Petrogenetic significance of chromian spinels from the Sudbury Igneous Complex, Ontario, Canada

Mei-Fu Zhou, Peter C. Lightfoot, Reid R. Keays, Michelle L. Moore, and Gordon G. Morrison

Abstract: Chromian spinels occur in mafic−ultramafic inclusions in the Sublayer of the Sudbury Igneous Complex (SIC) as well as in mafic−ultramafic rocks in the immediate footwall of the Sublayer. The host rocks are pyroxenite and melanorite with minor dunite, harzburgite, and melatroctolite. As common accessory phases in these rocks, the chromian spinels display euhedral or subhedral forms and are included in olivine and orthopyroxene. Chromian spinel grains generally have ilmenite lamellae and contain abundant inclusions (zircon, olivine, diopside, plagioclase, biotite, and sulfide). All the chromian spinels have similar trace element abundances and are rich in TiO_2 (0.5−15 wt.%). They have constant Cr# ($100Cr/(Cr + Al)$) (55−70) and exhibit a continuum in composition that traverses the normal fields of spinels in a $Al−(Fe^{3+} + 2Ti)−Cr$ triangular diagram. This continuum extends to that of the composition of chromian magnetite in the host norite matrix to the mafic−ultramafic inclusions. This continuum in composition of the spinels suggests that the noritic matrix to the Sublayer formed from the same magma as the inclusions. A positive correlation between the Cr and Al contents of the spinels was probably produced by dilution of these elements by Fe^{3+} contributed, perhaps, by a plagioclase-saturated melt. Zircon inclusions in a chromian spinel grain reflect incorporation of crustal, felsic materials into the magma before crystallization of chromian spinel. The chemical characteristics and mineral inclusions of the spinels suggest that the Sublayer formed in response to magma mixing. It is suggested that subsequent to the formation of the crustal melt, mantle-derived high-Mg magmas mixed vigorously with this and generated the magmatic sulfides that eventually formed the Ni − Cu − platinum-group elements sulfide ore deposits. Some of the early crystallization products of the high-Mg magma settled to the chamber floor, where they partially mixed with the crustal melt and formed the mafic−ultramafic inclusions and footwall complexes.

Résumé : Les inclusions mafiques−ultramafiques dans la Couche de base du Complexe igné de Sudbury contiennent des spinelles chromifères, on les retrouve aussi dans les roches mafiques−ultramafiques du mur attenant de la Couche de base. Les roches hôtes sont la pyroxénite et la mélanorite, elles sont accompagnées de dunite, harzburgite et mélanotroctolite. Les spinelles chromifères représentent dans ces roches des phases accessoires communes, avec des formes cristallines automorphes et subautomorphes en inclusions dans l'olivine et l'orthopyroxène. Les grains des spinelles chromifères renferment généralement des lamelles d'ilménite, ainsi que d'autres inclusions abondantes (zircon, olivine, diopside, plagioclase, biotite et sulfure). Tous les spinelles chromifères ont des teneurs en éléments traces similaires, et ils sont enrichis en TiO_2 (0,5−15% par poids). Leur nombre Cr# ($100Cr/(Cr + Al)$) (55−70) est constant, et leurs compositions exhibent un continuum traversant les champs normaux des spinelles représentés dans le diagramme ternaire $Al−(Fe^{3+} + 2Ti)−Cr$. Ce continuum s'étend à celui de la composition de la magnétite chromifère contenue dans la matrice de la norite hôte et jusque dans les inclusions mafiques−ultramafiques. Ce continuum de la composition des spinelles suggère que la matrice noritique de la Couche de base dérive de même magma qui a livré les inclusions. Une corrélation positive entre les teneurs en Cr et en Al des spinelles est probablement due à la dilution de ces éléments par le Fe^{3+} fourni, peut-être, par un magma saturé en plagioclase. Les inclusions de zircon dans un grain de spinelle chromifère témoignent de l'ajout de matériaux de croûte felsique dans le magma avant la cristallisation du spinelle chromifère. Les compositions chimiques caractéristiques et les inclusions minérales des spinelles suggèrent que la Couche de base est le produit d'un mélange de magmas. Il est proposé que, subséquemment, à la formation du magma crustal, il y a eu ajout et mélange vigoureux avec des magmas riches en Mg dérivés du manteau, ce qui aurait engendré les liquides sulfurés qui éventuellement formèrent les gîtes de sulfures de Ni − Cu − éléments du groupe de platine. Certains produits de cristallisation précoce du magma riche en Mg sédimentèrent sur le plancher de la chambre magmatique, où ils furent partiellement mélangés avec le magma crustal et formèrent les inclusions mafiques−ultramafiques ainsi que les complexes du mur.
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M.-F. Zhou[1] and R.R. Keays. Mineral Exploration Research Centre, Laurentian University, Sudbury, ON P3E 2C6, Canada.
P.C. Lightfoot[2] and G.G. Morrison. INCO Exploration Services, High Way 17 West Engineering Building, Copper Cliff, ON P0M 1N0, Canada.
M.L. Moore.[2] Geoscience Laboratories, Ministry of Northern Development and Mines, Sudbury, ON P3E 2C6, Canada.

[1] Corresponding author. Present address: Department of Earth Sciences, University of Hong Kong, Pokfulam Road, Hong Kong, People's Republic of China (e-mail: mfzhou@hkucc.hku.hk).
[2] Also at Mineral Exploration Research Centre, Laurentian University, Sudbury, ON P3E 2C6, Canada.

Introduction

Chromian spinel occurs as a ubiquitous phase in mafic–ultramafic inclusions within the Sudbury Igenous Complex (SIC), Ontario, Canada. Although there is only sparse information available (Pattison 1979; Naldrett et al. 1984; Scribbins et al. 1984; Farrell et al. 1994; Lightfoot et al.[3] 1994, 1995; Moore et al. 1995), the inclusions can potentially provide important new insights into the petrogenesis of the SIC. Chromian spinels are sensitive minerals for deducing the ambient conditions during magma crystallization (Irvine 1967; Dick and Bullen 1984; Roeder and Reynolds 1991; Zhou and Kerrich 1992). The wide compositional range of chromian spinel is a function of parental magma compositions and geological environment. Prior to this study, there were only sparse analytical data on chromian spinels from the Sublayer matrix and inclusions of the SIC (Naldrett et al. 1984). We have carried out a detailed study of the texture and composition of chromian spinels in mafic–ultramafic inclusions in the Sublayer of the SIC as well as in basal mafic–ultramafic complexes in the immediate footwall of the Sublayer. These new data allow us to place important constraints on the petrogenesis of the SIC.

Geological background and petrography

The basic geology of the Sudbury Structure has been extensively documented in the literature (see references in Pye et al. 1984; Lightfoot and Naldrett 1994). The Sudbury Structure includes (1) the SIC, (2) the Whitewater Group, and (3) the shocked footwall rocks and footwall breccias. The structure is located at the contact between Archean gneisses of the Superior Province to the north and the Proterozoic Huronian Supergroup of the Southern Province to the south. The Grenville Front, a major Proterozoic tectonic deformation zone marking the boundary between the Grenville Province and Southern Province, is only 10 km southeast of the Sudbury Structure. The SIC outcrops as an elliptical ring (Fig. 1) and includes, from the outside inwards, (1) concentric and radial offset dykes, (2) a discontinuous zone of Sublayer, (3) quartz-rich norite on the South Range and orthopyroxene poikilitic melanorite (mafic norite) on the North Range, (4) felsic norite, (5) transition zone quartz gabbro, and (6) granophyre. All of the units except the offsets and Sublayer have been grouped into the Main Mass of the complex.

The distribution of the Sublayer is controlled by the shape of the basal contact, with the greatest thicknesses being observed in kilometre-sized radial depressions called "troughs" (Morrison 1984). It is composed of a fine- to medium-grained norite with low modal quartz content and abundant pyroxenes. The Sublayer is characterized by abundant inclusions of footwall gneiss and mafic–ultramafic rocks (Pattison 1979). U–Pb ages of new zircons from the Main Mass, the Sublayer, the immediate footwall Levack gneisses, and shocked zircons from the Onaping Formation of the White-

water Group indicate an age of 1.85 Ga for the Sudbury event that produced the Sudbury Structure (Krogh et al. 1984; Corfu and Lightfoot 1996).

Magnetite and ilmenite occur throughout the SIC (Gasparrini and Naldrett 1972), but chromian spinel is only observed in the Sublayer environment and footwall ultramafic complexes. Sublayer samples investigated in this study are from drill core from the Craig mine and open pit samples from the Whistle mine (North Range) and the new Gertrude mine (South Range). We also present data of chromian spinels from ultramafic complexes in the footwall country rocks at the Fraser and Levack mines (Fig. 1). Both the inclusions and footwall complexes consist of melanorite, pyroxenite, harzburgite, melatroctolite, and dunite (Scribbins et al. 1984; Farrell et al. 1994; Lightfoot et al.[3]). The inclusions are set in a noritic matrix with disseminated sulfides. These rocks are all typically igneous textured, and are coarse- to medium-grained feldspathic rocks with variable contents of olivine, orthopyroxene, and clinopyroxene. Accessory phases include chromite, zircon, and apatite. Much of the olivine is serpentinized, and secondary magnetite is abundant. In less altered samples, olivine is generally rounded and enclosed in either orthopyroxene (Fig. 2a), clinopyroxene (Fig. 2b), or plagioclase (Fig. 2c). Crystal aggregates of olivine are also enclosed in these minerals (Figs. 2b–2d), suggesting a disequilibrium texture indicating that the olivine and enclosing minerals formed from different magmas. These inclusions are also commonly impregnated by fine-grained aggregates of plagioclase and quartz that are interstitial to large olivine grains (Figs. 2e, 2f). The felsic aggregate contains disseminated sulfides, while the host "dunite" is intruded by sulfide veins (Fig. 2f).

