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27.2 Magmatic platinum group elements

27. MAGMATIC NICKEL-COPPER-PLATINUM GROUP ELEMENTS

O.R. Eckstrand

A broad group of deposits containing nickel-copper-platinum group elements (PGE) occur as sulphide segregations associated with a variety of mafic and ultramafic magmatic rocks. Among such deposits, two main subtypes are distinguishable. In the first (27.1 "Nickel-copper sulphide"), nickel and copper are the main economic commodities, contained in sulphide-rich ores that are associated with differentiated mafic sills and stocks and ultramafic (komatiitic) volcanic flows and sills. The second subtype (27.2 "Magmatic platinum group elements") is mined principally for PGEs, which are associated with sparsely dispersed sulphides in medium to large, typically layered mafic-ultramafic intrusions.

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27.1 NICKEL-COPPER SULPHIDE

O.R. Eckstrand

INTRODUCTION

Nickel-copper sulphide deposits are sulphide concentrations that occur in certain mafic and/or ultramafic intrusions or volcanic flows. Nickel is the main economic commodity, copper may be either a coproduct or byproduct, and platinum group elements (PGEs) are usual byproducts. Other commodities recovered in some cases include gold, silver, cobalt, sulphur, selenium, and tellurium. These metals are associated with sulphides, which generally make up more than 10% of the ore. The locations of Canadian deposits are shown in Figure 27.1-1.

The mafic and ultramafic magmatic bodies that host the ores are diverse in form and composition, and can be subdivided into the following four subtypes:

(27.1a) an astrobleme-associated sill-like mafic intrusion that contains ores in which Ni:Cu is approximately 1:1 (Sudbury, Ontario is the only known example).

(27.1b) rift- and continental flood basalt-associated mafic sills and dyke-like bodies, in which Ni:Cu ratios of the related ores may be either somewhat greater or less than 1 (Noril'sk-Talnakh, Russia; Duluth Complex, Minnesota; Crystal Lake intrusion, Ontario; possibly Jinchuan, China).

(27.1c) komatiitic volcanic flows and related intrusions, which have ores with Ni:Cu ratios that are commonly greater than 10, but less in some cases (Thompson, Manitoba; Expo Ungava and Marbridge, Quebec; Langmuir, Ontario; Kambalda and Agnew, Australia; Pechenga, Russia; Shangani, Trojan, and Hunter's Road, Zimbabwe; Kabanga, Tanzania).

(27.1d) other tholeiitic intrusions, in which the Ni:Cu ratios of the ores are commonly in the range 2 to 3 (Lynn Lake, Manitoba; Giant Mascot, British Columbia; Kotalahti, Finland; Råna, Norway; Selebi-Pikwe, Botswana).

IMPORTANCE

As a group, magmatic nickel-copper sulphide deposits have accounted for most of the world's past and current production of nickel. International reserves of magmatic sulphide nickel remain large, though they are exceeded by those of lateritic nickel deposits, the only other significant source of nickel.

Sudbury, the sole known example of the astrobleme subtype (27.1a) constitutes the world's largest nickel-producing camp as measured by total past production plus reserves. It accounts for about two-thirds to three-quarters of Canada's current nickel production. As a deposit type, it is the second most important Canadian producer of copper, and the only producer of PGEs and cobalt.

The rift- and continental flood basalt-associated subtype (27.1b) includes Noril'sk in Russia and probably Jinchuan in China, the second and third largest nickel-producing camps in the world. The undeveloped, low-grade Great Lakes Nickel deposit is the only example known in Canada, and is similar to the much larger, but also undeveloped, low grade deposits in the Duluth mafic complex in Minnesota.

The komatiitic subtype (27.1c) is the third most important type in the world. Proterozoic komatiitic deposits of the Thompson Nickel Belt in Manitoba account for one quarter to one third of current nickel production in Canada. Archean komatiitic deposits at Kambalda and elsewhere in Western Australia yield most of that country's produced nickel. Several small nickel mines in the Abitibi greenstone belt of Ontario and Quebec are also Archean komatiitic deposits.

Nickel deposits of other tholeiitic affiliation (subtype 27.1d) have been significant producers in the past; but only Selebi-Pikwe in Botswana has continued to operate recently.

SIZE AND GRADE OF DEPOSITS

Grades and tonnages of some of the more significant Canadian and foreign nickel deposits are listed in Table 27.1-1, and illustrated in Figure 27.1-2.

Most nickel sulphide deposits consist of several closely adjacent, but discrete orebodies, therefore the definition of "deposit" is rather arbitrary. Individual orebodies may contain from a few hundred thousand to a few million tonnes of ore, and in some instances tens of millions of tonnes of ore. Mining grades are generally about 1 to 3% Ni, but may be higher in some small deposits. Noteworthy exceptions are some of the ore zones in the Talnakh camp of the Noril'sk area, where substantial orebodies average several per cent Ni and greater than 20% Cu.

GEOLOGICAL FEATURES

All subtypes of magmatic nickel sulphide deposits have some general similarities. For example, the host intrusions in all cases are either mafic or ultramafic in composition. In addition, most deposits occur as sulphide concentrations toward the base of their magmatic host bodies. Furthermore, all subtypes of nickel sulphide ores usually consist mainly of the simple sulphide assemblage pyrrhotite-pentlandite-chalcopyrite, either as massive sulphides,

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Table 27.1-1. Size and grade of nickel-copper sulphide deposits (production + reserves).

No.	Subtype	Deposit	Age	Size (Mt)	Ni%	Cu%	Reference
Canadian deposits							
1	27.1a	Sudbury (total), Ontario	Proterozoic	1648	1.20	1.03	Canadian Mines Handbook 91-92; Naldrett, 1994
2	27.1b	Great Lakes Nickel, Ontario	Proterozoic	45.6	0.183	0.344	Great Lakes Nickel Ltd., 1976 Annual Report
3	27.1c	Thompson Ni Belt (INCO), Manitoba	Proterozoic	89	2.5	0.13	INCO Prospectus, 1968; Naldrett, 1994
4	27.1c	Amax Area 1 ("Nose"), Manitoba	Proterozoic	7.3	1.33	na	Roth (1975)
5	27.1c	Manibridge, Manitoba	Proterozoic	1.409	2.55	0.27	Coats and Brummer (1971)
6	27.1c	Bucko, Manitoba	Proterozoic	2.5	2.23	0.17	Falconbridge Review, 1991
7	27.1c	Bowden, Manitoba	Proterozoic	80	0.6	na	Northern Miner, 1970-08-06
8	27.1c	Raglan deposits (6), Ungava, Quebec	Proterozoic	18.5	3.13	0.88	Northern Miner, 1992-11-02
9	27.1c	Expo Ungava, Quebec	Proterozoic	6.3	0.86	1.01	Northern Miner, 1992-11-02
10	27.1c	Texmont, Ontario	Archean	3.19	0.93	na	Coad (1979)
11	27.1c	Langmuir (No. 1 & 2), Ontario	Archean	1.6	2.09	0.08	Coats (1982)
12	27.1c	Marbridge, Quebec	Archean	0.774	2.82	0.1	Brett et al. (1976)
13	27.1c	Alexo Mine, Ontario	Archean	0.057	3.58	na	Shklanka (1969)
14	27.1c	Redstone, Ontario	Archean	1.22	2.39	0.09	Barrie et al. (1993)
15	27.1c	Dumont, Quebec	Archean	150	0.5	na	Duke (1986)
16	27.1c	Gordon Lake, Ontario	Archean	1.07	1.62	0.68	Coats (1982)
17	27.1c	Shebandowan, Ontario	Archean	15	1.5	1	Coats (1982)
18	27.1c	Namew Lake, Manitoba	Proterozoic	2.6	2.44	0.9	Canadian Minerals Yearbook, p. 45.2
19	27.1d	Montcalm, Ontario	Archean	3.56	1.44	0.68	Barrie and Naldrett (1989)
20	27.1d	St. Stephen (3 zones), New Brunswick	Devonian	1	1.05	0.53	Pactunç (1986)
21	27.1d	Macassa, Limerick Township, Ontario	Proterozoic	1.8	0.91	0.26	Northern Miner, 1971-10-14
22	27.1d	Lynn Lake, Manitoba	Proterozoic	20.151	1.023	0.535	Pinsent (1980)
23	27.1d	Giant Mascot, British Columbia	Cretaceous	2.05	1.4	0.5	Coats (1982)
24	27.1d	Canalask, Yukon Territory	Triassic	0.5	1.68	0.04	NMI 115F/15Ni001 **
25	27.1d	Wellgreen, Yukon Territory	Triassic	0.669	2.04	1.42	Hulbert et al. (1988)
26	27.1d(?)	Lorraine, Quebec	Archean	0.661	0.39	0.91	NMI 031M/07Cu002 **
Foreign deposits							
27	27.1b	Noril'sk-Talnakh district (Russia)	Triassic	555	2.7	2.07*	DeYoung et al. (1985); Naldrett (1994)
28	27.1b	Jinchuan (China)	Proterozoic	515	1.06	0.67	Chen and Mingliang (1987); Naldrett (1994)
29	27.1b	Duluth Complex (Minnesota)	Proterozoic	4000	0.2	0.66	Listerud and Meineke (1977)
30	27.1c	Pechenga (Russia)	Proterozoic	36	1	0.4*	DeYoung et al. (1985)
31	27.1c	Kambalda district (Australia)	Archean	48	3.6	0.25*	DeYoung et al. (1985); Naldrett (1994)
32	27.1c	Agnew (Australia)	Archean	46.764	2.08	0.1*	Billington (1984)
33	27.1c	Windarra district (Australia)	Archean	13.161	1.45	na	DeYoung et al. (1985)
34	27.1c	Mt. Keith (Australia)	Archean	270	0.6	na	DeYoung et al. (1985)
35	27.1c	Hitura (Finland)	Proterozoic	12.3	0.56	0.16	DeYoung et al. (1985)
36	27.1c	Shangani (Zimbabwe)	Archean	22	0.71	na	DeYoung et al. (1985)
37	27.1c	Trojan (Zimbabwe)	Archean	20.35	0.68	na	DeYoung et al. (1985)
38	27.1c	Hunter's Road (Zimbabwe)	Archean	30	0.7	na	DeYoung et al. (1985)
39	27.1c	Kabanga (Tanzania)	Proterozoic	11.7	1.72	0.26	Northern Miner 1993-03-08, p. 14
40	27.1d	Monchegorsk (Russia)	Proterozoic	47	0.7	0.4	Coates (1982)
41	27.1d	Kotalahti (Finland)	Proterozoic	23.2	0.7	0.3	DeYoung et al. (1985)
42	27.1d	Selebi-Pikwe (Botswana)	Archean	49.444	1.04	1.12	DeYoung et al. (1985)

* Cu grade approximate

** National Mineral Inventory file, Natural Resources Canada

na = not available

sulphide-matrix breccias, or disseminations of sulphides. Nickel-copper sulphide ores of any of the subtypes that have undergone tectonic remobilization have been converted to similar-appearing sulphide-matrix breccias.

However, the subtypes differ significantly in their geological-tectonic settings and in the geometric form and style of differentiation of the host magmatic bodies. They differ also in that the magmatic hosts in most subtypes are intrusions, but in the komatiitic subtype most are volcanic flows. Furthermore the ores of the various subtypes show some differences in composition, most noticeably in their Ni:Cu ratios. A general review of magmatic nickel sulphide deposits has been given by Naldrett (1989a).

Astrobleme-associated nickel-copper (Sudbury camp): subtype 27.1a

The Sudbury Igneous Complex is unique in a number of respects, including the exceptional concentration of associated nickel deposits. Perhaps its most unique characteristic

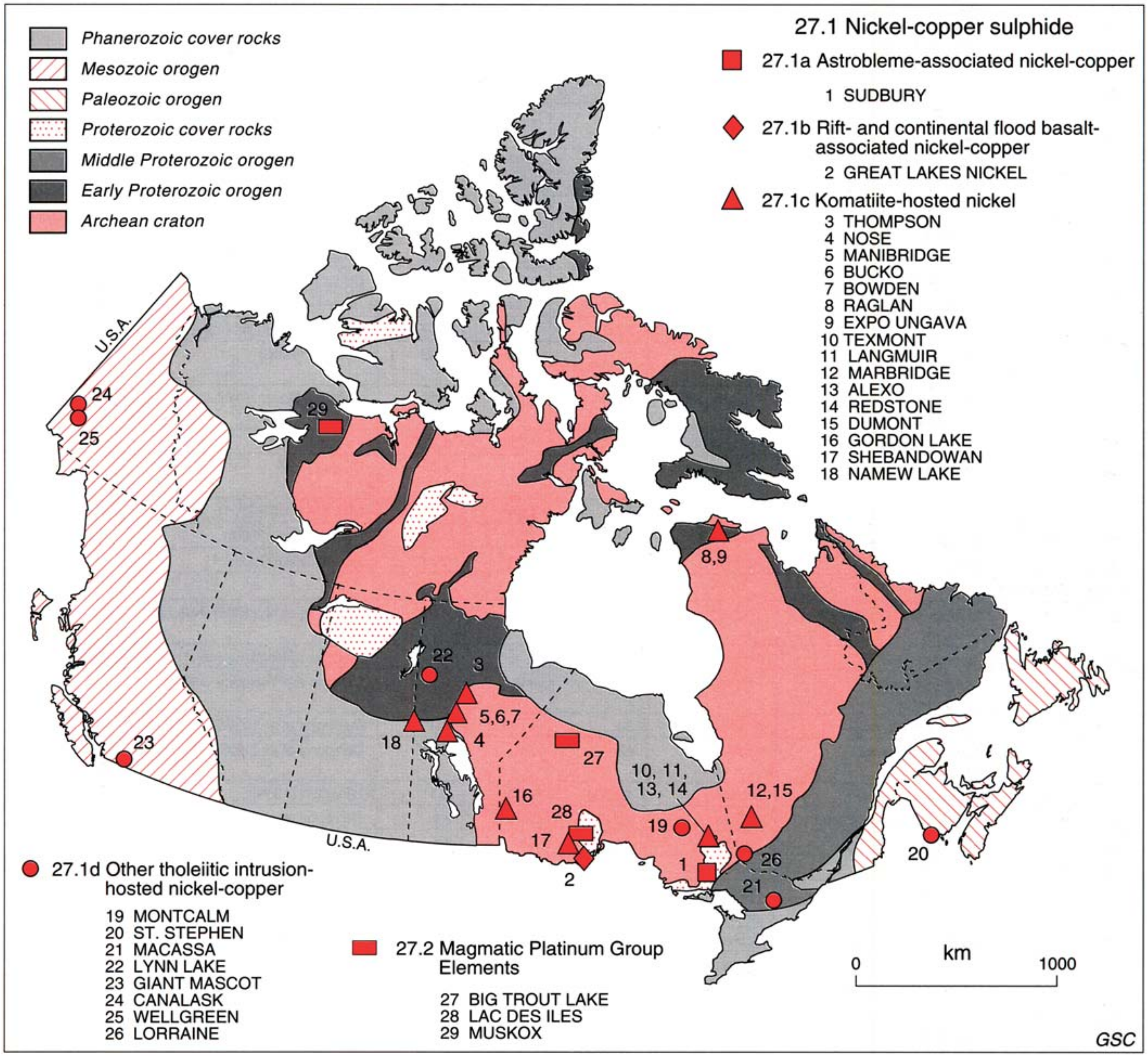

Figure 27.1-1. Locations of Canadian nickel deposits or districts. Numbers for nickel deposits refer to those listed in Table 27.1-1.

