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<td>Author(s)</td>
<td>Zhou, MF; Lightfoot, PC; Keays, RR; Moore, ML; Morrison, GG</td>
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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 magnete in the host norite matrix to the mafic–ultramafic inclusions. This continuum in composition of the spinels suggests that the norite 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$^{3+}$-saturated, 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 Coupe 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 Coupe de base. Les roches hôtes sont la pyroxénite et la mélanorite, elles sont accompagnées de dunite, harzburgite et mélanorctolite. Les spinelles chromifères représentent dans ces roches des phases accessoires communes, avec des formes cristallines automorphes et sousautomorphes dans les olivine et l'orthopyroxène. Les grains des spinelles chromifères renferment généralement des lamelles d'ilmenite, 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 matière de la roche hôte et des inclusions mafiques–ultramafiques. Ce continuum dans la composition des spinelles suggère que la matière norique de la Coupe 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 Coupe de base est le produit d'un mélange de magmas. Il est proposé que, subéquiment, à la formation du magma crustal, il y a eu ajout et mélange vigoureux avec des magmas riches en Mg dérivé du manteau, ce qui aurait engendré les liquides sulfureux qui finalement formèrent les gîtes de sulfures de Ni–Cu–éléments du groupe de platine. Certains produits de cristallisation précoces 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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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 1965; Dick and Bullen 1984; Roeder and Reynolds 1981; 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 gabbror, and (6) granophyre. All of the units except the offset 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-
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) and Fe$^{3+}$ and Fe$^{2+}$ were distributed by assuming an R$^{2+}$R$^{3+}$O$_4$ formula for the chromian spinel and balancing RO$\cdot$R$_2$O$_3$ = 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, (as total iron) and MgO contents similar to those of the chromite core, but higher MnO and TiO2 and lower Cr2O3 and Al2O3 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. 5. 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.

Cr₂O₃, Al₂O₃, and FeO, (Fig. 5). On the Cr₂O₃ versus MgO and FeO, versus MgO diagrams, samples from the Gertrude mine stand out, as they have higher Cr₂O₃ and significantly less FeO. 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, Cr₂O₃ covaries positively with Al₂O₃ and MgO, whereas there are negative correlations between MgO and FeO, as well as FeO, and Cr₂O₃ (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-ocean 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 – (Fe³⁺ + 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 basalt, 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 TiO₂ 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 TiO₂ contents of the SIC chromian spinel do not covary with any of Al, Cr, Fe, Mn, or Ni. In a Fe# (100Fe³⁺/(Fe³⁺ + Al + ...
Table 1. Representative analyses of chromian spinels from the mafic–ultramafic inclusions and complexes in the Sublayer.

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<td>0.04</td>
<td>0.13</td>
</tr>
<tr>
<td>NiO</td>
<td>0.24</td>
<td>0.08</td>
<td>0.40</td>
<td>0.36</td>
<td>0.25</td>
<td>0.22</td>
<td>0.05</td>
<td>0.13</td>
<td>0.16</td>
<td>0.40</td>
<td>0.08</td>
<td>0.19</td>
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<tr>
<td>Total</td>
<td>100.4</td>
<td>99.9</td>
<td>99.7</td>
<td>100.7</td>
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<td>68</td>
</tr>
<tr>
<td>Mg#</td>
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<td>3</td>
<td>4</td>
<td>3</td>
<td>13</td>
<td>18</td>
<td>33</td>
<td>21</td>
<td>27</td>
<td>15</td>
<td>17</td>
<td>23</td>
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</table>

Notes: Blank means that the element was not determined. Cr# = 100Cr/(Cr + Al); Mg# = 100Mg/(Mg + Fe²⁺).
Table 2. Representative analyses of silicate inclusions in chromian spinels from the mafic–ultramafic inclusions and complexes in the Sublayer.