Occurrence of the chromian spinel

Chromian spinel in the mafic–ultramafic rocks of the SIC occurs as euhedral to subhedral inclusions in olivine or orthopyroxene (Fig. 2a) and rarely in biotite, and ranges in size from 10 to 150 μm. Some grains are clearly eroded, with highly irregular shape. Many grains contain submicrometre to a few micrometres wide ilmenite exsolution lamellae (Fig. 3a) that may have formed by relatively high temperature exsolution along the (111) octahedral planes (Haggerty 1976).

Some chromian spinel grains contain inclusions of olivine, Cr-bearing diopside, orthopyroxene, plagioclase, biotite, zircon, and (or) sulfide (Figs. 3b, 3c). Olivine and diopside are the dominant inclusion types. Both biotite and plagioclase occur together in a chromian spinel grain (Fig. 3b). Associated with these two phases is a tiny sulfide grain (Fig. 3b). Some of the inclusions probably represent the crystallization product of melts trapped during chromian spinel crystallization.

Zircon grains in association with chromian spinel were observed in sample 93MLM34, a melatroctolite from the Fraser mine. This association is included in a large biotite grain that we suggest formed by replacement of olivine, as relict olivine and serpentine grains occur in biotite (Fig. 3c). Chromian spinel is altered along the margin to magnetite. Magnetite also occurs along the cleavage of biotite. Both zircon and chromian spinel are closely packed, and the boundaries of the zircon grains are smooth. The top grain has a euhedral outline and the whole grain seems strongly eroded. This relationship suggests that the zircon grains within the

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[3] P.C. Lightfoot, R.R. Keays, G.G. Morrison, A. Byte, and K.P. Farrell. Geochemical relationships in the matrix and inclusions of the Sublayer Norite, Sudbury Igneous Complex: a case study of the Whistle Mine embayment. Submitted for publication.

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Fig. 1. Geological map of the SIC showing sample locations at the Whistle, Fraser, Levack, and Craig mines of the North Range and the Gertrude mine of the South Range (after Pye et al. 1984).
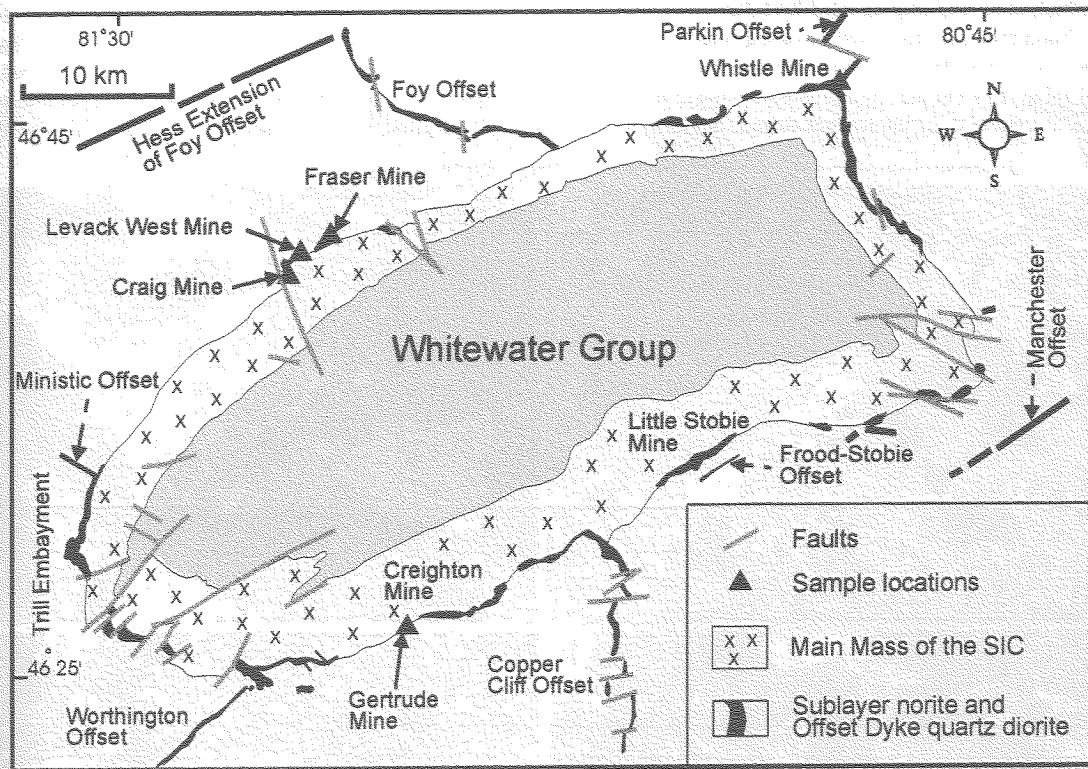
chromian spinel formed before the host chromian spinel.

Magnetite occasionally rims chromian spinel grains, but more commonly magnetite occurs along fractures within chromian spinel grains. In sample 94PCL8675, a harzburgite, some chromian spinel grains exhibit a zonation in which a euhedral chromian spinel core is mantled by ferrochromite, which in turn is rimmed by magnetite (Fig. 3d). The origin of this zonation can be interpreted as a replacement process, in which FeO and Fe_2O_3 substituted for MgO, Al_2O_3, and, to a lesser extent, Cr_2O_3; this replacement may have taken place during serpentinization in the greenschist and amphibolite facies of metamorphism (cf. Bliss and MacLean 1975). Such zonation is not observed in other rocks from the SIC, because chromian spinel grains in these rocks are normally included in primary silicates (olivine and orthopyroxene).

Analytical methods

Chromian spinel grains were analyzed using a fully automatic Cameca-SX50 electron microprobe at the Geoscience Laboratories of the Ministry of Northern Development and Mines (MNDM). An accelerating voltage of 20 kV, a 35 nA beam current, and a 5 μm electron beam were used. Synthetic and natural chromian spinels were used as standards. To obtain more precise results for Ni and Zn, the background values and peaks were counted for 60 and 200 s, respectively. ZAF corrections were applied to all microprobe analyses. Test analyses were performed on standard chromian spinel to determine the quality of calibration and analytical error. The analytical results of major and trace elements are better than 1%, and those for Ni and Zn are better than 5%.

Iron was determined as total iron (FeO_t) and Fe^{2+} and Fe^{3+} were distributed by assuming an $R^{2+}R^{3+}_2O_4$ formula for the chromian spinel and balancing $RO:R_2O_3 = 1$ for the chromian spinel. The extensive exsolution lamellae of ilmenite in chromian spinel made it difficult to establish the composition of the spinel prior to the final exsolution of ilmenite. A few points on each grain were analyzed and average values reported. However, these may or may not represent the original composition of the chromian spinel as it crystallized from the melt; for example, some components of the original chromian spinel have diffused out of the grains partially or completely to become incorporated in the ilmenite. The overall chemical variation, however, would be valid. Representative results, together with Cr# (100Cr/(Cr + Al)) and Mg# (100Mg/(Mg + Fe^{2+})), appear in Table 1.

Silicate inclusions in chromian spinel were analyzed using a JEOL 688 Superprobe equipped with a five wavelength dispersive spectrometer and an Oxford Link energy-dispersive system, also at the Geoscience Laboratories of MNDM. Due to the small size of the inclusions, we used a 1 μm electron beam. Operating conditions were a 15 kV accelerating voltage and a 20 nA beam current. Analyses of olivine, pyroxenes, biotite, and zircon inclusions in chromian spinel are given in Table 2.

Analytical results

Chromian spinel core-to-rim systematics

No significant core-to-rim compositional variations were observed in most analyzed grains. A microprobe traverse across a zoned chromian spinel grain in sample 94PCL8675 is shown in Fig. 4. It would appear that there is a major chemical discontinuity between the chromite core, inter-

