dynamic modelling (Foster et al. 1996) of the Re-Os data for Pilgujarvi massive ores is consistent with an apparent R-factor of ~ 200.

## A simplified genetic model

In summary, at ~ 1970 Ma a super heated ferropicrite melt escaped from an enriched mantle plume. This melt accessed upper crustal levels via major structures that likely controlled the framework of the Pechenga rift system. On reaching the structurally weak sediments of the Productive Formation, the melt formed a series of sill like bodies, conduits and flows. The high-MgO, low-viscosity, ferropicrite magma flowed through these conduits and where the conduits narrowed or 'necked', the magma velocity increased resulting in turbulent flow. Where turbulent flow occurred, effective heat transfer to the surrounding country rocks resulted in elevated rates of assimilation. This in turn caused the magma to reach sulphide saturation, resulting in the formation of an immiscible sulphide liquid (ISL). ISL droplets were transported along the high velocity conduits and deposited where the conduits enlarged. Flow-through of the magma continued with the result that the early-formed ISL became progressively enriched in the chalcophile elements. As magmatic activity waned the rate of assimilation declined. On cessation of flow, the magmas in the conduits began to crystallise, trapping any late-stage ISL droplets. Approximately 100 Ma after crystallisation a tectono-metamorphic event redistributed primary magmatic sulphides along faults and fractures.

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## Discovery and resources

The Noril’sk deposits were initially discovered during the Bronze Age and further worked during the 16th and 17th centuries by craftsman from the Mangasei settlement on the Taz River. N. N. Uranetsev studied the Noril’sk deposits from 1920-1921 and concluded they were similar to those found at Sudbury. In 1926 the Noril’sk 2 deposit was discovered to the south of Noril’sk. The Talnakh ore junction was found in 1960. Initial indications of its presence came from a surface water geochemical survey that found elevated concentrations of $SO_4^{2-}$ in the Talnakh River. This was followed-up by tracing boulders that indicated a source close to the base of the Kharayelakhsky Mountains. In 1960, a study of the scree along the slope of Otdelnaya Mountain led to the discovery of an outcropping mineralised intrusion (Kunilov, 1994).

Magmatic sulphide mineralisation is found in association with a series of regionally extensive sills that are coeval and cogenetic with the ~ 250 Ma Siberian Flood Basalt Province (SFBP). Reserves and production data for Noril’sk-Talnakh are classified but estimates include 900 mt at 2.7 % Ni (Naldrett, 1997) and 1500 mt at 3.9 % Cu, 1.8 % Ni, 2.5 g/t Pt and 9.7 g/t Pd (Diakov et al. 2002). An analysis of the published data by this author suggests a total resource figure of ~ 2100 mt at 0.9 % Ni, 1.8 % Cu, 1.5 g/t Pt and 2.9 g/t Pd. This equates to a total contained resource of ~ 18 mt Ni metal, ~ 38 mt Cu metal, ~ 100 moz Pt and ~ 200 moz Pd. Annual production is ~ 210 kt Ni metal and ~ 420 kt Cu metal.

## Regional geology

The ore deposits of the Noril’sk region are located at the northwestern corner of the Siberian platform. To the north, the platform is separated from a second platform, the Taimyr Peninsula, by the Khatanga rift zone. To the west, a third craton, the East European-Urals block, is separated from the Siberian platform by the West Siberian lowlands.

The geology in the vicinity of Noril’sk can be divided into four major phases of development. The first of these is represented by complex crystalline basement that includes granite-gneiss, gneiss, schist and migmatite with absolute ages that range from 2200 Ma to 1600 Ma. The second is a package of intensely deformed Riphean molasse formations; volcanics and carbonates that are in turn overlain by weakly deformed Riphean to Vendian copper-bearing molasse formations. The third phase comprises Vendian to early Carboniferous marine and continental- to shallow-marine sediments and terrigenous carbonates with anhydrite and gypsum. Conglomerates, arenites, argillites and coal measures of the mid-Carboniferous to late Permian Tunguska series represent the end of the third phase of development (e.g. Duzhikov and Strunin, 1992; Simonov et al. 1994). The final phase of development is marked by the formation of the SFBP and related intrusions.

