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ARTICLE

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World-class Ni-Cu-PGE deposits: key factors in their genesis

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Abstract Magmatic Ni-Cu sulfide deposits form as the result of segregation and concentration of droplets of liquid sulfide from mafic or ultramafic magma, and the partitioning of chalcophile elements into these from the silicate melt. Sulfide saturation of a magma is not enough in itself to produce an ore deposit. The appropriate physical environment is required so that the sulfide liquid mixes with enough magma to become adequately enriched in chalcophile metals, and then is concentrated in a restricted locality so that the resulting concentration is of ore grade. The deposits of the Noril'sk region have developed within flat, elongate bodies ($15 \times 2 \times 0.2$ km) that intrude argillites, evaporites and coal measures, adjacent to a major, trans-crustal fault and immediately below the centre of a 3.5 km-thick volcanic basin. Studies of the overlying basalts have shown that lavas forming a 500 m-thick sequence within these have lost 75% of their Cu and Ni and more than 90% of their PGE. Overlying basalts show a gradual recovery in their chalcophile element concentrations to reach "normal" values 500 m above the top of the highly depleted zone. The ore-bearing Noril'sk-type intrusions correlate with those basalts above the depleted zone that contain "normal" levels of chalcophile elements. The high proportion of sulfide (2–10 wt.%) associated with the Noril'sk-type intrusions, the high PGE content of the ores, the extensive metamorphic aureole (100–400 m around the bodies), and the heavy sulfur isotopic composition of the ores ($+8$–$+12$ ∂^{34}S) are explicable if the ore-bearing bodies are exit conduits from high level intrusions, along which magma has flowed en route to extrude at surface. The first magma to enter these intrusions reacted with much evaporitic sulfur, at a low "R" value and thus gave rise to sulfides with low metal tenors. Successive flow of magma through the system progressively enriched the sulfides in the conduits, losing progressively less of their chalcophile metals, and thus accounting for the upward increase in metals in successive lava flows above the highly depleted flows. The Voisey's Bay deposit lies partly within a 30–100 m-thick sheet of troctolite, interpreted as a feeder for the 1.334 Ga Voisey's Bay intrusion, and partly at the base of this intrusion, where the feeder adjoins it. Studies of olivine compositions indicate that an early pulse of magma through the feeder and into the intrusion was Ni depleted but that subsequent pulses were much less depleted. Trace element, Re-Os and S and O isotope data, and mineralogical studies indicate that the magma pulses interacted with country gneiss, probably principally in a deeper level intrusion, extracting SiO_2, Na_2O, K_2O and possibly sulfur form the gneiss, which accounts for the magma becoming sulfide saturated. The Jinchuan deposit of north central China occurs within a 6 km-long dyke-like body of peridotite. The compositions of olivine within the dyke, the igneous rocks themselves, and the ore are all inconsistent with derivation of the body from ultramafic magma, as originally supposed, and indicate that the structure forms the keel of a much larger intrusion of magnesian basalt magma. Flow of magma into the intrusion has resulted in olivine and sulfide being retained where the keel was widening out into the intrusion. The West Australian komatiite-related deposits occur in thermal erosional troughs which have developed due to the channelisation of magma flow and the resulting thermal erosion of underlying sediments and basalt by the hot komatiite magma. The sediments are sulfide-rich, and may have contributed substantially to the sulfide of the ores. The mineralisation in the Duluth complex occurs in troctolitic intrusions along the western margin of the complex as a result of magma interacting with and extracting sulfur from the underlying graphite- and sulfide-bearing sediments. No magma flow channels have been identified so far, and the lack of magma flow subsequent to the development of sulfide immiscibility is regarded as the reason

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why these deposits are not of economic grade. When most major Ni-Cu sulfide deposits are compared, they prove to have a number of features in common; olivine-rich magma, proximity to a major crustal fault, sulfide-bearing country rocks, chalcophile element depletion in related intrusive or extrusive rocks, field and/or geochemical evidence of interaction between the magma and the country rocks, and the presence of or proximity to a magma conduit. The features are thought to explain the three key requirements (sulfide immiscibilty, adequate mixing between sulfides and magma, and localisation of the sulfides) discussed and have important implications with respect to exploration.

Introduction

Magmatic sulfides can be viewed as belonging to one of two major groups (Naldrett et al. 1990), those that are richer in sulfide, and that are of interest primarily because of their contained Ni and Cu, and those that contain much less sulfide and for which the Platinum Group Elements (PGE) content is the principal economic interest. This study is concerned with the first group.

The relative importance of a selected group of the world's largest Ni-Cu sulfide deposits is illustrated in Fig. 1. The Noril'sk and Sudbury camps dominate in terms of contained Ni, although Noril'sk ore contains significantly more copper than does Sudbury, and the PGE:Ni ratio is more than five times that of Sudbury, so that the value of the mineralisation is far greater. Duluth represents a major Ni resource, but the low grade (0.2 wt.% Ni, 0.66 wt.% Cu), coupled with environmental constraints on operating large, low grade deposits means that as yet it has not been mined. Jinchuan ranks third in the world in terms of contained Ni, with Mt. Keith, Thompson, Voisey's Bay, Kambalda and Agnew in 4th to 8th places respectively. The Voisey's Bay figure is the current sum of reserves plus resources as quoted by INCO Ltd. (July 1998).

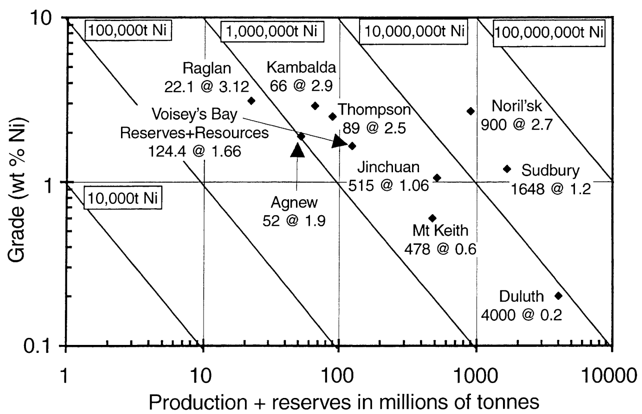


Fig. 1 Plot of grade in wt.% Ni versus production + reserves in millions of tonnes for major Ni sulfide deposits of the world, modified after Naldrett (1994). Data for Sudbury are personal communications from INCO Ltd. and Falconbridge Ltd. (1990); those for Noril'sk are an estimate only; for Duluth are from Listerud and Meineke (1977); for Jinchuan are from Chai and Naldrett (1992a); for Kambalda, Agnew and Mt. Keith are from posters exhibited by Western Mining Corporation at the 13th Australian Geological Convention, Canberra, February (1996); for Thompson are personal communication from, O.R. Eckstrand (1990); for Voisey's Bay are reserves plus indicated and inferred resources announced by Mike Sopko, Chairman, INCO Ltd., in July 1998

Segregation of liquid sulfide, coupled with settling of the sulfide to form rich basal accumulations, is not part of the normal cooling and crystallisation of mafic magma. The world's important deposits of Ni-Cu sulfides (as opposed to those of interest primarily because of their PGE content) occur almost exclusively at the base of their associated igneous bodies, which implies that the magmas involved were saturated in sulfide, and carrying excess sulfide at the time of their final emplacement. The high PGE content (1–10 ppb Pt, Pd) of most basaltic magma other than MORB implies that these magmas are not sulfide saturated as they leave the mantle, or during their ascent into the crust (Naldrett and Barnes 1986). Something has to happen to specific batches of magma prior to emplacement to cause sulfide saturation, if a significant magmatic deposit is to form.

Key aspects in the genesis of a magmatic sulfide ore deposit are therefore: (1) that the host magma becomes saturated in sulfide and segregates immiscible sulfide; (2) that these sulfides react with a sufficient amount of magma to concentrate chalcophile elements to an economic level[1]; and (3) that the sulfides are themselves concentrated in a restricted locality where their abundance is sufficient to constitute ore. It is my objective to examine some of the world's major magmatic sulfide camps with a view to determining how these aspects have been fulfilled. A discussion of Sudbury is omitted, since, as will become clear, Sudbury is unique, and lacks many of the characteristics common to most other deposits, probably due to its formation in the superheated environment created by extra-terrestrial impact (Naldrett 1999).

Noril'sk, Siberia

The deposits of the Noril'sk region comprise both those at Noril'sk itself and the more recently discovered (1962) deposits at Talnakh; they occur at the extreme north-western corner of the Siberian platform which is bordered by the Khatanga trough to the north and the Yenesei trough to the west. Their emplacement accompanied the "Siberian Trap" magmatic event (the extrusion of approximately 3×10^6 km^3 of basalt) which immediately followed collision of the East European and Siberian plates. This collision gave rise to the uplift of

[1] It is sometimes not appreciated that the grade of a deposit can never exceed the metal content in the sulfides themselves (i.e. in the original sulfide liquid), and that this metal content is characteristic of a given deposit and does not vary significantly within it