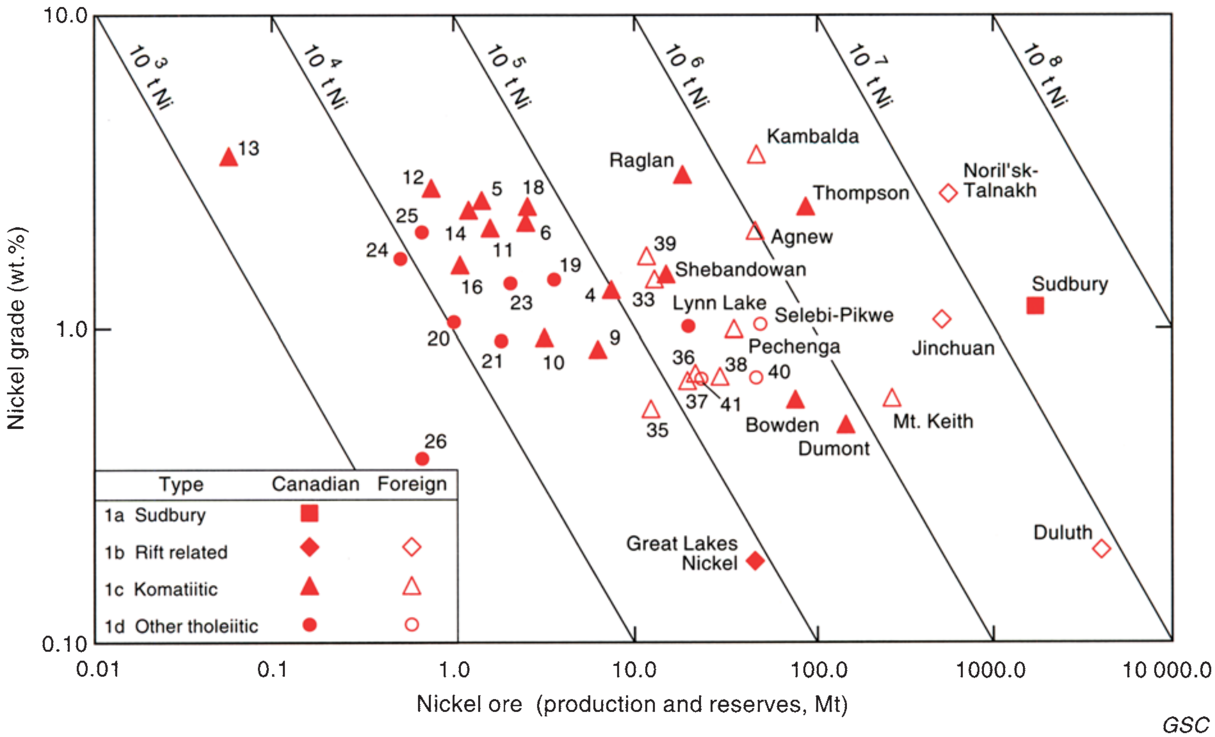

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Figure 27.1-2. Grades versus tonnages of selected Canadian and foreign nickel deposits or districts. Numbers refer to the deposits listed in Table 27.1-1.

is the evidence for an associated shock metamorphic event, which is now widely believed to have been a meteoritic impact. Nevertheless, though other deposits of this type have not yet been identified, there is no apparent geological reason why they could not exist.

Geological setting

A comprehensive account of the geology of the Sudbury camp is given in the volume edited by Pye et al. (1984). Ages cited for units discussed in the following are from Krogh et al. (1984) in that volume.

The Sudbury Igneous Complex (SIC; 1850 ± 1 Ma) and its nickel-copper ores (Fig. 27.1-3) occur near the southern limit of the Archean Superior Province craton which is overlain by the Proterozoic Huronian Supergroup (Card et al., 1984). The northern margin or "North Range" of the basin-shaped Sudbury Igneous Complex cuts Archean rocks, mainly migmatitic tonalitic gneisses (Levack Gneiss, 2711 Ma) and anorogenic granitic plutons (Cartier Granite, about 2680 Ma). The southern margin or "South Range" has intruded lower Huronian mafic and felsic metavolcanic rocks (about 2450 Ma) and felsic stocks (about 2388 Ma). A little more than ten kilometres to the southeast of the complex lies the faulted Grenville Front, the northwestern margin of the mid-Proterozoic Grenville Province.

The complex is overlain by the basin-shaped Early Proterozoic Whitewater Group, a conformable sequence consisting, in upward succession, of a heterolithic breccia (Onaping Formation), a carbonaceous and pyritic argillite (Onwatin Formation), and a proximal turbidite sequence (Chelmsford Formation). The base of the Onaping Formation has been intruded by the underlying granophyre of the complex.

The Sudbury Igneous Complex outcrops as a crude oval ring about 65 km long and 25 km across, representing a basin- or funnel-shaped intrusion (Fig. 27.1-3). The inward dip of the complex averages about 30° along the North Range, and 45 to 60° along the South Range. The complex consists of two main layer-like units (Naldrett and Hewins, 1984), the Lower Zone and the Upper Zone. The Lower Zone (0.5-2.5 km thick) comprises mainly norite and gabbronorite that grades upward into a quartz- and oxide-rich gabbro. The Upper Zone (1-2.5 km thick), which is made up mainly of granophyre, has an abruptly transitional contact with the underlying quartz-rich gabbro.

The Sudbury Igneous Complex has no obvious small-scale layering (Naldrett and Hewins, 1984), and only the Lower Zone shows a relatively weak, simple differentiation trend. Quartz-bearing gabbronorite is the most common rock type of the Lower Zone, and is composed of plagioclase-orthopyroxene cumulates, cumulus or intercumulus clinopyroxene, and intercumulus quartz, quartz-feldspar micrographic intergrowth, biotite, and Fe-Ti oxides. Grain size increases from fine grained at the base to medium- to coarse-grained. Transition to the overlying quartz- and oxide-rich gabbro involves loss of orthopyroxene and appearance of cumulus titaniferous magnetite and apatite. Gabbro passes upward into the relatively homogeneous granophyre which consists of about two-thirds micrographic intergrowth of quartz and feldspar, together with plagioclase and lesser amounts of mafic minerals.

At the base of the Lower Zone is the "Sublayer", which contains the nickel-copper sulphide deposits (Souch et al., 1969; Pattison, 1979). Its contact with the Lower Zone norite is reportedly sharp in some places, but is gradational in others. The Sublayer has two facies; (1) Contact Sublayer (generally less than 200 m thick) consists of discontinuous gabbronoritic lenses along the basal contact of the Sudbury Igneous Complex, which grade into (2) Offset Sublayer that constitutes apophyses of mainly quartz diorite which project outward into the footwall rocks. The Contact Sublayer (Souch et al., 1969; Pattison, 1979; Naldrett et al., 1984) is a gabbronorite that is characterized by the presence of nickel-copper sulphides and xenoliths of wall rock and mafic and ultramafic rocks of nonlocal origin. It typically consists of a fine grained assemblage of zoned plagioclase laths, subophitic hypersthene and augite, minor amounts of primary biotite and hornblende, and widely varying amounts of quartz. Although closely similar in composition, in the lithology of its xenoliths, and in the presence of sulphides,

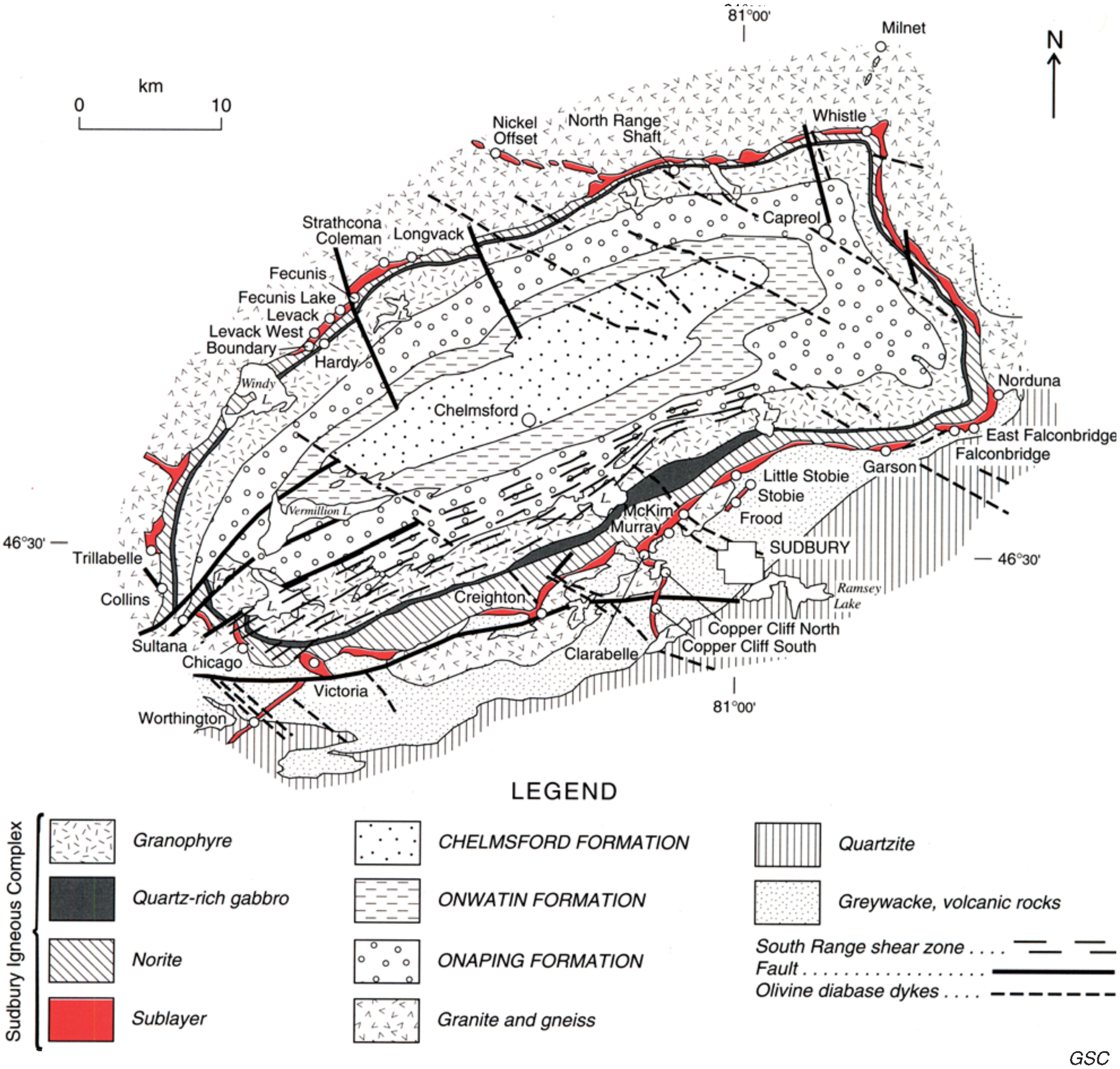

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Figure 27.1-3. Geological map of the Sudbury Igneous Complex, showing locations of some of the more important nickel-copper mines and deposits (after Naldrett, 1989d; Sublayer after Pattison, 1979, and Naldrett et al., 1984; South Range shear zone after Shanks and Schwerdtner, 1991).

the quartz dioritic Offset Sublayer has distinct mineralogy, and consists mainly of quartz, plagioclase, biotite, and hornblende, the last commonly pseudomorphic after pyroxene.

The composition of the Sudbury Igneous Complex reflects a strong influence by crustal rocks, quite likely the immediate footwall rocks (see "Genetic model"). This is indicated by the high silica and potash contents, the LREE enrichment (Naldrett, 1984), and Os isotopic ratios (Walker et al., 1991).

Features related to the intrusion of the Sudbury Igneous Complex (Dressler, 1984) include a contact metamorphic halo as much as 1.2 km in width, and a set of shock-induced structures generally attributed to a meteoritic impact. The shock features include shatter cones, and planar dislocations and kink bands in certain rock-forming minerals; these are found in footwall rocks and in clasts in the Onaping Formation and the granophyre. In addition, the complex is underlain by a quasi-conformable "Footwall Breccia" of variable thickness that is leucocratic and prominent in the North Range, but more obscure in the South Range due to its mafic nature. Outside the Footwall Breccia and around the entire periphery of the complex are irregular veins and masses of Sudbury Breccia that are known to be present at least 80 km outward from the complex. Clast compositions in both breccias suggest an essentially in situ genesis. The North Range Footwall Breccia is a highly variable unit whose clasts consist largely of Levack Gneiss set in a fine grained granoblastic matrix of plagioclase, quartz, biotite, amphibole, and pyroxene. Sudbury Breccia has clasts of all sizes (commonly as large as tens of metres), mainly consisting of wall rocks. Typically the finest matrix material is a dark rock flour (Dressler, 1984).

The Sudbury basin owes its elliptical shape to northwestward directed ductile thrusting probably related to the Penokean Orogeny (Rousell, 1984; Shanks and Schwertner, 1991; Milkereit et al., 1992; Cowan and Schwertner, 1994). A prominent element of this deformation is the east-northeast-trending South Range shear zone that transects the southern part of the Sudbury basin.

Nature of ore deposits

Five types of ore zones can be distinguished, based on the host rocks, controlling structures, and ore composition. The first four of these are in or adjacent to the Sublayer and comprise pyrrhotite-dominated sulphides with Ni:Cu ratios near 1. The fifth type occurs in footwall rocks and consists mainly of copper sulphides, highly enriched in PGEs.

In the South Range contact type (Souch et al., 1969), the ore typically occurs in noritic Sublayer, which occupies a depression in the base of the Sudbury Igneous Complex and plunges down the basal contact (Fig. 27.1-4A), as in the Creighton, Murray, and Little Stobie 1 mines. The ore generally has a Ni:Cu ratio greater than 1, and is zoned. The lowest zone consists of massive sulphide ore that contains angular wall rock fragments ("inclusion massive sulphide"), and stringers of sulphide that project into the underlying footwall rocks. This ore grades upward into a sulphide-matrix breccia with an increasing amount of norite in the matrix, and numerous pyroxenite and peridotite inclusions ("gabbro-peridotite inclusion sulphide"). Above this, the amount of sulphide matrix diminishes in the inclusion-rich Sublayer ("ragged disseminated sulphide").

Typical ores of the North Range type (Pattison, 1979; Coats and Snajdr, 1984), such as the Levack and Strathcona ore zones, occur in noritic Sublayer and underlying Footwall Breccia, which together occupy embayments that bulge downward from the base of the Lower Zone norite into the underlying Levack Gneiss (Fig. 27.1-4B). The ores are hosted mainly in the Footwall Breccia (considered by some authors to be a facies of the Sublayer). They consist of massive stringers and lenses of pyrrhotite-dominated Ni-Cu sulphides (Ni:Cu generally greater than 1) that are commonly concentrated in depressions at the base of the Footwall Breccia host, and are oriented subparallel to the dip of the Sudbury Igneous Complex. Some ore zones, such as the Deep Ore zone at Strathcona, extend downward 200 m into the Levack Gneiss footwall as lenses and stringers of massive sulphide. North Range ores are generally zoned, with Ni:Cu ratios decreasing downward from the complex; at Strathcona Ni:Cu goes from 3:1 in noritic Sublayer to 2:1 in the Footwall Breccia to 1:1 in the Deep Ore zone.

The "offset" type of ores is hosted in the quartz dioritic "offsets" (Fig. 27.1-4C), the dyke-like facies of Sublayer that projects outward from the Sudbury Igneous Complex and penetrates the footwall rocks (Pattison, 1979; Cochrane, 1984; Grant and Bite, 1984). The offsets typically follow dykes of Sudbury Breccia, are steeply dipping, and are either subradial or subparallel to the basal contact of the complex. The Copper Cliff and Frood-Stobie offsets contain the most important of these ores. The ore mineralization generally has a Ni:Cu ratio close to 1, and occurs in two main forms: as disseminated sulphide "blebs" in lenticular zones of inclusion-rich quartz diorite located centrally in the offset, or as sheaths of sulphide bleb-bearing quartz diorite or sulphide-matrix breccia along the margins of the offset.

The Falconbridge, East Falconbridge, and Garson mines contain ore zones of the fault-related type (Souch et al., 1969; Owen and Coats, 1984). All are associated with near-vertical faults that cut the South Range Lower Zone norite and adjacent Huronian footwall mafic metavolcanic rocks of the Stobie Formation (Fig. 27.1-4D). Ores are of two types: "contorted schist inclusion sulphide" within the shear zones constitute the Main zone; and "inclusion massive sulphide" occurs as discontinuous lenses ("Southwall ores") in adjacent metavolcanic rocks.

Ores of the deep copper vein type (Fig. 27.1-4B) occur within the footwall, as much as 500 m below the Sublayer. The Deep Copper zone at Strathcona (Abel et al., 1979; Li et al., 1992; Money, 1993; Morrison et al., 1994) is hosted mainly in masses of thermally metamorphosed Sudbury Breccia within Levack Gneiss. The ore consists of anastamosing veins and stringers of massive sulphides. The minerals are mainly chalcopyrite and cubanite, and include minor amounts of pentlandite, magnetite, millerite, and pyrrhotite. Platinum and palladium are more highly enriched than in any other type of ore at Sudbury, but nickel values are low (Ni:Cu <<1). The massive veins are asymmetrically zoned, with pentlandite and pyrrhotite occupying the footwall side of the veins.