The structure of this region is dominated by a series of positive and negative structures, partly pre- and partly post SFBP in age and major faults. The main negative structures are of post-SFPB age and include the Kharaelakh, Vologochan and Noril’sk basins. The Dudinka uplift forms the western boundary of the Vologochan and Noril’sk basins, the

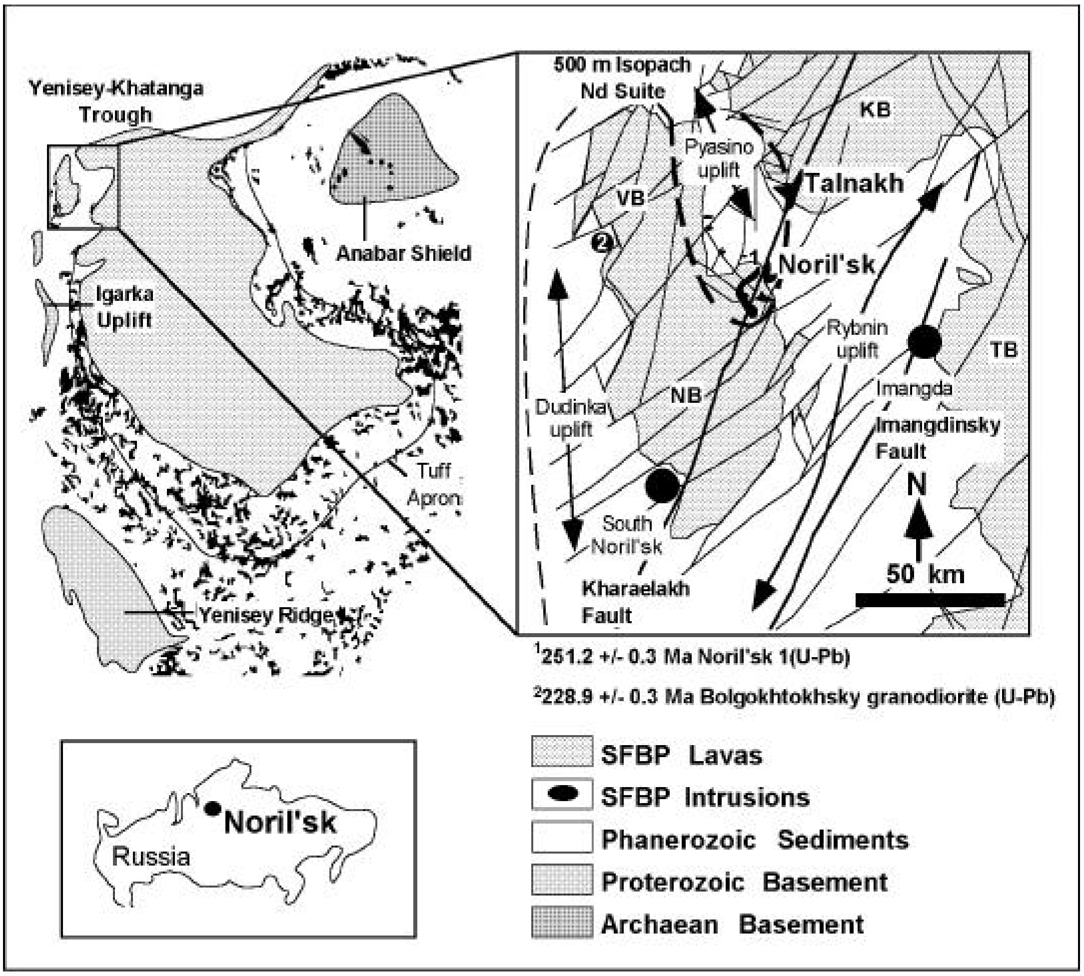

*Figure 1. Generalised geology of the Siberian Flood Basalt province and detail of the Noril'sk region in the vicinity of the Noril'sk-Talnakh camp.*

Pyasino uplift separates the Kharaelakh from the Vologochan and Noril'sk basins, and the Rybnin uplift separates the Noril'sk basin from the Tunguska basin to the east (Figure 1).

Faults within this region either trend northeast parallel to the Yenisey-Khatanga trough or north-northeast. The latter trend is significant as the Noril'sk-Talnakh deposits are spatially related to the Noril'sk-Kharaelakh fault. This fault is a major feature that has been activated periodically from the Precambrian to the Tertiary. Moreover, seismic data indicate the Mohorovicic discontinuity drops steeply from 45 km to 50 km depth east from this structure (Duzhikov et al. 1988). The boundary between Archaean and Proterozoic basement blocks is ~ 50 km to the east of Noril'sk and is defined by the Imangdinsky fault (Simonov et al. 1994).