Fig. 2. Photomicrographs showing reaction textures in mafic–ultramafic inclusions in the sublayers. (*a*) Harzburgite, rounded olivine grains and euhedral chromite grains in orthopyroxene; sample 16413, Frood mine. (*b*) Dunite showing olivine grains enclosed in clinopyroxene, which is in turn impregnated by felsic melt (on the left bottom); note also euhedral chromian spinel grains in clinopyroxene; sample 170332, Frood mine. (*c*) Rounded olivine grains in plagioclase, melanorite; sample 92PCL28, Whistle mine. (*d*) Dunite impregnated by clinopyroxene; sample 170332, Frood mine. (*e*) Dunite impregnated by felsic melt represented by interstitial plagioclase; sample C681448, Frood mine. (*f*) Dunite impregnated by felsic melt that crystallized to granophyre and by sulfide melt; sample 93PCL32, Whistle mine. Field views of all photos are 6 mm. Mineral abbreviations: Cpx, clinopyroxene; Ol, olivine; Opx, orthopyroxene; Pl, plagioclase.
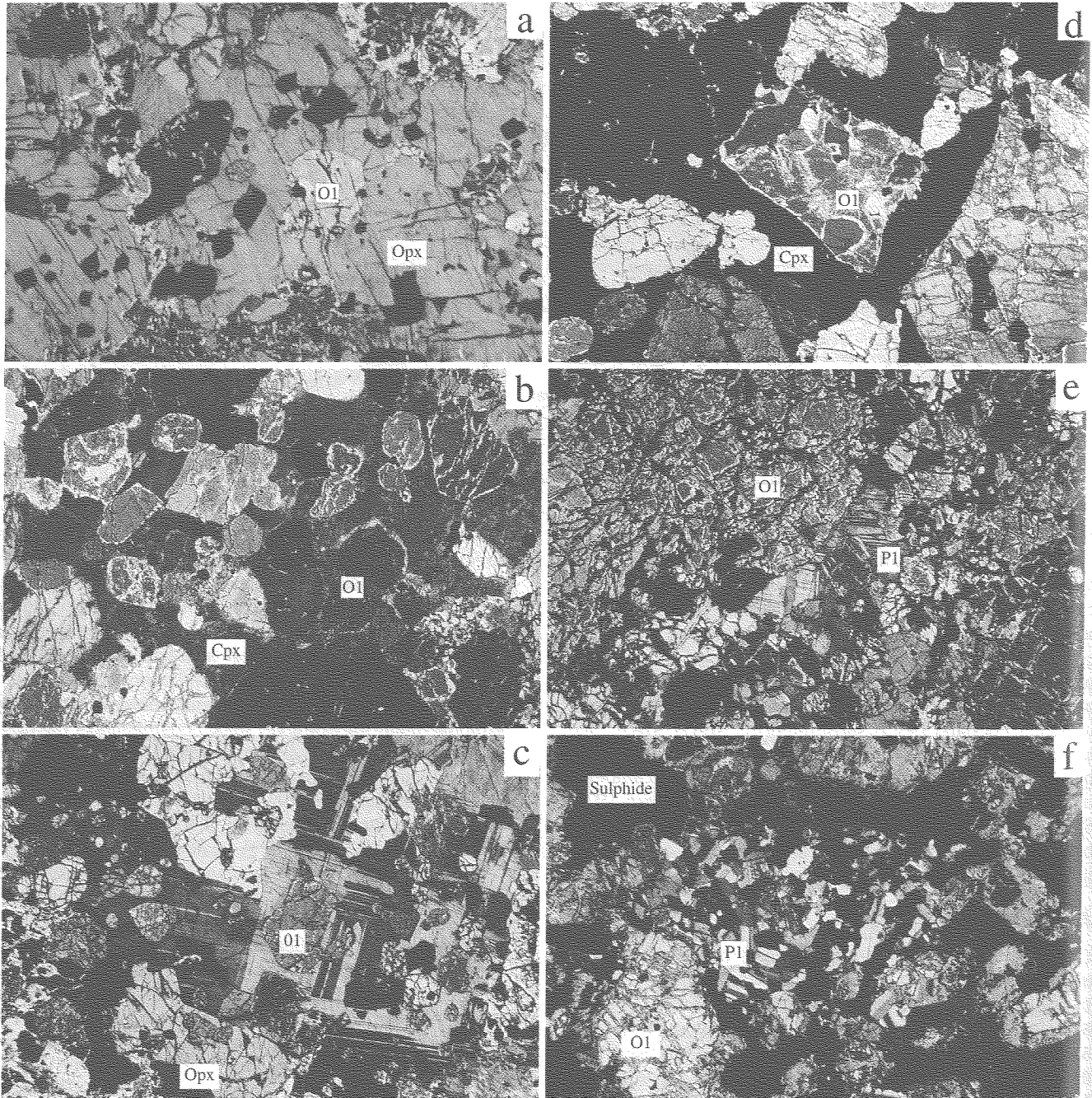

mediate magnetite (ferrochromite), and an ilmenite rim. The sharp discontinuities may reflect incomplete solid solution in spinel group, or, alternatively, a magmatic overgrowth. In general, from the chromite core to the ferrochromite rim, Cr, Al, Mg, Ti, and Mn decrease, while Fe increases. The ilmenite rim has FeO_t (as total iron) and MgO contents similar to those of the chromite core, but higher MnO and TiO_2 and lower Cr_2O_3 and Al_2O_3 contents (Fig. 4).

Overall compositional variations of chromian spinel

Chromian spinels from both the North Range and South Range environments of the SIC have the same trends between

Fig. 3. Photomicrographs of chromian spinels from the mafic—ultramafic inclusions within the SIC. (*a*) Ilmenite lamellae in chromian spinel; sample 92PCL28, Whistle mine. (*b*) Biotite and plagioclase inclusions in chromian spinel; sample 94PCL8675, Gertrude mine. (*c*) Zircon inclusions in chromian spinel; sample 92MLM32, Fraser mine. (*d*) A zoned chromian spinel grain with a zonation from a chromian spinel core rimmed by Cr-magnetite and ilmenite; sample 94PCL8675, Gertrude mine. Mineral abbreviations: Bi, biotite; Cr-Sp, chromian spinel; Mt, magnetite; Pl, plagioclase; Zr, zircon.
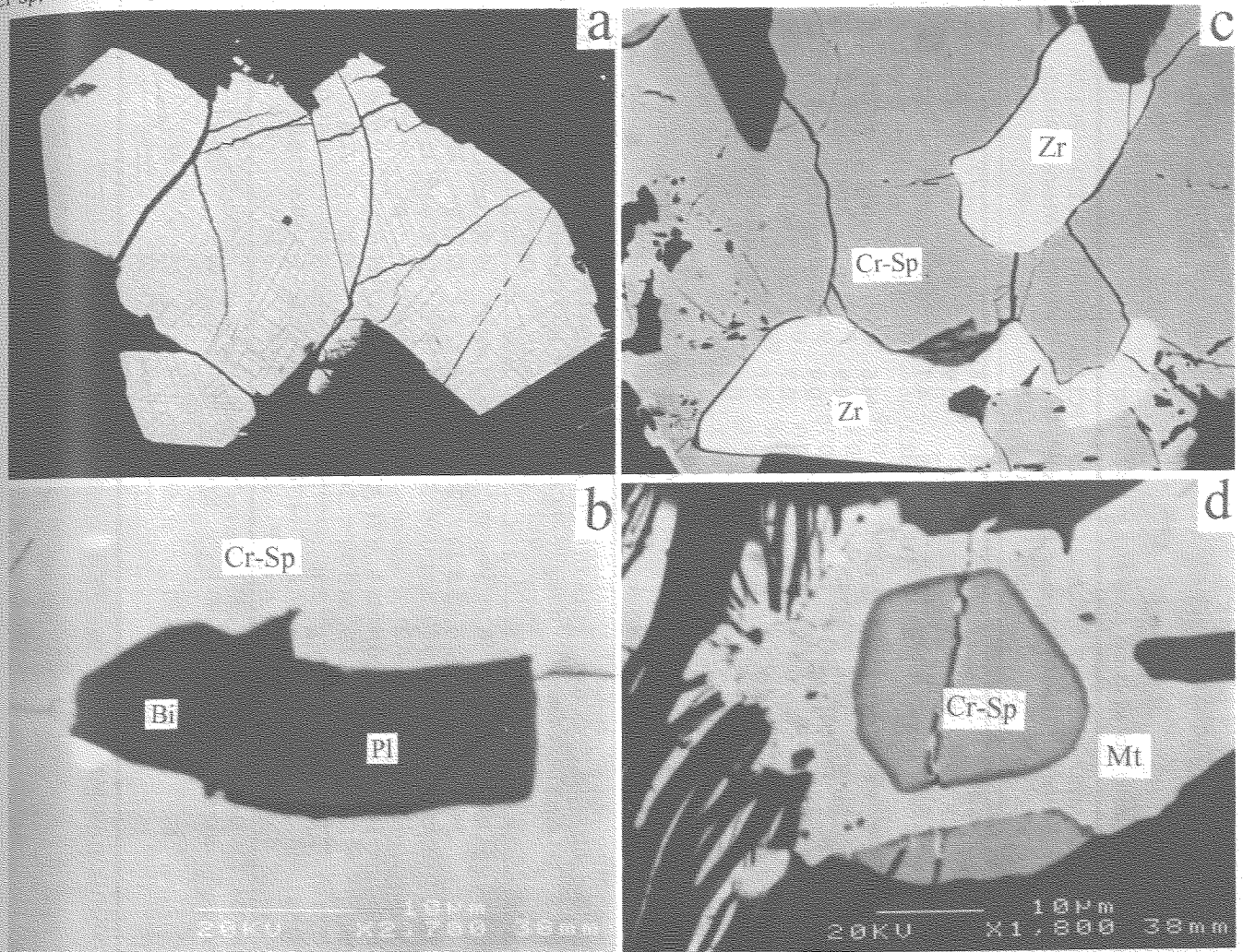
Cr_2O_3, Al_2O_3, and FeO_t (Fig. 5). On the Cr_2O_3 versus MgO and FeO_t versus MgO diagrams, samples from the Gertrude mine stand out, as they have higher Cr_2O_3 and significantly less FeO_t. Chromian spinels from the ultramafic complexes, both in the Fraser and Levack mines have compositions similar to those in Sublayer inclusions from both the Whistle and Craig mines (Fig. 5). Overall, Cr_2O_3 covaries positively with Al_2O_3 and MgO, whereas there are negative correlations between MgO and FeO_t as well as FeO_t and Cr_2O_3 (Fig. 5).