<table>
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<tr>
<th>Mineral: Sample</th>
<th>Opx MLM32</th>
<th>Opx MLM32</th>
<th>Opx PCL8675</th>
<th>Opx PCL8675</th>
<th>Opx PCL8675</th>
<th>Cpx PCL8675</th>
<th>Cpx PCL8675</th>
<th>Cpx PCL8675</th>
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<tr>
<td>SiO₂ (wt. %)</td>
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<td>38.51</td>
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<td>39.11</td>
<td>55.7</td>
<td>55.4</td>
<td>54.9</td>
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<td>Al₂O₃</td>
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<td></td>
<td></td>
<td>0.90</td>
<td>0.81</td>
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<td>1.20</td>
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<td>Cr₂O₃</td>
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<td>0.3</td>
<td>0.43</td>
<td>0.31</td>
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<td>0.50</td>
<td>0.50</td>
<td>0.40</td>
<td>0.70</td>
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<td>0.08</td>
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<td>0.10</td>
<td>0.10</td>
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<td>17.3</td>
<td>17.00</td>
<td>18.00</td>
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<tr>
<td>MgO</td>
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<td>44.2</td>
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<td>43.50</td>
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<td>31.4</td>
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<tr>
<td>NiO</td>
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<td>0.3</td>
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<td>0.80</td>
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<td>CaO</td>
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<td>0.04</td>
<td>0.04</td>
<td>0.30</td>
<td>0.31</td>
<td>0.05</td>
<td>0.20</td>
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<tr>
<td>Total</td>
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<td>101.4</td>
<td>100.45</td>
<td>101.89</td>
<td>100.56</td>
<td>101.4</td>
<td>101.7</td>
<td>99.8</td>
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<tr>
<td>SiO₂ (wt. %)</td>
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<td>31.3</td>
<td>32.3</td>
<td>31.7</td>
<td>31.1</td>
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</tr>
<tr>
<td>Al₂O₃</td>
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<td>14.5</td>
<td>15.8</td>
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<tr>
<td>Cr₂O₃</td>
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<td>0.84</td>
<td>1.43</td>
<td>1.49</td>
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<td>65.9</td>
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<tr>
<td>TiO₂</td>
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<td>1.30</td>
<td>1.30</td>
<td>2.63</td>
<td>0.03</td>
<td>0.01</td>
<td>0.04</td>
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<td></td>
</tr>
<tr>
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<td>5.03</td>
<td>6.44</td>
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<td>0.09</td>
<td>0.06</td>
<td>0.19</td>
<td>0.35</td>
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</tr>
<tr>
<td>MgO</td>
<td>22.8</td>
<td>22.4</td>
<td>22.8</td>
<td>23.1</td>
<td>0.19</td>
<td>0.10</td>
<td>0.15</td>
<td>0.11</td>
<td>0.09</td>
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</tr>
<tr>
<td>CaO</td>
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<td>1.73</td>
<td>0.05</td>
<td>1.24</td>
<td>1.76</td>
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<tr>
<td>Na₂O</td>
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<td>0.88</td>
<td>0.19</td>
<td>0.52</td>
<td>99.4</td>
<td>100.8</td>
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<tr>
<td>Total</td>
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<td>91.2</td>
<td>96.3</td>
<td>94.7</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Notes: Cpx, clinopyroxene; Opx, orthopyroxene; Zr, zircon.
Cr) versus TiO₂ diagram (Fig. 8), the Gertrude mine chromian spinels have lower Fe# than the other chromian spinels, although they have similar TiO₂. The lack of the positive correlation contrasts with chromian spinels in Hawaiian basalts in which there is a positive correlation between Fe³⁺ and Ti (Fig. 8). The SIC chromian spinels exhibit TiO₂ 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 V₂O₅ (0.02–0.46 wt.%), and those from the Whistle mine have even higher V₂O₅ 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 Cr₂O₃ contents (0.29–0.57 wt.%) than does the inclusion matrix olivine. Diopside contains 0.80–1.71 wt.% Cr₂O₃; orthopyroxene also has considerable chromium contents (Cr₂O₃ = 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/(Fe₂⁺ + Mg) ratios (Fe₂⁺, total Fe as Fe²⁺) of 0.85–0.91 and high Cr contents (Cr₂O₃ = 0.33–1.49 wt.%). They also have higher K₂O (6.33–8.74 wt.%) than Na₂O (0.19–1.10 wt.%) contents (Table 2). These phlogopite 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.
Fig. 3. Major oxide relationship of chromian spinels within the SIC: Al₂O₃ versus Cr₂O₃, MgO versus Cr₂O₃, FeO, (as total iron) versus Cr₂O₃, and MgO versus FeO.