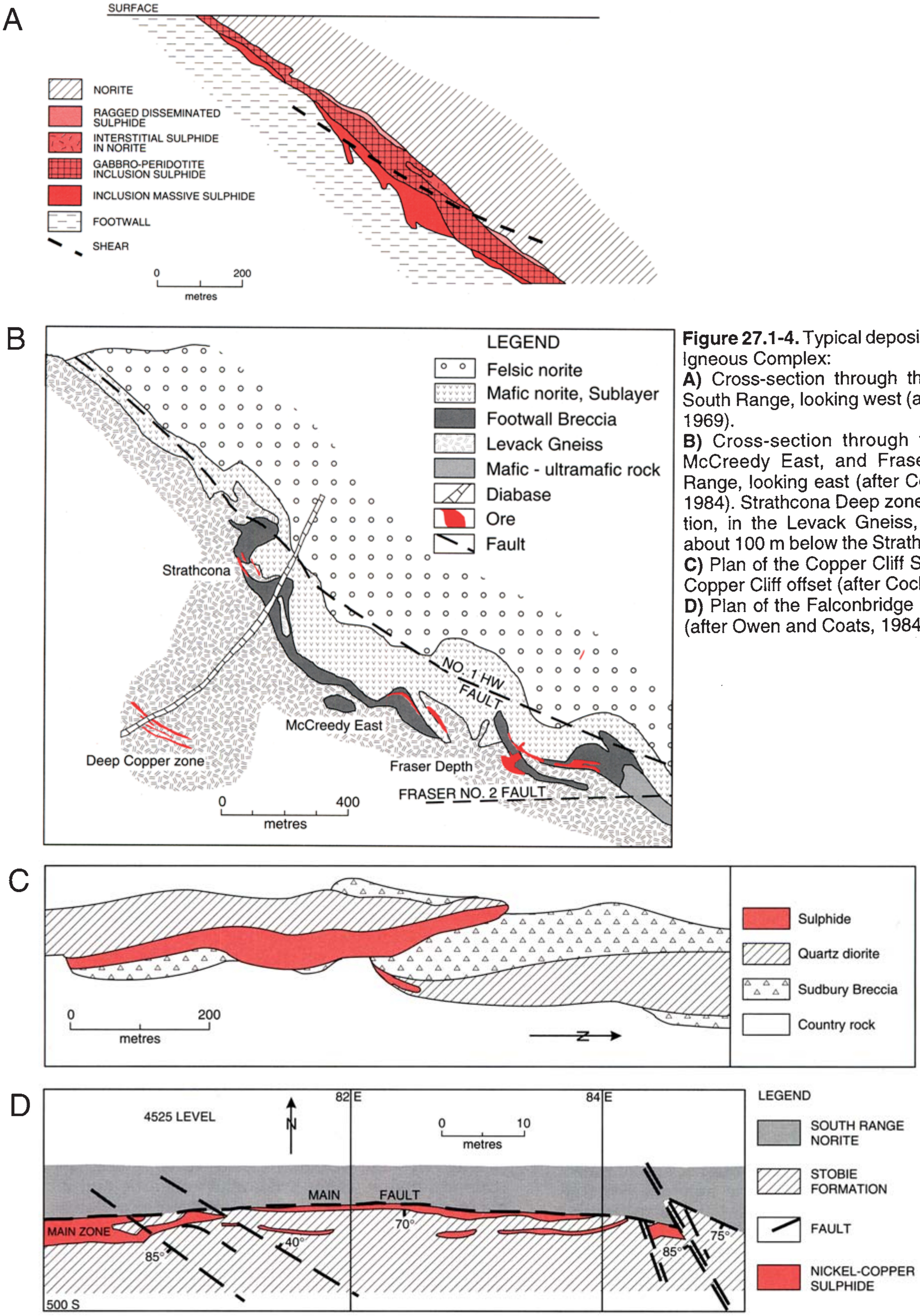

Figure 27.1-4. Typical deposits of the Sudbury Igneous Complex:
A) Cross-section through the Murray mine, South Range, looking west (after Souch et al., 1969).
B) Cross-section through the Strathcona, McCreedy East, and Fraser mines, North Range, looking east (after Coats and Snajdr, 1984). Strathcona Deep zone lies off this section, in the Levack Gneiss, stratigraphically about 100 m below the Strathcona Main zone.
C) Plan of the Copper Cliff South mine in the Copper Cliff offset (after Cochrane, 1984).
D) Plan of the Falconbridge mine, 4525 level (after Owen and Coats, 1984).

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Table 27.1-2. Compositions of typical Sudbury ores.

Deposit	Type	no.*	Ni	Cu	Co	Pt	Pd	Rh	Ru	Ir	Os	Au	Ni:Cu	Pd:Ir
Levack West	NR	21	5.73	3.72	0.16	1150	1250	186	60	7	22	150	1.54	178
Strathcona Main	NR	18	3.40	1.20	0.14	413	380	20	12	7	4	78	2.83	54
Strathcona Deep	FW	8	4.00	2.30	0.13	750	701	16	4	4	3	112	1.74	175
Strathcona Deep Copper	FW	32	1.97	28.27	0.03	4719	5213	<0.16	<2	0.11	<0.53	296	0.07	47 000
Little Stobie 1	SR	23	3.83	4.41	0.19	1930	2120	119	123	62	29	862	0.87	34
Falconbridge	FR	23	5.35	1.52	0.22	546	381	287	225	144	40	174	3.52	2.6

* no. of samples
Ni, Cu, Co in wt. %; Pt, Pd, Rh, Ru, Ir, Os, Au in ppb
NR = North Range, FW=Footwall, SR=South Range, FR=Fault-related
Data for Levack West, Little Stobie 1, and Falconbridge from Naldrett et al. (1982); data for Strathcona zones from Li et al. (1992).

Ore composition and zoning

Typical compositions of ore samples from several Sudbury deposits are given in Table 27.1-2. Data shown for Levack West and Strathcona Main are representative of the main North Range type, and those for Little Stobie 1 and Falconbridge are typical of two types found in the South Range.

In the North Range, ores are compositionally zoned from the mafic norite of the Sudbury Igneous Complex downward through the Footwall Breccia into the Levack Gneiss (Li et al., 1992). Figure 27.1-4B in conjunction with Table 27.1-2 illustrate the downward increase of Cu, Pt, Pd, and Au contents and decrease of Rh, Ru, Ir, and Os contents exhibited by the Main, Deep, and Deep Copper zones within the Strathcona mine. Enrichment of Cu, Pt, and Pd is extreme in the Copper and Deep Copper zones. Some South Range deposits exhibit similar zoning, e.g., the Lindsley deposit (Binney et al., 1994).

Mineralogy

The mineral assemblages of the Contact Sublayer, Offset Sublayer, and Footwall Breccia, which are the main hosts to ore, have been described above. The main ores (Naldrett, 1984) consist largely of the assemblage pyrrhotite (dominant, both hexagonal and monoclinic), pentlandite, chalcopyrite, pyrite, and magnetite. Bornite occurs locally in copper-rich zones. South Range ores are characterized by higher arsenic content, expressed as the arsenides niccolite and maucherite, and the sulpharsenides gersdorffite and cobaltite. The copper-rich vein ores deep in the footwall are dominated by chalcopyrite and cubanite, and contain lesser pentlandite, magnetite, and pyrrhotite. A considerable number of platinum-group minerals have been identified, the most abundant of which are michenerite (PdBiTe), moncheite ($PtTe_2$), and sperrylite ($PtAs_2$).

Rift- and continental flood basalt-associated nickel-copper: subtype 27.1b

The two best known examples of deposits of this type, the Noril'sk-Talnakh deposits of northern Siberia, and deposits in the Duluth Complex, Minnesota are associated with large continental flood basalt provinces. In Canada, this type is represented only by the Great Lakes Nickel deposit in the Crystal Lake intrusion, which is probably a northern extension of the Duluth Complex. The world-class Jinchuan deposit in China may also belong to this type. Though broadly similar in tectonic setting, the geology of these three districts is rather different in many respects, and they are described separately.

Noril'sk-Talnakh camp

The Permo-Triassic Noril'sk-Talnakh deposits (Fig. 27.1-5) occur near the northwestern margin of the Siberian Platform (Naldrett, 1989a; Simonov et al., 1994). The margin has a crystalline Proterozoic basement overlain by Riphean molassic strata, Lower Paleozoic marine dolostones, argillites, and sandstones, and Devonian marls and evaporites. Carboniferous shallow water limestones and continental sedimentary rocks that include coal measures are capped by a 3.5 km thickness of traps and tuff of the Permo-Triassic Siberian Flood Basalt Province, one of the largest in the world. Large mafic masses underlying the traps are indicated by aeromagnetic anomalies (Rempel, 1994). Near the base of the traps and related to them are small mafic-ultramafic hypabyssal intrusions (248 Ma; Likhachev, 1994) with which the Noril'sk-Talnakh nickel-copper-PGE deposits are associated. These sill-like intrusions occur along the regional north-northeast-trending Noril'sk-Kharayelakh fault, and have intruded strata from mid-Devonian to lower Triassic in age (Fig. 27.1-5).

Contents

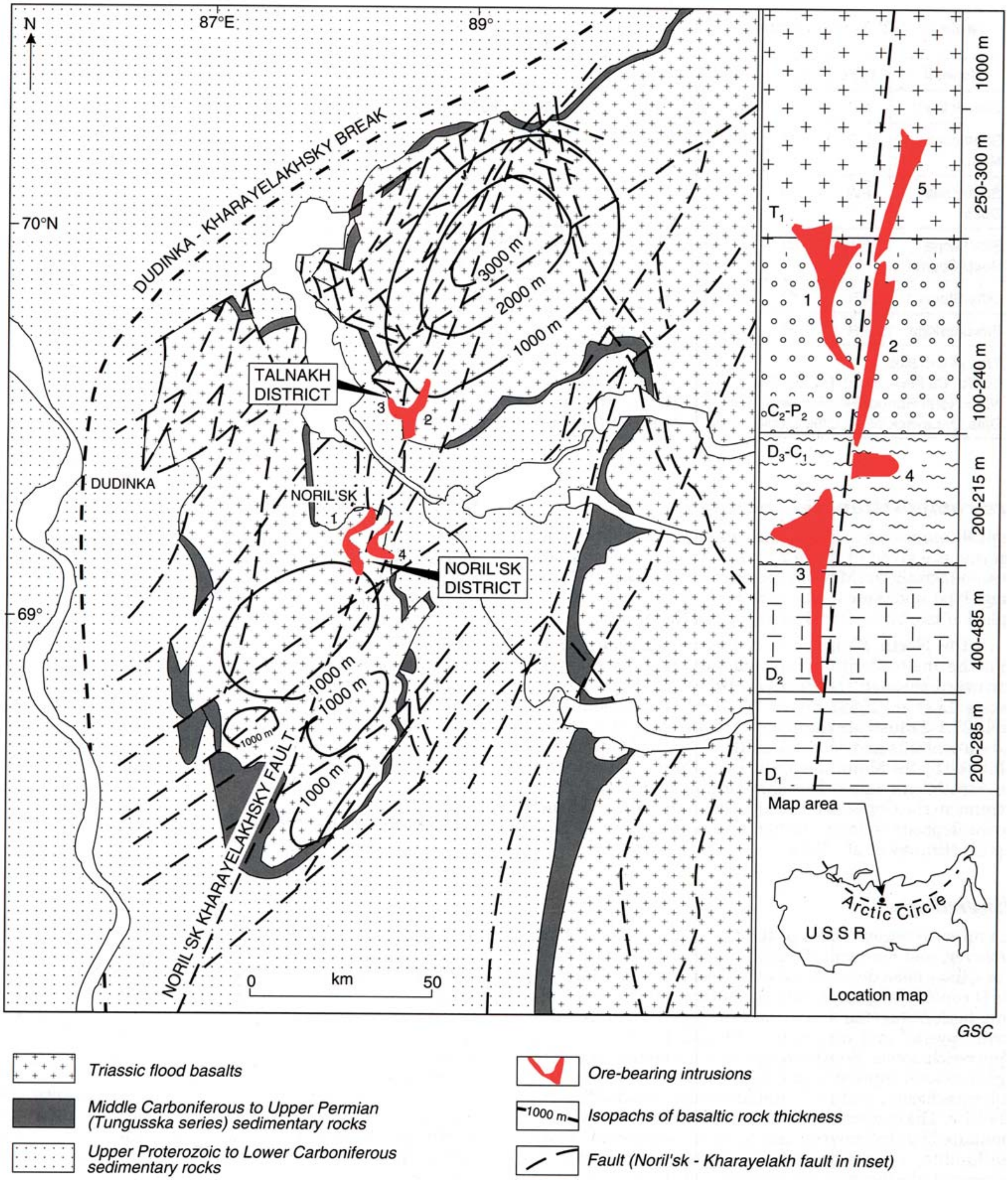


Figure 27.1-5. Regional geology of the Noril'sk-Talnakh area, showing the vertically projected locations of ore-bearing intrusions: 1 – Noril'sk I; 2 – Talnakh; 3 – Kharayelakh; 4 – Chernogorsky; 5 – (sic, not identified, not shown in plan) D = Devonian, C = Carboniferous, P = Permian, T = Triassic. The inset shows the stratigraphic position of the intrusions (after Likhachev, 1994).

The Noril'sk-Talnakh ore-bearing intrusions (Likhachev, 1994; Zen'ko and Czamanske, 1994) are mostly sill-like with known dimensions as great as 15 km in length, 0.5 to 2 km in width, and 50 to 300 m in thickness (Fig. 27.1-6). A typical intrusion consists of a highly differentiated main sill that passes from olivine-bearing, melanocratic gabbro-dolerites near the base upward through the succession of mafic units shown in Figure 27.1-7 to leucocratic gabbro-dolerites near the top. This sequence is considered by some to result from multiple magmatic pulses of different compositions. Olivine and plagioclase exhibit compositions ranging from Fo_{85} to Fo_{60}, and An_{95} to An_{40}, respectively (Likhachev, 1994). An exceptionally thick hornfels halo, as great as 250 m in thickness above and 100 m below, has affected the surrounding wall rocks.

The three main types of ore mineralization are disseminated, massive, and "copper" ores. The disseminated ores consist of droplets, schlieren, and fine sulphide veinlets dispersed through picritic, taxitic, and contact gabbro-dolerite in the lower portions of the intrusions, and form sheet-like conformable orebodies that in some cases exceed 40 m in thickness. Massive ores are also sheet-like bodies, but they undulate along the basal contacts of the intrusions, and commonly depart from the contacts to intrude the underlying metasedimentary footwall rocks. These ores are the most important type in the Talnakh camp, and form massive sulphide bodies as large as 1.5 km long, several hundreds of metres wide, and several tens of metres thick (Distler, 1994). The bulk of these ores have a uniform composition (pyrrhotite-dominated chalcopyrite-pentlandite, Cu:Ni=0.8), but some portions exhibit striking compositional zoning which gives rise to zones having extreme copper- and PGE-enrichment. The resulting succession of sulphide assemblages ranges from pyrrhotite-chalcopyrite-pentlandite, through decrease in the proportion of pyrrhotite and increase in copper sulphide, to one consisting almost entirely of cubanite, mooihoekite, and talnakhite. The "copper" ores are of two types; one consists of disseminated veinlets of copper-rich sulphides that form a halo around the periphery of massive ore in both sedimentary and intrusive rocks; while the other comprises breccia ores with a copper sulphide matrix that occur in the foundered roofs of some intrusions (Fig. 27.1-7).

Noril'sk ores are probably the richest in PGEs of all known Ni-Cu sulphide (subtype 27.1) deposits. The ordinary massive pyrrhotite-chalcopyrite-pentlandite ores reported by Zientek et al. (1994) and Distler (1994) contain 0.6-3 g/t Pt and 4-13 g/t Pd. The PGE contents increase with