Most chromian spinels from the Gertrude mine have slightly lower Cr#'s than the other chromian spinels, although they have similar Mg#'s (Fig. 6). The chromian spinels from the SIC are much lower in Mg# than chromian spinels from mid-oceanic ridge basalt (MORB) and from stratiform complexes, although they are similar in Cr# to chromian spinels from a number of mafic volcanic and intrusive rocks (Fig. 6). On the $Al-(Fe^{3+} + 2Ti)-Cr$ triangular diagram, all chromian spinels from the SIC form a continuum in composition

and they define a trend crosscutting the normal fields of spinel compositions (Fig. 7). Although there is a compositional break between the Gertrude samples and the remainder of the samples, it is possible that this will be filled in as more samples become available. Again, chromian spinels from other mafic rocks are plotted in this diagram for comparison. Those in komatiites from Western Australia are characterized by higher Cr contents. Some of the chromian spinels from the SIC seem similar to the Disko basalts, Greenland, Hawaiian basalts, and gabbro—picrites of the Insizwa Complex, South Africa, although the SIC chromian spinels define a more complete trend toward the magnetite member (Fig. 7).

The SIC chromian spinels have high TiO_2 contents ranging from 0.5 to 15 wt.% (Table 1). Some extremely low or high values may be due to ilmenite exsolution lamellae. Allen et al. (1988) reported a strong negative correlation between Ti and Al in MORB chromian spinels. The TiO_2 contents of the SIC chromian spinel do not covary with any of Al, Cr, Fe, Mn, or Ni. In a Fe# ($100Fe^{3+}/(Fe^{3+} + Al +$

Table 1. Representative analyses of chromian spinels from the mafic–ultramafic inclusions and complexes in the Sublayer.

Sample:	MLM32	MLM32	MLM30	MLM30	MLM30	MLM107	MLM107	MLM24	PCL28	PCL28	PCL40	PCL31	PCL28	PCL18	PCL18
Location:	Fraser	Fraser	Fraser	Fraser	Fraser	Fraser	Fraser	Fraser	Whistle	Whistle	Whistle	Whistle	Whistle	Whistle	Whistle
Host:	Ol	Ol	Opx	Ol	Ol	Ol	Ol	Ol	Pl	Pl	Pl	Pl	Ol	Ol	Pl
TiO_2 (wt.%)	0.93	1.10	2.11	0.67	6.08	3.18	1.43	3.12	3.29	2.8	3.4	2.73	7.51	1.16	8.27
Cr_2O_3	16.1	19.1	13.4	17.5	22.0	21.8	22.1	7.2	9.0	13.9	3.2	4.9	8.1	8.5	7.4
Al_2O_3	3.67	5.71	6.26	4.96	5.99	7.31	7.44	3.08	3.48	4.7	0.0	0.09	2.89	0.82	3.33
V_2O_3								0.44			0.10	0.61	0.36	0.72	0.53
Fe_2O_3	48.5	43.2	45.5	44.8	33.9	36.8	38.0	53.7	52.3	46.6	61.9	60.1	47.3	57.5	46.8
FeO	30.0	29.0	28.9	26.9	28.7	27.6	29.0	29.6	31.3	30.9	32.0	31.4	31.5	30.5	32.2
MgO	0.59	1.68	0.96	1.27	3.42	3.83	2.43	0.71	0.41	0.9	0.1	0.02	0.51	0.05	0.14
MnO	1.22	1.00	2.16	2.60	0.33	0.31	0.38	0.63	0.74	0.7	0.2	0.37	0.92	0.46	0.98
NiO	0.30	0.33	0.10	0.11	0.12	0.08	0.16	0.06	0.13	0.1	0.1	0.01	0.05	0.19	0.25
ZnO	0.28	0.16	0.27	0.74	0.11	0.09	0.17	1.05	0.39	0.1	0.1	0.02	0.56	0.28	0.69
Total	101.7	101.3	99.7	99.6	100.6	101.0	101.1	99.6	101.1	100.9	101.1	100.3	99.9	100.3	100.7
Cr#	75	69	59	70	71	67	67	61	63	66	99	97	65	87	60
Mg#	3	9	6	8	18	20	13	4	2	5	0	0	3	0	1

Sample:	PCL67	PCL67	MLM102	MLM102	MLM106	MLM108	PCL4001	PCL4001	PCL4001	PCL8675	PCL8675	PCL8676	PCL8676	PCL8676
Location:	Levack	Levack	Levack	Levack	Levack	Levack	Craig	Craig	Craig	Gertrude	Gertrude	Gertrude	Gertrude	Gertrude
Host:	Ol	Ol	Ol	Ol	Ol	Ol	Ol	Ol	Ol	Opx	Opx	Opx	Opx	Ol
TiO_2 (wt.%)	2.01	1.30	6.05	3.48	3.87	2.86	2.25	1.31	2.47	1.69	9.50	1.59	5.20	0.98
Cr_2O_3	16.6	10.4	12.1	12.3	19.1	24.3	25.9	25.2	24.0	38.1	32.2	43.3	35.1	40.8
Al_2O_3	5.54	1.71	4.60	4.93	6.68	7.34	8.57	7.11	7.70	14.7	11.8	13.5	12.8	16.3
V_2O_3					0.29	0.34								
Fe_2O_3	44.3	55.0	43.5	46.9	37.8	34.0	33.3	35.4	35.4	12.4	11.6	9.60	13.0	11.2
FeO	29.0	30.4	31.1	31.2	28.8	27.9	23.2	26.3	24.7	29.4	30.2	27.0	29.2	22.7
MgO	2.18	0.58	0.73	0.60	2.51	3.39	6.37	3.86	5.23	2.99	3.59	4.51	3.56	7.47
MnO	0.27	0.32	1.08	0.77	0.56	0.27	0.39	0.42	0.34	0.35	0.56	0.42	0.47	0.33
NiO	0.10	0.14	0.07	0.10	0.14	0.08	0.32	0.32	0.38	0.02	0.04	0.13	0.04	0.18
ZnO	0.24	0.08	0.40	0.36	0.25	0.22	0.05	0.13	0.16	0.40	0.08	0.19	0.16	0.17
Total	100.4	99.9	99.7	100.7	100.0	100.6	100.5	100.1	100.4	100.1	99.5	100.3	99.6	100.1
Cr#	67	80	64	63	66	69	67	70	68	63	65	68	65	63
Mg#	12	3	4	3	13	18	33	21	27	15	17	23	18	37

Notes: Blank means that the element was not determined. $Cr\# = 100Cr/(Cr + Al)$; $Mg\# = 100Mg/(Mg + Fe^{2+})$.

Table 2. Representative analyses of silicate inclusions in chromian spinels from the mafic–ultramafic inclusions and complexes in the Sublayer.

Mineral:	Olivine	Olivine	Olivine	Olivine	Olivine	Opx	Opx	Opx	Opx	Cpx	Cpx	Cpx	Cpx
Sample:	MLM32	MLM32	MLM32	MLM102	PCL8675	MLM32	MLM32	PCL8675	PCL8675	PCL8675	PCL8675	PCL8675	MLM32
SiO_2 (wt.%)	39.0	38.8	38.51	39.70	39.11	55.7	55.4	54.9	54.6	56.1	52.6	52.9	53.2
Al_2O_3	0.10	0.07				0.90	0.81	1.01	1.20	2.29	1.96	1.91	1.84
Cr_2O_3	0.38	0.3	0.43	0.31		0.50	0.50	0.40	0.70	0.89	1.71	1.23	0.85
TiO_2	0.01	0.1	0.05	0.08	0.05	0.10	0.10	0.20	0.20	0.36	0.41	0.50	0.19
FeO	17.3	17.3	17.00	18.00	17.59	12.0	12.1	11.4	11.4	4.88	5.16	4.74	6.65
MnO	0.29	0.3	0.59	0.20	0.33	0.30	0.32	0.28	0.30	0.05	0.15	0.12	0.14
MgO	44.5	44.2	43.37	43.50	43.15	30.8	31.4	30.6	30.4	22.3	16.7	16.9	16.5
NiO	0.31	0.3	0.41	0.06	0.29	0.80	0.75	1.03	0.80	12.9	22.1	21.9	21.3
CaO	0.05	0.1	0.03	0.04	0.04	0.30	0.31	0.05	0.20	0.29	0.28	0.33	0.57
Na_2O													
Total	101.9	101.4	100.45	101.89	100.56	101.4	101.7	99.8	99.8	100.1	101.1	100.7	101.3

Note: For Opx and Cpx columns the row labels read SiO_2 (wt.%), Al_2O_3, Cr_2O_3, TiO_2, FeO, MnO, MgO, CaO, Na_2O, Total.

Mineral:	Mica	Mica	Mica	Mica	Zr	Zr	Zr	Matrix Zr	Matrix Zr
Sample:	MLM32	MLM32	PCL8675	PCL8675	MLM32	MLM32	MLM32	MLM32	MLM32
SiO_2 (wt.%)	36.7	36.8	39.9	37.0	31.3	32.3	31.7	31.1	30.8
Al_2O_3	15.1	14.9	14.5	15.8					
Cr_2O_3	0.98	0.84	1.43	1.49					
TiO_2	2.32	1.30	1.30	2.63					
FeO	7.10	6.47	5.03	6.44					
MgO	22.8	22.4	22.8	23.1					
CaO	0.06	0.29	1.73	0.05					
Na_2O	0.91	0.88	0.19	0.52					
K_2O	7.67	7.13	8.74	7.50					
HfO_2					0.87	1.02	1.03	1.17	1.46
ZrO_2					65.7	65.6	65.9	65.9	65.8
ThO_2					0.03	0.01	0.04	0.0	0.0
Y_2O_3					0.09	0.09	0.06	0.19	0.35
P_2O_5					0.19	0.10	0.15	0.11	0.09
FeO					1.24	1.76	0.86	0.16	0.19
Total	93.7	91.2	96.3	94.7	99.4	100.8	99.8	98.7	98.7

Notes: Cpx, clinopyroxene; Opx, orthopyroxene; Zr, zircon.