## SFBP: Volcanics, intrusions and mineralisation

The 250 Ma SFBP is one of the world's largest Continental Flood Basalt (CFB) provinces and likely formed from and in response to a mantle plume (e.g. Wooden et al. 1993). The plume derived melts produced a relatively continuous sequence of basalt that now covers an area of at least $3.4 \times 10^5$ km$^2$. Milanovskiy (1976) estimated that rocks associated with this early Mesozoic flood-basalt magmatism once covered an area of $4 \times 10^6$ km$^2$ and had a volume of 2 to $3 \times 10^6$ km$^3$. In contrast to other flood basalt provinces, SFBP activity is characterised by initial and continuing explosive volcanism; the lava:tuff volume ratio is estimated at 4:1 for the entire province. Basaltic tuffs typically contain 10-15 vol% of fine-grained minerals and lithic fragments derived from the underlying sedimentary rocks and crystalline basement. Moreover, SFBP lavas have high proportions of amygloidal material that may account for 40 % of a given flows thickness. Mafic intrusions are common and widespread (e.g. Duzhikov and Strunin, 1992). Rhyodacite lavas of the Delkansky suite from an area ~ 500 km to the east-northeast of Noril'sk represent one of the youngest magmatic events associated with the development of the SFBP. These lavas yield an age of 251.1 +/- 0.5 Ma within error of the U-Pb zircon/baddeleyite age of 251.2 +/- 0.3 Ma for the Noril'sk 1 intrusion (Kamo et al. 2000).

### *Volcanics*

In the Norils'k region volcanic rocks commonly rest on terrigenous rocks of the Tunguska series above a slight unconformity; a few tens of meters to as much as 300 m of sedimentary rocks was eroded. Locally, Tunguska series argillites conformably grade into SFBP tuffs indicating in this instance that no significant uplift preceded volcanism. In this region a ~ 3700 m thick sequence of volcanic rocks is preserved. The distribution of lavas and lava thickness is directly related to northeast and north-northeast trending linear eruption zones (e.g. Kharaelakh fault). The volcanics comprise lava flows (from a few meters to 100 m thick) and tuff horizons (from several tens of centimetres to 100 m thick, rarely 200-400 m thick). There are approximately 200 lava flows and 30 tuff horizons. Lava flows of similar composition and texture are grouped into units tens to hundreds of meters thick. Single lava and tuff units typically extend tens to hundreds of kilometres and have sharp contacts (Duzhikov and Strunin, 1992). There is no evidence of either interflow sediments or palaeosoils (Wooden et al. 1993).

The volcanic sequence of the Noril'sk area is divided into eleven suites on the basis of chemical composition, texture and correlation of tuff units. These suites are from the base up: the Ivakinsky (Iv), Syverminsky (Sv), Gudchikhinsky (Gd), Khakanchansky (Kh), Tuklonsky (Tk), Nadezhdinsky (Nd), Morongovsky (Mr), Mokulaevsky (Mk), Kharaelakhsky (Hr), Kumginsky (Km) and the Samoedsky (Sm). These eleven suites correspond to a geochemically distinct Lower Sequence (Iv to Gd) and Upper Sequence (Kh to Sm). In contrast Fedorenko (1991) groups the suites into three principal assemblages (c.f. Lightfoot et al. 1994).

The Lower Sequence lavas comprise subalkaline andesitic basalts, subalkaline basalts, tholeiites and picrites that are characterised by high $TiO_2$ (> 1.5 wt%), variable La/Sm (2 to 4), and high Gd/Yb (> 2). Picrites of the Gd picritic basalt unit have MgO contents ~ 17 wt % (Wooden et al. 1993; Lightfoot et al. 1994), however the MgO content of olivine from this suite does not exceed 44 wt % and indicates that these picrites formed from a melt with ~ 8.5 wt% MgO.

The Upper Sequence lavas are separated from the Lower Sequence by the Khakanchansky tuff. This Sequence is dominated by tholeiites, alkaline to subalkaline basalts and picrites that are characterised by low $TiO_2$ (< 1.5 wt%), variable La/Sm (2 to 4) and low Gd/Yb (< 2). A diatreme exposed within the Mr suite contains xenoliths of crystalline basement and Riphean volcanic and sedimentary rocks, perhaps indicating chamber processing at depths in excess of ~ 10 km. Picrites of the Tk picritic basalt unit have MgO contents ~ 17 wt% and are absent in the direct vicinity of Noril'sk and Talnakh. Some picrites are known to have spinifex like textures indicating a superheated melt. The melt temperature at the time of emplacement would be ~ 1370$^o$ C (c.f. Renner et al. 1989), if one assumes that the MgO content reflects the liquid composition and not the presence of cumulus olivine.

