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MAFIC AND ULTRAMAFIC INCLUSIONS IN THE SUBLAYER OF THE SUDBURY IGNEOUS COMPLEX

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ABSTRACT

Three hundred and ninety inclusions from the igneous sublayer of the Sudbury Igneous Complex have been examined, and many of them analyzed by microprobe. The 264 samples from the Strathcona mine of the North Range vary from dunite through harzburgite, wehrlite and clinopyroxenite to norite and gabbro, whereas the 126 samples from mines of the South Range include only rock types with orthopyroxene dominant, such as harzburgite and melanorite. The texture of the rocks ranges from that of a well-developed adcumulate, mesocumulate or orthocumulate to an extensively granulated and recrystallized fabric. On both the North and South Ranges, olivine varies from 85 to 73 mole % Fo, hypersthene from 13.5 to 31 mole % Fs, augite from 5 to 15 mole % Fs, plagioclase (including both cumulus and intercumulus phases) from 90 to 30 mole % An, and chromite contains up to 50.8 wt. % Cr_2O_3. The textures, presence of plagioclase and evidence of olivine reacting to give orthopyroxene suggest that the inclusions crystallized at crustal pressures. The range of rock types and the observed correlation of increasing MgO/(MgO + FeO) ratio in mafic minerals with increasing content of mafic minerals in the host rocks suggest strongly that these rocks are derived from one (or more than one) hidden layered intrusive bodies. Our data do not allow us to state that this intrusive body is cogenetic with the Sudbury norite, but they are consistent with this interpretation.

Keywords: Sudbury Igneous Complex, irruptive, inclusions, sublayer, harzburgite, norite, gabbro, olivine, hypersthene, plagioclase, Ontario.

SOMMAIRE

On a étudié trois cent quatre-vingt-dix enclaves de la sous-couche du complexe igné de Sudbury et analysé plusieurs d'entre elles à la microsonde. La composition des 264 échantillons de la mine Strathcona au flanc septentrional s'échelonne de la dunite, harzburgite, wehrlite et clinopyroxénite à la norite et au gabbro, alors que les 126 échantillons des mines du flan méridional comprennent seulement les types de roches à prédominance d'orthopyroxène tels que harzburgite et mélanorite. La texture de la roche va de celle d'une adcumulite, mésocumulite ou orthocumulite bien formée à une fabrique très granulée et recristallisée. Sur un flanc comme sur l'autre, l'olivine varie de 85 à 73 mol. % Fo, l'hypersthène, de 13.5 à 31 mol. % Fs, l'augite, de 5 à 15 mol. % Fs, le plagioclase (phases cumulus et intercumulus), de 90 à 30 mol. % An, et la chromite contient jusqu'à 50.8% (en poids) de Cr_2O_3. Les textures, la présence de plagioclase et l'évidence de la transformation de l'olivine en orthopyroxène font penser que les enclaves ont cristallisé aux pressions de la croûte. D'après l'éventail des types de roche et les corrélations relevées entre le rapport MgO/(MgO + FeO) des minéraux mafiques et la quantité de ces derniers dans leur roche hôte, les enclaves seraient dérivées d'un (ou plus d'un) massif stratifié sous-jacent invisible. Nos données ne nous permettent pas d'affirmer que ce massif soit cogénétique de la norite de Sudbury, mais au moins elles concordent avec cette interprétation.

(Traduit par la Rédaction)

Mots-clés: complexe igné de Sudbury, massif irruptif, enclaves, complexe intrusif sous-jacent, harzburgite, norite, gabbro, olivine, hyperstène, plagioclase, Ontario.

INTRODUCTION

Since the discovery of Ni–Cu ore in 1883, the Sudbury structure has been the subject of numerous geological studies. Despite the voluminous literature recently reviewed by Stevenson (1979), consensus has yet to be reached about the origin of the complex. The elliptically shaped, mid-Proterozoic basin, 60 km long by 27 km wide, consists of plutonic rocks of the Sudbury Igneous Complex overlain by and enclosing the predominantly sedimentary rocks of the Whitewater Group. The North and South Ranges of the complex have average inward dips of 42° and 65°, respectively; the South Range is believed to have been faulted up at least 5 km with respect to the North Range (Souch *et al.* 1969).

Concentric outcropping rings of Lower Zone norite (the outermost), Middle Zone gabbro and Upper Zone granophyre (the innermost) constitute the main body of the complex. Cryptic variation in the composition of pyroxene and plagioclase (Naldrett *et al.* 1970) as well as in the opaque oxides (Gasparrini & Naldrett 1972) suggest gravitational differentiation of the complex.