Fig. 4. Compositional profiles across a zoned chromian spinel grain in sample 94PCL8675. Oxide plotted against the distance. The zonation is shown in microphoto Fig. 3d. Note the log scale for TiO_2.
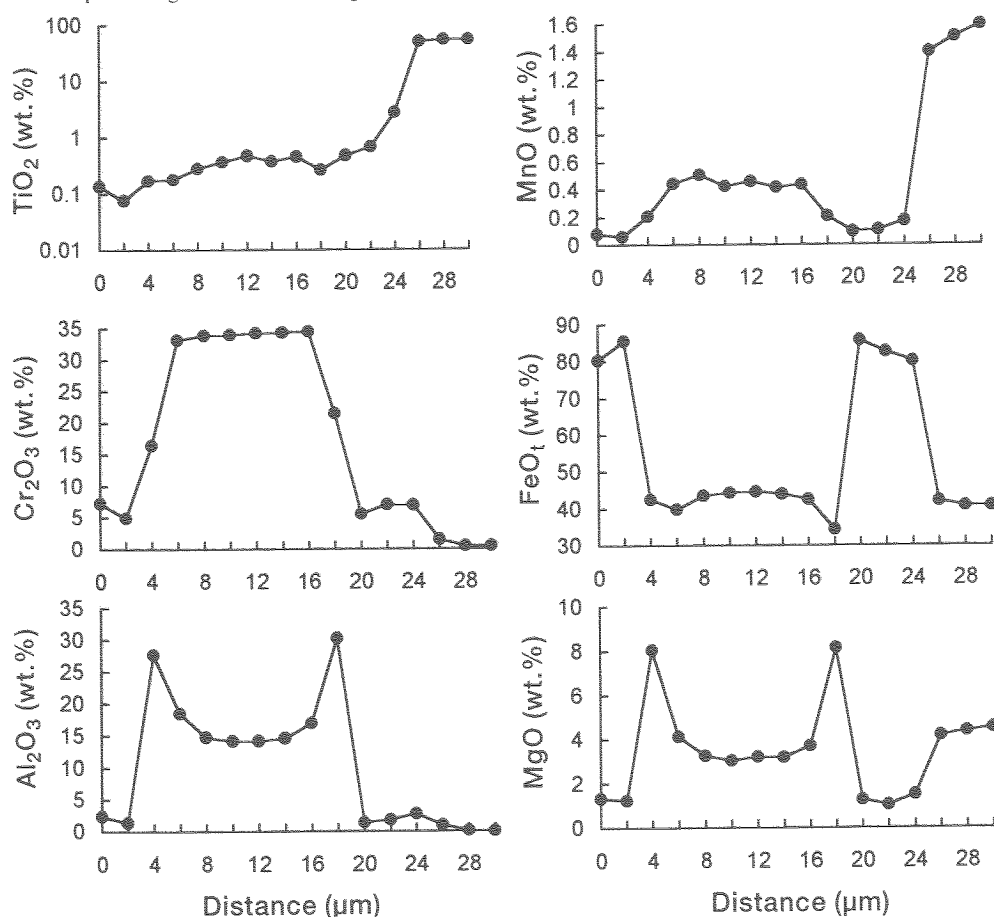
Cr)) versus TiO_2 diagram (Fig. 8), the Gertrude mine chromian spinels have lower Fe# than the other chromian spinels, although they have similar TiO_2. The lack of the positive correlation contrasts with chromian spinels in Hawaiian basalts in which there is a positive correlation between Fe^{3+} and Ti (Fig. 8). The SIC chromian spinels exhibit TiO_2 contents similar to those of their equivalents from other mafic volcanic and intrusive rocks.

All the chromian spinels have similar trace element abundances (Table 1, Fig. 9). NiO contents range from 0.1 to 0.45 wt.%. Most chromian spinels have significant amounts of V_2O_3 (0.02−0.46 wt.%), and those from the Whistle mine have even higher V_2O_3 contents (0.36−1.0 wt.%). The MnO contents of the SIC chromian spinels range from 0.02 to 1.5 wt.%, with some magnetite having up to 4.7 wt.% MnO. ZnO contents are typically in the range of 0.00−0.35 wt.% (Table 1). The high-V chromian spinels and magnetites are also high in Zn (up to 1.36 wt.% ZnO) (Fig. 9).

Chemical compositions of silicate inclusions
Olivine inclusions in the chromian spinels have Fo values of 85−90, higher than those of olivine in the inclusion matrix (Table 2). This can be attributed to subsolidus Fe−Mg exchange between silicates and chromites (Lehmann 1983). They have higher Cr_2O_3 contents (0.29−0.57 wt.%) than does the inclusion matrix olivine. Diopside contains 0.80−

1.71 wt.% Cr_2O_3; orthopyoxene also has considerable chromium contents (Cr_2O_3 = 0.37−0.72 wt.%) (Table 2).

According to the classification of Deer et al. (1962), the micas occurring as inclusions in the SIC chromian spinels are all phlogopite. They have Mg/(Fe$_t$ + Mg) ratios (Fe$_t$, total Fe as Fe^{2+}) of 0.85−0.91 and high Cr contents (Cr_2O_3 = 0.33−1.49 wt.%). They also have higher K_2O (6.33 − 8.74 wt.%) than Na_2O (0.19−1.10 wt.%) contents (Table 2). These phol:gopite inclusions are different from those in the inclusion matrix in having relatively high MgO contents.

A few points were analyzed for each of the two zircon grains in the chromian spinel (Fig. 3c); they do not show compositional zoning. They have much higher FeO contents (0.86−1.76 wt.%) than those of zircons (FeO <0.20 wt.%) in the inclusion matrix and in the Sublayer norites. Besides, both types of zircon have different Si, Hf, and Y contents, although Zr contents are basically indistinguishable (Table 2).

Discussion

Relations of the mafic−ultramafic inclusions and complexes to the sublayer matrix
Many inclusions in the Sublayer were derived from the adjacent wall rocks. For example, inclusions of gneissic rocks in the Sublayer of the North Range are believed to be equivalents of the Archean gneisses of the Superior Province.

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Fig. 5. Major oxide relationship of chromian spinels within the SIC: Al_2O_3 versus Cr_2O_3, MgO versus Cr_2O_3, FeO_t (as total iron) versus Cr_2O_3, and MgO versus FeO_t.
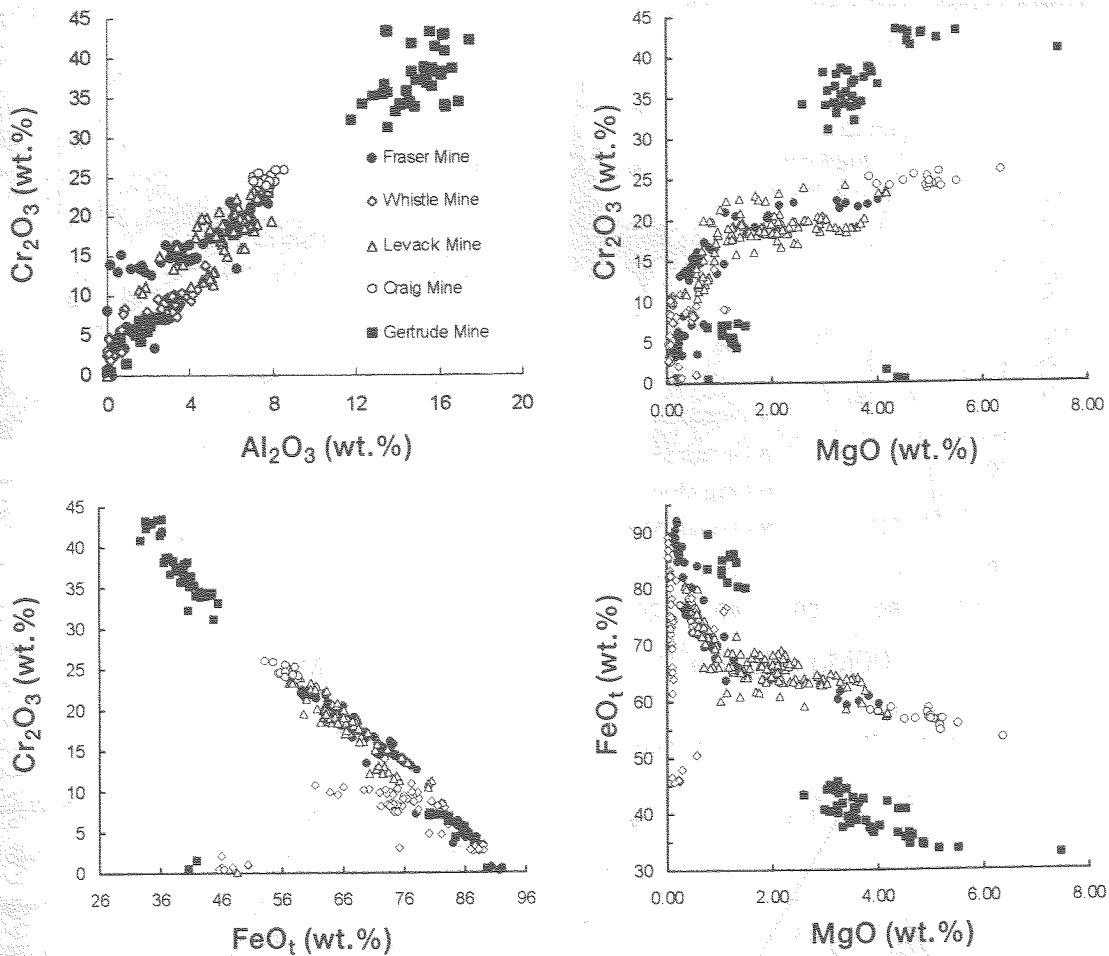
whereas inclusions of Huronian sedimentary rocks are only observed in the Sublayer of the South Range overlying the Huronian Supergroup.