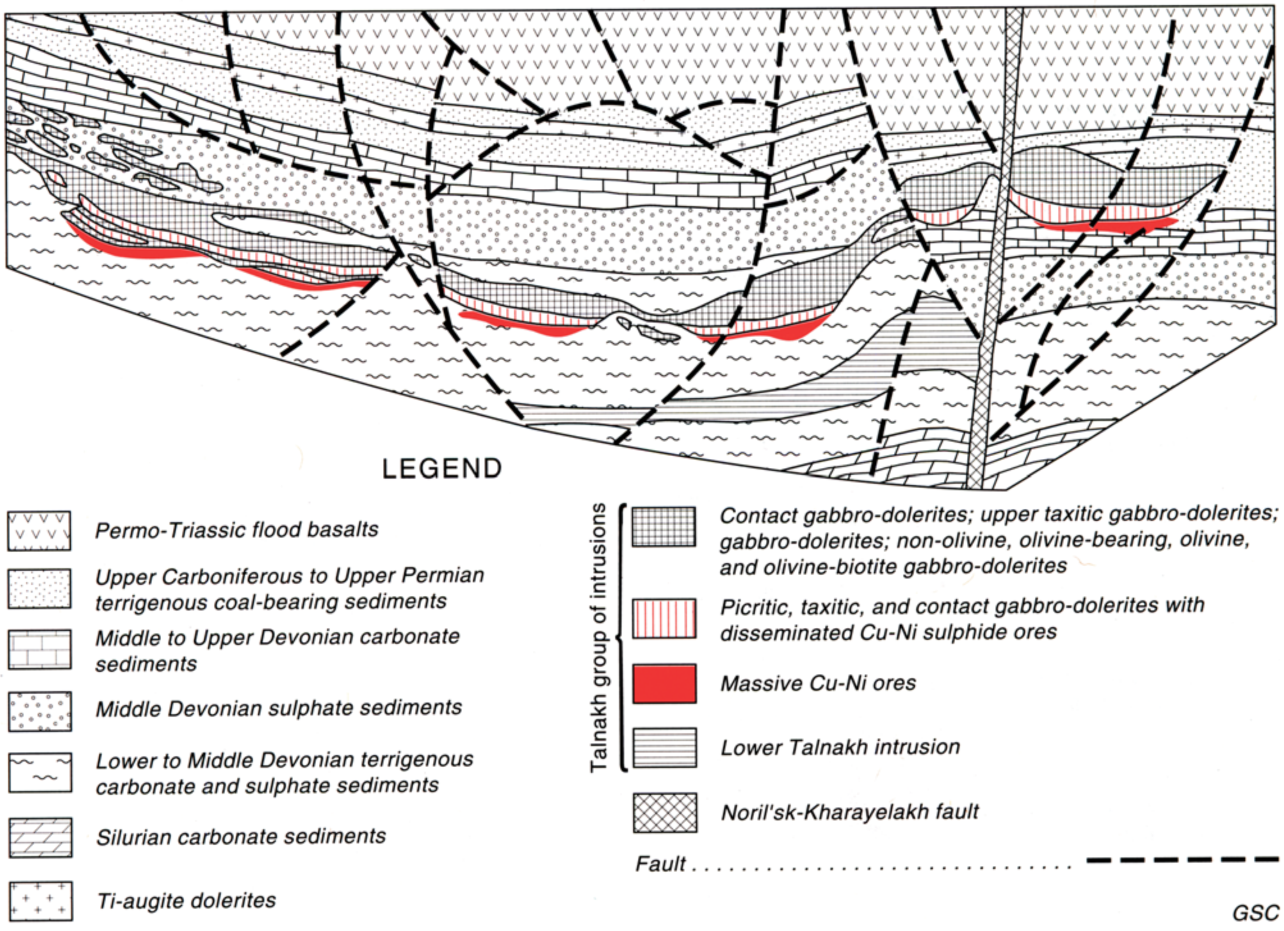


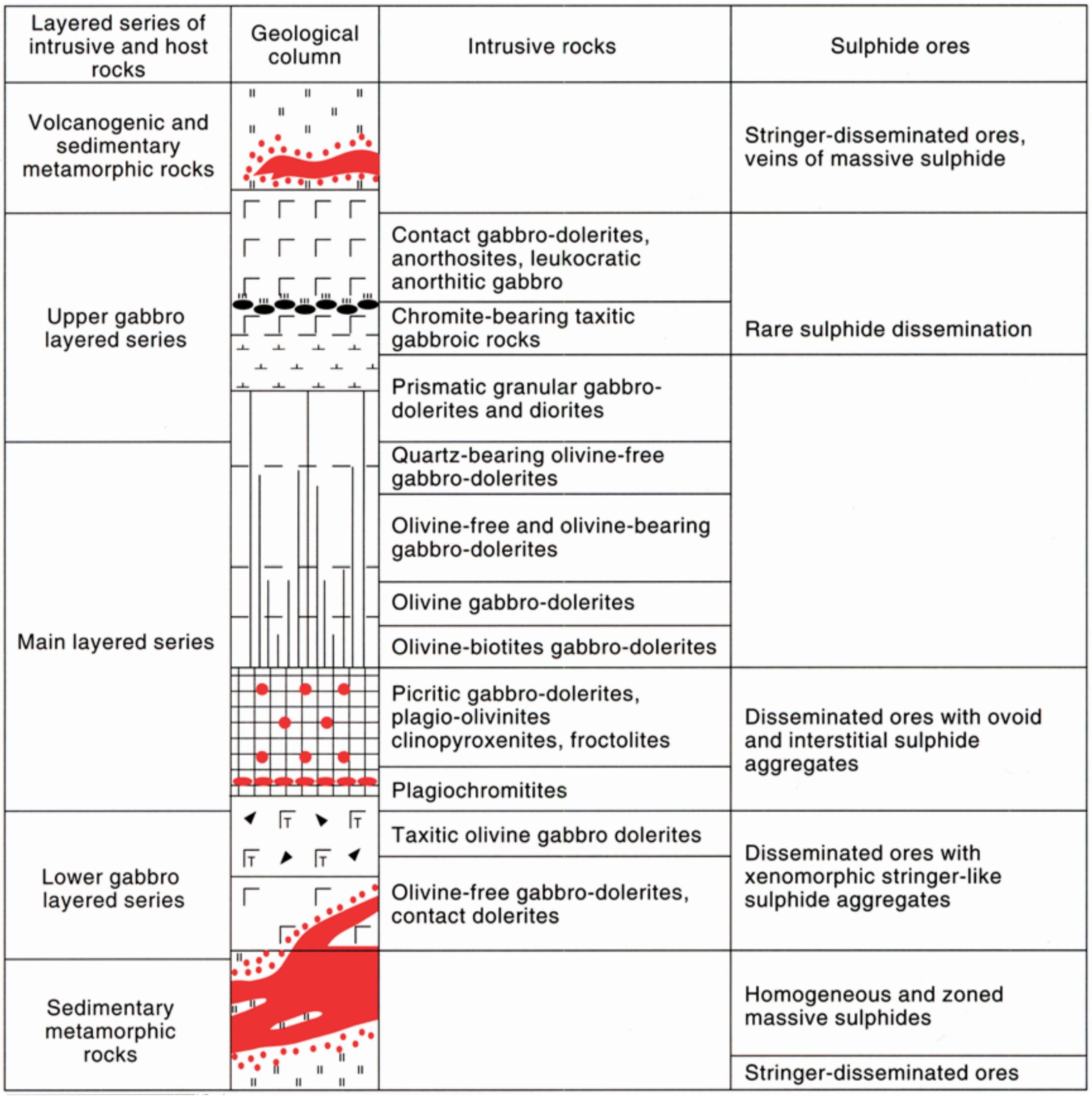
Figure 27.1-6. Sckematic cross-section through Talnakh camp, showing stratigraphic setting of ore-bearing intrusions and locations of sulphide ores (after Duzhikov et al., 1992).

Cu grade, achieving their highest values in massive sulphides that have >25% Cu, namely 5-24 g/t Pt and 30-140 g/t Pd.

Duluth Complex-related copper-nickel mineralization

The Duluth Complex in Minnesota is an arcuate mass of mafic intrusions more than 225 km in length that constitute part of a major 1.1 Ga intracontinental rift structure known as the Mid-Continent Rift system (Green, 1983). The complex is closely associated with the overlying tholeiitic flood basalts (North Shore Volcanics); together they have a combined thickness of 15 km. South of Thunder Bay in Ontario, the Crystal Lake gabbro is a small intrusion that appears to be a northern satellite of the Duluth Complex. Both contain similar, low-grade disseminated copper-nickel mineralization, as yet undeveloped, but representing significant resources.

The Duluth Complex as a whole dips gently southeastward, and is made up of an extensive cap of layered anorthositic rocks and a suite of younger troctolitic intrusions that forms the basal portion of the complex (Weiblen and Morey, 1980; Weiblen, 1982; Naldrett, 1989a). The intrusions also include dunite, peridotite, pyroxenite, gabbro, and norite. The base of the complex lies in contact with Archean granite and greenstone, and Lower Proterozoic graywacke, slate, and iron-formation. The lower parts of the troctolitic masses are characterized by abundant xenoliths, which include gabbroic and anorthositic rocks, but also Lower Proterozoic metasedimentary rocks.



Layered series of intrusive and host rocks	Geological column	Intrusive rocks	Sulphide ores
Volcanogenic and sedimentary metamorphic rocks			Stringer-disseminated ores, veins of massive sulphide
Upper gabbro layered series		Contact gabbro-dolerites, anorthosites, leucocratic anorthitic gabbro	Rare sulphide dissemination
		Chromite-bearing taxitic gabbroic rocks	
		Prismatic granular gabbro-dolerites and diorites	
Main layered series		Quartz-bearing olivine-free gabbro-dolerites	
		Olivine-free and olivine-bearing gabbro-dolerites	
		Olivine gabbro-dolerites	
		Olivine-biotites gabbro-dolerites	
		Picritic gabbro-dolerites, plagio-olivinites clinopyroxenites, froctolites	Disseminated ores with ovoid and interstitial sulphide aggregates
		Plagiochromitites	
Lower gabbro layered series		Taxitic olivine gabbro dolerites	Disseminated ores with xenomorphic stringer-like sulphide aggregates
		Olivine-free gabbro-dolerites, contact dolerites	
Sedimentary metamorphic rocks			Homogeneous and zoned massive sulphides
			Stringer-disseminated ores

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Figure 27.1-7. Differentiation units and ore distribution in the Talnakh ore-bearing intrusions (after Distler, 1994).

Copper-nickel mineralization in the Duluth Complex (Ripley, 1986) occurs as numerous zones (combined in the composite grade/tonnage data shown in Table 27.1-1), mainly in the basal portions of two of the troctolitic intrusions (South Kawishiwi, Partridge River). The mineralization consists principally of disseminated pyrrhotite, chalcopyrite, cubanite, and pentlandite. Massive sulphides are significant in only a few of the mineralized zones. The mineralization generally occurs within 100 m of the basal contact, but some zones are 300 to 400 m above the contact. The mineralized zones are typified by abundant metasedimentary xenoliths, textural heterogeneity of the host rock, and variable rock composition.

The Crystal Lake intrusion in Ontario (Geul, 1970; Eckstrand et al., 1989b; Cogulu, 1990, 1993), though much smaller, bears many similarities to the Duluth Complex. It is dyke-like in plan, about 700 m wide, and canoe-shaped in cross-section. Internal layering is trough-shaped. The intrusion comprises a basal contact gabbro, a lower zone of olivine gabbro, an overlying cyclically layered zone of anorthosite-troctolite, and an upper zone of olivine gabbro. The lower zone contains the Great Lakes Nickel deposit (see Table 27.1-1) which consists of pyrrhotite-chalcopyrite-cubanite-pentlandite mineralization that is disseminated within olivine gabbro. Like the mineralized troctolite of the Duluth Complex, the olivine gabbro has heterogeneous texture, and abundant cognate and hornfelsed metasedimentary xenoliths.

Jinchuan camp

The Jinchuan nickel-copper sulphide deposits are located in Gansu province, north central China in a northwesterly trending, uplifted and faulted belt that forms the southwestern margin of the Sino-Korean platform (Chai and Naldrett, 1992a, b). The deposits are hosted by a dyke-like ultramafic body that has intruded Lower Proterozoic migmatite, gneiss, and marble. Chai and Naldrett (1992a) have suggested that the intrusion may have been a feeder for continental rift-associated basaltic volcanism.

Rock types range from dunite to olivine pyroxenite, but the matrix and disseminated nickel-copper sulphide ores occur mainly in dunite and peridotite in the lower part of the intrusion. The main ore minerals are pyrrhotite, pentlandite, violarite, chalcopyrite, and cubanite.

Komatiite-hosted nickel subtype 27.1c

Geological setting

Naldrett (1989a) has recognized two types of komatiite-hosted nickel deposits, the first found in Archean greenstone belts, and the second in rifted, mainly Lower Proterozoic, continental margins.

Komatiites in Archean greenstone belts

The greatest concentration of nickel deposits within Archean greenstone belts is in Western Australia, in the northerly trending, 800 km long Norseman-Wiluna greenstone belt in the eastern part of the Yilgarn craton (Marston et al., 1981; Groves et al., 1984; Lesher, 1989). Most of the deposits (Kambalda, Agnew, Mt. Keith, Nepean, Scotia) are confined to a central fault-bounded rift zone as much as 200 km wide, characterized by abundant komatiites and sulphidic cherts thought to represent a deep marine environment. The sequence of nickel ore-bearing spinifex-textured komatiitic peridotite flows in the Kambalda dome (Fig. 27.1-8) is believed to be correlative with similar ore-bearing komatiites (Gemuts and Theron, 1975) throughout an extensive surrounding part of this central rift zone. On either side of the central rift, the greenstone sequences comprise platformal suites of basalts, shallow-water volcaniclastic rocks, and oxide facies iron-formation, and contain a few komatiitic nickel deposits (Windarra and Forrestania districts).

Most of the Canadian Archean nickel deposits are found in the Abitibi greenstone belt of the Superior province (e.g., Langmuir, Redstone, Marbridge, Texmont, Alexo; Coad, 1979; Barnes, 1985; Barrie et al., 1993). Those in the Shaw dome area south of Timmins are associated with a discontinuous horizon of spinifex-textured komatiitic flows (probably 2707 Ma; Corfu, 1993) at the base of a volcanic cycle which comprises an ultramafic-mafic-felsic succession. Other nickel deposit-bearing komatiites in the Timmins area are considered to be part of the same horizon. Furthermore, in both the Kambalda and Shaw dome-Timmins areas, most of the ore-bearing komatiites are directly underlain by sulphidic sediments (Coad, 1979; Lesher, 1989). Many believe these sediments are the source of sulphur that became incorporated in the komatiitic magmas and gave rise to the ores.

In both the Norseman-Wiluna and Abitibi greenstone belts, some larger, but subeconomic, low grade disseminated nickel sulphide deposits occur in thicker and larger dunitic sills of komatiitic affiliation. These are generally separate from the areas in which extrusive komatiite-hosted nickel deposits occur.

Komatiites in rifted (Proterozoic) continental margins

The most important komatiitic nickel deposits associated with rifted continental margins are those in the early Proterozoic Thompson Nickel Belt of northern Manitoba (Zurbrigg, 1963; Peredery et al., 1982). These deposits are associated with peridotitic lenses that typically occur in sulphidic metapelites (biotite schist) of a sedimentary-volcanic shelf sequence (Ospwagan Group) on the northwestern margin of the Archean Superior province craton (Bleeker, 1990). The supracrustal rocks include siltstone, sandstone, quartzite, shale, phyllite, dolomite, iron-formation, and pillowed basalts. Subsequent Hudsonian (early Proterozoic) collisional deformation has given rise to the pronounced linearity of the belt, and juxtaposed it with upper amphibolite and granulite gneisses (Kisseynew Group) of the Trans-Hudson orogen to the northwest. Several periods of folding and amphibolite facies metamorphism have pervasively reworked the original ore-host relationships in many deposits.

The komatiitic nickel deposits of the early Proterozoic Cape Smith belt in the Ungava Peninsula of northern Quebec, like those of Thompson, are also related to the rifted continental margin of the Superior Province craton (Baragar and Scoates, 1981). The deposits occur in a Hudsonian fold-and-thrust belt in a series of peridotitic lenses along a particular sediment-volcanic contact in an allochthonous, recumbently folded sequence of marine

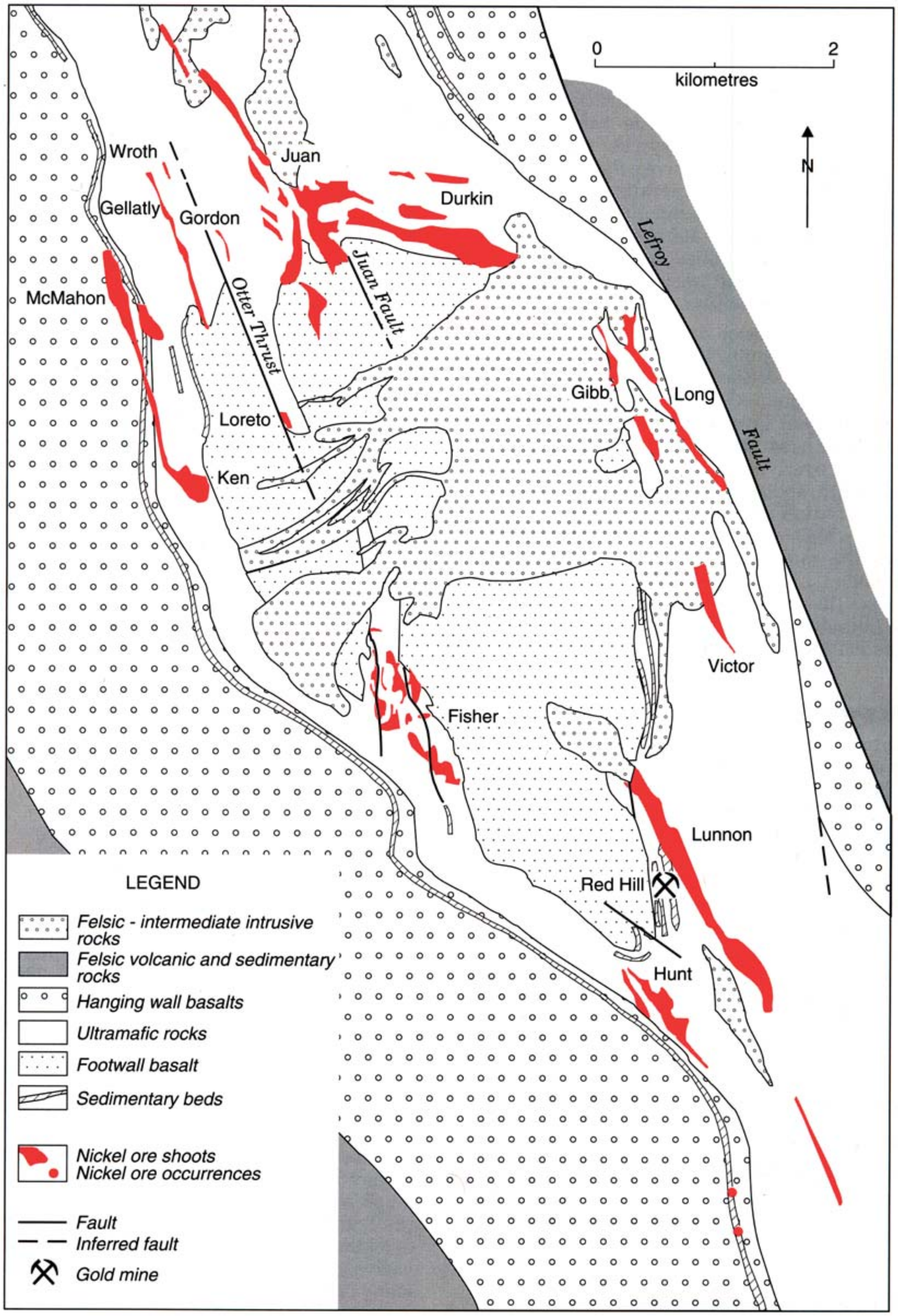

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Figure 27.1-8. Plan of general geology of the Kambalda camp showing surface projections of orebodies (after Gresham and Loftus-Hills, 1981).