whereas inclusions of Huronian sedimentary rocks are only observed in the Sublayer of the South Range overlies the Huronian Supergroup.

On the other hand, there is no obvious source of the ultramafic inclusions, which are uniformly 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 Bohl 1985). While the 2.25 Ga Nipissing Diabases are similar in many respects to diabase inclusions in the Sublayer (Lightfoot et al. 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 TiO₂ and many have ilmenite lamellae. All the spinels form a continuum in the Al – (Fe³⁺ + 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. 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; McElhuff 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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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.
(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 chrome in the Muskox intrusion (Irving 1975).

The euhedral biotite inclusions are different from post-magmatically entrapped inclusions, which tend to be spherical in appearance (McDonald 1965; Lorand and Cotrin 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 H₂O and other components into the Sublayer. This scenario would require recrystallization of the chromite.

The plagioclase 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 co-precipitation of chromian spinel and plagioclase. This co-precipitation 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 trian-
gular diagram Al—Fe**2+** + 2Ti—Cr (Fig. 7).

The SIC chromian spinels have considerably more Fe-rich
compositions than those that would normally coexist with
FO8—FO9 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
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 ex-
change 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 chromite oversaturation and chromian spinel crys-
tallization (Irvine 1975, 1977), because such contamination
would increase fO2 and Si contents of the magma and there-
fore 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 com-
position. 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# simi-
lar 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 (Czarnianske
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 TiO2 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
(TiO2 = 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 intru-
sion, and the Insizwa Complex have similarly high TiO2
contents as the SIC chromian spinel (Fig. 8). Other close
analogs of the SIC chromian spinels are the Ti—chromian
spinel with 7.8—15.1 wt. % TiO2 from the Snake River
Plain basalts that were thought to be derived from an iron-
and alkali-rich basaltic magma (Thompson 1973). Titanium-
borne chromian spinels (TiO2 = 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 TiO2 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 foot-
wall 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 require-
ment 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 indi-
cate that a component of the Main Mass magma was present
in the hybrid magma that formed the Sublayer (Lightfoot
et al.). 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 base-
ment, where they formed the footwall mafic—ultramafic
complexes, such as those at Fraser and Levack mines.
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. 2/1). 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 spinel 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; Czarnanko 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 serpentization 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 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 (Czarnanko 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). Peltomén (1995) also reported high-Zn chromian spinel (ZnO = >0.8 wt. %) of sulfide deposits in the Ventamala 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 postmagmatic alteration (Wyle 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 sulfide 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 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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References


McElhuff, B., and Stumpf, E.F. 1991. The chromian spinel deposits of the Troodos complex, Cyprus—evidence for the role
of a fluid phase accompanying chromian spinel formation.
Mineralium Deposita, 26: 307–318.

and geochemistry of northern range footwall ultramafic rocks,
Sudbury Igneous Complex, Sudbury, Canada. Ontario Geological

structure in relation to an impact origin. In The geology and ore
deposits of the Sudbury Structure. Edited by E.G. Pye, A.J.
Naldrett, and P.E. Giblin. Ontario Geological Survey, Special
Volume 1, pp. 513–520.

mineralization of the Sudbury Igneous Complex. In Proceedings
of the Sudbury–Noril’ sk Symposium. Edited by P.C. Lightfoot
and A.J. Naldrett. Ontario Geological Survey, Special Volume 5,
p. 57–64.