On the other hand, there is no obvious source of the ultramafic inclusions, which are uniformily distributed in the Sublayer, in the footwall rocks of the SIC. While mafic intrusions occur in the pre-Sudbury event rocks, ultramafic rocks are rare. The East Bull Lake suite of 2.45 Ga Early Proterozoic intrusions is dominated by leucogabbros with only very minor pyroxenites and harzburgites (James and Born 1985). While the 2.25 Ga Nipissing Diabases are similar in many respects to diabase inclusions in the Sublayer (Lightfoot et al.[4] 1993), no ultramafic rocks are associated with the Nipissing Diabases. Finally, Corfu and Lightfoot (1996) have demonstrated that the ultramafic inclusions at the Whistle mine have ages of 1.85 Ga. While the age of the inclusions may have been reset by the SIC event, these ages do not support a pre-Sudbury event age for the inclusions. The chromian spinels in these rocks are unique enough to

further exclude the possibility that they were xenoliths inherited from the basement. The similar trace elemental abundances of all the chromian spinels in the inclusions and the footwall ultramafic complexes suggest that they are comagmatic; for example, they all contain appreciable TiO_2 and many have ilmenite lamellae. All the spinels form a continuum in the $Al-(Fe^{3+} + 2Ti)-Cr$ triangular diagram and define a trend crosscutting the normal fields of spinel compositions (Fig. 7); this continuum in compositions extends from the (Ti-)Cr- and Al-rich spinels in the mafic−ultramafic inclusions and footwall complexes through to chromian magnetite in the Sublayer matrix. It further compliments whole-rock trace element geochemistry, which indicates that the Sublayer matrix norites and the mafic−ultramafic inclusions were derived from compositionally similar magmas (Farrell et al. 1994; Lightfoot et al.[3] 1994, 1995).

Significance of crustal contamination

Mineral inclusions such as phlogopite, pargasite, olivine, orthopyroxene, and clinopyroxene have been described in chromian spinel from ophiolites (Johan et al. 1983; Lorand and Cottin 1989; McElduff and Stumpfl 1991) and layered intrusions (McDonald 1965; Irvine 1975; Lorand and Cottin 1989). Albite inclusions in chromian spinel are also known

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[4] P.C. Lightfoot, R.R. Keays, G.G. Morrison, A. Byte, and K.P. Farrell. Geochemical relationships in the Sudbury Igneous Complex: origin of the Main Mass and Offset Dykes. Submitted for publication.

Fig. 6. 100Cr/(Cr + Al) versus 100Mg/(Mg + Fe^{2+}) of chromian spinels within the SIC. Reference data of chromian spinels from other mafic volcanic and intrusive rocks are based on Lightfoot and Naldrett (1983) and Cawthorn et al. (1991) (Insizwa Complex, South Africa), Pedersen (1985) (Disko, Greenland), Czamanske et al. (1995) (Noril'sk intrusion, Russia), Yang et al. (1994) (Jinchuan intrusion, China), and Groves et al. (1977) (sulfide-bearing volcanic rocks from Western Australia).
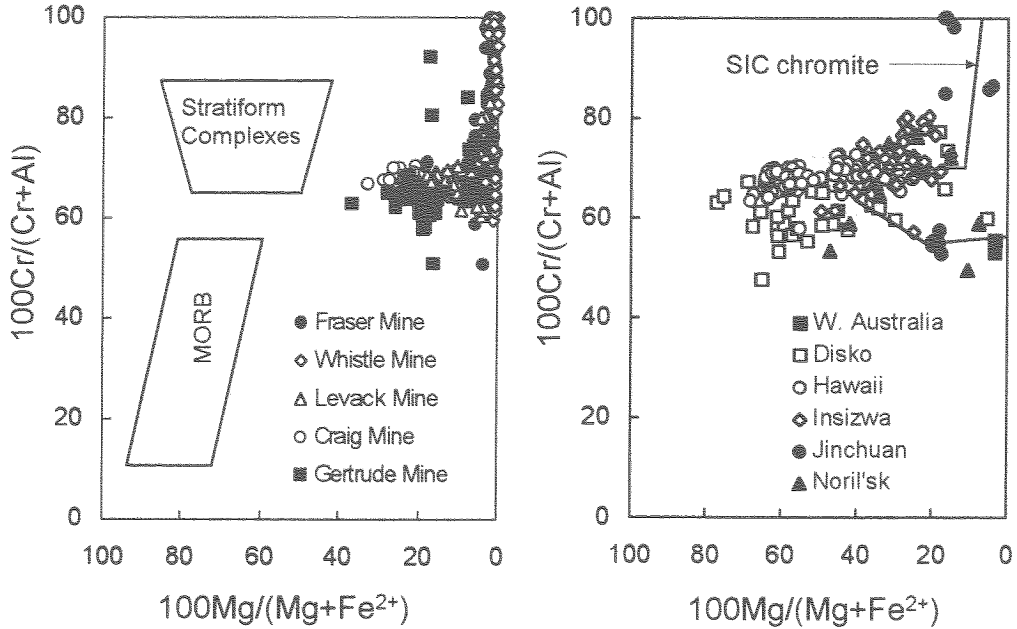
Fig. 7. Triangular diagram of Al−(Fe^{3+} + 2Ti)−Cr of chromian spinels within the SIC. See Fig. 6 for reference data.
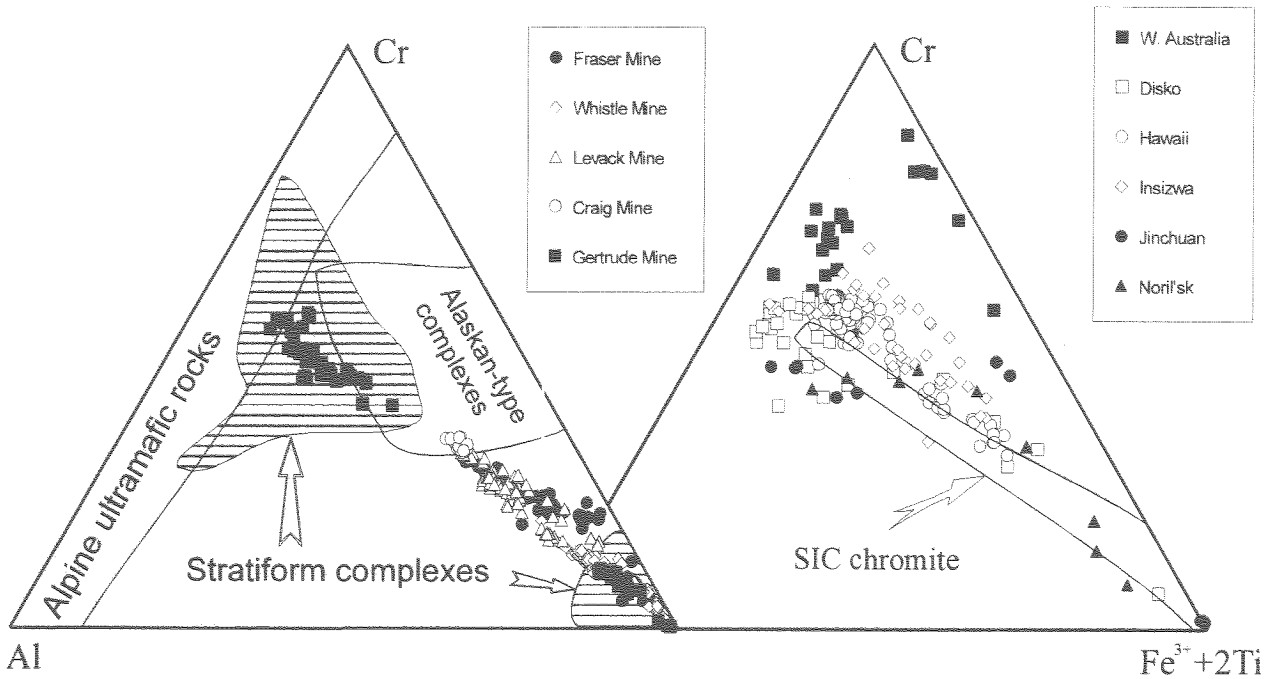
in layered intrusions (Irvine 1975) and komatiites (Zhou and Kerrich 1992), but zircon grains have not previously been reported as inclusions in chromian spinel. Irvine (1975) interpreted the albite as representing droplets of contaminant granitic melt that were trapped in the chromian spinel at various stages of mixing two magmas.