Table 27.1-3. Comparison of komatiitic hosts and nickel ores.

Deposit	MgO% (rock)	FeO/FeO+MgO (rock)	Olivine composition (%Fo)	Type of pyroxene	Ni:Cu	Reference
Langmuir (Archean, Ontario)	48.5	0.24	na	na	16	Green and Naldrett, 1981
Kambalda (Archean, Australia)	43	0.16-0.20	94	cpx	13	Marston et al., 1981; Lesher, 1989
Thompson (Proterozoic, Manitoba)	44	0.15	90	opx>>cpx	14	Peredery, 1979; Peredery et al., 1982; Paktunç, 1984
Pipe 2 (Proterozoic, Manitoba)	na	0.25	na	opx>>cpx	12	Peredery, 1979; Peredery et al., 1982
Katiniq (Proterozoic, Quebec)	36	0.31	na	cpx	4.3	Barnes et al., 1982

na = not available
Fo = forsterite, cpx = clinopyroxene, opx = orthopyroxene

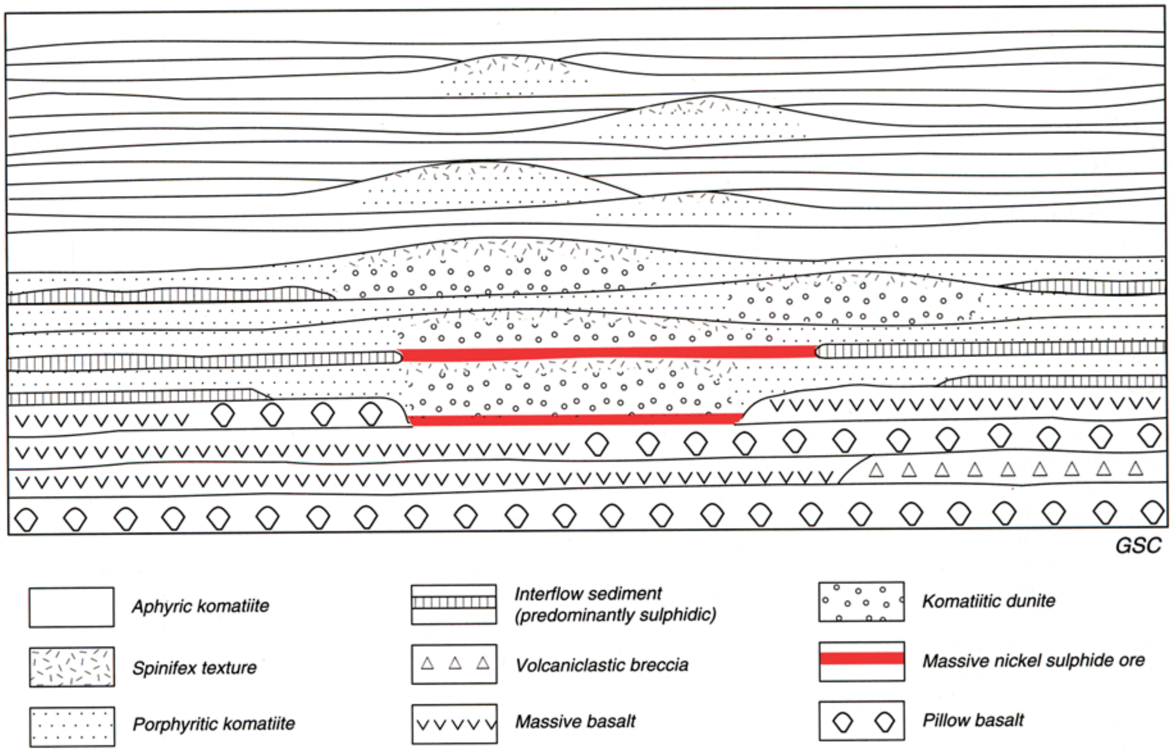

Figure 27.1-9. Schematic cross-section of komatiitic flow sequence showing position of basal and hanging wall orebodies, and graben-like depressions in which basal ores are typically located (after Lesher, 1989).

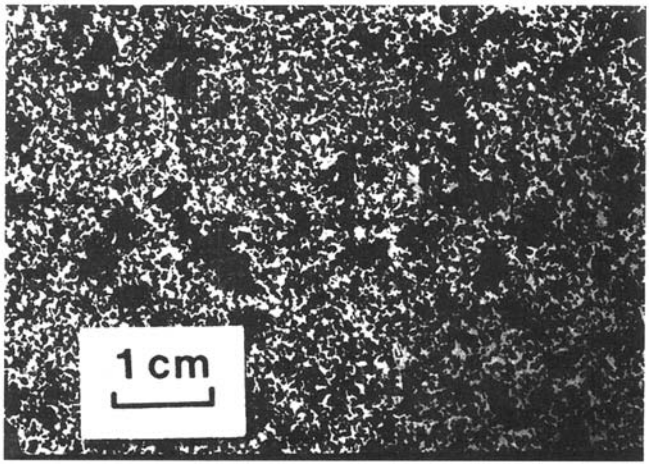

Figure 27.1-10. Matrix sulphides (white) enclose relict cumulus olivine (black) in serpentinized komatiitic peridotite, Alexo mine, Timmins, Ontario. GSC 203887

shales and komatiitic basalts (St-Onge and Lucas, 1990). The peridotites were originally regarded as intrusions (Barnes et al., 1982), but an extrusive origin now seems more likely (Barnes and Barnes, 1990), and they appear to form part of the lower Chukotat volcanic sequence (Lesher et al., 1991).

Nature of ore deposits

Most komatiite-hosted nickel sulphide deposits occur at or near the base of an extrusive sequence, and are typically in the lowest, thickest, and most magnesian of the flows. Barrie et al. (1993) have noted that MgO contents (marginal chilled zone, anhydrous) of ore-bearing komatiites are 20 to 35% whereas those of barren komatiites are 10 to 25%.

The ores comprise conformable lenses of mineralization concentrated within, and near the basal contact of the layer-like or lenticular peridotitic host unit. Most ore bodies occur in the lowermost flow unit, but some, generally smaller, are in overlying units (Fig. 27.1-9). The mineralization includes matrix (continuous network of sulphides enclosing olivine crystals) and massive sulphides, and in many cases, disseminated sulphides. The common sequence of sulphides from the base upward is massive, matrix, and disseminated. The ores commonly occur in local depressions of one kind or another in the base of the host unit. At Kambalda, many of these depressions resemble fault-bounded troughs (Fig. 27.1-9), but their mode of formation remains unclear (Lesher, 1989). Similarly, the Langmuir deposits in the Timmins area of Ontario are controlled by basal trough-like structures (Green and Naldrett, 1981). In the less structurally disrupted deposits of the Cape Smith Belt, the ore-bearing basal depressions appear to be simple embayments, which Lesher (1989) has interpreted as thermal erosion channels (see "Genetic model").

The host rocks and ores differ from district to district in the magnesian character of the host rocks, and the Ni:Cu ratios of the ores (Table 27.1-3), and may also show variation within a single district. On a district comparison basis, MgO content of the ultramafic hosts correlates roughly with Ni:Cu ratio of the ores. Thompson appears unique in that the peridotitic host rocks are harzburgites rather than wehrlites as they are in most other cases.

Metamorphism and alteration

Komatiitic ores and their hosts have generally been subjected to regional metamorphism at grades ranging from prehnite-pumpellyite (e.g., Alexo, east of Timmins, Ontario) to upper amphibolite (e.g., Thompson, Manitoba). In general, this has profoundly affected silicate mineralogy and texture, whereas sulphide-rich ores have simply recrystallized with a new fabric but with little change in the original pyrrhotite-pentlandite-pyrite assemblage (Lesher, 1989). At low metamorphic grades, peridotitic hosts become serpentinized but typically retain relict cumulus olivine and intercumulus matrix sulphide textures (Fig. 27.1-10). At intermediate grades (lower amphibolite), the new metamorphic minerals may form intimate intergrowths with sulphides that seriously hamper efficient mechanical recovery of nickel sulphides. At these metamorphic grades, carbonate (magnesite-dolomite) alteration is common. This destroys primary textures, and partially or completely converts pyrrhotite-pentlandite assemblages to pyrite-millerite (NiS). In leaner mineralization (<5% sulphides), serpentinization results in replacement of pentlandite by heazlewoodite (Ni_3S_2) or awaruite (~$FeNi_3$), and of pyrrhotite by magnetite (Eckstrand, 1975), rendering metallurgical recovery more complex.

Effects of deformation

Because sulphide concentrations (especially massive sulphides) are structurally incompetent, and because the ores generally occur at basal contacts where there is a competency contrast with wall rocks, later quasiconformable faulting has commonly been localized within the ore zones. This has in certain deposits (e.g. Kambalda, Langmuir) produced sheet-like zones of mobilized sulphide-matrix breccia ores which in some cases extend beyond the host ultramafic unit.

Deformation of ores and host rocks at the Thompson mine has been extreme, and little remains of their original physical relationships. The parent harzburgitic sill(s) has been stretched and dismembered into a horizon of ultramafic blocks and boudins that are enclosed in the sulphide-rich pelitic schist unit that hosts the ores (Bleeker, 1990). The pyrrhotite-dominated nickel sulphide ores are zones in the pelitic schist that contain abundant quasiconformable lenses and stringers of massive sulphides which enclose numerous wall rock inclusions. Other deposits and their hosts in the Thompson Nickel Belt (Pipe, Birchtree, Soab, Manibridge, Bucko, Bowden) show similar though less extreme effects of deformation. In general, most komatiitic sulphide-rich ores have undergone some deformation, typically resulting in sulphide-matrix breccias containing wall rock clasts (Fig. 27.1-11).

Mineralogy

The main ore minerals at Kambalda in order of decreasing abundance are pyrrhotite, pentlandite, pyrite, magnetite, chromite, millerite, and violarite. This ore assemblage is representative for most komatiitic deposits.

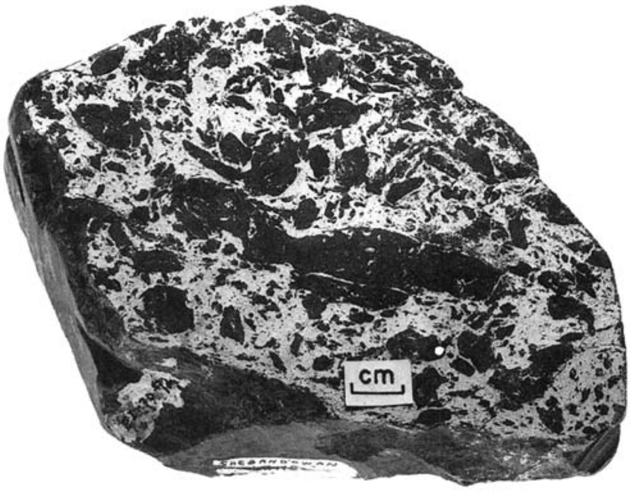

Figure 27.1-11. Suphide-matrix (white) breccia ore with clasts of mafic metavolcanic wall rocks (black), Shebandowan, Ontario. GSC 203886-F

Original minerals in komatiites comprised mainly olivine, clinopyroxene, glass, and chromite (Lesher, 1989). However all komatiitic rocks have been metamorphosed and/or altered to assemblages that include combinations of lizardite, antigorite, tremolite, chlorite, talc, magnesite, dolomite, magnetite, and ferrochromite. The particular assemblage depends on the composition of the ultramafic precursor, metamorphic conditions, and the extent and intensity of carbonate metasomatism.

Other tholeiitic intrusion-hosted nickel-copper: subtype 27.1d

Geological setting

A diverse group of mostly small nickel-copper deposits are associated with tholeiitic, commonly stock-like, intrusions that occur in a variety of terranes. These include Lynn Lake (Pinsent, 1980), Giant Mascot (Aho, 1956), Montcalm (Barrie and Naldrett, 1989), and St. Stephen (Paktunc, 1989) in Canada. The most notable foreign examples are Monchegorsk in Russia (Gorbunov et al., 1985), Kotalahti in Finland (Gaál, 1980; Papunen and Koskinen, 1985), and Selebi-Pikwe in Botswana (Table 27.1-1). Ages range from Archean to Mesozoic, and the settings include Archean greenstone belts, and Proterozoic and Phanerozoic, weakly to strongly metamorphosed, sedimentary-volcanic fold belts. The intrusions are generally small, for example the Lynn Lake pluton is 1.5 km by 3.5 km in surface plan. They are strongly differentiated, generally ranging in composition from peridotite to quartz diorite. Most of the intrusions appear to have been deformed and metamorphosed.

Nature of ore deposits

The nickel-copper ores are mainly associated with the mafic and ultramafic facies of the intrusions, rarely with the intermediate or felsic facies. This is the case at Kotalahti where most ore zones occur in peridotites and pyroxenites, and only a few are in gabbro (Papunen and Koskinen, 1985). At St. Stephen, the main ores are hosted in troctolite and olivine gabbro (Paktunc, 1989). The ores typically form lenticular shoots, such as those in the Lynn Lake deposit (Pinsent, 1980) where many of the orebodies are subvertically oriented cigar-shaped zones of mineralization within similarly oriented masses of peridotite, gabbro, and amphibolite. All the three usual types of mineralization, massive, matrix, and disseminated, are present in most deposits. The massive type is commonly sulphide-matrix breccia or massive veins that result from deformation of sulphide-rich ore, as for example at Lynn Lake and Montcalm. The less sulphide-rich ores commonly consist of lenticular or ribbon-like zones of disseminated sulphide blebs and stringers.

Ore composition

The sulphide minerals consist of the usual pyrrhotite-pentlandite-chalcopyrite-pyrite assemblage. Pyrrhotite is more abundant than in ores of the other subtypes, reflecting the generally lower bulk content of Ni (mostly <5 wt.%), Cu, and PGEs in sulphides of this subtype. Nickel:copper ratios typically lie in the range 3:1 to 1:1.

The Voisey Bay Ni-Cu deposit near Nain in Labrador, discovered in 1994, adds a significant new example to the tholeiitic intrusion-hosted type of nickel deposits (27.1d). It consists of a lens of massive sulphide up to 100 m thick which contains a minimum of 27 Mt grading 3.6% Ni, 2.17% Cu and 0.15% Co. The lens is hosted in a melatroctolitic dyke-like body that may be an apophysis of a troctolitic member (Reid Brook intrusion) of the anorogenic Nain Plutonic Suite (1350-1290 Ma). The deposit is located near the 1800 Ma collisional boundary between the Archean Nain Province and the Paleoproterozoic Churchill Province (Ryan et al., 1995).

DEFINITIVE CHARACTERISTICS

General

1. All magmatic sulphide deposits are associated with mafic and/or ultramafic igneous rocks. In most subtypes of these deposits, these bodies are intrusions, but in the case of the komatiitic subtype (27.1c) they are extrusive flows.
2. The sulphide ores are commonly segregated at or near the base of the hosting magmatic body, and consist of the assemblage pyrrhotite-pentlandite-chalcopyrite(-pyrite-magnetite).

Astrobleme-associated nickel-copper: subtype 27.1a

1. The Sudbury deposits are uniquely characterized by the associated presence of shock metamorphic features in the wall rocks to the intrusion, attributed by most geologists to meteoritic impact. Most ores that extend into footwall rocks are hosted by breccias which are considered shock or impact related.
2. The ores are contained in the Sublayer, a unit at the base of the Sudbury Igneous Complex that is characterized by the presence of nickel-copper sulphides and ultramafic xenoliths of nonlocal origin. The Sublayer

consists of a discontinuous noritic basal contact unit and quartz dioritic apophyses ("Offsets") that project into footwall rocks.

Rift- and continental flood-basalt-associated nickel-copper: subtype 27.1b

1. These deposits are associated with mafic-ultramafic intrusions that are related to continental rifting and flood basalt suites.
2. At Noril'sk-Talnakh, the richest ores are separate apophyses of massive sulphide that lie below the associated differentiated sill.
3. At Jinchuan, the ore consists of matrix and disseminated sulphides in dunitic and peridotitic facies of a dyke-like ultramafic host intrusion.

