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MORPHOLOGY AND COMPOSITION OF CHROMITE IN KOMATIITES FROM THE BELINGWE GREENSTONE BELT, ZIMBABWE

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ABSTRACT

Chromite grains in nearly fresh Archean komatiites from the late Archean Belingwe greenstone belt (*ca.* 2.7 Ga), in Zimbabwe, have diverse morphologies: skeletal and dendritic chromite is restricted to spinifex zones, whereas euhedral grains occur throughout the flows. Systematic differences in chromite compositions are present between the spinifex (top) and cumulate (base) zones of the flows and between skeletal and euhedral chromite. Two stages of crystallization have been identified: an early euhedral core is mantled later by skeletal chromite. The core is enriched in Mg and Cr, but depleted in Fe, Ti and Mn relative to the skeletal rim, in a manner similar to variations in compositions of euhedral chromite from the top to the base of the flows. Accordingly, the euhedral chromite and the core of skeletal chromite in the spinifex zones could have formed at an early stage, in equilibrium with a large volume of magma, whereas the skeletal mantle could have formed rapidly from a small volume of evolved residual liquid after eruption of the magma. Thermometry based on the pair chromite–olivine may provide an estimate of the ambient conditions of the komatiitic liquids. Chromite in komatiites has uniform Al contents and characteristic compositional trends, distinct from chromite in mafic–ultramafic rocks from other geodynamic settings, thereby providing an independent means of discriminating its origin.

Keywords: chromite, morphology, chemical composition, late Archean, komatiite, geodynamic setting, Zimbabwe.

SOMMAIRE

Dans les komatiites de la ceinture de roches vertes de Belingwe, au Zimbabwe, presque fraîches malgré leur âge archéen tardif (environ 2.7 Ga), les grains de chromite possèdent des morphologies diverses. Les grains skelettiques et dendritiques sont limités aux zones à spinifex, tandis que les grains idiomorphes sont répandus à travers les coulées. Nous remarquons des différences systématiques dans la composition entre la chromite des zones à spinifex et des cumulats, située vers le haut et à la base des coulées, respectivement, et entre les grains skelettiques et idiomorphes. Deux étapes de cristallisation sont envisagées: un coeur idiomorphe est recouvert par des surcroissances skelettiques. Le coeur montre un enrichissement en Mg et Cr, et un appauvrissement en Fe, Ti et Mn par rapport aux surcroissances skelettiques, de façon parallèle aux variations compositionnelles décelées dans la chromite idiomorphe entre le haut et la base des coulées. Les grains idiomorphes et le coeur des grains skelettiques des zones à spinifex se seraient formés à un stade précoce, en équilibre avec un volume important de magma, tandis que les surcroissances skelettiques ont cristallisé rapidement, à partir de volumes restreints de liquides plus évolués, suite à l'épanchement du magma. Une analyse thermométrique fondée sur la chromite et l'olivine en équilibre permet de caractériser les conditions ambiantes des liquides komatiitiques. La chromite des komatiites possède une teneur uniforme en Al et des compositions caractéristiques qui la distinguent de la chromite des roches mafiques et ultramafiques d'autres milieux géodynamiques. Ceci permet une discrimination de son mode d'origine par une méthode indépendante.

(Traduit par la Rédaction)

Mots-clés: chromite, morphologie, composition chimique, archéen tardif, komatiite, milieu géodynamique, Zimbabwe.

INTRODUCTION

Chromite is a sensitive indicator of magmatic environments (*e.g.*, Irvine 1965, 1967, Dick & Bullen 1984). Studies of chromite compositions have been mainly limited to Alpine ultramafic rocks and layered intrusions. No systematic analyses of chromite from komatiites have been conducted, although its occurrence in these rocks has been documented (*e.g.*, Fleet & MacRae 1975, Arndt *et al.* 1977, Donaldson 1982, Donaldson *et al.* 1986). This may stem from the fact that komatiites predominantly occur in Archean greenstone sequences, where they have experienced variable intensities of hydrothermal alteration and metamorphism into assemblages of serpentine, talc and chlorite; fresh primary chromite rarely is preserved. Komatiites formed from distinctive high-Mg magmas that have had histories of crystallization, cooling, alteration and metamorphism quite different from those of mafic and ultramafic magmas emplaced in plutonic or upper mantle environments. Accordingly, fresh chromite in komatiites may provide critical information about their conditions of crystallization.