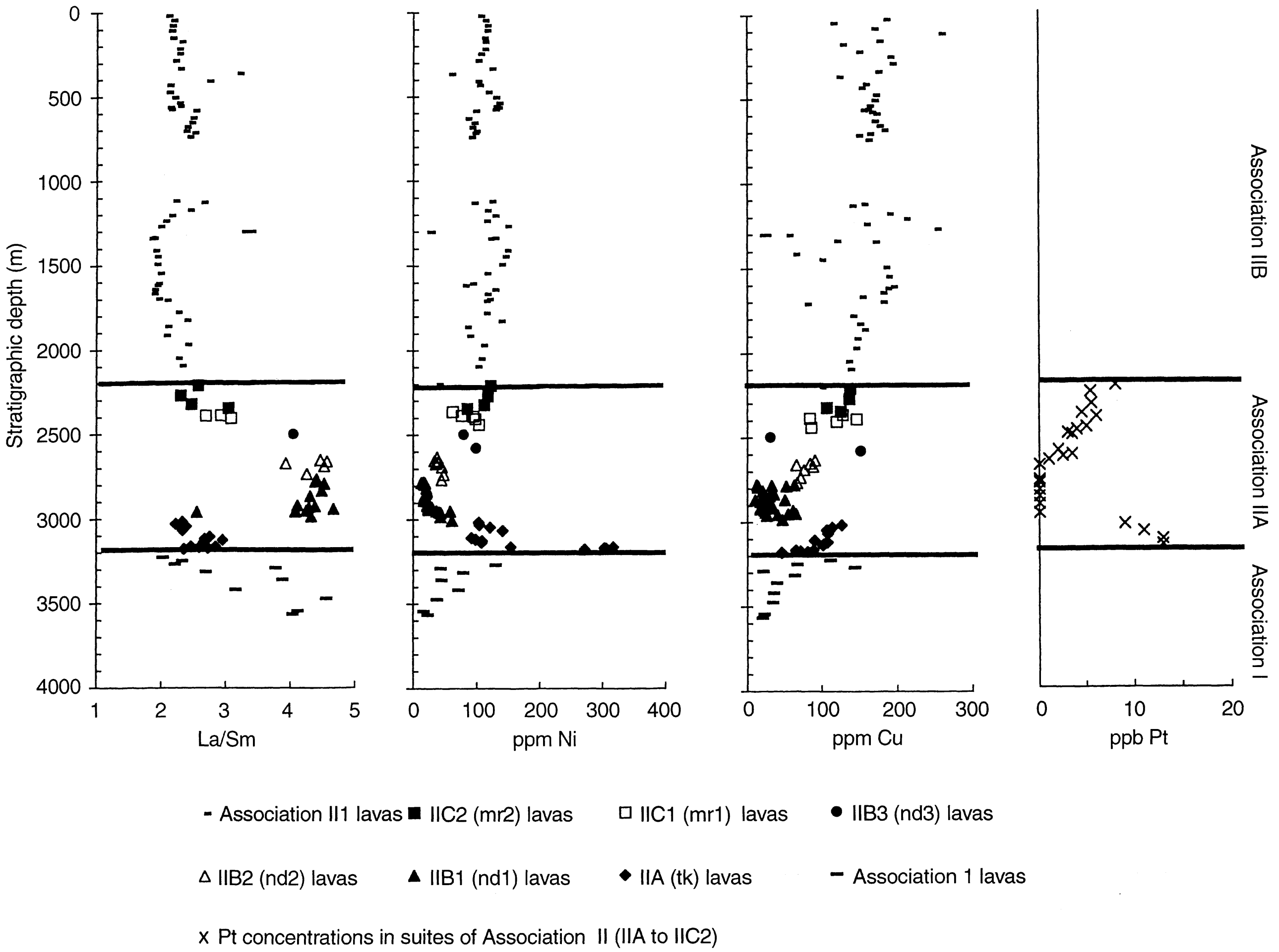
the Ural mountains. Recent descriptions of the Noril'sk area that are available in English include Duzhikov et al. (1992) and Lightfoot and Naldrett (1994).

Naldrett et al. (1995) have argued that the deposits occur within feeder conduits to a specific phase of the 3.5 km of lavas comprising the Siberian Trap in the Noril'sk region. The sequence of lavas provides a historical record as to what was occurring in the underlying magma reservoir(s) and conduits feeding them. Figure 2 shows variations of La/Sm, Ni, Cu and Pt with depth through the sequence (La, Sm, Ni and Cu data are from Lightfoot et al. 1990, 1993, 1994 and Hawkesworth et al. 1995; Pt data are from Brugmann et al. 1993) which Lightfoot et al. (1994) have divided into three associations. Critical to understanding the development of the mineralisation is the abrupt increase in La/Sm ratio at the base of the IIB1 formation, which coincides with equally abrupt changes in other parameters, including ϵSr, ϵNd, and wt.% SiO_2 and has been interpreted (Lightfoot et al. 1990, Wooden et al. 1993; Lightfoot et al. 1994; Fedorenko 1994; Hawkesworth et al. 1995; Naldrett et al. 1996a) as the consequence of this magma having been contaminated by 8–15% of a granitic partial melt derived from mid-crustal gneisses. The subsequent gradual decrease in La/Sm is attributed (Lightfoot et al. 1994; Naldrett et al. 1995) to repetitive pulses of a different magma type (typified by the uppermost flows of the IIC2 formation) entering the plumbing system for the lavas and progressively "diluting" the compositional characteristics that had resulted from the contamination.

As seen in Fig. 2, the increase in La/Sm coincides with pronounced decreases in the Ni, Cu and PGE concentrations of the lavas. Naldrett et al. (1992), Brugmann et al. (1993) and Fedorenko (1994) proposed that the chalcophile elements missing from the lavas are those giving rise to the ores. These authors point out that chalcophile element depletion of this magnitude can only be explained in terms of equilibration with sulfide.

The initiation of sulfide immiscibility might have been brought about by one or both of two mechanisms. The mixing of mafic magma with a felsic contaminant can so lower the ability of the resulting hybrid to dissolve sulfides that immiscibility can result even if the two magmas involved in the mixing are sulfide unsaturated (Irvine 1975; Li and Naldrett 1993). Additionally, the heavy isotopic signature of the ores (∂^{34}S is in the range

Fig. 2 Stratigraphic variation in La/Sm, ppm Ni, ppm Cu and ppb Pt across the 3.5 km vertical succession of flood basalts in the Noril'sk region (data from Hawkesworth et al. 1995; Peter Lightfoot, personal communication 1996)



+8 to +12, Grinenko 1985) suggests that contamination may have involved the ingestion of crustal sulfur from the surrounding anhydrite evaporites.

Significant mineralisation occurs only in the Noril'sk-type intrusions which lie within 7 km of the Noril'sk-Kharayelakh fault and which appear to be slightly younger than the Lower Talnakh type. An appreciation of a typical mineralised intrusion can be obtained from the Bears Brook open pit in the Noril'sk I intrusion, in which it can be seen that the main body (MB) of the intrusion is differentiated and cuts at high angle across 200 m of stratification in the sedimentary and volcanic country rocks, a feature which this author can only ascribe to thermal erosion (Fig. 3). The MB is flanked by and connected with peripheral sills which appear to be injection "push-apart" structures.

The Noril'sk-type (mineralised) intrusions are unusual in a number of ways:

1. They contain or are associated with a very high proportion of sulfide, ranging between 2 and 10 wt.% of their total mass (Naldrett et al. 1992).
2. These sulfides contain a very large concentration of PGE, which, according to Naldrett et al. (1992), must have come from a mass of magma at least 200 times that represented by the intrusions.
3. It has been emphasised repeatedly in the Russian literature on Noril'sk that the mineralised intrusions are surrounded by an intense metamorphic and metasomatic aureole (Genkin et al. 1981; Likhachev 1994). In many cases this extends farther into the country rocks than the thickness of the intrusions themselves, in some cases 400 m (Genkin et al. 1981).
4. The sulfur isotopic composition of the sulfides is too heavy for mantle-derived sulfur, ranging from +8 to $+12\delta^{34}S$ (Godlevsky and Grinenko, 1963; Grinenko, 1985).

Naldrett et al. (1995) noted that these aspects are explicable if the mineralised intrusions have acted as feeders to the 5000–10 000 km^3 of volcanic magma represented by the IIB1-IIC2 formations, and if much of the sulfide has formed at a shallow level in the crust, essentially *in situ*. On the basis of La/Sm, Gd/Yb and Th/Ta ratios coupled with Nd isotopic data they concluded that the last magma to flow through these bodies was that feeding the IIC2 volcanic formation. They propose that although the bulk of the chalcophile metals were extracted from magma giving rise to the IIB1 and IIB2 lavas, magma continued to flow through the system up until the IIC2 lavas.

The flow of a large amount of magma through a plumbing system of which the mineralised intrusions are part, accounts for the very extensive metamorphism associated with them. It also accounts for the very high proportion of sulfide, and of PGE associated with the sulfide, in comparison with the amount of magma represented by the mineralised intrusions themselves. Naldrett et al. (1995) noted that the geochemical data are explicable if the IIB1-IIB2 magma underwent two stages of contamination (Fig. 4), a mid-crustal stage giving rise to the high La/Sm ratio and the other geochemical characteristics indicative of crustal interaction, and a second stage, at essentially the present level of the mineralisation, in a chamber developed within the argillites, evaporites and coal measures, to which the mineralised intrusions are exit channels. It is likely that the magma was eroding the walls of its chamber at this stage, ingesting Devonian evaporite and C-bearing Tungusskaya formation, and reducing the evaporite to produce sulfide; this accounts for the high $\delta^{34}S$ values of the sulfides. The sulfides were then swept out from the central differentiation chamber southward in the case of Noril'sk I and northward in the case of Talnakh, and became lodged in the thicker (thermally eroded) parts of these magma conduits. Fresh magma then surged through the system, stirring up the trapped sulfides which interacted with the magma and, in the process, progressively upgraded the sulfides in chalcophile metals. The extent of this upgrading depended on the amount of magma flowing through the different conduits of the system. Progressively later pulses of magma encountered sulfides that had progressively higher concentrations of Ni, Cu and PGE, with the result that the magmas lost less of their chalcophile elements. This accounts for the "recovery" in the concentrations of these metals observed in lavas from the IIC1 to IIIA units (Fig. 2).