The Ni–Cu deposits are associated with a sublayer

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of rocks that occur discontinuously at the base of the complex and in dyke-like bodies (offset sublayer) projecting into the country rocks. The sublayer consists of an igneous (contact and offset sublayer) and a nonigneous portion; the igneous sublayer is commonly inclusion-rich, with a matrix varying from norite to gabbro (in the contact sublayer) to quartz diorite (in the offset sublayer), whereas the nonigneous portion consists of leucocratic breccias, now referred to as footwall breccia (Naldrett *et al.* 1972). The inclusions consist of footwall rocks and a diverse suite of mafic to ultramafic rocks (Pattison 1979).

The form of the complex has been postulated to be that of a folded sill (Coleman 1905, Collins 1934), a ring-dyke complex (Knight 1923, Thomson 1956) and a funnel-shaped intrusion (Wilson 1956, Naldrett *et al.* 1970). The origin of the ores has been attributed to either hydrothermal activity (Knight 1917, Wandke & Hoffman 1924, Fleet 1977) or magmatic segregation (Coleman 1905, Hawley 1962, Naldrett & Kullerud 1967). The hypothesis of a meteorite impact has been put forward to explain the elliptical outline of the basin, shatter cones in the surrounding country-rocks, shock-deformation lamellae in minerals in the rocks overlying the complex, and a wide range of breccias (Dietz 1964, 1972, French 1968), although recently, Fleet (1979) suggested a tectonic origin for the shatter cones. The various theories regarding meteorite impact have been reviewed recently by Stevenson & Stevenson (1980).

In this paper, textural, mineralogical and chemical characteristics of the mafic to ultramafic inclusions are discussed. Owing to their close relationship with the ore-bearing sublayer, the inclusions are regarded as an integral part of the Sudbury Igneous Complex.

The mafic and ultramafic inclusions within the contact sublayer at Strathcona mine were briefly described by Vos & Moorhouse (1965), whereas their widespread occurrence around the margin of the complex was emphasized by Souch *et al.* (1969). Naldrett & Kullerud (1967) analyzed olivine and pyroxenes in inclusions from Strathcona and found a positive correlation between their Fe content and the proportion of felsic minerals in the samples. They suggested that the inclusions were derived from a cryptically layered ultramafic-to-mafic hidden zone of the Complex. Greenman (1970) also examined inclusions in the vicinity of the Strathcona mine; he noted that the olivine-free inclusions are highly recrystallized, with a clinopyroxene to orthopyroxene ratio of 3:1, and that the olivine-bearing inclusions appear concentrated toward the base of the contact sublayer. Pattison (1979) suggested that at least some of the mafic to ultramafic inclusions may have been derived from early igneous bodies in the country rocks.

Description of the Inclusions

The diameter of the inclusions varies from a few millimetres (Hewins 1971) to several metres. Typical inclusions examined underground at Copper Cliff South, Creighton and Strathcona mines have diameters varying from 8 cm to 1.5 m and a subrounded shape, in contrast to the more angular shape of football inclusions.

Two hundred and sixty-four thin sections of inclusions from the Strathcona mine on the North Range of the Sudbury Complex have been examined in this study. An additional one hundred and twenty-six sections were chosen from Inco's very extensive collection to represent the diversity of inclusion rock-types on the South Range. The majority of these are from the Murray (34), Little Stobie (32), Creighton (26) and Frood (25) mines.

The classification of rock types used in this study is a slightly modified version of Streckeisen's (1973) classification of mafic and ultramafic rocks. One hundred and eight sections have been point-counted, with the remainder being classified visually. The classification has been hampered by recrystallization, alteration and heterogeneity. The totals and percentages of the various rock-types from the South Range mines and Strathcona mine on the North Range are summarized in Table 1. Direct comparison of the percentages is not possible since the Strathcona samples were collected at random at a series of selected localities in the mine, whereas the South Range samples were culled from a much larger collection to illustrate the diversity of types. A noticeable feature of Table 1 is the almost complete absence of clinopyroxene-dominant rock types such

TABLE 1. ROCK TYPES FOUND AS INCLUSIONS IN THE IGNEOUS SUBLAYER

	South Range		Strathcona	
	Total	%	Total	%
Orthopyroxenite	4	4.6	7	2.9
Olivine Orthopyroxenite	5	5.7	2	0.8
Harzburgite	36	40.8	15	6.3
Clinopyroxenite	2	2.3	8	3.4
Olivine Clinopyroxenite	0	0	8	3.4
Wehrlite	0	0	17	7.1
Websterite	0	0	14	5.9
Olivine Pyroxenite	0	0	6	2.5
Lherzolite	0	0	8	3.4
Dunite	0	0	1	0.4
Olivine Norite	1	1.1	1	0.4
Olivine Melanorite	2	2.3	15	6.3
Olivine Melatroctolite	2	2.3	0	0
Melatroctolite	0	0	7	2.9
Leuco Norite	1	1.1	1	0.4
Norite	2	2.3	2	0.8
Melanorite	10	11.3	47	19.8
Augite Norite	2	2.3	0	0
Augite Melanorite	13	14.7	46	19.4
Gabbro	0	0	1	0.4
Melagabbro	0	0	1	0.4
Hypersthene Gabbro	4	4.6	1	0.4
Hypersthene Melagabbro	4	4.6	30	12.7
	88	100.0%	238	100.0%

as clinopyroxenite, wehrlite, websterite and lherzolite among the South Range inclusions.