The Nd suite is one of the major keys to understanding the genesis of the giant Noril'sk-Talnakh ore system and is best developed close to Talnakh, where it attains a maximum thickness of ~ 500 m (Lightfoot et al. 1990; Fedorenko, 1994). The Nd suite is further divided into three subsuites, $Nd_1$ to $Nd_3$. The lower two subsuites ($Nd_1$ and $Nd_2$)

comprise alternating flows of porphyritic basalt and tholeiitic basalt. In contrast, the $Nd_3$ subsuite is dominated by glomeroporphyritic basalt.

Geochemically, the lower parts of the Nd suite are characterised by lavas with high $SiO_2$ ~ 52 wt%, high La/Sm ~ 4, low Nb/Th ~ 2, unradiogenic Nd ($^{\varepsilon}Nd_{(250\ ma)}$ ~ –10) and radiogenic Sr ($^{87}Sr/^{86}Sr_{(250\ ma)}$ ~ 0.7097). Furthermore, these lavas are depleted in the chalcophile elements with Ni ~ 50 ppm, Cu ~ 40 ppm and Pd ~ 0.5 ppb (e.g. Brugmann et al. 1993). These geochemical features are consistent with the parental magma to these flows assimilating ~ 8% continental crust (Lightfoot et al. 1994). The isotopic characteristics indicate that the crust must be Proterozoic in age and or contain a significant Proterozoic component. Moreover, the concurrent depletion in the chalcophile elements is consistent with the separation of an Immiscible Sulphide Liquid (ISL). Reverse modelling of the chalcophile element data for the lower lavas yields an apparent R-factor of ~ 300

The geochemistry of the upper Nd suite lavas progressively changes to lower $SiO_2$ ~ 49 wt %, less enriched La/Sm ~ 2.5, moderately unradiogenic Nd ($^{\varepsilon}Nd_{(250\ ma)}$ ~ -1) and moderately radiogenic Sr ($^{87}Sr/^{86}Sr_{(250\ ma)}$ ~ 0.7065) consistent with declining levels of crustal contamination and or the mixing of Mr type magmas with Nd type magmas. Moreover, the chalcophile elements increase in concentration to ~ 100 ppm Ni, ~ 100 ppm Cu and ~ 7 ppb Pd. This increase is progressive and modelling indicates that an ISL may be being progressively removed with R increasing to ~ 3000 (e.g. Naldrett et. 1992; Brugmann et al. 1993; Foster and Lambert, 1997).

### *Intrusions*

The mafic intrusions of the Noril'sk area are sill-like bodies and comprise as much as 15-20% of the sedimentary section for at least 2 km below the base of the basalts. These intrusion can be divided into six groups (1) those of alkaline and subalkaline affinity, (2) hi Ti dolerite dikes, (3) dolerite sills, (4) differentiated mafic to ultramafic intrusions that are not related to ore junctions, (5) differentiated mafic to ultramafic intrusions that occur only in the vicinity of ore junctions and (6) a series of unclassified intrusions (Naldrett et al. 1992). Group 5 intrusions are further divided into two subgroups (5a) mineralised intrusions e.g. Kharaelakh, Talnakh and Noril'sk 1; and (5b) essentially unmineralised intrusions in close proximity to mineralised bodies e.g. Lower Talnakh and Lower Noril'sk.

The sills are extensive with strike lengths that may exceed 15 km and show variable form with thicknesses that range from 120 m to 250 m in the vicinity of mineralisation to less than 40 m in the distal parts of the bodies (apophyses). Moreover, the frontal parts of sills are transgressive with respect to local country rock layering. Thick metamorphic aureoles are common with both prograde and retrograde contact metamorphic assemblages. Prograde metamorphism has given rise to hornfels and marble, retrograde metamorphism to calc-silicates and skarns. The hornfels facies is up to 250 m thick above and ~ 100 m thick below an intrusion (Likhachev, 1994).

A typical section through a mineralised body would include the following: basal hornfels, contact gabbrodolerite, taxitic gabbrodolerite, olivine gabbrodolerite, picritic gabbrodolerite, olivine poikilitic gabbrodolerite, olivine gabbrodolerite, taxitic gabbrodolerite and upper hornfels. The peripheral sills are dominated by gabbrodolerite.