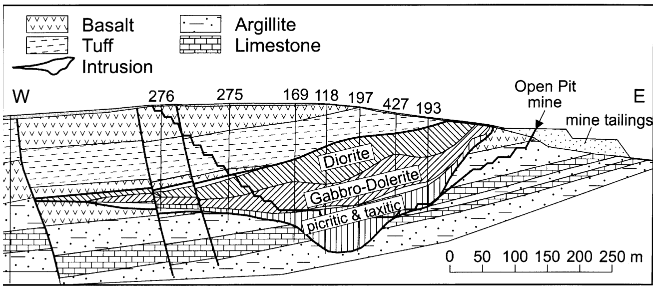


Fig. 3 Vertical section through the east branch of the Noril'sk I intrusion at the Bear's Brook open pit (from Distler and Kunilov 1994)

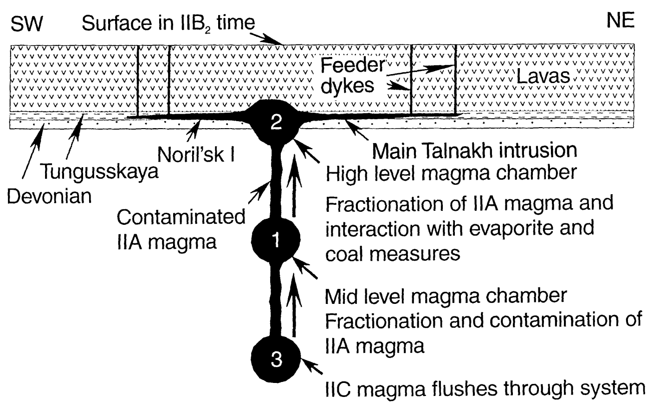


Fig. 4 A model for the development of the lavas and intrusions at Noril'sk during the eruption of the IIB1 (*nd1*), IIB2 (*nd2*), IIB3 (*nd3*), IIC1 (*mr1*) and IIC2 (*mr2*) formations. Modified after and illustrating the views expressed by Naldrett et al. (1995)

Voisey's Bay Ni-Cu-Co deposit

Description of the deposit

The Voisey's Bay deposit (Naldrett et al. 1996b, 1997; Ryan 1997) is associated with the 1.334 Ga (Amelin et al. 1997) Voisey's Bay complex. This is a member of the Nain Plutonic Suite (1.35–1.29 Ga) which is an anorthosite-granite-troctolite-ferrodiorite complex that transects the east-dipping 1.85 Ga collisional boundary between interbanded garnet-sillimanite and quartzo-feldspathic (Tasiuyak) gneisses of the Proterozoic Churchill Province to the west and quartzo-feldspathic gneisses of the Nain Province to the east (Ryan et al. 1995).

At the present level of understanding (Fig. 5) the Voisey's Bay deposit comprises two, east-plunging intrusions (Reid Brook and Eastern Deeps intrusions), one situated about 2 km vertically above the other, linked by a steeply dipping igneous sheet. The lower, Reid Brook, intrusion is situated in Proterozoic (Tasiuyak) gneiss. To date, the Reid Brook body has only been intersected in the western part of the mine area, where it is seen to narrow upward and merge with the linking sheet. At the point of merger, the sheet tends to be choked by "feeder breccia" comprising numerous partially reacted inclusions of gneiss in a matrix of norite or troctolite accompanied by variable amounts of sulfide.

The thickness of the linking sheet varies from 10–100 m. Mineralisation is restricted to the wider parts, which occur as a series of elongate lenses, within the plane of the sheet, all raking to the east. In the discovery zone, where the dip of the sheet varies between 70 and 40°N, a well developed stratigraphy has been observed, with an upper chill zone giving way downward to 5–20 m of unmineralised olivine gabbro (Feeder Olivine Gabbro or FOG), which quickly passes downward into troctolite with 30–50 percent interstitial sulfide (Leopard Troctolite or LT). The LT is in sharp contact with the Basal Breccia Sequence (BBS, similar to the Feeder Breccia), which consists of inclusions of variably reacted gneiss and fresh troctolite, pyroxenite and peridotite in a troctolitic to noritic matrix. Elsewhere, where the attitude of the sheet is nearly vertical, this simple stratigraphy is not present but the FOG is always developed adjacent to one or other of the walls.

The Eastern Deeps intrusion occurs at surface, with its base plunging at 20–25° east southeast (Fig. 6). Several tens of metres of BBS occur along the base and are overlain by a troctolite with numerous inclusions, variable amounts (commonly 10–20 vol %) of sulfide and a variable texture (Varied Textured Troctolite or VTT). This passes upward into a troctolite with even texture and less sulfide and inclusions (Normal Troctolite) which appears to be intrusive into the uppermost unit of the Eastern Deeps observed so far, the Olivine Gabbro. A feeder sheet intersects the base of the Eastern Deeps intrusion along much of its explored length. Naldrett et al. (1996b) showed that massive sulfide occurs over a significant length of the intrusion close to and within the mouth of the feeder.

The richest zone of mineralisation discovered so far is known as the "Ovoid". This is a 300 × 600 m basin of massive sulfide, up to 110 m deep, that has developed above and to the south of the sheet linking the two intrusions. Naldrett et al. (1996b) interpreted it to represent the base of the Eastern Deeps intrusion, now exposed at surface.

Li and Naldrett (1997) reported that the olivines in the gabbros and troctolites of the Voisey's Bay complex comprise two groups on the basis of their Ni content. The olivine gabbro at the top of the Eastern Deeps intrusion, the FOG and some zones within the troctolite of the Reid Brook body contain Ni-depleted olivine, while

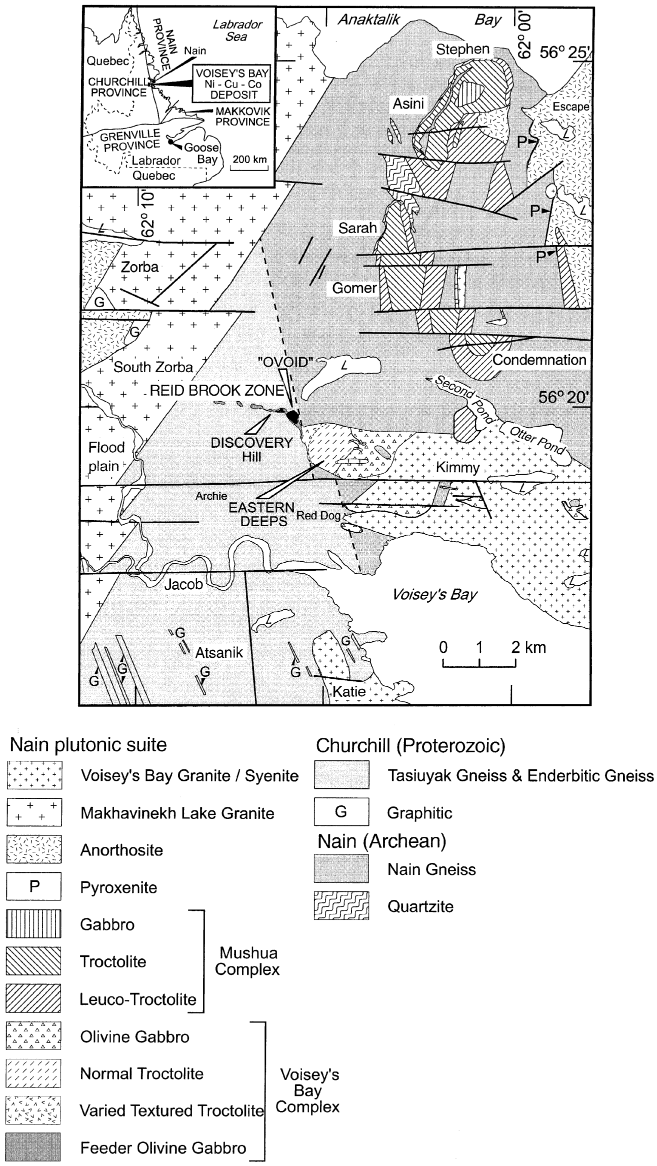


Fig. 5 Surface plan of the Voisey's Bay deposit (after Li and Naldrett 1998)

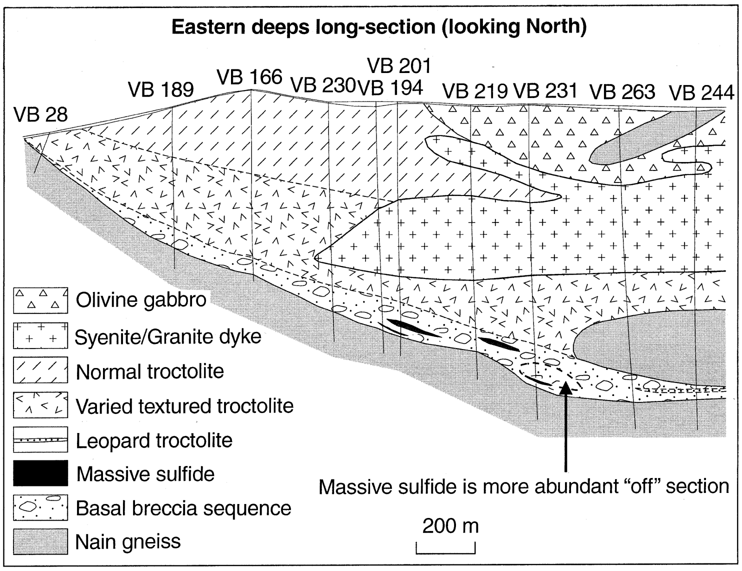


Fig. 6 ESE-WNW section through the "Eastern Deeps", modified after Naldrett et al. (1996)

the NT and VTT of the Eastern Deeps, and LT of the linking sheet contain olivine with a higher Ni content. Olivines within ultramafic-mafic inclusions within the BBS define a trend on the Ni vs Fo diagram (Fig. 7) which is consistent with protracted fractional crystallisation of olivine from troctolitic magma, leading to Ni-depleted magma (and thus Ni-depleted olivines). Some gabbros from the Reid Brook intrusion, the FOG and Eastern Deeps olivine gabbro lie on an extension of this trend. They propose a two-stage model of ore genesis. Troctolitic magma rose to form a chamber (Reid Brook intrusion) within the Tasiuyak gneiss, where it fractionated, giving rise to ultramafic cumulates, reacted with Tasiuyak gneiss, and became sulfide saturated. Application of experimentally derived partition coefficients to the Ni-depleted olivines indicate that the sulfides segregating from the Ni depleted magma would have contained 1.5–2.0 wt.% Ni. This magma then progressed up the linking sheet to form the OG of the upper (Eastern Deeps) chamber; the FOG is a relict of its passage which adhered to the walls of the sheet. At the same time, fresh magma was entering the lower chamber, disrupting the cumulates and mixing with residual magma, BBS and the sulfides within it, enriching the sulfides in Ni and Cu and transporting them up to form the mineralisation in the linking sheet, the Ovoid, the massive ore at the base of the Eastern Deeps and the disseminated ore of the VTT. The sulfides became concentrated in widened zones within the linking sheet, and at the mouth of the feeder where the rate of magma flowed decreased as the magma entered the chamber.