Murek, B.W., and Campbell, I.H. 1986. The effects of temperature,
oxygen fugacity and melt composition on the behaviour of
chromium in basic and ultrabasic melts. Geochimica et Cosmo-

Naldrett, A.J. 1969. A portion of the system Fe–S–O between
900°C and 1080°C and its application to sulfide ore magmas.

Sudbury Igneous Complex. In The geology and ore deposits of the
Sudbury Structure. Edited by E.G. Pye, A.J. Naldrett, and
235–252.

Naldrett, A.J., Hewins, R.H., Dressler, B.O., and Rao, B.V.
1984. The contact Sublayer of the Sudbury Igneous Complex.
In The geology and ore deposits of the Sudbury Structure. Edited

at Sudbury and its role in ore formation. In Metallogeny of basic
and ultrabasic rocks. The Institution of Mining and Metallurgy,

Paktunc, A.D., and Cabri, L.J. 1995. A proton- and electron-
microprobe study of gallium, nickel and zinc distribution in

Pattison, E.F. 1979. The Sudbury sublayer: Its characteristics and
relationships with the Main Mass of the Sudbury Irruptive.
Canadian Mineralogist, 17: 257–274.

Pedersen, A.K. 1985. Reaction between picrite magma and con-
tiinental crust: early Tertiary silicic basals and magnesian andes-
sites from Disko, West Greenland. Greenlandes Geologiske
Undersøgelse, Bulletin 152, pp. 41–50.

Platonov, P. 1995. Petrogenesis of ultramafic rocks in the Vammala
Nickel Belt: implications for crustal evolution of the early
Proterozoic Svecofennian arc terrane. Lithos, 34: 253–274.

Pereedery, W.V., and Morrison, G.G. 1984. Discussion of the
origin of the Sudbury Structure. In The geology and ore deposits
of the Sudbury Structure. Edited by E.G. Pye, A.J. Naldrett,
and P.E. Giblin. Ontario Geological Survey, Special Volume 1,
pp. 491–512.

geology and ore deposits of the Sudbury Structure. Ontario
Geological Survey, Special Volume 1.

reactions on composition chrome-spinels from the Jibmerlana

spinel and chromium solubility in basaltic melts. Journal of
Petrology, 32: 909–934.

of chromian spinels within the Kilauea Iki lava lake, Hawaii.
Contributions to Mineralogy and Petrology, 107: 8–12.

Scribbins, B.T., Rae, D.R., and Naldrett, A.J. 1984. Mafic and
ultramafic inclusions in the Sublayer of the Sudbury Igneous

Stosch, H.G. 1981. Sc, Cr, Co, Ni partitioning between minerals
from spinel peridotite xenoliths. Contributions to Mineralogy

Thompson, R.N. 1973. Titanian chromian spinel and chromium
titanomagnetite from a Snake River Plain basalt, a terrestrial
analogue of Lunur spinels. American Mineralogist, 58: 826–830.

Walker, R.J., Morgan, J.W., Naldrett, A.J., Li, C., and Fassett,
J.D. 1991. Re–Os isotope systematics of Ni–Cu sulfide ores,
Sudbury Igneous Complex, Ontario: evidence for a major crustal

results and applications to geochemistry. Contributions to
Mineralogy and Petrology, 70: 407–419.

Wilson, A.H. 1982. The geology of the Great Dyke, Zimbabwe: the

zoning in unusual Zn-rich chromian spinel from the Sykesville
district of Maryland and its bearing on the origin of the "terri-
cromit." American Mineralogist, 72: 413–422.

Yang, X.-Z., Matsueda, H., and Ishihara, S. 1994. Mode of occurrence,
chemical composition, and origin of Cr–Fe–Ti oxides of the Jinchuan Ni–Cu–PGE deposits, China. International

chromian spinel in komatites from the Bellingwe greenstone