The taxitic gabbrodolerite is similar to magmatic breccias and is medium to coarse grained with large glomeroporphyritic concentrations of magmatic minerals with xenoliths of country rock that are cemented by finer grained magmatic material. The major rock forming minerals are plagioclase, clinopyroxene, orthopyroxene and olivine. In the layers above the taxitic unit the main minerals are olivine, clinopyroxene, plagioclase, magnetite and minor chromite. There are two phases of olivine $Ol_1$ ($Fo_{83\text{-}78}$) and $Ol_2$ ($Fo_{76\text{-}65}$), and two phases of anorthite An$_1$ (An$_{95-85}$) and An$_2$ (An$_{85-40}$). Ol$_1$ and An$_1$ are intratelluric phenocrysts (c.f. Likhachev, 1994; Czamanske et al. 1995; e.g. Barnes et al. 2000). The composition of the most primitive olivine would be in equilibrium with a melt with ~ 8.5 wt% MgO.

The MgO content of a typical mineralised intrusion ranges from ~ 6 wt% in the contact gabbrodolerite to ~ 27 wt% in the picritic gabbrodolerite to less than 5 wt% in the upper more evolved gabbroic portions of the body. The light rare-earth elements are enriched with La/Sm ~ 2 to 3 and the heavy rare-earth elements have Gd/Yb ~ 1.6. Moreover, the Nd isotope signatures are variable with ${}^{\varepsilon}\mathrm{Nd}_{(250\ \mathrm{ma})}$ ranging from –3 to +1. The trace element and isotope characteristics of the mineralised intrusions are consistent with their formation from multiple inputs of variably mixed Nd and Mr type magmas (c.f. Hawkesworth et al. 1995).

The unmineralised Lower Talnakh (Group 5b) type intrusions have MgO contents that range from ~ 4 wt% to ~ 24 wt%. In contrast to the mineralised intrusions, they are highly enriched in the light rare-earth elements with La/Sm ~ 4 and have unradiogenic Nd isotope signatures with ${}^{\varepsilon}\mathrm{Nd}_{(250\ \mathrm{ma})}$ ranging from –6 to –4. Furthermore, these intrusions are depleted in Cr (< 150 ppm) and the chalcophile elements e.g. Y/Pd > 5 and Cu/Pd > 100. The latter point is further supported by low concentrations of Ni in olivine (c.f. Duzhikov and Strunin, 1992; e.g. Naldrett et al. 1992). The trace element and isotope signatures of these intrusions are consistent with their formation from Nd type magmas. Moreover, the depletions in Cr and the chalcophile elements require the removal of dense chromite and ISL from the parental melt prior to the emplacement of the bodies.

Based on field relationships the intrusions were emplaced in the following order, Lower Talnakh and Lower Noril'sk followed by Kharaelakh, Talnakh and Noril'sk 1 (e.g. Duzhikov et al. 1992). The mineralised sills formed by repeated injection and flow-through (e.g. Naldrett, 1997) of magmas that resulted in the formation of thick contact metamorphic aureoles and are best described as transgressive composite sills.

### *Mineralisation*

There are three broad groups of mineralisation: massive ore, disseminated ore and veinlet-disseminated to breccia ore. The massive and disseminated ores will be considered here.

Massive ores form thin veinlets to sheet like accumulations that can extend for several kilometres with thickness ranging up to 50 m. They are spatially associated with the mineralised intrusions and commonly found below them, separated by hornfels. Contacts are often sharp and in some instances the massive ores cut the basal contact and taxitic gabbrodolerite units. Where massive ores are well developed they show complex mineralogical zonation consistent with fractionation of the original sulphide liquid (e.g. Naldrett et al. 1994). This is best developed in the Oktyabr'sky mine (Kharaelakh intrusion) where the following assemblages occur (all with pentlandite) pyrrhotite, pyrrhotite + chalcopyrite, chalcopyrite+ pyrrhotite, chalcopyrite + cubanite, cubanite + mooihoekite, mooihoekite + cubanite and mooihoekite (Duzhikov et al. 1992).

The grade of massive ores is highly variable as a function of the sulphide fractionation event. The initial ISL may have had the following composition 5 % Ni, 6 % Cu and ~ 10 ppm Pd (R ~ 700). The evolved mooihoekite rich assemblages show spectacular enrichment in Pd ~ 100 ppm and Cu ~ 27 % as these elements are incompatible with respect to the mss-cumulate and are thus enriched in the evolved liquid (Naldrett et al. 1994).