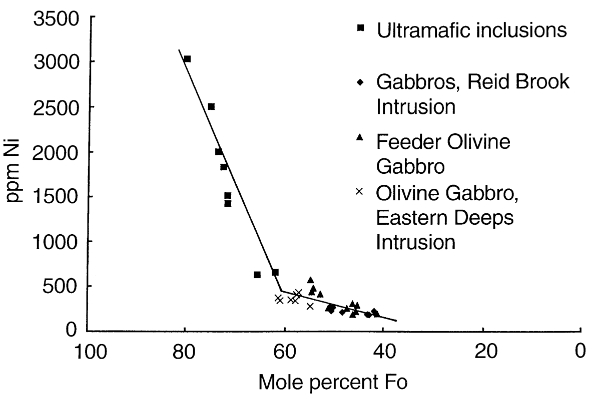


Fig. 7 Plot of ppm Ni in olivine versus Fo content of olivine for ultramafic inclusions, troctolite of the Reid Brook intrusion and Feeder Olivine Gabbro at Voisey's Bay, showing a trend consistent with protracted crystallisation of olivine from troctolitic magma

Jinchuan, China

Geology

The Jinchuan deposit is located in north central China, within but close to the southern margin of the Sino-Korean craton. It lies within one of a series of mafic-ultramafic bodies that intrude a marginal, northwest-trending, uplifted belt, the Longshoushan belt. Lower Proterozoic migmatites, gneisses, schists and marbles form a southeasterly facing monoclinal sequence, overlain to the southwest by Upper Proterozoic conglomerates, sandstones, limestones and schists (Tang 1993). Major northwesterly striking faults bound and occur within the uplifted block, and the Jinchuan body occupies one of these which cuts Lower Proterozoic strata. Tang et al. (1992) cite a Sm-Nd age for the intrusion of 1.501 ± 0.031 Ga. Chai and Naldrett (1992b) have concluded that the host intrusion was emplaced in a rift zone that formed at the boundary between the Sino-Korean craton and a developing Proterozoic ocean; this subsequently closed with the welding of folded Upper Proterozoic strata onto the craton.

The host to the deposit comprises a mass of dunite, lherzolite, olivine websterite and websterite, 6500 m in length by a few m to >500 m in width. It has a V-shaped cross section, tapering downward to pinch out at depths of 500–1300 m. Northeast-trending faults offset different portions of the intrusion, which have been developed as separate mining blocks (Fig. 8).

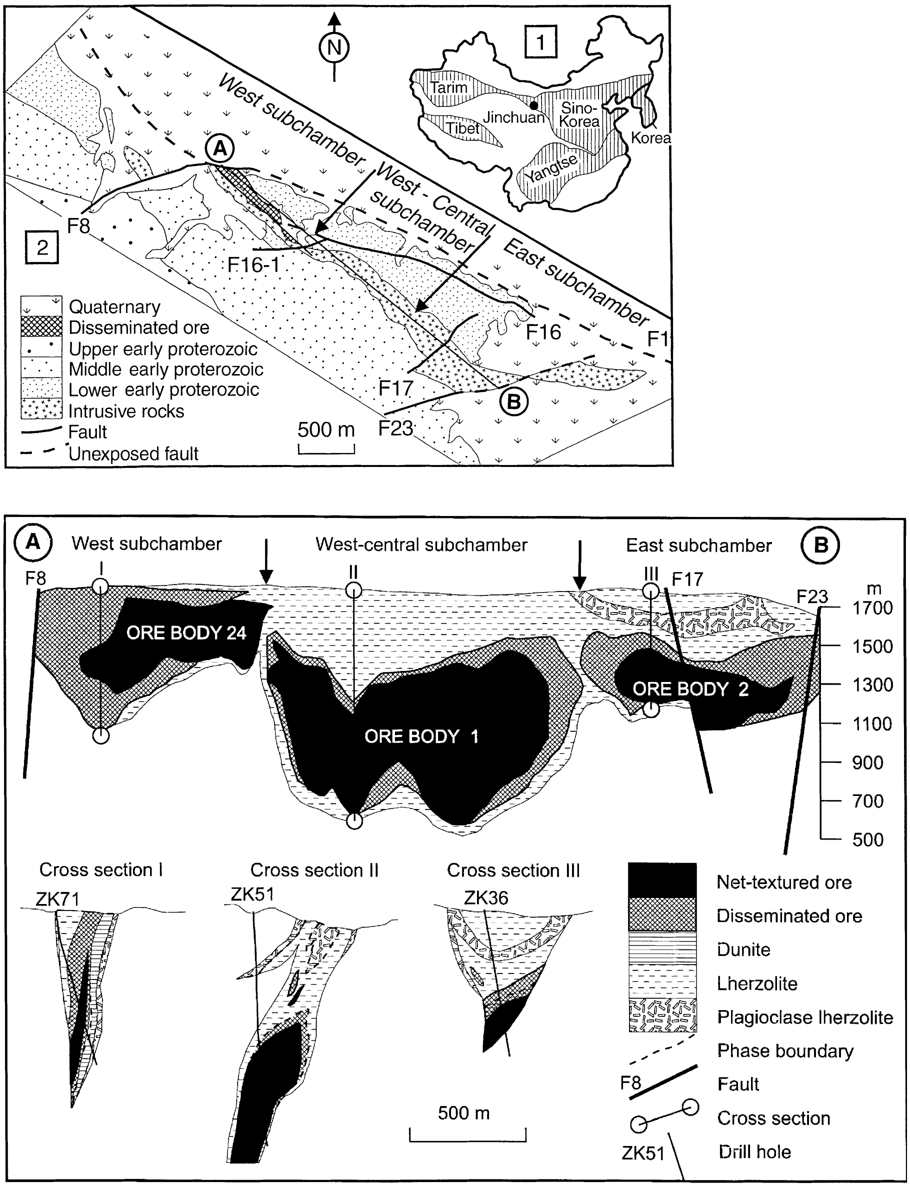
The internal structure of the intrusion varies along its length, from block to block. At the northwest end internal contacts are steep (Fig. 8) with dunite predominating at depth, and lherzolite increasing toward the top, and forming thin marginal zones to the dunite at depth. In the central and southeastern parts of the intrusion, dunite is also predominant at depth, but layering between lherzolite, plagioclase lherzolite, websterite and olivine websterite is present, parallel to the margins at the margins but flattening and becoming horizontal close to the axis of the body (Fig. 8).

The predominant ore types are "net-textured ore", in which olivine grains are enclosed in a continuous network of sulfide and lower grade "disseminated ore" in which sulfides occur both interstitial to silicate minerals and as discrete blebs. In general, dunite is the principal host to mineralisation, and essentially all dunite is of ore grade.

Origin of the intrusion and its mineralisation

The nature of the magma responsible for the ultramafic body hosting the mineralisation (mafic or ultramafic) has been a source of controversy. Chai and Naldrett (1992a) have demonstrated using a plot of FeO versus MgO, that the liquid intercumulus to the olivine of the peridotites that constitute the intrusion contained

Fig. 8 *(top)* Geological map of the Jinchuan intrusion; *(bottom)* longitudinal and transverse vertical sections through the Jinchuan intrusion showing the distribution of rock types and the nature of the Ni-Cu mineralisation that they contain, from Chai and Naldrett (1992a)