Petrographic descriptions of the five most common rock-types are summarized in Table 2. In some harzburgite samples, subrounded, resorbed olivine grains poikilitically enclosed within orthopyroxene illustrate reaction between early-formed olivine and silicate liquid. Coronas of orthopyroxene surrounding olivine within plagioclase are also common (Fig. 1). In one section of melanorite, the plagioclase laths and elongate orthopyroxene grains show a parallelism similar to that noted for plagioclase in the South Range norite, where it is considered to reflect the orientation assumed by plagioclase during crystal accumulation (Naldrett *et al.* 1970).

Cumulus textures, as described by Wager *et al.* (1960), are common amongst inclusions. Most of the harzburgites, olivine melatroctolites and olivine orthopyroxenites are heteradcumulates, with cumulus olivine poikilitically enclosed within orthopyroxene and plagioclase (Fig. 2). Some of the olivine-rich harzburgites can be interpreted as mesocumulates in which orthopyroxene and plagioclase are interstitial to large olivine grains. The wehrlites and olivine clinopyroxenites are mesocumulates in which optically zoned orthopyroxene and plagioclase are interstitial to olivine and clinopyroxene. The websterites are meso- to adcumulates, and the norites and gabbros are meso- to orthocumulates (Fig. 3) with cumulus pyroxene

TABLE 2. PETROGRAPHY OF MAJOR ROCK-TYPES FOUND AS INCLUSIONS

Rock Type	Minerals Present	Approx. Mode %	Approx. Grain Size	Characteristics
Harzburgite	Olivine	45-75%	Up to 2mm (rarely to 6mm)	Anhedral, subequant; also as subrounded; resorbed grains 0.2 to 1mm poikilitically enclosed within orthopyroxene and plagioclase
	Orthopyroxene	15-50%	1 to 3mm	Tabular; coronas of orthopyroxene in places surround olivine enclosed in plagioclase
	Plagioclase	5-10%	<0.5mm	Interstitial; antithetic relationship between olivine size and plagioclase abundance
	Clinopyroxene	0-5%	0.5 to 1mm	Ragged, interstitial grains
Wehrlite	Olivine	45-60%	Up to 10mm	Large equant to elongate anhedral grains; also as spherical resorbed grains 0.1 to 0.2mm poikilitically enclosed within orthopyroxene and plagioclase
	Clinopyroxene	30-50%	<3mm	Smaller and more variable in size than olivine; simple twinning common to large grains
	Plagioclase	<10%	<0.5mm	Interstitial
	Orthopyroxene	<5%	0.2 to 0.4mm	Generally poikilitically enclosed within plagioclase
Websterite	Clinopyroxene	65-85%	0.4 to 3mm	Anhedral; generally cloudy owing to exsolution blebs
	Orthopyroxene	10-25%	0.1 to 3mm	Anhedral with ragged edges except for subhedral to euhedral terminations within plagioclase
	Plagioclase	<10%	<0.5mm	Interstitial
	Olivine	0-10%	<0.4mm	Resorbed, subrounded grains poikilitically enclosed within both pyroxenes
Melanorite	Orthopyroxene	60-80%	0.5 to 2mm (rarely to 5mm)	Subhedral, generally tabular
	Plagioclase	10-30%	Up to 2mm	Interstitial, subhedral grains; also as laths subophitic to ophitically enclosed within orthopyroxene
	Clinopyroxene	<5%	<1mm	Interstitial or intergrown with orthopyroxene
	Olivine	0-10%	0.1 to 2mm	Subrounded 0.1 to 0.2mm grains are poikilitically enclosed within orthopyroxene and plagioclase
Augite Melanorite	Orthopyroxene	45-60%	1.5 X 0.4mm (tabular) 0.5mm (prismatic)	Common ragged appearance; often intergrown with clinopyroxene
	Plagioclase	20-30%	<1.5mm	Interstitial, anhedral grains; also as laths subophitically enclosed within orthopyroxene
	Clinopyroxene	10-25%	Up to 1.5mm	Ragged, anhedral grains intergrown with orthopyroxene
	Olivine	0-5%	0.05 to 0.2mm	Resorbed grains poikilitically enclosed within plagioclase orthopyroxene

and intercumulus plagioclase, although occasionally cumulus plagioclase is present.