Given that chromian spinel is an early-formed magmatic mineral in mafic−ultramafic magmas, the zircon grain in

Fig. 3c is either also an early-formed mineral in such a magma or a xenolith trapped during crystallization of chromian spinel. The latter explanation is more likely, because zircon is a stable mineral in magmas saturated or nearly saturated with silica, but would crystallize at a later stage from a mafic magma (Butterman and Foster 1967; Watson 1979). All zircon separates from the SIC, including those in ultramafic inclusions, have yielded ages of ca. 1.85 Ga

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Fig. 8. $100Fe^{3+}/(Fe^{3+} + Al + Cr)$ versus TiO_2 of chromian spinels within the SIC. See Fig. 6 for reference data.
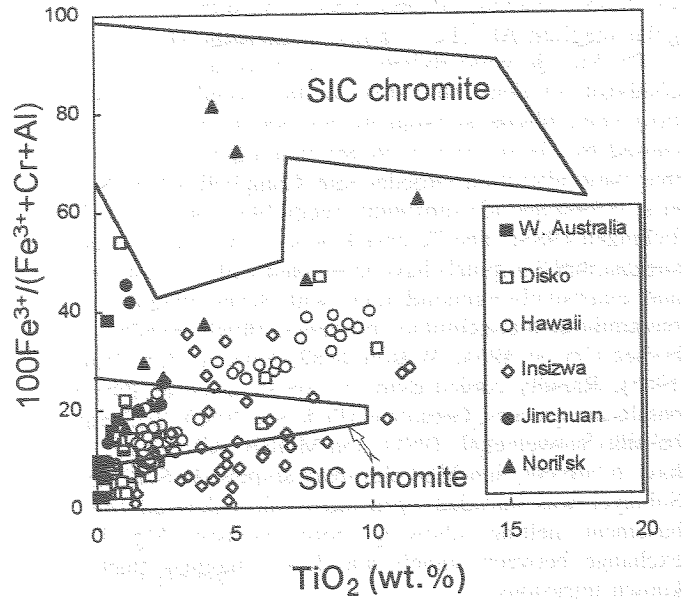

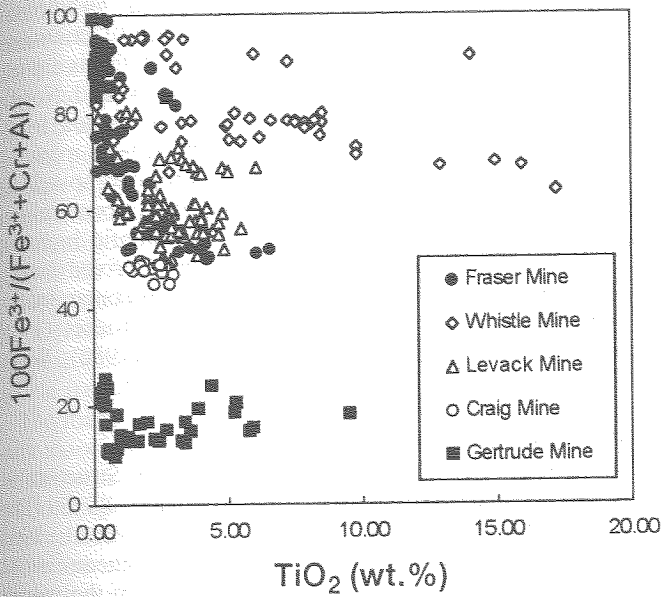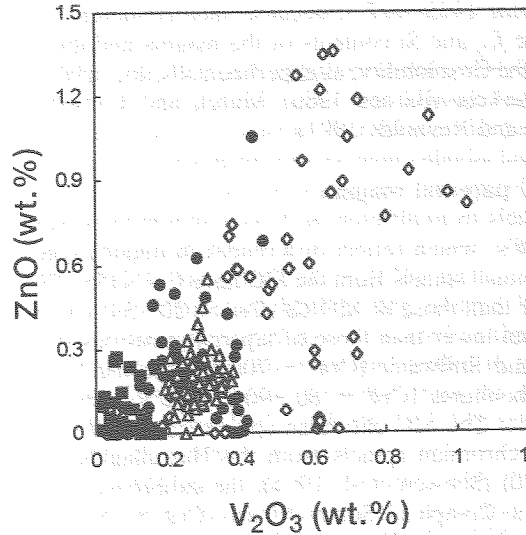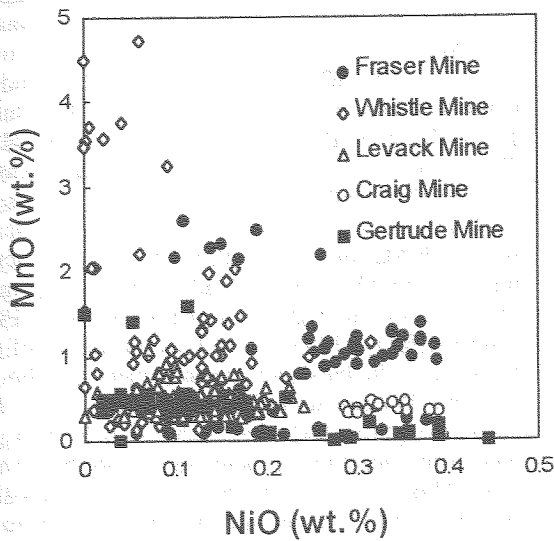**Fig. 9.** Trace elements of chromian spinels within the SIC: NiO versus MnO and V_2O_3 versus ZnO.

(Krogh et al. 1984; Corfu and Lightfoot 1996). The two zircon grains reported in this study were likely derived from a felsic melt and therefore suggest a magma mixing process, as previously proposed for chromite in the Muskox intrusion (Irvine 1975).

The euhedral biotite inclusions are different from post-magmatically entrapped inclusions, which tend to be spherical in appearance (McDonald 1965; Lorand and Cottin 1989). This suggests that the biotite had a magmatic origin, which in turn demands that the magma from which they formed be hydrous. Another possibility is that all of the Sublayer rocks, including both mafic−ultramafic inclusions and the Sublayer matrix, were invaded by either hydrous fluids or melts that introduced H_2O and other components into the Sublayer. This scenario would require recrystallization of the chromite.

The plagiolase inclusion would again indicate a mixing process involving a plagioclase-saturated felsic melt and a high-Mg magma. This felsic magma is presumably crustally derived and hydrous. It would be the source of the zircon and plagioclase inclusions and water required for the igneous biotite.

Because magmas contain trace Cr and major Al, crystallization of chromian spinel alone would deplete Cr far more rapidly than Al. The positive relationship between these two elements in the SIC chromian spinels (Fig. 5) might suggest a coprecipitation of chromian spinel and plagioclase. This coprecipitation would again support a mixing process between mantle-derived, Cr-rich magma and crust-derived, plagioclase-saturated felsic melt. The crustal melt would have contained more Fe than the mantle-derived magma and was presumably more oxidized than the high-Mg magma. The mixing of these two melts increases the mafic magma in Fe and Ti, and as

a result, chromian spinels therefore become depleted in both Cr and Al, forming a continuous chemical trend in the triangular diagram $Al-(Fe^{3+} + 2Ti)-Cr$ (Fig. 7).

The SIC chromian spinels have considerably more Fe-rich compositions than those that would normally coexist with $Fo_{80}-Fo_{90}$ olivine at magmatic temperatures. This might be caused by (1) reaction with residual liquid and (or) post-magmatic alteration (Roeder and Campbell 1985; Scowen et al. 1991) and (2) subsolidus reequilibration (Irvine 1967; Lehmann 1983). The Fe enrichment of the SIC spinels may suggest that the spinels have interacted with Fe-rich magmas and extensively reequilibrated with felsic magmas. Such reequilibration is a common process in slowly cooled igneous bodies (Irvine 1965; Wilson 1982; Roeder and Campbell 1985). Rapidly cooled extrusive rocks, such as the Disko basalts and picrites, Greenland (Pedersen 1985), the Hawaiian basalts (Scowen et al. 1991), and MORB (Allen et al. 1988), have relatively high Mg# chromian spinels. In Sudbury, the Sublayer was intruded by felsic veinlets derived from the basement melting, allowing more extensive Mg−Fe ion exchange between spinels and felsic magmas than other known intrusions.

Chromian spinel crystallization may have been induced by mixing of the mantle-derived magma with the crustal melt, leading to chrome oversaturation and chromian spinel crystallization (Irvine 1975, 1977), because such contamination would increase f_{O_2} and Si contents of the magma and therefore decrease the Cr solubility, as experimentally documented by several workers (Barnes 1986; Murck and Campbell 1986; Roeder and Reynolds 1991).

Nature of the parental magma

Chromian spinels from different tectonic environments have distinctive Cr#'s, which reflect differences in magma composition. Chromian spinels from the SIC have Cr#'s (55−70) that are higher than those of MORB (Cr# = 20−54) (Allen et al. 1988), but lower than those of layered intrusions such as Bushveld and Stillwater (Cr# = 70−85) (Irvine 1967) and those of boninites (Cr# = 80−90) (e.g., Roeder and Reynolds 1991). The SIC chromian spinels have Cr# similar to that of chromian spinels from the Hawaiian basalts (Cr# = 60−70) (Scowen et al. 1991), the gabbro−picrites of the Insizwa Complex, South Africa (Cr# = 57−80) (Lightfoot and Naldrett 1983; Cawthorn et al. 1991), the basalts from Disko Island, West Greenland (Pedersen 1985), and the intrusions of the Noril'sk region, Russia (Czamanske et al. 1995). This similarity of the Cr#'s suggests that the SIC chromian spinel may have formed from a magma with basaltic composition.