Komatiite-hosted nickel: subtype 27.1c

1. The ores are typically hosted by Precambrian komatiitic volcanic flows.
2. The orebodies are generally lenses of matrix and massive sulphides that occupy depressions in the floors of the flows.
3. These are the most nickel-rich ores of all subtypes; the more magnesian komatiitic hosts contain ores that commonly have Ni:Cu ratios >10.

Other tholeiitic intrusion-hosted nickel-copper: subtype 27.1d

1. The ores are associated with well differentiated, generally stock-like tholeiitic ultramafic-mafic intrusions of a wide range of ages and tectonic settings.

GENETIC MODEL

Genetic models for all subtypes of nickel sulphide deposits require (1) the generation of a sulphide melt associated with a mafic or ultramafic silicate magma, and (2) its accumulation into economic concentrations of nickel-copper sulphide. If such a sulphide melt is brought into equilibrium with a sufficiently large volume of silicate magma containing normal background levels of nickel, copper, and PGEs, the preference of these metals for the sulphide phase (i.e., their chalcophile tendency) will produce ore grade concentrations in the melt. Experiment-based numerical modelling involving partition coefficients and "R factors" (ratio of silicate magma to sulphide melt) has demonstrated that the melt should acquire the approximate Ni, Cu, and PGE contents that are observed in magmatic sulphide deposits (Campbell and Naldrett, 1979; Naldrett, 1989a, b; Fleet et al., 1993). Furthermore, variations in the contents and ratios of base and precious metals in these sulphide deposits can be attributed to differences in the proportions (R factors) of silicate and sulphide melts that came into equilibrium, and the compositions of the original silicate melts.

An important corollary of the silicate-sulphide equilibration just described is that the resulting silicate mass should be depleted of some of its original metal content. This depletion has been identified in a number of komatiitic hosts containing nickel deposits (Thompson and Naldrett, 1984; Duke, 1986; Lesher, 1989).

It is generally considered that Ni, Cu, and PGEs were present in the original magmas in quantities sufficient to produce the sulphide ores in which these metals became concentrated. Whether there was also enough sulphur in the original magma to produce the sulphide ores is not clear; in fact this seems doubtful. Evidence from a number of magmatic nickel deposits such as Thompson (Eckstrand et al., 1989a), Kambalda, and other Archean komatiitic deposits, Ungava, Duluth Complex (Ripley, 1986), Crystal Lake (Eckstrand et al., 1989b), and St. Stephen (Paktunc, 1989) suggests that nickeliferous sulphide melts were generated by contamination of the mafic magma with sulphur from crustal rocks, generally sulphidic sediments. The evidence is based on isotopic data (S, Sr, Nd, Os), Se/S ratios, and the presence of xenolithic material. Mechanisms of contamination that have been suggested include assimilation of sulphidic wall rock and metasomatic migration of sulphur out of the wall rock, into the magma. Consistent with this hypothesis of a crustal source of sulphur, is the fact that virtually all nickel sulphide deposits occur in rocks underlain by continental crust.

However, some deposits have characteristics that contradict crustal contamination. In the Noril'sk deposits, although S isotopic evidence reflects a crustal source of sulphur (Grinenko, 1985), Os isotopes indicate a mantle source (Walker et al., 1994). Abitibi komatiitic flows that host nickel deposits show little isotopic evidence of crustal contamination (Barrie et al., 1993). Cases such as these could possibly be explained by invoking uncontaminated mantle-derived magmas that were affected in the crustal regime only by the addition of sulphur through metasomatism.

Basal massive and matrix sulphides suggest early separation (liquation) of sulphide melt out of the magma, and its gravitational settling. In contrast, internal zones of disseminated sulphides more likely result from separation when silicate crystallization was more advanced, and settling of sulphide droplets was impeded (Lesher, 1989).

When a large body of sulphide melt accumulates and solidifies, it will undergo fractional crystallization, and, analogous to silicate magmas, produce crystallized sulphides of a range of compositions. Naldrett et al. (1994b) have proposed that this mechanism operated in the case of the Sudbury sulphide ores of the North Range (Fig. 27.1-4B). It has given rise to a sequence of ore zones that range from pyrrhotite-rich and Cu-poor at the base of the Lower zone (representing early crystallized monosulphide solid solution) to Cu-Pt-Pd-rich and lacking in pyrrhotite well down in the footwall (representing late residual liquids). The same mechanism could explain the dramatic compositional zoning of copper, platinum, and palladium content in massive sulphide ore at Talnakh (Naldrett et al., 1994c; Zientek et al., 1994).

The different subtypes of deposits differ in detail with regard to modes of emplacement of the magmatic hosts and the accumulation of the sulphide ores.

The Sudbury Igneous Complex and its ores (subtype 27.1a) are considered to have been emplaced at the site of a major explosive event, probably a meteoritic impact, which is the most favored hypothesis, or possibly a volcanic explosion (Naldrett, 1984). Shock features identified in footwall rocks indicative of peak pressures of 20 GPa (Müller-Mohr, 1992) appear to require a meteoritic impact origin. The composition of the Sudbury Igneous Complex indicates a large crustal component, and the hypotheses proposed to explain this range from strongly contaminated, mantle-derived basaltic magma (Naldrett, 1984) to a completely locally derived melt resulting from meteoritic impact (Golightly, 1994; Grieve, 1994). An intermediate hypothesis proposes that the Upper zone granophyre represents impact melt, and the Lower zone norite is a highly contaminated mantle-derived magma (Chai and Eckstrand, 1994).

In other respects, however, the genesis of the Sudbury ores seems explicable by normal terrestrial processes. After recognition of the Sublayer and of its significance as the main ore-bearing unit (Souch et al., 1969), it came to be regarded as a separate intrusion at the base of the complex. However, whether the Sublayer is older or younger than the main Irruptive remains controversial because of apparently conflicting evidence. It seems possible that the Sublayer simply represents the chilled basal border zone of the complex in which sulphides and dense xenoliths have accumulated gravitationally from the overlying Lower zone (Golightly, 1994).

Rift- and continental flood basalt-associated nickel-copper deposits (subtype 27.1b) are associated with major magmatic provinces. In the case of Noril'sk-Talnakh, the Noril'sk-Kharayelakh fault zone was the main conduit for this magmatism, and gave rise to the thick and geochemically varied trap sequence and sill-like intrusions. Though differing degrees of crustal contamination have affected the flows, the ore-bearing intrusions and ores seem curiously devoid of crustal influence (Czamanske et al., 1994), except that sulphur in the ores ($\delta^{34}S$ = 10-12‰) must clearly have come in large part from a crustal source that has not yet been identified.

Many komatiitic nickel deposits (subtype 27.1c) have been shown to contain sulphur that was most likely derived from the sulphide in sediments (Groves et al., 1979; Eckstrand et al., 1989a). Lesher (1989) has proposed that the sulphur was gained by melting and assimilation of sulphidic sediments under the main channel of komatiite flow whose extrusion temperature was significantly greater than its solidus, 1200°C.

The komatiitic magmas themselves were derived by significant partial melting of mantle material. Their great abundance in the Archean and Lower Proterozoic, and subsequent virtual disappearance is believed to reflect the greater thermal flux and lesser thickness of the Archean crust.

RELATED DEPOSIT TYPES

The Fe-rich immiscible sulphide melts from which nickel sulphide deposits originate can only exist at relatively high temperature (greater than ~900°C); this limits the possible host magmas to those of Mg-rich mafic and ultramafic composition, whose minimum solidus temperatures would be about 1000°C. In such primitive (i.e., high temperature) magmas, the only available elements that will preferentially enter the coexisting sulphide melt in sufficient quantity to produce ore grade concentrations are Ni, Cu, Co, PGEs, and Au. These are the very elements that occur in magmatic nickel-copper sulphide (subtype 27.1) and magmatic platinum group element (subtype 27.2) deposits. Consequently the apparent lack of other, related magmatic sulphide deposits is not surprising.

Magmatic nickel arsenide-chromite occurrences have been reported in peridotitic massifs in Spain and Morocco (Leblanc et al., 1990). These deposits also contain Cu, Co, PGEs, and Au, and appear similar in many respects to the nickel-copper sulphide subtype (27.1), but are rare, and seem to have little economic significance.

Mafic-ultramafic-hosted chromite deposits (Type 28) occur in similarly primitive magmatic rocks, in some cases even in the same magmatic complex. However chromite deposits do not require formation of an immiscible sulphide phase, a process that is fundamental for the genesis of magmatic sulphide deposits.

EXPLORATION GUIDES

The features of interest as guides to exploration can be subdivided into those applicable at different scales ranging from regional scale, through camp scale, to deposit scale.

Regional

- Magmatic nickel-copper sulphide deposits are universally associated with mafic and ultramafic magmatic rocks.
- These are intrusions associated with flood basalt provinces and/or continental rift regimes in the case of subtype 27.1b. The late Proterozoic Franklin diabase-gabbro suite on Victoria Island may have potential for rift-flood basalt-related nickel deposits similar to those of the Noril'sk-Talnakh region of Russia (Jefferson et al., 1993).
- Nickel deposits of the komatiitic subtype (27.1c) occur in Archean greenstone belts, and Proterozoic sedimentary-volcanic fold belts.
- The ore-related highly differentiated tholeiitic intrusions of subtype 27.1d can occur in a variety of terranes.

Camp scale

- Selection of the most favorable intrusion or flow sequence may be aided by recognizing depletion of Ni, Cu, or PGEs in the prospective host rock (Fedorenko, 1994). Such depletion should ideally indicate the equilibration of the magma with a sulphide melt that may have resulted in an economic nickel sulphide deposit.
- Chemical indications of sulphide contamination that could potentially generate economic nickel sulphide concentrations would include: (1) $\delta^{34}S$ values distinctly different from those of the mantle; (2) Se/S ratios much lower than those of the mantle; and (3) anomalously high Zn contents in associated chromite, indicative of the assimilation of Zn-bearing sulphidic metasediments.

Deposit scale

- The preferred site for nickel sulphide ores is at the stratigraphic base of the hosting mafic-ultramafic intrusion or flow sequence. In the case of komatiitic flows, orebodies may also occur at the base of flows higher in the sequence.
- At Sudbury and Noril'sk, some orebodies lie a few metres to hundreds of metres below the associated intrusion. These were the sites of original emplacement of the sulphide ores.
- The thickened parts of komatiitic sequences is where komatiitic ores are most commonly found.
- Nickel deposits that have been deformed, particularly by strike-parallel faults, have, in some cases, been mobilized along the faults well beyond the lateral extent of the associated host intrusion or flow (e.g., Falconbridge mine, Gordon Lake mine, Redstone mine).

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27.2 MAGMATIC PLATINUM GROUP ELEMENTS

C. Tucker Barrie

INTRODUCTION

The platinum group elements: Os, Ir, Ru, Rh, Pt, and Pd (collectively referred to as PGEs) are group VIIIA transition elements with strong siderophile and chalcophile characters. Although they are concentrated in a variety of geological settings, the principal PGE-dominant ores are associated with mafic-ultramafic intrusions. Platinum group element ores are rare: only a dozen mafic-ultramafic intrusions world-wide have economic or near-economic concentrations.

There are two principal deposit types: reef-type or stratiform PGE deposits, such as the Merensky Reef and UG-2 chromitite layer of the Bushveld Complex, South Africa, and the J-M Reef of the Stillwater Complex, Montana, are the most important. Canadian examples include the Big Trout Lake and Muskox occurrences (Fig. 27.2-1). A second type is termed here the "supersolidus intrusion breccia" type (SIB type), and is exemplified by the Lac des Iles deposit, Ontario (Fig. 27.2-1).

SIZE AND GRADE OF DEPOSITS

Nine-tenths of the PGEs mined are recovered from PGE-dominant ores (Table 27.2-1), with the bulk of the remainder recovered from magmatic Ni-Cu or alluvial deposits (Naldrett, 1989). Individual deposits in the Bushveld Complex (Fig. 27.2-2) have several millions to many tens of millions of tonnes of mined ore plus mineable reserves, whereas the Lac des Iles deposit has a geological reserve of approximately 6 million tonnes (Table 27.2-1). As precious metals, the PGEs have comparable values to gold, and the economics of PGE deposits are broadly analogous to those of gold-only deposits, with ore grades from 8 to 20 g/t combined PGE+Au (Table 27.2-1). Platinum group element deposits differ from gold deposits in that each of the PGEs are valued separately, with values that range from one-third that of gold for Pd, to more than three times that of gold for Rh. Platinum (which generally has one to two times the value of gold) and palladium make up 75% to 90% of the PGEs present in magmatic ore deposits, so the Pt to Pd ratio (Pt:Pd) has a profound effect on the economic value of the deposit. Rhodium constitutes 8% of the PGEs in the UG-2 chromite ore of the Bushveld Complex, the world's largest Rh reserve (Buchanan, 1979).

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1996: Magmatic platinum group elements; in Geology of Canadian Mineral Deposit Types, (ed.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Geological Survey of Canada, Geology of Canada, no. 8, p. 605-614 (also Geological Society of America, The Geology of North America, v. P-1).

GEOLOGICAL FEATURES

Reef- and supersolidus intrusion breccia-type PGE deposits share a number of geological features, but they contrast with each other in several important respects. The geology and mineral deposits of the Bushveld and Stillwater complexes are presented here to highlight the features of reef-type deposits, and the Lac des Iles Complex and its deposit are presented to represent the supersolidus intrusion breccia-type mineralization.

Geological setting

The Bushveld Complex (Fig. 27.2-2A), one of the world's great repositories for PGEs, chromite, and magnetite (+vanadium+titanium), is a 240 km by 400 km, Mid-Proterozoic layered intrusion within Early Proterozoic

Transvaal siliciclastic rocks and Late Archean granitoid plutons. It comprises mafic and ultramafic cumulates around a cloverleaf-shaped perimeter, and three granitic suites in its central portion. The cumulate rocks are well-layered, and form a stratigraphic section more than 7 km thick known as the Rustenburg Layered Suite. The cumulate rocks are divided into four zones: the Lower zone of olivine-bronzite-chromite cumulates; the Critical zone of plagioclase-pyroxene cumulates, with local cumulus olivine and chromite; the Main zone of plagioclase-pyroxene cumulates; and the Upper zone of plagioclase-pyroxene-Fe-Ti oxide (+apatite+Fe-rich olivine+hornblende) cumulates (Fig. 27.2-2B).

The Merensky Reef and UG-2 chromitite layers, the major reef-type PGE deposits of the complex, are within the lower 500 m of the Critical zone. Other types of PGE mineralization are found in the Platreef in the north-eastern limb of the complex, and in dunite pipes that cut the Lower and Critical zones. The Platreef, where the lower Critical zone is in contact with country rocks, comprises lower grade mineralization within altered, mafic and ultramafic cumulates that contain xenoliths of Transvaal Group dolomite, and has agmatitic and back-veined textures with granitoid rocks. The dunite pipes contain mineralization that is locally of high grade and in which much of the PGE ore is present as metals, Fe-alloys, and arsenides (Sharpe, 1985; Naldrett, 1989).

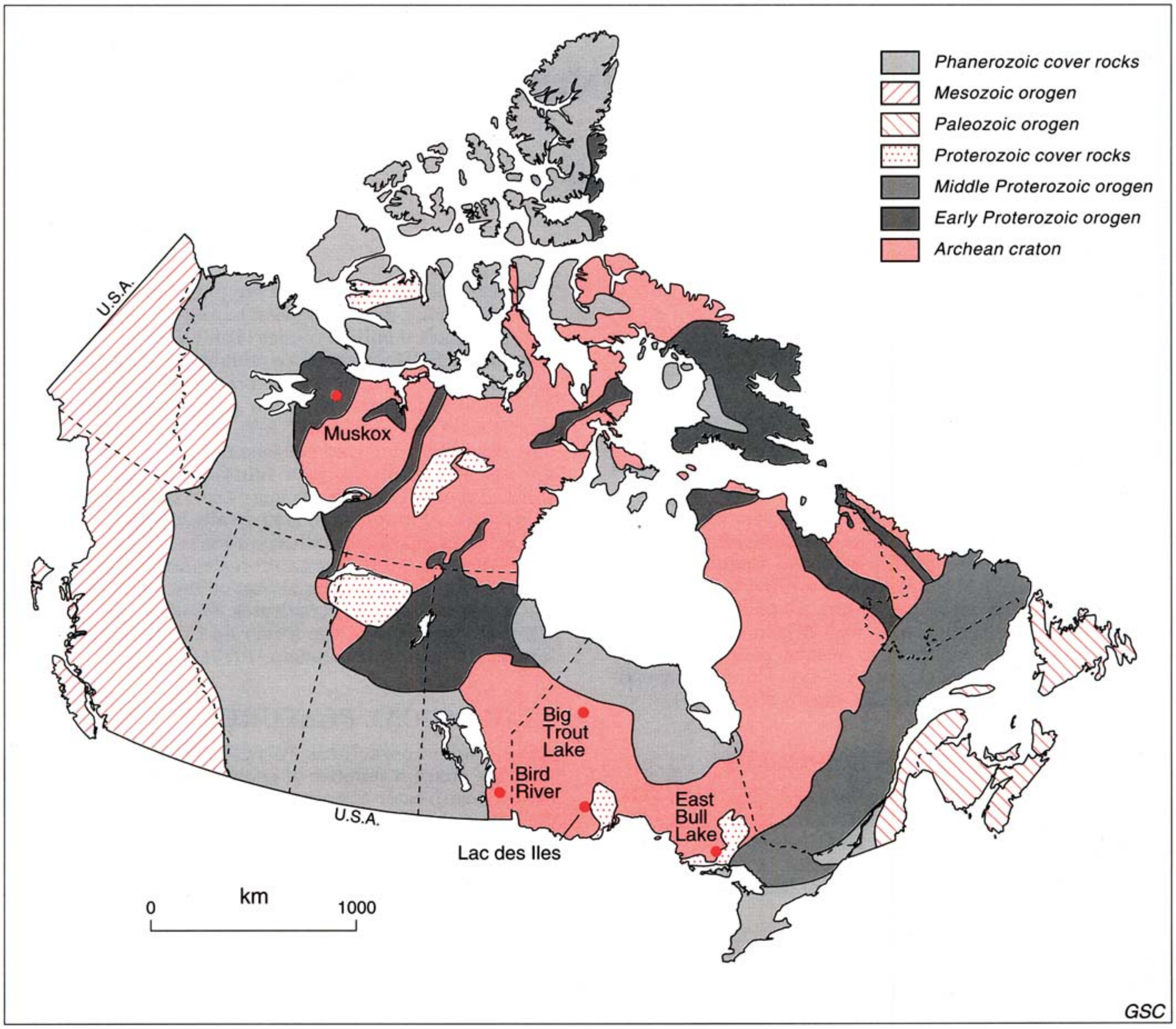

Figure 27.2-1. Locations of Canadian deposits of platinum group elements.