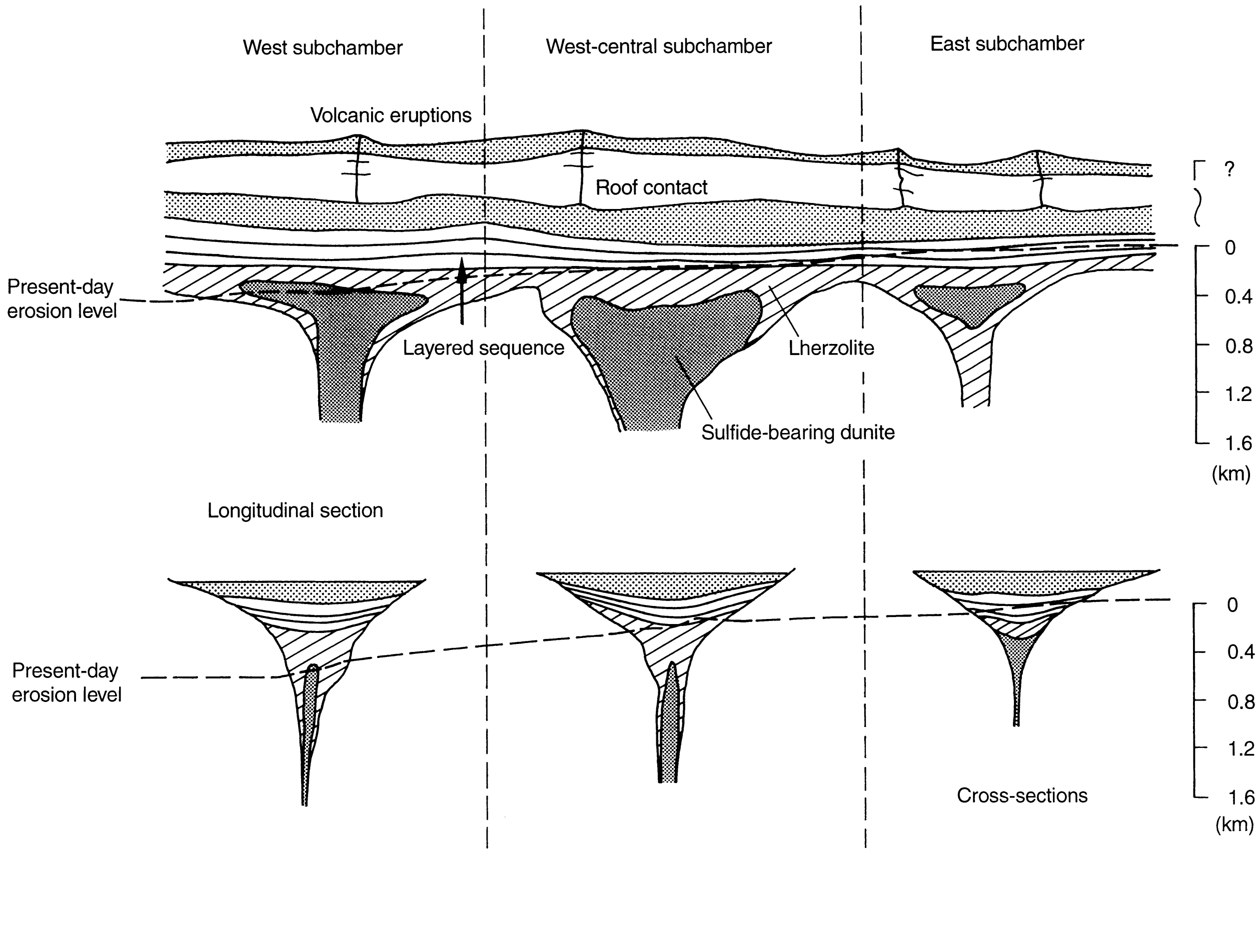
12 wt.% MgO and 11.5 wt.% FeO. When coupled with the other geochemical characteristics, such as the Ni/Cu ratio of 1.5 and the gabbroic-type PGE profiles (i.e. high (Pt + Pd)/((Ru + Ir + Os) ratios), this is strong evidence that the composition of the initial magma at Jinchuan was not ultramafic, but that of a magnesian basalt. Chai and Naldrett (1992a) proposed that the gabbroic cumulates which would also have resulted from a differentiating magnesian basalt magma have been removed by erosion, and that the Jinchuan body is the root zone of a linear body of overall gabbroic composition and trumpet shaped cross section, similar to but smaller than that of the Great Dyke of Zimbabwe, as is illustrated in Fig. 9. They interpret the deeper parts of the roots as conduits up which magma entered the intrusion. Dense sulfide and olivine were carried along in rapidly flowing magma in the narrow parts of conduits feeding the intrusion, but collected where these conduits widened out on entering the main body.

Komatiite-related deposits, Norseman-Wiluna belt, Western Australia

Komatiitic ore deposits of the Wiluna-Norseman belt can be considered, as can all other komatiite-related deposits, as falling into one of two groups: Group 1 are generally small (1 to 5×10^6 tonnes), high grade (1.5–3.5% Ni) deposits which occur at the base of mesocumulate dunitic flows; group 2 comprise very large (100–500×10^6 tonnes), low-grade (0.6% Ni) deposits of finely disseminated sulfide in channel-like lenses of adcumulate dunite. Examples of group 1 include the deposits of the Kambalda district (Ross and Hopkins 1975; Gresham and Loftus-Hills 1981; Gresham 1986) and the Widgiemooltha dome (Fisher 1979; McQueen 1981). Examples of group 2 include the Six–Mile and Mt. Keith deposits near Yakabindie, Western Australia (Burt and Sheppy 1975; Naldrett and Turner 1977; Hill et al. 1989; 1995).

Hill et al. (1989, 1990) and Hill (1997) have discussed the internal structure of komatiite flows and have shown that the komatiitic lavas can be subdivided into a number of distinctive facies, which relate to their distance from the eruptive source and the rate of eruption (Fig. 10). Flows that are close to their source, and therefore are hottest, tend to develop as very extensive sheets (in some cases in excess of 35 × 150 km by several hundreds of metres thick) of adcumulate dunite. When this facies develops over a substrate with low melting temperature, such as felsic volcanic rocks, the flow may become channelled with the principal flow restricted to a number of channels. These channels have been cut into the underlying substrate by thermal erosion of the flowing komatiitic magma (Huppert and Sparks 1985). Farther downstream, where flow is less rapid and probably lamina, “lava plains” composed of sheet flows

Fig. 9 Model for the Jinchuan intrusion after emplacement as envisaged by Chai and Naldrett (1992b)



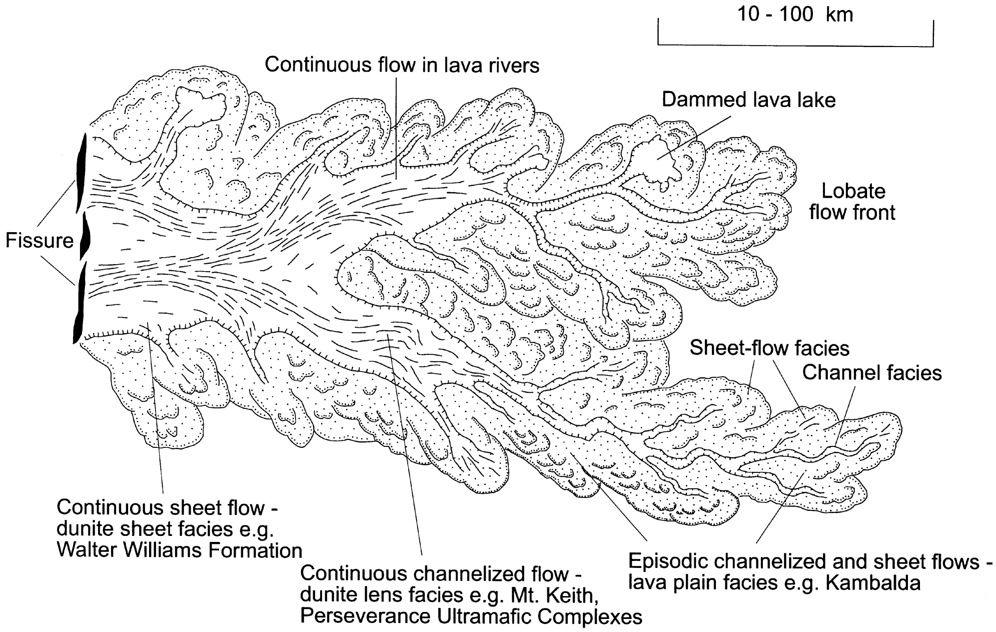


Fig. 10 Schematic illustration of an interpreted regional komatiite volcanic complex, formed by cataclysmic sustained eruption. Note that adcumulate (dunite) sheet flow facies develops close to the vent, and becomes channeled to adcumulate channel flow facies farther from the vent. Downstream, cooling lava gives rise to orthocumulate sheet flow facies within which a facies composed of mesocumulate dunite channel flows may be present. The margins and farthest extremities of the volcanic complex consist of lava plains comprising flows intermixed with or capped by thin "Munro-type" flows after Hill et al. (1990)

with orthocumulate rather than adcumulate dunite develop. Channelisation under these circumstances can give rise to lenses of mesocumulus olivine (several hundreds of metres wide and up to 100 m thick), which represent the main flow channels separated by lava plains in which the upper parts of the flows have well-developed spinifex texture.

Group 1 deposits are associated with the more distal portions of komatiite flows, occurring within well-developed erosional troughs that have formed at the base of lava rivers characterised by olivine mesocumulates (40–44 wt.% MgO). The Group 2 deposits are thought to be more proximal in nature, occurring in dunite lenses which represent channelised flows of adcumuls dunite lava (45–50 wt.% MgO).

The source of the sulfur in komatiitic lava flows is still an open question. Values of $\delta^{34}S$ in the Kambalda ores are generally within ± 5 of 0 per mil, which is not diagnostic because the sedimentary sources of sulfide show a similar variation, although Lesher (1989) has demonstrated a close match between $\delta^{34}S$ in ores and footwall sulfides at a number of localities, including Kambalda and Mt. Windarra.

Mineralisation of the Duluth complex

The Duluth complex comprises a large composite intrusion of troctolite-gabbroic anorthosite, that crops out as an arcuate body extending about 240 km northeast from Duluth, Minnesota, to the Canadian border, close to the northwestern shoreline of Lake Superior. Lake Superior itself overlies a graben, defined by major faults and hinge lines, within which Archean crust has been thinned to less than 1/4 of its previous thickness, and over 17 km of volcanics and sediments have accumulated. It is situated where the North American "mid-continent rift", which is marked by well-defined gravity and magnetic anomalies, changes its trend from southwest-northeast to northwest-southeast, and is probably the triple junction of a failed rift system that developed in response to an underlying hot-spot.

The Duluth Complex is a 1.2 Ga (Faure et al. 1969) composite intrusion which the studies of Grout (1918), Green et al. (1966), Bonnichsen (1972), Phinney (1970, 1972), Weiblen and Morey (1975, 1980), Martineau (1989), Severson (1988, 1991) and Severson and Hauck (1990) have shown to consist of two series, an older series of anorthositic rocks which is cut towards its western margin by a series of later intrusions consisting predominantly of troctolite. It is closely associated petrogenetically with Keewanawan basalts of the Lake Superior area and was intruded close to the contact of these rocks with older Precambrian basement rocks which are now exposed to the northwest (Fig. 11). These basement rocks consist, in the north, of a complex of Archean felsic intrusions and volcanics, primarily the Giants Range Granite, which are overlain unconformably to the south by the south-dipping, mid-Proterozoic, Biwabik Iron Formation. The iron formation is itself overlain by black argillites, greywackes, siltstones, graphitic slates, and sulfide facies iron-formation comprising the Virginia Formation.