The disseminated ore is found concentrated in the middle and lower parts of the picritic gabbrodolerites and the upper and middle parts of the taxitic gabbrodolerites near the lower margin of the intrusions. The sulphides take the form of centimeter-sized globules and interstitial sulphides that form irregular shapes moulded against silicates. The globular sulphides found at the Medvezhy Creek mine (Noril'sk 1 intrusion) are spectacularly fractionated with an upper chalcopyrite-rich cap and pyrrhotite-pentlandite rich base (Czamanske et al. 1992).

The grade of disseminated ores is substantially higher than that of the proposed ISL for the massive ores. Kharaelakh disseminated ores average ~ 8.5 % Ni, ~ 12.5 % Cu and ~ 40 ppm Pd in 100 % sulphides. These grades are consistent with an R-factor (or N-factor) of ~ 3000 (c.f. Brugmann et al. 1993).

Sulphur isotope data for the ores show some discrete variations. In the case of the Noril'sk 1 intrusion $\delta^{34}S_{cdt}$ values average +8 $^{0}/_{00}$, whereas ores from the Talnakh ore junction typically average +11 $^{0}/_{00}$ (Grinenko, 1985). The assimilation of sulphur-rich anhydrite and gypsum ($\delta^{34}S_{cdt}$ ~ +22) from the local stratigraphy has been proposed as one mechanism that resulted in key melts reaching sulphide saturation (e.g. Naldrett et al. 1992; Naldrett, 1997). The ore sulphur isotope values may be achieved if the donor melt experienced ~ 0.3 % contamination with this type of material, a finding that must be considered in conjunction with the contamination and chalcophile element depletion history recorded by the Nd suite lavas and the Lower Talnakh type intrusions (c.f. Lightfoot et al. 1994; Hawkesworth et al. 1995).

The radiogenic isotopes display some heterogeneity. For example, ores from Noril'sk 1 have $^{206}Pb/^{204}Pb_{(250\ ma)}$ ~ 18.060 significantly lower than Talnakh ores that are typically ~ 18.180. These data and the sulphur isotope data indicate the ores from these two geographically distinct ore junctions have somewhat different processing histories. The Re-Os isotope data typically yield $^{\gamma}Os_{(250\ ma)}$ values in the range +6 to +14. There are some subtle differences between ore deposits and ore types e.g. Kharaelakh massive ore ~ $^{\gamma}Os_{(250\ ma)}$ +10 to +14 and Noril'sk 1 disseminated-globular ore $^{\gamma}Os_{(250\ ma)}$ +6 to +8. These values are within the range ascribed to plume derived melts. The subtle differences may either reflect variations in the mantle source region from which the melts originated (Walker et al. 1994) or differences in contamination history variably masked by differing R-factors (Lambert et al. 1998).

## A simplified genetic model

At ~ 250 Ma, a plume derived superheated Tk-like picritic *liquid* migrated upward through the crust via a series of staging chambers that were emplaced up and along deep-seated faults. In one or more chambers the melt assimilated ~ 10 % crust. As a result of this crustal contamination process the melt achieved sulphide saturation and an ISL formed. The early-formed ISL depleted the silicate melt in the chalcophile elements (R ~ 500). This residual highly contaminated and chalcophile element depleted Nd-like magma rose through the crust and formed a series of sills (Lower Talnakh type) that in part vented at the surface resulting in the formation the lower Nd suite lavas. The deep level chamber was partly replenished by Mr-like melt that mixed with the residual Nd-like melt and its entrained sulphide droplets. This hybrid melt rapidly migrated to the surface and formed a series of sills at the next permeable level above the Lower Talnakh type sills. Droplets of sulphides were enriched in the chalcophile elements during transit by the zone refining process (N ~ 3000). This stage of 'disseminated' ore formation may have occurred as a series of pulses initially forming the Kharaelakh sill closely followed by the Talnakh sill. Significant magma flow-through occurred and resulted in the formation of thick metamorphic aureoles. Eventual venting of this magma led to the formation of the upper Nd to lower Mr suite lavas. The residual early-formed ISL was then emplaced in close proximity to the Kharaelakh and Talnakh sills. This was aided by zones of enhanced permeability caused by cooling and contraction of the Talnakh and Kharaelakh sill. Slow cooling followed and the ISL fractionated forming Fe-Os-Ir-Rh rich mss cumulates and evolved Cu-Pt-Pd-Au rich liquids.

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