The Stillwater Complex is a 48 km (strike) by 2-7 km (across strike), Late Archean mafic-ultramafic intrusion that intruded ca. 3.3 Ga granitoid and metasedimentary rocks. Its cumulate stratigraphy has been divided into three zones: the Basal Contact zone of pyroxene-plagioclase cumulates with abundant inclusions of hornfelsed wall rock and low grade Ni-Cu sulphide locally; the Ultramafic zone of olivine-bronzite-chromite cumulates, which is overlain by the Banded zone of plagioclase-pyroxene-olivine (+chromite) cumulates. More fractionated cumulates are probably present up-section but are covered by Phanerozoic rocks. The principal PGE reef of the complex, J-M Reef, is located approximately 500 m above the base of the Banded zone, whereas a second lower grade reef, the G-Chromite layer, is found about 500 m below the top of the Ultramafic zone. Minor Pd-rich PGE mineralization such as the Picket Pin occurrence is present as transgressive and semiconformable zones in the anorthositic upper sections of the Banded zone (Czamanske and Zientek, 1985).

The Lac des Iles intrusion (Fig. 27.2-3A) is a 10 km by 2-4 km, Late Archean mafic-ultramafic intrusion, one of at least three broadly similar mafic-ultramafic intrusions in the region, all found within coeval, or nearly coeval granitoid rocks. It comprises a well layered, funnel-shaped northern ultramafic zone of olivine-pyroxene cumulates which dip moderately to steeply toward the centre; a southern ultramafic zone of similar composition but with a less well defined cumulate stratigraphy; a more southerly gabbro zone with plagioclase-pyroxene cumulates, mafic pegmatites, and intrusion breccia zones; and hornblendite and pegmatitic gabbroic rocks along the central western margin of the complex. Supersolidus intrusion breccia-type PGE mineralization occurs within the gabbro zone in and near the "Robie zone", and minor stratiform PGE occurrences are present in the northern ultramafic zone (Brugmann et al., 1989; Sutcliffe et al., 1989).

Age of host rocks and mineralization

The majority of PGE deposits and their hosting mafic-ultramafic intrusions or intrusive complexes are Precambrian (Stillwater, Munni Munni, Lac des Iles, Bird River, Big Trout Lake at 2.7 Ga; Great Dyke and East Bull Lake at 2.45 Ma; Bushveld at 2.05 Ga, Muskox at 1.3 Ga); the Tertiary Skaergaard Intrusion is an exception. For the reef-type deposits, the host intrusions are generally >200 Ma younger than the country rock, reflecting a stable cratonic setting at the time of emplacement. In contrast, the Lac des Iles intrusion and supersolidus intrusion breccia-type mineralization are nearly coeval with adjacent granites; and regional granitoid rocks are only ca. 30 Ma older.

Form of deposits and relationship of ore to host rocks

Reef-type mineralization is stratiform, but there are differences in the degree of conformity with adjacent cumulate layers from deposit to deposit. The Merensky Reef comprises a layer one to two metres thick that is continuous over hundreds of kilometres within the lower Critical zone. In detail, however, it is disrupted by numerous syn- and postmagmatic faults, and by "potholes": circular depressions from a few metres to several thousand metres in

Table 27.2-1. Magmatic platinum-group element deposits.

	Grade (g/t) PGE+Au	Pt:Pd	Geological reserves (t x 10^6)	Reference
WORLD **Reef-type**				
Bushveld Complex, South Africa				Buchanan, 1979
Merensky Reef	8.1	2.4:1	2160	
UG-2 Chromite	8.7	1.2:1	3700	
Platreef	7.3	0.9:1	1700	
Stillwater Complex, Montana				Zientek, 1993
J-M Reef	18.8	0.3:1	421	
G chromite	2.4	0.4:1	3.4	
Great Dyke, Zimbabwe	4.7	1.4:1	1680	Naldrett, 1989
Munni Munni, Australia	2.9	0.6:1	25*	Barnes et al., 1990
Skaergaard, E. Greenland	~2	0.1:1	–	Bird et al., 1991
CANADA **Reef-type**				
Muskox Intrusion, Northwest Territories	~1	0.1:1	–	Hulbert et al., 1988
Bird River Sill, Manitoba	~0.6	0.5:1	–	Scoates et al., 1989
Big Trout Lake, Ontario	~2	1:1	–	Borthwick, 1984
Supersolidus mixing-type				
Lac des Iles, Ontario	5.4	0.14:1	6.7	Natural Resources Canada Mining Industry Quarterly Report, Fall 1993
East Bull Lake, Ontario	2.5	0.3:1	–	Peck et al., 1993

* Geological resource
– = no published data

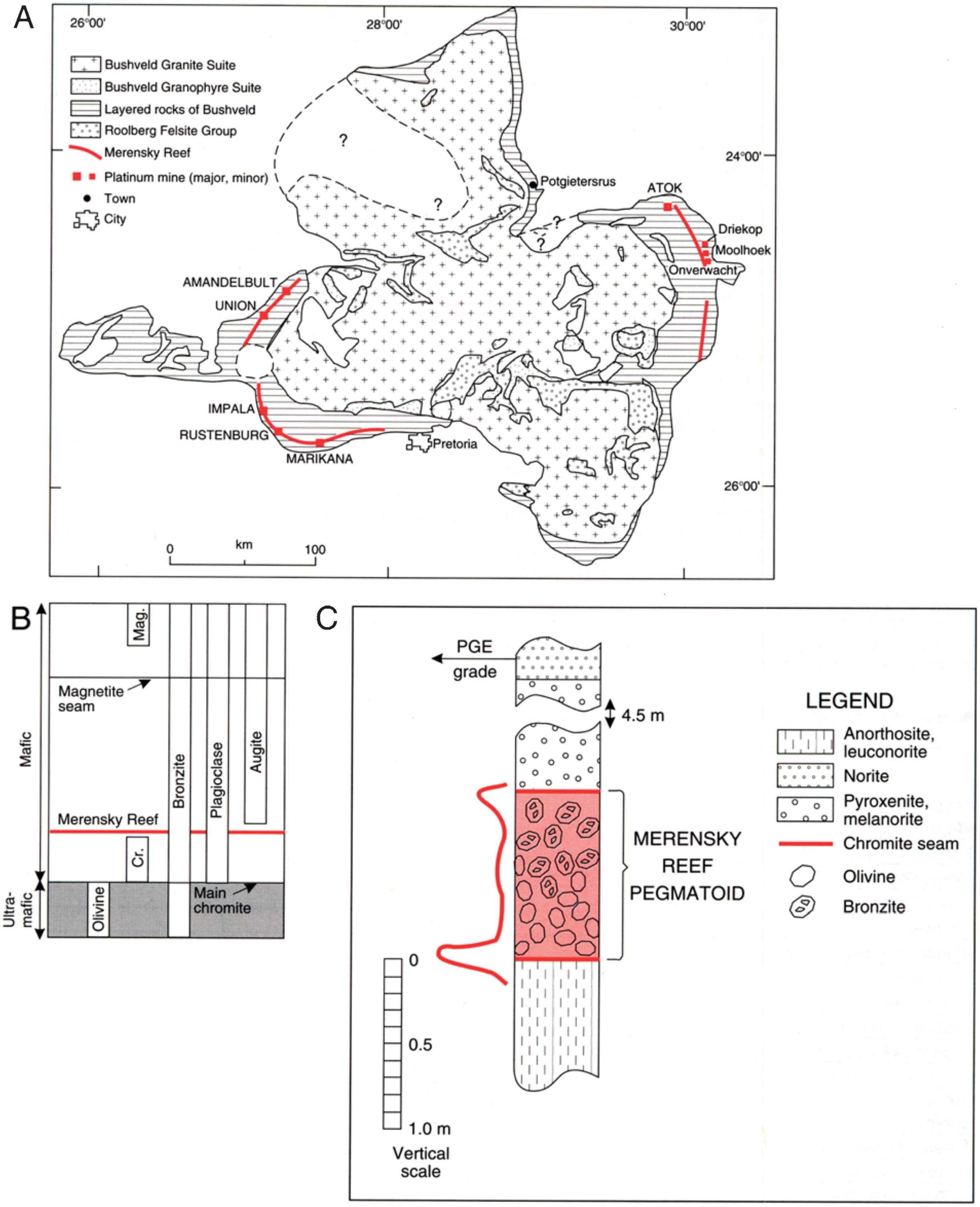

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Figure 27.2-2. A) Geology of the Bushveld Complex, South Africa (after Campbell et al., 1983). **B)** Stratigraphy and cumulus phases in the Bushveld Complex (after Campbell et al., 1983) Cr.= chromite, Mag.= magnetite. **C)** Lithological section of the Merensky Reef at the Union mine, Bushveld Complex (after Naldrett, 1989). The PGEs are concentrated at the base and top of the Merensky Reef.

diameter and as much as to 30 m deep where the reef transects footwall cumulate stratigraphy (Campbell, 1986). The Merensky Reef corresponds to a marked increase in whole rock initial strontium isotopic ratios across stratigraphy (Kruger and Marsh, 1982), and represents a separate cyclic unit as defined by mineral chemistry (Naldrett, 1989). The J-M Reef of the Stillwater Complex is more erratic. It constitutes a 1-5 m thick zone within a 4-25 m thick "reef zone" of olivine-rich, plagioclase-olivine cumulates in the lower Banded zone (Barnes and Naldrett, 1986). The reef zone and many cumulate layers at Stillwater Complex, have less well defined stratigraphic boundaries than the cumulate stratigraphy of the Bushveld Igneous Complex (Czamanske and Zientek, 1985).

Supersolidus intrusion breccia-type mineralization at Lac des Iles (Fig. 27.2-3B) forms irregularly-shaped zones from several square metres to 50 m by 500 m (Robie zone), within lithologically complex gabbros and pyroxenite dykes. Mineralization cuts cumulate layering and is associated with pegmatitic mafic and ultramafic dykes as much as several metres thick. It is also associated with complex intrusion breccias that have mutual crosscutting relationships between gabbroic and pyroxenitic rocks, and gabbro-pyroxenite-hornblendite pegmatite dykes and apophyses (Macdonald, 1987a). Minor leucotonalite dykes related to wall rock granitoid bodies cut supersolidus intrusion breccia-type mineralization, with textures that indicate intrusion prior to complete crystallization of the gabbroic rocks.

Nature of the ore, distribution of ore minerals, and ore textures

In detail, Merensky Reef ore varies from bronzite-olivine pegmatoid cumulate, with thin chromitite seams at the top and bottom (Union mine: Fig. 27.2-2C), to bronzite-olivine-chromite pegmatoid and cumulate (Rustenberg and Atok mines), to bronzite cumulate with thin chromitite seams (Marikana mine: Naldrett, 1989). Intercumulus phases are predominantly plagioclase and bronzite; sulphides and the PGE minerals constitute 3-7 volume per cent (generally as much as 2 wt.% S), and in places are concentrated at the base or top of the reef. Coarse pegmatitic textures are present locally and may contain quartz, graphite, apatite, hornblende, and other hydrous silicates with appreciable chlorine contents (Ballhaus and Stumpfl, 1986). The UG-2 chromitite, from one to two and half metres thick, has 60 to 90 modal per cent chromite, and the remainder consists of bronzite, plagioclase, sulphides, PGE minerals, oxides, and biotite (Naldrett, 1989). The UG-2 and other PGE-bearing chromitite layers of the Bushveld Igneous Complex have much lower total sulphide contents than the Merensky Reef. The J-M Reef at Stillwater comprises a relatively olivine- and sulphide-rich "layer" or layers, from one to three metres thick, within the reef-zone. The PGE-rich layers rarely overlap where more than one are present in the same area (Radeke and Vian, 1986). The J-M Reef has cumulus, amoeboid-shaped olivine, oikocrystic bronzite locally, and intercumulus plagioclase, sulphide (as much as 2 wt.% S), and minor phlogopite, apatite, and chromite. "Mixed rock" reef ore contains additional pegmatitic pods of plagioclase and olivine.

In addition to intrusion breccia and pegmatitic dykes and apophyses, the supersolidus intrusion breccia-type mineralization at Lac des Iles has a variety of textures on a scale of decimetres to metres and which are common to metasomatic rocks in porphyry molybdenum systems. These include pegmatitic comb layering, orbicular textures, miarolitic enclosures of pegmatitic quartz gabbro with crystal growth directed inward, and "brain-rock" (Macdonald, 1987a). Similar textures are found in supersolidus intrusion breccia-type PGE mineralization at the margins of Huronian mafic intrusions in central Ontario, particularly the East Bull Lake and Shakespeare-Dunlop intrusions. There the mineralization is characterized by rounded anorthositic nodules, dendritic and pegmatitic mafic pods, and intrusion breccias (Peck et al., 1993).

Ore mineralogy and zonation

In reef- and supersolidus intrusion breccia-type settings, the PGEs are found almost exclusively in sulphides and PGE minerals: chalcopyrite, pentlandite, pyrrhotite, pyrite, braggite ((Pt, Pd, Ni)S), cooperite (PtS), laurite (RuS_2), Pt-Fe and PGE alloys, and PGE arsenides and antimonides. Kinloch (1982) documented mineralogical (and compositional) zonation on a scale of tens of kilometres for the Merensky and UG-2 reefs, and reported zonation near reef pothole depressions, where normal reef mineralogy gives way to Pt-Fe alloys at the pothole floor. Chromitite reefs are relatively enriched in Os, Ir, and Ru, and depleted in sulphur, in comparison to the Merensky and J-M reefs, and this is reflected in their ore mineralogy (Naldrett, 1989). The Pd-rich mineralization at Lac des Iles has vysotskite (PdS) as an important constituent (Watkinson and Dunning, 1979).

Alteration

Reef-type PGE deposits are commonly within near-pristine cumulate and pegmatitic rocks, but they may have deuteric mineral assemblages confined to a zone that is within metres of the reef horizon and that extends for tens of metres to kilometres along strike. Pegmatite-rich areas of the reefs may have intercumulus biotite, chlorite, amphibole, serpentine, talc, and graphite associated with intercumulus sulphide, and interstitial plagioclase may be sericitized (Ballhaus and Stumpfl, 1986; Boudreau et al., 1986; Mathez et al., 1989). At Lac des Iles, the central Robie zone is characterized by moderate deuteric (uralitic) alteration with an irregular distribution, and is gradational with less-altered gabbroic rocks to the west and east (Watkinson and Dunning, 1979; Brugmann et al., 1989).

DEFINITIVE CHARACTERISTICS

Reef-type and supersolidus intrusion breccia-type deposits share the following features:

- Located within primitive, medium to large mafic-ultramafic intrusions of tholeiitic (+ultramafic) affinity;
- Cumulate layering in host intrusion;
- Pegmatitic textures within largely cumulate rocks;
- Platinum group element enrichment, accompanied by minor sulphide with recoverable Ni and Cu contents, or by significant chromite;
- Presence of minor hydrous silicates locally.