The Complex is the host to more than 4×10^9 tonnes of mineralisation averaging 0.66 wt.% Cu and 0.2 wt.% Ni (Listerud and Meineke 1977). The mineralisation occurs along the western margins (stratigraphic bases) of the troctolitic intrusions which define the western extremity of the Complex (Fig. 11). In most deposits, the mineralisation consists of pyrrhotite, chalcopyrite, pentlandite, and cubanite weakly disseminated in troctolite and norite within 300 m of the base of the

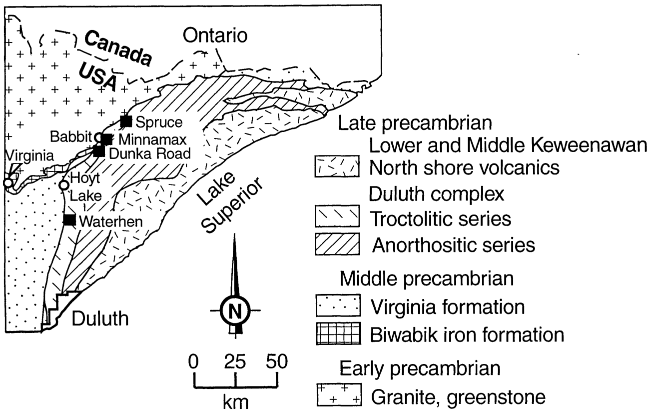


Fig. 11 Map of the western end of Lake Superior, showing the location of the Duluth complex and its relationship to the country rocks (after Mainwaring and Naldrett 1977)

complex. The mineralised zones are characterised by numerous inclusions of country rocks consisting of hornfelsed Virginia and Biwabik Formations, together with barren gabbro and peridotite. At both the Minnamax and Dunka Road deposits (Fig. 11), norite is more common and troctolite less common in the vicinity of the sulfide horizons, attesting to reactions between the troctolite and country rock inclusions. An unusual feature of many of the deposits is the occurrence of as much as 10% graphite in certain zones. Other unusual features of the sulfide environment include the presence of green hercynite (Mg-Al.) spinel in some of the troctolites, and the local occurrence of cordierite. As in other deposits, numerous partially resorbed remnants of what appear to be hornfelsic Virginia slate occur in the troctolite.

Sulfur in the Duluth deposits is heavy, with values of $\delta^{34}S$ ranging from 11–16 in the Waterhen intrusion (Mainwaring and Naldrett 1977); and 0.2–15.3 per mil in the Dunka Road deposit and 2–7 in the Babbit deposit (Ripley 1981, 1986). Pyrrhotite in the underlying Virginia Formation shows a similar range in isotopic composition, also supporting a country rock source for much of the sulfur. The heterogeneous distribution of the sulfur isotope values throughout many of the deposits, coupled with a wide range in the nickel contents of olivine in the mineralised zones led Ripley (1986) to suggest that sulfur introduction had occurred essentially *in situ*, and that widespread equilibration between the sulfides and their enclosing silicates had not occurred. Citing the lack of geochemical evidence supporting widespread bulk assimilation, he proposed that the sulfur had been introduced in a volatile phase that was released from the footwall rocks as they were metamorphosed by the intrusion. This is supported by the common association of hydrous minerals such as biotite and amphibole and patches of pegmatite with the mineralisation.

Conclusions and application to exploration

The preceding discussion indicates that there are many geological features in common amongst the world's major concentrations of Ni-Cu sulfides. Some of the most important of these are summarised in Table 1. They include (1) a magma capable of crystallising substantial amounts of olivine, (2) a prominent crustal suture, (3) plentiful sulfur in the adjacent or subjacent country rocks, (4) evidence of chalcophile element depletion in associated silicate magmas, (5) evidence of interaction with country rocks and (6) the occurrence of mineralisation within or close to a conduit along which magma flow has been concentrated.

To discuss each of these features in turn, olivine-rich magmas have been important at Noril'sk, Voisey's Bay, Jinchuan, Kambalda and Duluth. The rocks of the Sudbury Igneous Complex stand out in their absence of olivine, except for a suite of inclusions that are closely associated with mineralised Sublayer. The olivine ranges from highly forsteritic in the Kambalda komatiites (Fo90–95) to quite forsteritic at Jinchuan (Fo80) and Noril'sk (Fo80) to moderately forsteritic at Voisey's Bay (Fo50–65) and Duluth (Fo50–65). The importance of the presence of olivine is thought to be 3-fold; (1) olivine-normative magmas are generally hotter than those with a higher SiO_2 content, (2) the Ni content of olivine-normative magmas tends to be higher than those with no normative olivine (the Ni content depends, of course, on the Fo content of the normative olivine, and on whether the magma has become chalcophile depleted as discussed later), and (3) an olivine normative magma will react with SiO_2-bearing country rocks more readily than one that is richer in SiO_2 (see later).

Prominent crustal sutures have clearly played an important role in providing zones of weakness up which magma has ascended into supercrustal rocks at Noril'sk (Noril'sk-Kharayelakh fault), Jinchuan (faulting bounding the Sino-Korea platform) and Duluth (mid-continent rift structure). The Voisey's Bay complex lies close to the southerly extension of the Abloviak shear zone which marks the collisional suture between the Nain and Churchill provinces.(Ryan et al. 1995) and along which the last documented deformation is dated at 1.73–1.75 Ga (Van Kranendonk 1996); it is possible that this remained a zone of weakness and facilitated emplacement of the 1.35–1.29 Nain Plutonic Suite. Early structural elements are much harder to recognise in Archean terrains, but the Eastern Goldfields are characterised by a series of NNW-trending faults which may reflect ancient sutures, possibly those associated with early rifting. In contrast, the Sudbury deposits and their associated astrobleme owe their origin to activation from above, rather than below!

Sulfur-bearing country rocks adjacent or subjacent to deposits are present at Noril'sk (Middle Devonian evaporites containing anhydrite or gypsum), Voisey's Bay (sulfide and graphite-bearing Tasiuyak gneiss), Kam-

Table 1 Comparison of Ni-Cu deposits

Key factor	Noril'sk	Voisey's Bay	Jinchuan	Kambalda	Duluth	Sudbury
Olivne-rich magama	Yes-picrite Fo $_{80}$	Yes-troctolite Fo $_{50–65}$	Yes-harzburgite & dunite Fo $_{84}$	Yes-komatiitic lavas Fo $_{90–95}$	Yes-troctolite Fo $_{50–65}$	No
Prominent crustal suture	Yes-Noril'sk kharayelakh Fault	Yes?-Abloviak shear zone	Yes-continental margin	Yes?-NNW faults	Yes-Lake Superior Rift	No
Source of sulfur in country rock	Yes-Evaporites	Yes-Tasiuyak Gneiss	Not established	Yes-underlying sediments	Yes-Virginia Formation	No
Chalcophile depletion	Yes-in Nd-Mr volcanics	Yes-olivine gabbro, Feeder troctolite	Not established	Yes-on a regional scale	Not established	Not established
Evidence of interaction with country rocks	Yes-taxitic gabbro and chemical data	Yes-basal breccia sequence and chemical data	Not established	Yes-chemical data	Yes-visual and chemical	Yes-chemical and field observation
Magma conduit	Yes-marked by thickened zones of picritic and taxitic gabbro	Yes-thickened zones in feeder sheet and entry of sheet to intrusion	Yes-funnel shaped feeder	Yes-lava channels	No-sulfides appear to have formed *in situ*	Not established

balda (chemical sediments which lie on the basalt substrate to the komatiitic lavas) and Duluth (pyrite and graphite-bearing Virginia formation). No obvious crustal source of sulfur is available at Jinchuan or at Sudbury. At Noril'sk and Duluth, isotopic evidence argues strongly for the incorporation of crustal sulfur into the ores. At Voisey's Bay isotopic evidence is suggestive that sulfur from the Tasiuyak gneiss has played a role in ore formation (Ripley et al. 1997) and at Kambalda the sulfur isotopic data are consistent with a crustal source but provide no compelling evidence for it. Values of $\delta^{34}S$ in the Sudbury ores are close to zero, and thus provide no support for a crustal source.

At Noril'sk, chalcophile element depletion is well documented in basalts representative of magma that just pre-dated that hosting the ores, although this is less apparent in the basalts correlative with the mineralised intrusions. The same is true at Voisey's Bay, where the initial magma to flow through the system is chalcophile-depleted, but that associated most directly with the mineralisation is not notably depleted. Duke and Naldrett (1978) pointed out that the komatiites and komatiitic basalts are Ni-depleted in a regional sense at Kambalda, but the rocks most directly related to the mineralisation do not show significant depletion, even in their PGE content (Lesher 1989), which would be more sensitive to chalcophile element depletion than Ni and/or Cu. In each of these cases it appears that fresh magma has flowed through the mineralised magma channels subsequent to that which shows chalcophile element depletion. Chalcophile depletion has not been established at Duluth, Jinchuan or Sudbury.

The geochemical data discussed demonstrate strong interaction between certain of the Noril'sk magmas and crustal rocks. Furthermore the Taxitic Gabbro, which is a variable-textured rock containing many partially digested inclusions of intrusive and country rocks is field evidence of such interaction. Lambert et al.'s (1997) Re-Os data, and the intense alteration experienced by inclusions in the BBS is compelling evidence that such interaction has occurred at Voisey's Bay. Geochemical data of Frost and Groves (1989), McNaughton et al. (1988) and Arndt and Jenner (1986) support the interaction of komatiitic magma with crust in the Kambalda district. Field observation, and Ripley's (1986) chemical and O isotopic data support at least limited interaction at Duluth. Crustal interaction has not been documented at Jinchuan, although the chemical and isotopic measurements which are required to prove this geochemically have yet to be made. The most intense interaction is present at Sudbury, where Naldrett et al. (1986) suggested that the SIC consisted of flood basalt magma contaminated by 50% of impact melt, and Faggart et al. (1985) and Grieve (1994), amongst others, have suggested that the whole complex may be an impact melt. Naldrett et al. (1986) and Li and Naldrett (1993) suggested that 50% intermixing of sulfide-unsaturated primitive mantle-derived basalt and a felsic impact melt could induce sulfide saturation, and thus account for the widespread mineralisation at Sudbury.