Recrystallization of varying intensity is common in many of the inclusions and is attributed to the heating effect of the sublayer magma. The South Range xenoliths generally show more extensive recrystallization and alteration than those from Strathcona. Initial recrystallization resulted in small (0.1 to 0.3 mm) olivine and pyroxene grains within larger original grains. More intense recrystallization gave rise to granoblastic, polygonal aggregates of olivine and pyroxene that commonly show 120° grain-boundary intersections (Fig. 4). Plagioclase also recrystallized to form aggregates of interlocking, sheaf-like grains 0.01 to 0.1 mm in diameter.

Mineral Chemistry

Chemical compositions of olivine, pyroxene, plagioclase and oxide phases were determined using the electron microprobe; the South Range inclusions were analyzed using energy dispersion, whereas wavelength dispersion was used for those from Strathcona. Representative compositions are given in Tables 3A, B,C and D.

Olivine compositions range from $Fo_{74.4}$ to $Fo_{85.6}$ for the South Range inclusions, compared with $Fo_{73.4}$ to $Fo_{84.4}$ for the Strathcona inclusions; the latter are similar to the range of compositions from $Fo_{72.8}$ to Fo_{85} observed by Naldrett & Kullerud (1967), also at Strathcona. In Figure 5, olivine compositions are plotted against the modal percentage of plagioclase in the rock along with the data of Naldrett & Kullerud. The more forsteritic compositions of olivine tend to occur in the more mafic rocks, although it should be recognized that this relationship is not supported by the South Range inclusions by themselves owing to the absence amongst these of plagioclase-bearing ultramafic rocks.

Orthopyroxene and clinopyroxene compositions

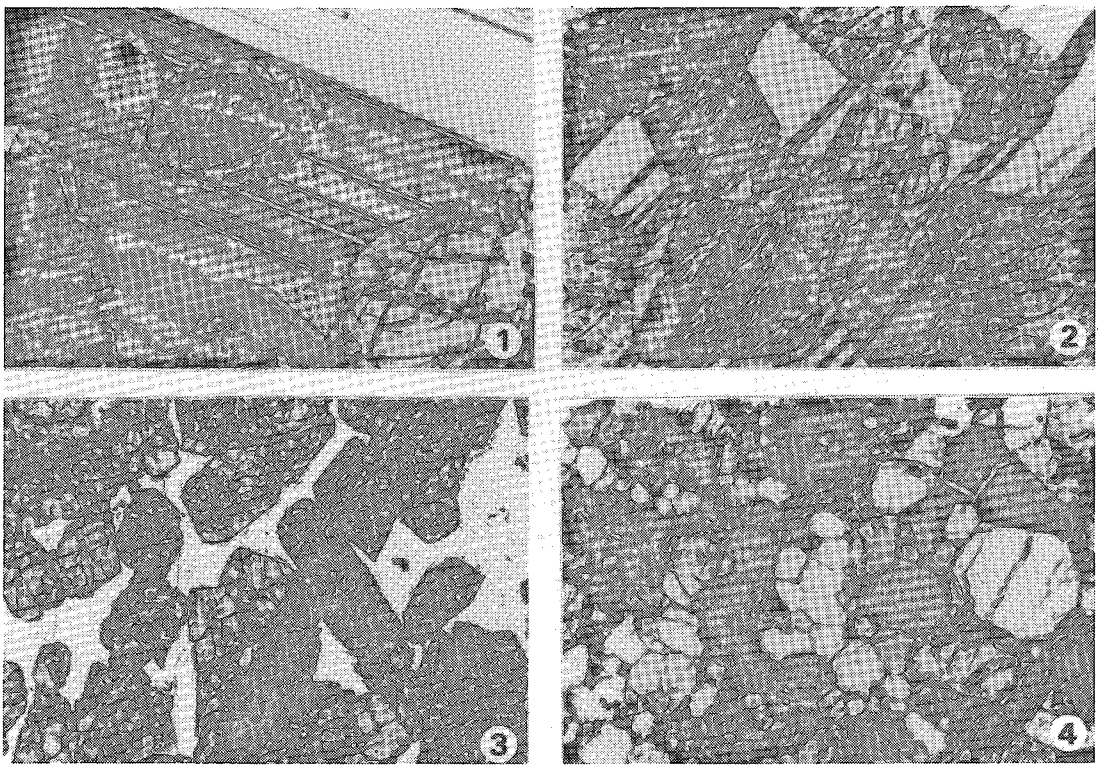

FIG. 1. Olivine melanorite. Olivine with coronas of orthopyroxene, poikilitically enclosed within plagioclase. Crossed nicols, magnification × 116.

FIG. 2. Olivine melatroctolite. Heteradcumulate with cumulus olivine poikilitically enclosed within plagioclase. Crossed nicols, magnification × 29.

FIG. 3. Norite with orthocumulate fabric consisting of cumulus orthopyroxene and intercumulus plagioclase. Plane light, magnification × 34.