Reef-type deposits have the following additional characteristics:

- Host intrusion emplaced into stable cratonic settings;
- Host intrusion with primitive and boninitic chill compositions that may have been sulphur undersaturated and PGE-enriched prior to emplacement.
- Evidence for magma influxes during formation of cumulus stratigraphy: the recurrence of high temperature phases such as olivine and/or chromite; an increase in Mg number in mafic phases; or a significant change in radiogenic isotope initial ratios in whole rocks;

Supersolidus intrusion breccia-type deposits are characterized by the following features in addition to the five shared features above:

- Textural evidence for mingling of two distinct magmas after formation of cumulus stratigraphy under supersolidus conditions;
- Significant metasomatic enrichment of PGEs in complex zones of intrusion breccia;
- Volatile input from adjacent granitic intrusions or partially melted wall rock.

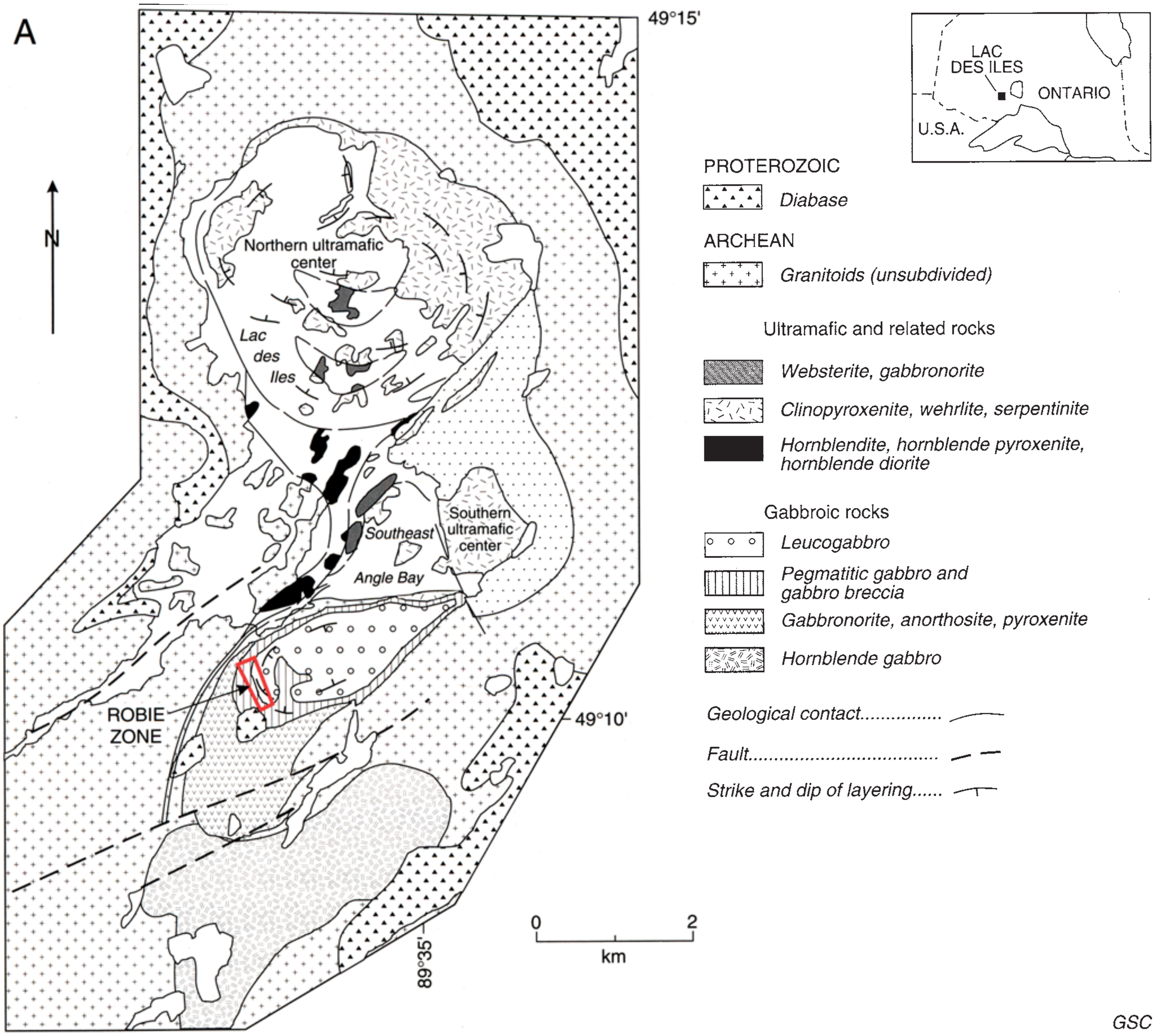

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Figure 27.2-3. A) Geology of the Lac des Iles Complex, Ontario (after Sutcliffe et al., 1989). **B)** Mineralized outcrop 200 m south of the Robie zone (after Sutcliffe et al., 1989). The PGEs are concentrated in and at the margins of the pegmatitic gabbro dyke as indicated.

Contents

GENETIC MODELS

Considering the characteristics listed above, the genesis of PGE-dominant deposits must involve a balance of magmatic and volatile-related processes. Campbell et al. (1983) outlined a model for reef-type deposits in which magma mixing was considered as the fundamental process for enrichment. This model, and subsequent refinements, are summarized as follows (Fig. 27.2-4): 1) a large, density-stratified magma chamber with cumulus layers forming at the base is injected by a new pulse of hot, primitive magma as a turbulent plume; 2) the newly injected magma rises to a density level equal to its own and spreads out laterally, mixing turbulently with entrained resident magma; 3) during turbulent mixing, minor amounts of immiscible sulphide liquid precipitate due to mixing (Naldrett and von Gruenewaldt, 1989) or to a decrease in temperature (Haughton et al., 1974); 4) the sulphide mixes with a proportionally large volume of silicate magma (high "R" factor: silicate magma-to-sulphide ratio) and efficiently scavenges PGEs from the silicate magma due to their chalcophile affinity (sulphide-silicate partition coefficients of approximately 10^5); 5) with further cooling and crystallization, the mixed magma layer, containing PGE-enriched sulphide, crystals, and liquid, becomes more dense than underlying liquid and descends (as downspouts) to the base of the intrusion, forming a loosely-packed, PGE-rich orthocumulate layer, the PGE reef (Naldrett, 1989). An alternative model, similar to the Campbell et al. (1983) model in most respects, has mixing internal to a single, fractionating magma rather than between resident and new primitive magmas (Hoatson and Keays, 1989).

Pegmatitic textures and hydrous minerals common to PGE reefs may be products of: 1) the trapping of excess volatiles migrating upward from lower cumulates by relatively abundant intercumulus liquid within the orthocumulate reef; and 2) recrystallization of the reef cumulate phases in the presence of volatile-rich intercumulus liquid under supersolidus conditions (Naldrett, 1989).

Brugmann et al. (1989) proposed a model for the supersolidus intrusion breccia-type mineralization at Lac des Iles, using zone refining as the principal mechanism of PGE enrichment. Their model involves: 1) formation of plagioclase-pyroxene cumulates; 2) injection of fractionated pyroxenite dykes enriched in PGEs; 3) partial remelting of the plagioclase-pyroxene cumulates under supersolidus conditions due to volatile-rich magma fluxing, with the partial melt phase progressively enriched in incompatible elements, including Au, Pt, Pd, and volatiles, and the oxide-bearing residuum retaining Ir and Os; 4) precipitation of PGE-enriched sulphide from the volatile-rich liquid due to

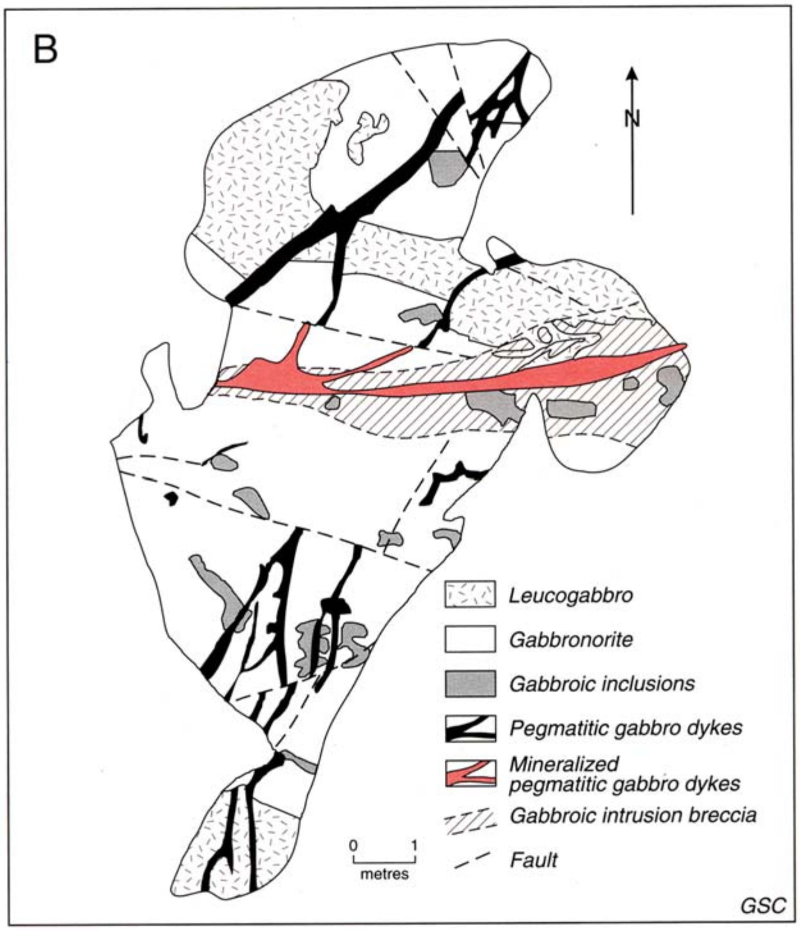

Figure 27.2-3. (cont.)

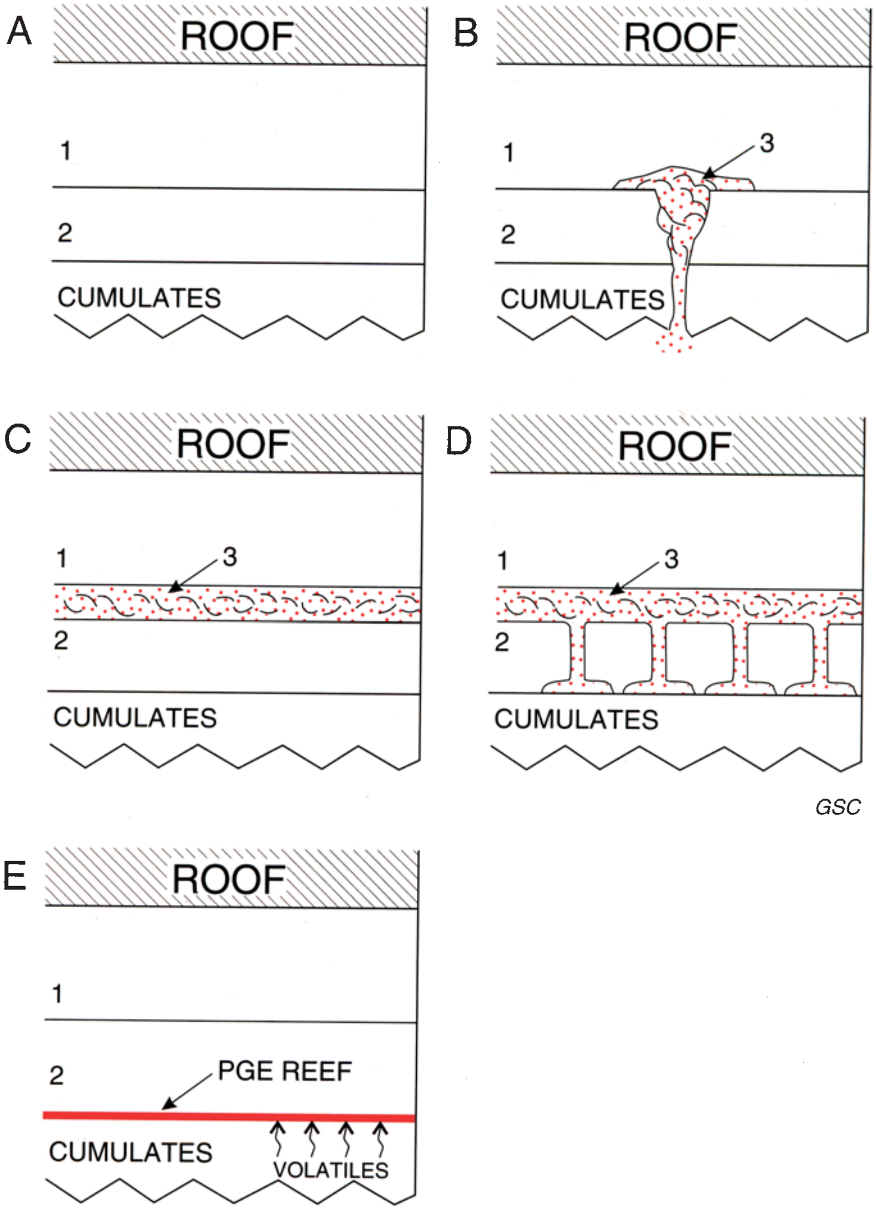

Figure 27.2-4. Model for the formation of the Merensky and J-M reefs. **A)** Initial, density-stratified magma chamber, with cumulates forming at base. **B)** Influx of new, hot primitive magma "3", as turbulent plume, rises to a level equal to its own density between layers 1 and 2. **C)** Primitive magma mixes turbulently at its own density level, entraining adjacent magma. Minor amounts of immiscible sulphide globules form due to magma mixing processes or to temperature decrease, and scavenge PGEs from silicate magma. **D)** With cooling, new turbulently-mixed magma layer becomes more dense than underlying layer and descends, probably as downspouts, through underlying layer, forming new cumulate layer at base. **E)** PGE-rich reef forms at the base as a stratiform, orthocumulate layer, traps volatiles migrating upward from underlying cumulate layers under supersolidus conditions, and crystallizes, with pegmatitic textures developed locally. Modified after Naldrett (1989).

sulphur saturation. Prior PGE enrichment occurred by magma mixing processes within the ultramafic magma (Brugmann et al., 1989; Sutcliffe et al., 1989). The volatiles responsible for pegmatite and hornblendite development may have been derived from adjacent, contemporaneous granitoid rocks during tectonism.

In summary, genetic models for both reef-type and supersolidus intrusion breccia-type PGE mineralization involve two processes: an initial enrichment in PGEs in magmatic sulphide by magma mixing, and a secondary enrichment or redistribution of the PGEs by volatiles or a volatile-enriched magma under supersolidus conditions. Efficient magma mixing in large intrusions in density-stratified layers that have very high silicate magma-to-sulphide ratios adequately accounts for the extreme PGE enrichment in the Merensky and J-M reefs; volatile-related processes account for local, minor redistribution. Magma mixing plays a subordinate role for supersolidus intrusion breccia-type mineralization, and volatile-induced zone refining under supersolidus conditions can adequately explain most of the geological features and the PGE enrichment.

RELATED DEPOSIT TYPES

Reef-type PGE deposits are most similar to chromite, Fe-Ti oxide, and gold (e.g., Skaergaard: Bird et al., 1991) deposits concentrated in stratiform cumulate layers in large mafic-ultramafic intrusions. They are also akin to magmatic sulphide Ni-Cu-PGE deposits, and to PGE deposits in transgressive dunite pipes that cut cumulate layering in the Bushveld Igneous Complex (Schiffries, 1982). Supersolidus intrusion breccia-type deposits are distantly analogous to Cu-PGE-rich metasomatic apophyses and breccias found in mafic alkaline porphyry Cu-Au deposits (Mutschler et al., 1985). Other related deposit types are PGE-enriched footwall quartz sulphide veins (e.g., Sudbury: Li et al., 1992); magmatic PGE enrichments in intrusions with alkaline affinity (e.g., Coldwell Complex, Ontario: Good and Crocket, 1994; Tulameen Alaska-type intrusion, British Columbia: Nixon et al., 1990); and unconformity-related U-PGE-Au deposits (e.g., Nicholson Bay, Saskatchewan: Hulbert et al., 1988).

EXPLORATION GUIDES

Geological and geochemical criteria that indicate favourable environments for magmatic PGE deposits are: 1) the presence of a large, layered mafic-ultramafic intrusion, particularly in a stable cratonic setting where the country rock is >200 Ma older than the intrusion; 2) evidence for mixing of primitive magma with more fractionated magma within the magma chamber, such as the recurrence of cumulus olivine or chromite within a thick plagioclase-pyroxene cumulate sequence in a well-layered intrusion, or complex metasomatic and intrusion breccia textures; 3) presence of sulphide- and/or oxide-bearing, stratiform or transgressive pegmatitic mafic rocks, within or at the margin of cumulate rocks of the intrusion; 4) determination of PGE-enriched, S-undersaturated, primitive (e.g., mantle-derived, ultramafic or tholeiitic) or boninitic chilled marginal rocks (e.g., Hamlyn and Keays, 1986); and 5) determination of metal contents in magmatic sulphides that indicate a primitive character (high Ni/Cu, Ir/Pd) and a high R factor (R = silicate magma-to-sulphide ratio: Campbell et al., 1983; Naldrett, 1989; Barnes, 1990).

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