Turning to the importance of some form of magma flow channel, it is argued that thermally eroded feeder channels for overlying volcanics have served as traps for sulfides and now constitute the ore zones. Some of the ore at Voisey's Bay is in a similar environment, and the remainder occurs at the line of entry of the feeder to the intrusion. The ore at Jinchuan occurs within what is interpreted to be the funnel-shaped (in cross section) feeder to an intrusion that has largely been removed by erosion. The Kambalda ores occur at the base of channels within which much of the komatiite magma flow was localised. It is only at Duluth and Sudbury that magma conduits do not appear to be a major ore control. It is this author's opinion that if the sulfide-bearing magma at Duluth had continued intruding farther, after it had reacted with the Virginia Formation and immiscible sulfides had developed, the related deposits might have become much richer in sulfide and would have been mined long ago. Sudbury is a totally different environment, that of the chaos attending a meteorite impact, and so far one has an excellent picture of where the deposits occur, but not of why they occur where they are.

One can now re-visit the introduction to this paper, and discuss possible answers to the three key factors outlined there. With respect to the first factor, why did sulfide immiscibilty occur?, in many of the major Ni-Cu camps discussed here deep crustal sutures have facilitated the ascent of olivine-rich magma into the crust, where this has reacted with crustal rocks, acquiring crustal sulfur. Extensive assimilation of crust, or mixing with a crustal melt, has been documented for all occurrences except Jinchuan, at which it has not been looked for. At Sudbury, where the addition of crustal sulfur is unlikely, felsification of a mafic melt has been suggested as the cause of sulfide saturation. Turning to the second factor of the concentration of sulfides from a large volume of magma, the entrapment of sulfides within a magma flow channel stands out as an extremely important mechanism. This feature of many deposits also provides an answer to the question of the third key factor, that of how the sulfides were able to interact with sufficient magma to concentrate Ni, Cu and PGE to economic levels. At Noril'sk it has been shown that continued flow of magma through the conduit, after initial deposition of sulfide, and the continued interaction of this magma with the sulfides has resulted in their being upgraded. The latest studies at Voisey's Bay and Kambalda have indicated that this upgrading process has also occurred in these deposits, thus providing an answer to the third key factor. This aspect is extremely important; the battle field of Ni exploration is littered with the corpses of projects in which massive sulfides were located but in which, to the dismay of investors, subsequent analysis proved the sulfides to contain inadequate tenors of Ni, Cu, Co and PGE.

References

Amelin Y, Li C, Naldrett AJ (1997) Multi-stage evolution of the Voisey's Bay complex, Labrador, Canada revealed by U-Pb systematics of zircon, baddeleyite and apatite. Volume of Abstracts, American Geophysical Union fall meeting, San Francisco, December 1997

Arndt NT, Jenner GA (1986) Crustally contaminated komatiites from Kambalda, Western Australia. Chem Geol 56: 229–256

Bonnichsen W (1972) Southern part of the Duluth complex. In: Sims PK, Morey GB (eds) Geology of Minnesota: a centennial volume: St. Paul, Minnesota Geological Survey, pp 361–387

Brugmann GE, Naldrett AJ, Asif M, Lightfoot PC, Gorbachev NS, Fedorenko VA (1993) Siderophile and chalcophile metals as tracers of the evolution of the Siberian trap in the Noril'sk region, Russia, Geochim Cosmochim Acta 57: 2001–2018

Burt DRL, Sheppy NR (1975) Mount Keith nickel sulfide deposit, In: Knight CL (ed) Economic geology of Australia and Papua New Guinea, I. Metals: Australasian Institution Mining and Metallurgy Mon. 5, pp 159–168

Chai G, Naldrett AJ (1992a) Petrology and geochemistry of the Jinchuan ultramafic intrusion: cumulate of a high-Mg basaltic magma. J Petrol 33: 1–27

Chai G, Naldrett AJ (1992b) PGE mineralisation of the Jinchuan Ni-Cu sulfide deposit, NW China. Eco Geol 87: 1475–1495

Distler VV, Kunilov VY (1994) Geology and ore deposits of the Noril'sk region, Guidebook to Noril'sk Field Trip, VII Int Platinum Symp, Moscow-Noril'sk

Duke JM, Naldrett AJ (1978) A numerical model of the fractionation of olivine and molten sulfide from komatiite magma. Earth Planet Sci Lett 39: 255–266

Duzhikov OA, Distler VV, Strunin BM, Mkrtychyan AK, Sherman ML, Sluzhenikin SS Lurje AM (1992) Geology and metallogeny of sulfide deposits of Noril'sk Region, USSR. (English translation of 1988 Russian edition) Society of Economic Geologists, Special Publication 1, 242 pp

Faggart BE, Basu AB, Tatsumoto M (1985) Origin of the Sudbury Complex by meteorite impact: neodymium isotopic evidence. Science 230: 436–439

Faure G, Chaudhuri S, Fenton M (1969) Ages of the Duluth gabbro complex and the Endion sill, Duluth, Minnesota: J Geophys Res 74: 720–725

Fedorenko VA (1994) Evolution of magmatism as reflected in the volcanic sequence of the Noril'sk region. In: Lightfoot PC, Naldrett AJ (eds) Proc Sudbury-Noril'sk Symp. Ontario Geological Survey Special Vol. 5: 171–184

Fisher D (1979) The petrology of the Mt. Edwards nickel sulfide deposit, Widgiemooltha, Western Australia: Unpub PhD Thesis, University of Toronto, 320 p

Frost KM, Groves DI (1989) Ocellar units at Kambalda: evidence for sediment assimilation by komatiite lavas. In: Prendergast MD, Jones MJ (eds) "Magmatic sulphides – The Zimbabwe Volume" Special Publication, Institution of Mining and Metallurgy, London, pp 207–214

Genkin AD, Distler VV, Gladyshev GD, Filiminova AA, Evstigneeva TL, Kovalenker VA, Laputina IP, Smirnov AV, Grokhovskaya TL (1981) Sulfide copper-nickel ores of the Noril'sk deposits. Moscow, Nauka, 234 pp (in Russian)

Godlevsky MN, Grinenko LN (1963) Some data on the isotopic composition of sulfur in the sulfides of the Noril'sk deposit. Geochemistry 1: 335–41

Green JC, Phinney WC, Weiblen PW (1966) Gabbro Lake Quadrangle, Lake County, Minnesota Geological Survey Miscellaneous Map M2

Gresham JJ (1986) Depositional environments of volcanic peridotite-associated nickel sulphide deposits with special reference to the Kambalda Dome. In: Freidrich GH, Genkin AD, Naldrett AJ, Ridge JD, Sillitoe RH, Vokes FM (eds) Geology and metallogeny of copper deposits Springer-Verlag, Heidelberg Berlin, pp 63–90