FIG. 4. Recrystallized harzburgite. Granoblastic, polygonal aggregates of olivine (right side of photo, veined by serpentine) and plagioclase. Crossed nicols, magnification × 49.

are plotted in the pyroxene quadrilateral in Figures 6a and 6b. The fields of pyroxene compositions for the Strathcona and South Range inclusions are similar, although orthopyroxene in the South Range shows a greater variation in Mg:Fe ratio and Ca content than that from Strathcona. The orthopyroxene is bronzite and ranges from $Fs_{13.5}$ to Fs_{31}, whereas the clinopyroxene generally varies from augite to salite in composition. Orthopyroxene in ultramafic inclusions, as would be expected, has a higher Mg:Fe ratio than that in mafic inclusions.

TABLE 3A. REPRESENTATIVE AVERAGE COMPOSITIONS OF OLIVINE

Sample No.	15114.2	C730381	15182.2	C721968	15158.4
SiO_2	39.5	39.7	40.2	38.6	37.5
FeO	14.4	14.6	15.3	19.8	23.3
MgO	45.8	45.2	45.0	41.4	37.8
MnO	0.23	0.2		0.2	0.33
Total	99.93	99.7	100.5	100.0	98.93
Recalculation on the basis of 4 oxygens					
Si	0.991	0.997	1.002	0.992	0.992
Fe	0.301	0.307	0.319	0.423	0.513
Mg	1.71	1.692	1.673	1.585	1.489
Mn	0.005			0.005	0.008
Total	3.007	2.996	2.994	3.005	3.002
fo	85.03	84.64	83.99	78.93	74.38

Plagioclase compositions vary from $An_{89.6}$ to $An_{29.7}$ for the South Range inclusions, compared to $An_{78.1}$ to An_{33} for the Strathcona inclusions. The most anorthite-rich plagioclase occurs interstitially

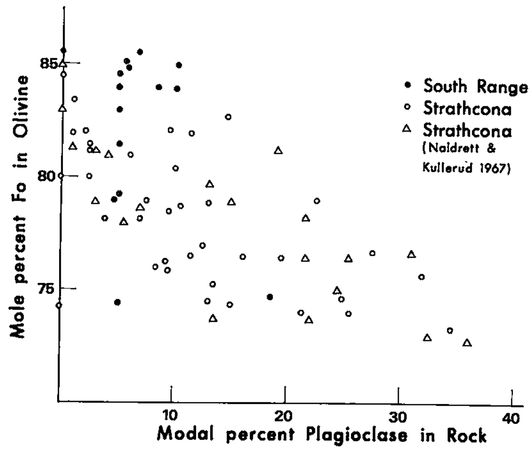

FIG. 5. Mole percent forsterite in olivine *versus* modal percent plagioclase in rock. The observation that the olivine becomes more fractionated as the rock becomes more leucocratic is consistent with the overall trend that one would expect in a fractionating layered intrusive complex.

TABLE 3B. REPRESENTATIVE AVERAGE COMPOSITIONS OF ORTHOPYROXENE

Sample No.	C702051	15114.2	C730381	C721968	15158.4	C714413	17533.2	15130.1	9090	C711033	C702038
SiO_2	55.1	55.5	55.2	55.5	55.5	56.9	54.3	53.7	54.4	56.2	53.8
Al_2O_3	1.74	1.6	1.42	0.24	0.69	0.68	0.95	0.81	0.93	1.03	0.68
TiO_2	0.11	0.07	0.07	0.14	0.22		0.18	0.25	0.09	0.11	0.08
FeO	8.93	9.61	9.03	13.3	15.2	10.5	15.8	19.4	12.5	14.9	16.8
MnO	0.71	0.23	0.1	0.26	0.24	0.13	0.16	0.29	0.13	0.2	0.19
MgO	30.7	30.3	30.3	28.7	27.7	31.4	26.9	23.5	27.6	27.3	25.1
Cr_2O_3	0.47	0.5	0.57			0.5	0.16	0.2	0.36	0.27	0.3
CaO	1.74	1.49	2.34	0.79	0.83	0.41	1.25	1.68	3.02	1.94	3.07
Total	99.5	99.3	99.03	98.93	100.38	100.52	99.7	99.83	99.03	101.95	100.0
Recalculation on the basis of 6 oxygens											
Si	1.95	1.964	1.961	2.0	1.989	1.989	1.969	1.98	1.968	1.983	1.967
Al	0.05	0.036	0.039		0.011	0.011	0.031	0.02	0.032	0.017	0.033
Al	0.022	0.034	0.021	0.01	0.018	0.017	0.01	0.015	0.027	0.026	
Ti	0.003	0.002	0.002	0.003	0.006		0.005	0.007	0.002	0.003	
Fe	0.263	0.285	0.267	0.401	0.454	0.306	0.477	0.598	0.378	0.439	0.512
Mn	0.021	0.006	0.002	0.009	0.006	0.004	0.004	0.009	0.004	0.006	0.007
Mg	1.616	1.599	1.603	1.54	1.476	1.635	1.456	1.293	1.486	1.437	1.367
Cr	0.013	0.014	0.015			0.014	0.005	0.006	0.01	0.007	0.009
Ca	0.066	0.057	00.09	0.03	0.032	0.015	0.048	0.066	0.117	0.072	0.121
Total	4.004	3.997	4.0	3.993	3.992	3.991	4.005	3.994	4.024	3.99	4.012
wo	3.39	2.94	4.59	1.52	1.63	0.77	2.42	3.37	5.91	3.7	6.05
en	83.08	82.38	81.79	78.13	75.23	83.59	73.5	66.07	75.01	73.76	68.35
fs	13.53	14.68	13.62	20.35	23.14	15.64	24.08	30.56	19.08	22.54	25.6
f/fm	0.14	0.151	0.143	0.207	0.235	0.158	0.247	0.316	0.203	0.234	0.272