The TiO$_2$ contents of chromian spinel from the SIC are high compared with those of chromian spinel from layered intrusions such as Bushveld and Stillwater. Low Ti values (TiO$_2$ = 0.16−0.85 wt.%) were reported in chromian spinel from MORB (Dick and Bullen 1984; Allen et al. 1988). Chromian spinels from the Disko basalts, the Noril'sk intrusion, and the Insizwa Complex have similarly high TiO$_2$ contents as the SIC chromian spinel (Fig. 8). Other close analogues of the SIC chromian spinels are the Ti-chromian spinel with 7.8−15.1 wt.% TiO$_2$ from the Snake River Plain basalts that were thought to be derived from an iron- and alkali-rich basaltic magma (Thompson 1973). Titanium-

bearing chromian spinels (TiO$_2$ = 6.7−15.7 wt.%) from the Insizwa Complex were interpreted to indicate an extremely high-Ti parental magma, distinct from typical continental basaltic melts (Cawthorn et al. 1991), although this is arguable (Lightfoot et al. 1987). The Insizwa, Disko, and Noril'sk intrusions have been interpreted as having formed from a mantle-derived magma contaminated by crustal materials. The high TiO$_2$ contents of the SIC chromian spinels are consistent with their formation from crustally contaminated magmas; hence, although the mafic−ultramafic inclusions are believed to have formed from a mantle-derived magma, this magma must have been subject to crustal contamination, supporting the previous view of Kuo and Crocket (1979), Naldrett and Hewins (1984), Naldrett et al. (1986), Walker et al. (1991), and Chai and Eckstrand (1994).

Petrogenetic implication for the SIC

It is now generally accepted that the Sudbury Structure was produced by a major meteorite impact at ca. 1.85 Ga (Dietz 1964; Peredery and Morrison 1984; Grieve et al. 1991). Associated with the meteorite impact was an igneous activity that produced the SIC, although the sources of the magmas remain poorly understood (see references in Pye et al. 1984; Lightfoot and Naldrett 1994).

Lightfoot et al. (1995) have recently argued that it is necessary to invoke the introduction of a mantle-derived high-Mg melt to account for the generation of the sulfide ore bodies, because the impacted Archean and Proterozoic country rocks contain insufficient Ni, Cu, and platinum-group elements (PGE) to provide all of the metals in the ores. The presence of the mafic−ultramafic inclusions and footwall bodies together with the chromian spinels within these rocks gives powerful evidence that the mantle-derived magma was high-Mg in composition, possibly a picrite. Such a magma would have been S undersaturated, a primary requirement for the formation of major Ni−Cu−PGE sulphide deposits (Keays 1995), as well as the source of the Cr in the spinels and the base and precious metals in the sulphide ore deposits. We concur with other workers (e.g., Grieve et al. 1991; Golightly 1994) that a crustal melt sheet generated by meteorite impact played a major role in the formation of the Main Mass. In addition, the gross geochemical similarities between the Main Mass and the Sublayer norite matrix indicate that a component of the Main Mass magma was present in the hybrid magma that formed the Sublayer (Lightfoot et al.[4]). We suggest that subsequent to meteorite impact and generation of a crustal melt sheet, a mantle-derived high-Mg magma entered the magma chamber.

The high-Mg mafic magma mixed vigorously with the crustal melt, prompting S saturation of the previously S-undersaturated and Ni−Cu−PGE-rich high-Mg magma. This led to production of immiscible sulphide droplets, which, because of their high density, settled to the floor of the chamber. The resultant hybrid magma formed the Main Mass of the SIC as well as the offset dykes. In other cases, a part of the high-Mg magma settled directly to the floor of the chamber, where it underwent variable degrees of mixing with the felsic crustal melt. It is also possible that the less-contaminated mantle magmas intruded into the basement, where they formed the footwall mafic−ultramafic complexes, such as those at Fraser and Levack mines.

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As an impact site, the bottom of the magma chamber would have been hot enough to continue melting the basement rocks, forming granitic droplets (Fig. 2f). The felsic basement rocks would have contained residual heat from the meteorite impact; additional heat was provided by the superheated crustal melt and by the high-Mg magma. The basement-derived partial melts may have percolated upwards through the high-Mg magma and mixed with it, thereby causing chromite formation. The early-formed rocks (inclusions) were also modified by interaction with impregnated felsic melt. Many of the Sublayer inclusions and matrix would have formed through mixing of various proportions of a high-Mg magma and a felsic melt. This led to locally different whole-rock compositions, and also caused the difference of chromian spinels from different embayments (Fig. 5).

The mafic—ultramafic inclusions in the Sublayer are spatially associated with sulfide ores. Both these inclusions and sulfide melts might have been deposited downwards from the hybrid magma by gravity and (or) convection current to terraces inside the troughs of the Sublayer environment (Morrison et al. 1994). The Sublayer would represent an interaction zone through which the basement continuously supplied granitic melts to the magma chamber. This interaction zone is also the hottest and last-solidified part of the Sudbury impact melt sheet. Chilled margins would not be expected in this interaction zone.

Implications for the SIC sulfide deposits

Some trace elements (Ni, Zn, Mn, V) in chromian spinel are believed to be sensitive during the formation of sulfide ores (Naldrett 1969; Ewers et al. 1976; Czamanske et al. 1976; Groves et al. 1977, 1983). Nickel contents (NiO = 0.1–0.45 wt.%) of the SIC chromian spinel are much lower than those of chromian spinel from the Great Dyke (NiO = 0.9–1.7 wt.%) (Wilson 1982). The release of Ni from silicates during serpentinization and incorporation of Ni in magnetite may result in an enrichment of Ni in the secondary magnetite rim of zoned chromian spinel grains (Bliss and MacLean 1975). It is believed that the low Ni contents of the SIC chromian spinels are not due to alteration. The range of Ni partition coefficient between olivine and chromian spinel is 0.93–2.27 (Stosch 1981); much higher partition coefficients can be expected between sulfide and chromian spinel. The lower Ni contents of the SIC chromian spinel may reflect the presence of sulfide melts, which, in turn, may indicate S saturation of the magma during or before chromian spinel crystallization. This seems consistent with the presence of sulfide inclusions in the chromian spinel (Fig. 3).

Chromian spinels formed in sulfide melts are rich in Cr but poor in Al and Mg, and have high Zn, V, and Mn contents (Czamanske 1976; Ewers et al. 1976; Groves et al. 1977, 1983). As noted by Ewers et al. (1976), spinels thought to have crystallized from a sulfide melt are chemically distinct from those in the rocks that host the massive sulfide bodies. Chromian spinels in the Kambalda sulfide ores have relatively high Zn (ZnO = 0.53–2.92 wt.%) (Groves et al. 1977, 1983). Peltonen (1995) also reported high-Zn chromian spinel (ZnO = >0.8 wt.%) of sulfide deposits in the Vammala belt, Finland. Chromian spinel from the Thompson nickel belt is rich in Zn (up to 0.98 wt.%) (Paktunc and Cabri 1995). Bushveld chromian spinel in the sulfide upper zone

has 6500 ppm Zn, while that in the lower chromitite layers of the lower zone has 3900 ppm Zn (Paktunc and Cabri 1995). Anomalously high Zn contents (>0.5 wt.%) of chromian spinel are thought to be a useful indicator of Ni—Cu—PGE-bearing rocks (Groves et al. 1977; Peltonen 1995). The Zn contents of the SIC chromian spinel are unusually low (ZnO = 0.00–0.35 wt.%) compared with chromian spinels from other sulfide-bearing bodies. Although high Zn contents in some chromian spinels may be caused by post-magmatic alteration (Wylie et al. 1987), the high Zn contents of chromian spinel associated with Ni—Cu—PGE sulfide ores are believed to be due to crustal contamination (Groves et al. 1977, 1983; Peltonen 1995). In the case of komatiite-associated Ni—Cu—PGE sulfide ores such as those at Kambalda and the Thompson nickel belt, it has long been thought that the Zn in chromian spinels was derived from sulfidic sediments assimilated by high-Mg magmas. The low Zn values of the SIC spinels may suggest a paucity of Zn in the contaminants in the basement rocks.

Conclusions

1. Chromian spinels in mafic—ultramafic inclusions in the Sublayer as well as in mafic—ultramafic bodies in the footwall to the Sublayer and in the Sublayer noritic matrix exhibit a continuum in the composition from chromite to chromian magnetite.
2. The compositional variations in the spinels suggest that the mafic—ultramafic inclusions and footwall bodies are genetically linked to the magma that formed the Sublayer matrix.
3. The silicate inclusions (zircon, plagioclase, and biotite) and compositional variations in the spinels, particularly the covariation of Al and Cr, were caused by mixing a plagioclase-saturated, Fe-rich, oxidized crustal melt with a Cr-rich, mantle-derived, high-Mg melt.
4. Contamination of the high-Mg magma by the resident felsic crustal melt may have occurred as the high-Mg melt entered the magma chamber and settled to the floor of the chamber. Partial melts generated from the basement rocks percolated upwards through the high-Mg magma and were variably mixed with it.
5. High-Mg melt mixed vigorously with the felsic crustal melt, leading to S saturation of the hybrid and generation of immiscible droplets of Ni—Cu—PGE sulfides, which settled to the floor of the magma chamber and later formed the ore deposits.

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