Gresham JJ, Loftus-Hills GD (1981) The geology of the Kambalda Nickel Field, Western Australia. Econ Geol 76: 1373–1416
Grieve RAF (1994) An impact model of the Sudbury Structure, In: Lightfoot PC, Naldrett AJ (eds) Proc Sudbury-Noril'sk Symp Ontario Geological Survey Special Vol 5: 119–132
Grinenko LN (1985) Sources of sulfur of the nickeliferous and barren gabbro-dolerite intrusions of the northwest Siberian platform. Int Geol Rev 27: 695–708
Grout FF (1918) The lopolith; an igneous form exemplified by the Duluth Gabbro. Am J Sci (4th Ser) 46: 516–522
Hawkesworth CJ, Lightfoot PC, Fedorenko VA, Blake S, Naldrett AJ, Doherty W, Gorbachev NS (1995) Magma differentiation and mineralization in the Siberian continental flood basalts. Lithos 34: 61–88
Hill RET (1997) Komatiite volcanology and associated nickel sulphide deposits. In: Papunen H (ed) Mineral deposits: research and exploration, where do they meet? Proc fourth Biennial SGA Meeting, Turku Finland, August 1997, Balkema, Rotterdam, 5–6
Hill RET, Gole MJ, Barnes SJ (1989) Olivine adcumulates in the Norseman-Wiluna greenstone belt, Western Australia: implications for the volcanology of komatiites. In: Prendergast MD, Jones MJ (eds) Magmatic sulfides – the Zimbabwe volume. Special Publication, Institution Mining and Metallurgy, London, pp 189–206
Hill RET, Barnes SJ, Gole MJ, Dowling SE (1990) Physical volcanology of komatiites, Excursion Guide Book 1, Geological Society of Australia (W.A. Division), East Perth, Western Australia
Hill RET, Barnes SJ, Gole MJ, Dowling SE (1995) The volcanology of komatiites as deduced from field relationships in the Norseman-Wiluna greenstone belt, Western Australia. Lithos 34: 159–188
Huppert HE, Sparks RSJ (1985) Komatiites I: eruption and flow. J Petrol 26: 694–725
Irvine TN (1975) Crystallization sequences of the Muskox intrusion and other layered intrusions – II. Origin of chromitite layers and similar deposits of other magmatic ores. Geochim Cosmochim Acta 39: 991–1020
Lambert DD, Foster JG, Frick LR, Li C, Naldrett AJ, MacKenzie C (1997) Re-Os systematics of the Voisey's Bay Ni-Cu-Co magmatic ore system, Labrador, Canada, Vol Abstr, American Geophysical Union Fall Meeting, San Francisco, December 1997
Lesher CM (1989) Komatiite-associated nickel sulfide deposits. In: Whitney JA, Naldrett AJ (eds) Ore deposition associated with magmas. Reviews in Economic Geology, Society of Economic Geologists, pp 45–102
Lesher CM, Groves DI (1986) Controls on the formation of komatiite-associated nickel-copper sulfide deposits. In: Freidrich GH, Genkin AD, Naldrett AJ, Ridge JD, Sillitoe RH, Vokes FM (eds) Geology and metallogeny of copper deposits. Springer-Verlag, Heidelberg Berlin, pp 43–62
Li C, Naldrett AJ (1999) Geology and olivine stratigraphy of the Voisey Bay complex: evidence for multiple intrusion. Lithos (in press)
Li C, Naldrett AJ (1997) The Voisey's Bay Ni-Cu-Co deposit, Labrador, Canada: variations of olivine composition related to multiple magma injections and sulfide segregation. In: Papunen H (ed) Mineral deposits: research and exploration where do they meet? Proc Fourth Biennial SGA Meeting, Turku Finland, August 1997, Balkema, Rotterdam, pp 461–462
Li C, Naldrett AJ (1993) Sulfide capacity of magma: a quantitative model and its application to the formation of sulfide ores at Sudbury. Econ Geol 88: 1253–1260
Lightfoot PC, Naldrett AJ (1994) Proceedings of the Sudbury – Noril'sk Symposium, Ontario Geological Survey spec Vol 5. p 423
Lightfoot PC, Naldrett AJ, Gorbachev NS, Doherty W, Federenko VA (1990) Geochemistry of the Siberian trap of the Noril'sk area, USSR, with implications for the relative contributions of crust and mantle to flood basalt magmatism. Contrib Mineral Petrol 104: 631–644
Lightfoot PC, Hawkesworth CJ, Hergt J, Naldrett AJ, Gorbachev NS, Fedorenko VA, Doherty W (1993) Remobilisation of continental lithosphere by mantle plumes: major, trace element, and Sr-, Nd-, and Pb-isotope evidence for picritic and tholeiitic lavas of the Noril'sk district, Siberian trap, Russia. Contrib Mineral Petrol 114: 171–188
Lightfoot PC, Naldrett AJ, Gorbachev NS, Fedorenko VA, Hawkesworth CJ, Doherty W (1994), Chemostratigraphy of Siberian trap lavas, Noril'sk district, Russia: implications and source of flood basalt magmas and their associated Ni-Cu mineralization. Proc Sudbury-Noril'sk Symp. Ontario Geological Survey Spec Vol 5: 283–312
Likhachev AP (1994) Ore-bearing intrusions of the Noril'sk region. Proc Sudbury-Noril'sk Symp. Ontario Geological Survey Spec Publ 5: 185–202
Listerud WH, Meineke DG (1977) Mineral resources of a portion of the Duluth Complex and adjacent rocks in St. Louis and Lake counties, northeastern Minnesota. Minnesota Department of Natural Resources, Division of Minerals, Minerals Exploration Section, Report 93
Mainwaring PR, Naldrett AJ (1977) Country-rock assimilation and the genesis of Cu-No sulfides in the Waterhen intrusion, Duluth Complex, Minnesota. Econ Geol 72: 1269–1284
Martineau MP (1989) Empirically derived controls on Cu-Ni mineralisation: a comparison between fertile and barren gabbros in the Duluth complex, Minnesota, USA. In: Prendergast MD, Jones MJ (eds) Magmatic sulfides – the Zimbabwe volume. Special Publication, Institution Mining and Metallurgy, London, pp 117–138
McNaughton NJ, Frost KM, Groves DI (1988) Ground melting and ocellar komatiites: a lead isotopic study at Kambalda, Western Australia. Geol Mag 125: 285–295
McQueen KG (1981) Volcanic-associated nickel deposits from around the Widgiemooltha dome, Western Australia. Econ Geol 76: 1417–1443
Naldrett AJ (1994) The Sudbury-Noril'sk Symposium, an overview. Ontario Geological Survey Spec Publ 5: 3–10
Naldrett AJ (1999) Summary: the development of ideas on Sudbury geology, 1992–1998. In: Dressler B, Grieve R, and Sharpton VL (eds) Large meteorite impacts and planetary evolution. Geological Society of America, Memoir (in press, accepted August 1998)
Naldrett AJ, Turner AR (1977) The geology and petrogenesis of a greenstone belt and related nickel sulfide mineralization at Yakabindie, Western Australia. Precamb Res 5: 43–103
Naldrett AJ Barnes, S-J (1986) The behavior of platinum group elements during fractional crystallization and partial melting with special reference to the composition of magmatic sulfide ores. Forschritte der Min 64: 113–133
Naldrett AJ, Rao BV, Evensen NM (1986) Contamination at Sudbury and its role in ore formation. In: Gallagher MJ, Ixer RA, Neary CR, Pritchard HM, (eds) Metallogeny of basic and ultrabasic rocks. Spec Publ Inst Mining Metal, London, pp 75–92
Naldrett AJ, Brugmann GE, Wilson AH (1990) Models for the Concentration of PGE in Layered Intrusions. Can Mineral 28: 389–408
Naldrett AJ, Lightfoot PC, Fedorenko VA, Gorbachev NS, Doherty W (1992) Geology and geochemistry of intrusions and flood basalts of the Noril'sk region, USSR, with implications for the origin of the Ni-Cu ores. Econ Geol 87: 975–1004
Naldrett AJ, Fedorenko VA, Lightfoot PC, Kunilov VA, Gorbachev NS, Doherty W, Johan J (1995) Ni-Cu-PGE deposits of the Noril'sk region, Siberia: their formation in conduits for flood basalt volcanism. Trans Inst Mining Metal 104: B18-B36
Naldrett AJ, Fedorenko VA, Asif M, Lin S, Kunilov VI, Stekhin AI, Lightfoot PC Gorbachev NS (1996a) Controls on the composition of Ni-Cu sulfide deposits as illustrated by those at Noril'sk, Siberia. Econ Geol 91: 751–773

Naldrett AJ, Keats H, Sparkes K, Moore R, MacKenzie C (1997) The Voisey's Bay Ni-Cu-Co deposit, Labrador, Canada: implications for exploration in: International Exploration. Institution of Mining and Metallorgy

Naldrett AJ, Keats H, Sparkes K, Moore R (1996b) Geology of the Voisey's Bay Ni-Cu-Co deposit, Labrador, Canada. Explor Mining Geol J 5: 169–179

Naldrett AJ, Fedorenko VA, Asif M, Lin S, Kunilov VI, Stekhin AI, Lightfoot PC, Gorbachev NS (1996) Controls on the composition of Ni-Cu sulfide deposits as illustrated by those at Noril'sk, Siberia. Econ Geol 91, 751–773

Phinney WC (1972) Northwestern part of the Duluth complex. In: Sims PD, Morey GB (eds) Geology of Minnesota: a centennial volume: St.Paul, Minnesota Geological Survey, pp 335–345

Phinney WC (1970) Chemical relations between Keewanawan lavas and the Duluth complex, Minnesota. Bull Geol Soc Am 81: 2487–2496

Ripley EM (1981) Sulfur isotopic abundances of the Dunka Road Cu-Ni deposit, Duluth Complex, Minnesota. Econ Geol 76: 619–620

Ripley EM (1986) Applications of stable isotope studies to problems of magmatic sulfide ore genesis with special reference to the Duluth Complex, Minnesota. In: Friedrich GH, Genkin AD, Naldrett AJ, Ridge JD, Sillitoe RH, Vokes FM (eds) Geology and metallogeny of copper deposits. Society for Geology Applied to Ore Deposits Spec Publ 4. Springer-Verlag, Berlin Heidelberg, pp 25–42

Ripley EM, Park Y-R, Li C, Naldrett AJ (1997) Sulfur and oxygen isotopic studies of the Voisey's Bay Ni-Cu-Co deposit, Labrador, Canada, Vol Abstr, American Geophysical Union Fall Meeting, San Francisco, December 1997

Ross JR, Hopkins GMF (1975) The nickel sulfide deposits of Kambalda, Western Australia. In: Knight C (ed), Economic geology of Australia and Papua-New Guinea. Australian Institution of Mining and Metallurgy Monograph 5, (1) Metals, pp 100–121

Ryan B (1997) The Voisey's Bay nickel-copper-cobalt deposit, Labrador, Canada: magmatic sulphide in anorogenic troctolitic rocks. Chron Rech Miniere 525: 3–11

Ryan B, Wardle RJ, Gower CF, Nunn GAG (1995) Nickel-copper sulphide mineralisation in Labrador: the Voisey Bay discovery and its exploration implications, Current Research, 95-1, Geological Survey, Department of Natural Resources, Government of Newfoundland and Labrador, 177–204

Severson MJ (1991) Geology, mineralisation, and geostatistics of the Minnamax/Babbitt Cu-Ni deposit (Local Boy area), Minnesota, Part I: Geology Techn Rep NRRI/TR-91/13a Natural Resources Research Institute, University of Minnesota, Duluth, 96 pp

Severson MJ (1988) Geology and structure of a portion of the Partridge River intrusion: a progress report. (Technical Report NRRI/GMIN-TR-88-08) Natural Resources Research Institute, University of Minnesota, Duluth, 78 pp

Severson MJ, Hauck S (1990) Geology, geochemistry and stratigraphy of a portion of the Partridge River intrusion: a progress report. Techn Rep NRRI/GMIN-TR-89-11 Natural Resources Research Institute, University of Minnesota, Duluth, 230 pp

Tang Z (1993) Genetic models of the Jinchuan nickel-copper deposit, In: Kirkham RV, Sinclair WD, Thorpe RI, Duke JM (eds) Mineral deposit modeling, Geological Association of Canada Spec Pap 40: 389–401

Tang Z et al. (1992) Sm-Nd dating of the Jinchuan ultramafic rock body. Chinese Sci Bull 37: 9

Van Kranendonk M (1996) Tectonic evolution of the Paleo-proterozoic Torngat orogen: evidence from pressure-temperature-time deformation paths in the North River map area. Tectonics 15: 843–869

Weiblen PW, Morey GB (1980) A summary of the stratigraphy, petrology and structure of the Duluth complex. Am J Sci 280-A: 88–133

Weiblen PW, Morey GB (1975) The Duluth complex – a petrographic and tectonic summary: 36th Ann Minn Min Symp Department of Conferences and Continuing Education, University of Minnesota, pp 72–95

Wooden JL, Czamanske GK, Fedorenko VA, Arndt NT, Chauvel C, Bouse RM, King B-SW, Knight RJ, Siems DF (1993) Isotopic and trace element constraints on mantle and crustal contributions to characterization of Siberian continental flood basalts, Noril'sk area, Siberia. Geochim Cosmochim Acta 57: 3677–3704