TABLE 3C. REPRESENTATIVE AVERAGE COMPOSITIONS OF CLINOPYROXENE

Sample No.	C702054	C702019	9090	C702038	9459.3
SiO_2	51.9	52.3	52.3	53.2	52.5
Al_2O_3	2.63	2.47	1.61	0.78	1.24
TiO_2	0.87	0.48	0.31	0.19	0.94
FeO	3.88	6.24	6.97	6.8	9.16
MnO		0.2		0.14	0.17
MgO	17.0	16.0	16.7	15.9	14.9
Cr_2O_3	0.74	0.48	0.8	0.35	
CaO	21.8	20.9	20.8	22.2	21.7
Total	98.82	99.07	99.49	99.56	100.61
Recalculation on the basis of 6 oxygens					
Si	1.916	1.867	1.941	1.975	1.948
Al	0.094	0.133	0.059	0.025	0.052
Al	0.02	0.124	0.011	0.009	0.002
Ti	0.025	0.013	0.009	0.006	0.026
Fe	0.12	0.186	0.216	0.212	0.283
Mn		0.006		0.004	0.004
Mg	0.938	0.848	0.919	0.876	0.823
Cr	0.022	0.013	0.024	0.011	
Ca	0.858	0.795	0.826	0.88	0.86
Total	3.993	3.985	4.005	3.998	3.998
wo	44.78	43.47	42.12	44.72	43.74
en	48.96	46.36	46.86	44.51	41.86
fs	6.26	10.17	11.02	10.71	14.4
f/fm	0.113	0.18	0.19	0.195	0.256

TABLE 3D. REPRESENTATIVE AVERAGE COMPOSITIONS OF CHROMITE

Sample No.	C730381	C702446	15182.2	C702053	C721968
Al_2O_3	11.8	14.9	18.1	18.4	21.1
TiO_2	0.45	0.43	0.68	2.45	1.27
Cr_2O_3	50.4	45.4	42.2	39.2	31.2
FeO	29.0	25.1	28.2	30.2	31.4
Fe_2O_3	3.96	6.82	6.93	5.17	11.9
MgO	2.9	5.61	4.66	4.36	2.9
MnO	0.6	0.67	0.43	0.51	0.51
NiO		0.1			
Total	99.11	99.03	101.2	100.29	100.28
Recalculation on the basis of 6 oxygens					
Al	0.491	0.606	0.716	0.732	0.855
Ti	0.012	0.011	0.017	0.062	0.033
Cr	1.405	1.237	1.118	1.045	0.849
Fe^{2+}	0.855	0.724	0.793	0.846	0.905
Fe^{3+}	0.107	0.179	0.176	0.132	0.310
Mg	0.153	0.289	0.234	0.219	0.149
Mn	0.017	0.019	0.012	0.014	0.019
Ni		0.002			
Total	3.04	3.067	3.066	3.05	3.12

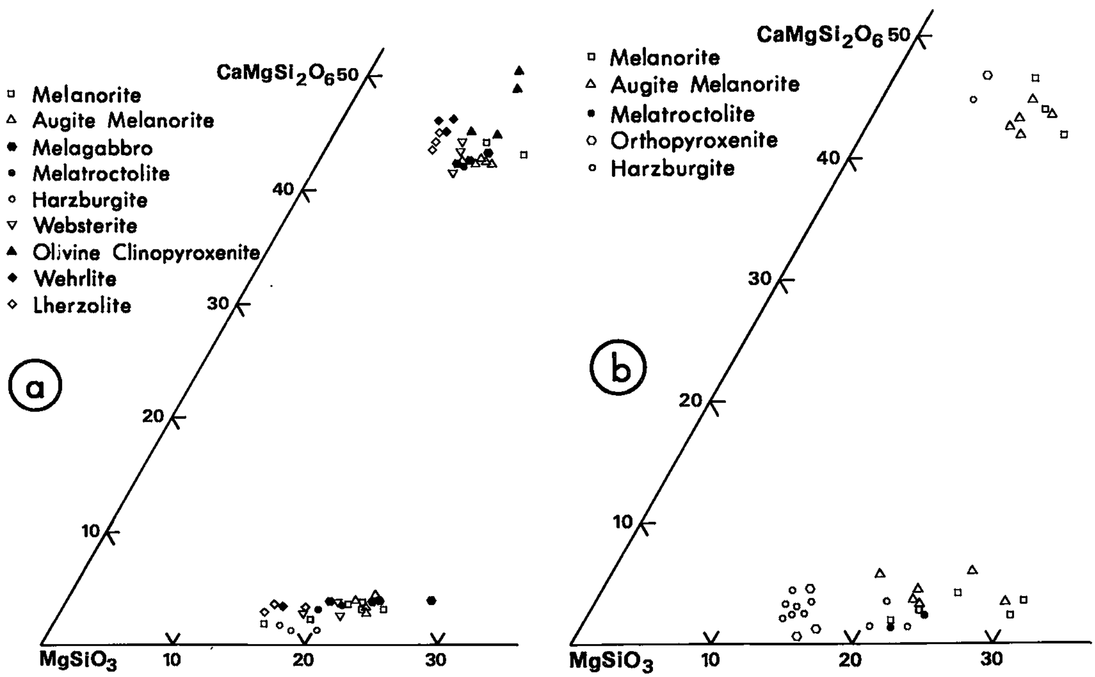

FIG. 6. Composition of pyroxenes (a) from Strathcona and (b) from the South Range, plotted in the pyroxene quadrilateral.

in olivine melatroctolite ($An_{89.5}$), in harzburgite ($An_{87.4}$), and as cumulus grains in norite ($An_{89.6}$).

Chromite from one orthopyroxenite and eight harzburgite inclusions from the South Range has a Cr_2O_3 content ranging from 31.2 to 50.4 wt. %, similar to that recorded in chromite from the Strathcona inclusions, which attains 50.8 wt. % Cr_2O_3. Partitioning of Fe between Fe^{3+} and Fe^{2+} was accomplished for chromite using the expression: $(Fe_{tot} + Mg + Mn) - (2Ti + \frac{1}{2} Al + \frac{1}{2}Cr) = \frac{3}{2}Fe^{3+}$. Analytical data are shown on Figure 7 along with compositional fields for chromite from layered intrusive complexes, alpine-type ultramafic bodies, ultramafic nodules (Irvine 1967) and mid-Atlantic-Ridge serpentinites (Aumento & Loubat 1971); the data for the Sudbury inclusions plot almost entirely within the field of chromite from layered intrusive complexes.

Origin of the Inclusions

Naldrett & Kullerud (1967) considered three possible sources for the contact sublayer inclusions at Strathcona: (i) a pre-Sudbury Complex mafic to ultramafic body; (ii) the mantle, and (iii) a genetically related layered sequence hidden beneath the exposed portion of the Complex.

Pattison (1979) suggested that some of the inclusions may have been derived from pre-Sudbury Complex anorthosite–gabbro–pyroxenite bodies, the Nipissing diabase, and also from mafic gneisses of the Levack complex. Olivine, attaining up to 25 modal %, is only present in intrusive bodies of the Nipissing diabase in the Cobalt area (Card & Pattison 1973). The layered gabbro–anorthosite complex described by James & Harris (1977) is similar to others in the vicinity of Sudbury and does not contain olivine. Thus, whereas it is agreed that some of the inclusions may have originated from pre-existing country rocks, a local source for the numerous olivine-bearing inclusions has yet to be documented.

The possibility of an origin for the inclusions as mantle-derived nodules is negated by several factors: (i) The inclusions occur in plutonic tholeiitic sublayer rocks and attain several metres in diameter, whereas mantle nodules are found in alkali basalt or

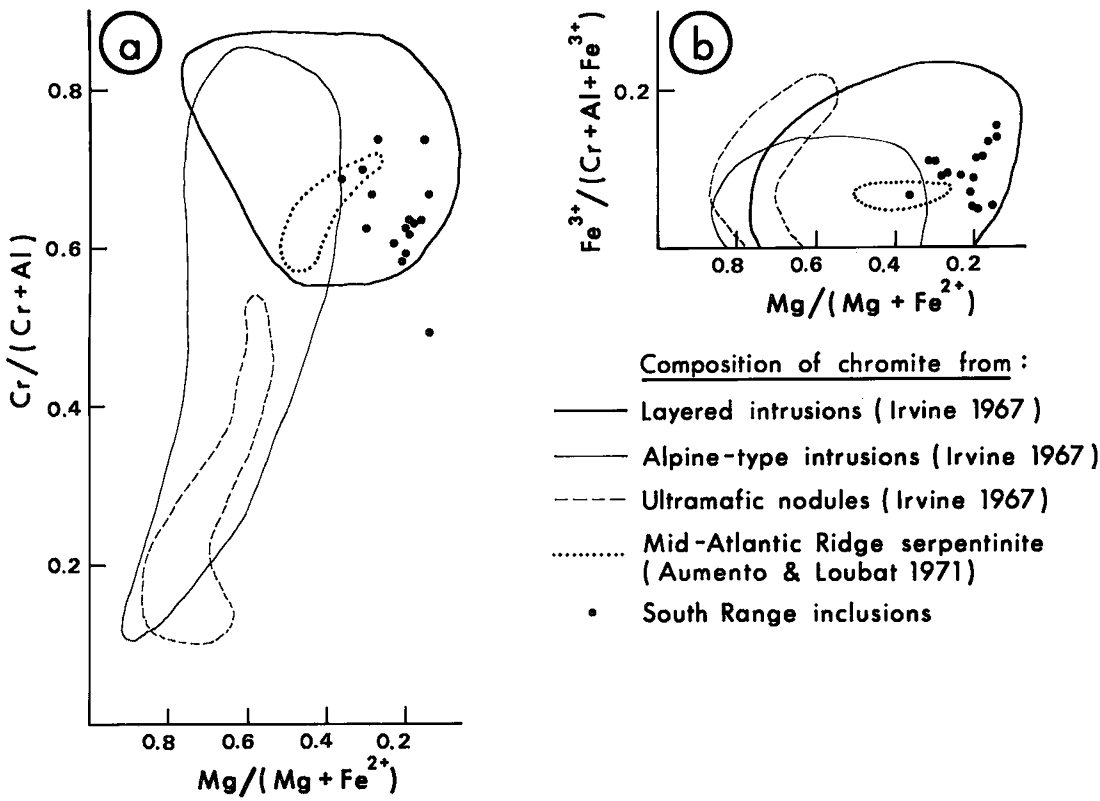

FIG. 7. Composition of chromite from South Range inclusions compared with the compositional fields of chromite from other layered intrusive complexes, alpine-type ultramafic bodies and deep-ocean serpentinites. (a) The Cr/(Cr + Al) *versus* Mg/(Mg + Fe^{2+}) diagram. (b) The Fe^{3+}/(Fe^{3+} + Cr + Al) *versus* Mg/(Mg + Fe^{2+}) diagram.

kimberlite hosts and rarely exceed 50 cm in diameter. (ii) Harzburgite, wehrlite, pyroxenite, websterite, norite and gabbro are the most common inclusion rock-types, in contrast to mantle nodules, in which spinel lherzolite, garnet lherzolite, and eclogite predominate. (iii) The inclusions have cumulus textures, common to layered complexes, whereas mantle nodules are generally metamorphic tectonites showing features of plastic flow and other solid-state deformation. (iv) The presence of plagioclase in many of the inclusions implies a depth of 25–30 km or less for final equilibration (Green & Hibberson 1970), thus indicating a crustal origin. (v) Textural evidence indicates that olivine in the inclusions has reacted with intercumulus liquid to form orthopyroxene, a process believed to occur only at low pressures (less than 5 kbar) if the parent magma was relatively dry (Kushiro 1969). In addition, high-pressure minerals such as aluminous spinel and garnet, which are commonly present in mantle xenoliths, are unknown in the Sudbury inclusions. (vi) Olivine compositions from the inclusions range from $Fo_{73.4}$ to $Fo_{85.6}$. This compares closely with the range found in many layered intrusive bodies: Fo_{80} to Fo_{90} in the Stillwater complex (Jackson 1967) and Fo_{70} to Fo_{85} in the Muskox complex (Irvine & Smith 1967). In contrast, olivine from mantle nodules has a relatively restricted range of composition, from Fo_{88} to Fo_{94} (Ringwood 1975). (vii) The chromite in the inclusions is compositionally analogous to that in layered intrusive complexes rather than in mantle-derived materials (Fig. 7).

Consideration of the characteristics discussed above leads to the conclusion that the inclusions represent fragments of one or more hidden layered complexes. Our data do not allow us to speculate on any cogenetic relationship between the body (or bodies) and the Sudbury Igneous Complex, other than to point out that the magma(s) giving rise to the inclusions was (or were) less fractionated than those giving rise to the Sudbury Complex, which thus is consistent with an interpretation that the two were cogenetic. Kuo (1976) has drawn attention to the similarity in the shape of the *REE* profiles of the sublayer inclusions and the contact-sublayer magmas themselves, with the inclusions having lower *REE* contents; he concluded that the *REE* data are consistent with the model that the magma responsible for the inclusions was cogenetic with that giving rise to the Sudbury Igneous Complex.

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