Samples of relatively unaltered komatiite, composed almost totally of primary minerals and slightly devitrified glass, have been obtained from the Belingwe greenstone belt and are the freshest Archean samples yet found (Nisbet *et al.* 1987). In the present investigation, a detailed petrographic and electron-microprobe study of the different textural varieties of chromite has been performed. On the basis of their chemical composition, these varieties can be compared with chromite from "normal" ultramafic rocks; differences between them are discussed in terms of the implications for the conditions of their crystallization.

GEOLOGICAL SETTING OF KOMATIITES

The Belingwe greenstone belt, a late Archean granite–greenstone terrane with *ca.* 2.7 Ga isotopic ages, is located in the southeastern part of the Zimbabwe Archean craton (Nisbet *et al.* 1977, Nisbet 1987). This supracrustal belt consists of a well-preserved succession of Archean lavas and sedimentary rocks, which were deposited on an older tonalitic crust (Bickle *et al.* 1975, Nisbet *et al.* 1977, Nisbet 1987). The volcanic–sedimentary sequence has been divided into two groups: the lower or Mtshingwe Group (2.8–2.9 Ga) and upper or Ngez Group (2.7 Ga) (Bickle *et al.* 1975, Nisbet *et al.* 1977, Nisbet 1987). The lower group occurs in the western, southwestern, and southeastern parts of the area, and is uncomformably overlain by the upper group, which consists of the Manjeri (thin sedimentary rocks), Reliance (komatiites and komatiitic basalts), Zeederbergs (basalts) and Cheshire (mainly shallow-water sedimentary rocks) formations (Fig. 1A). Komatiites occur in the Bend and Brooklands formations in the lower group, and in the Reliance Formation in the upper group. The Reliance Formation has been studied in the greatest detail (Nisbet *et al.* 1977, Nisbet 1987). This formation, which is 0.5–1.0 km thick, consists principally of komatiitic basalts, komatiites and komatiitic basalts from stratigraphic base to top. Komatiitic flows in this formation are the freshest that have been observed in an Archean terrane, particularly as found along the SASKMAR 1 drill hole, which intersects several flows (Nisbet *et al.* 1987) (Fig. 1B); the samples for this study have been chosen from this section.

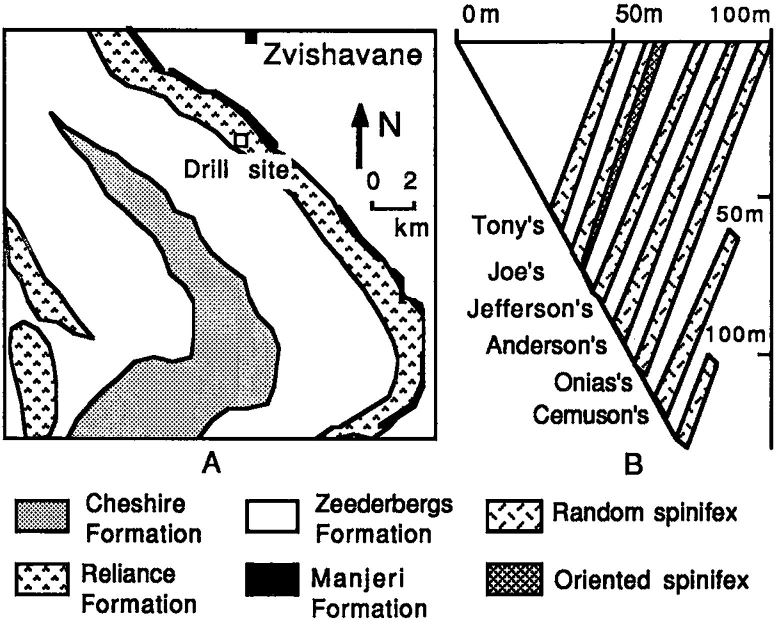


FIG. 1. (A) Simplified geological map of the upper group, Belingwe greenstone belt, south-central Zimbabwe, illustrating the location of the SASKMAR drill core, which penetrated the Reliance Formation. Modified after Nisbet *et al.* (1987). (B) Stratigraphic section of the SASKMAR drill core showing that the sequence of komatiitic flows intersected in the core corresponds with surface outcrop in the area [after Renner *et al.* (1992)].

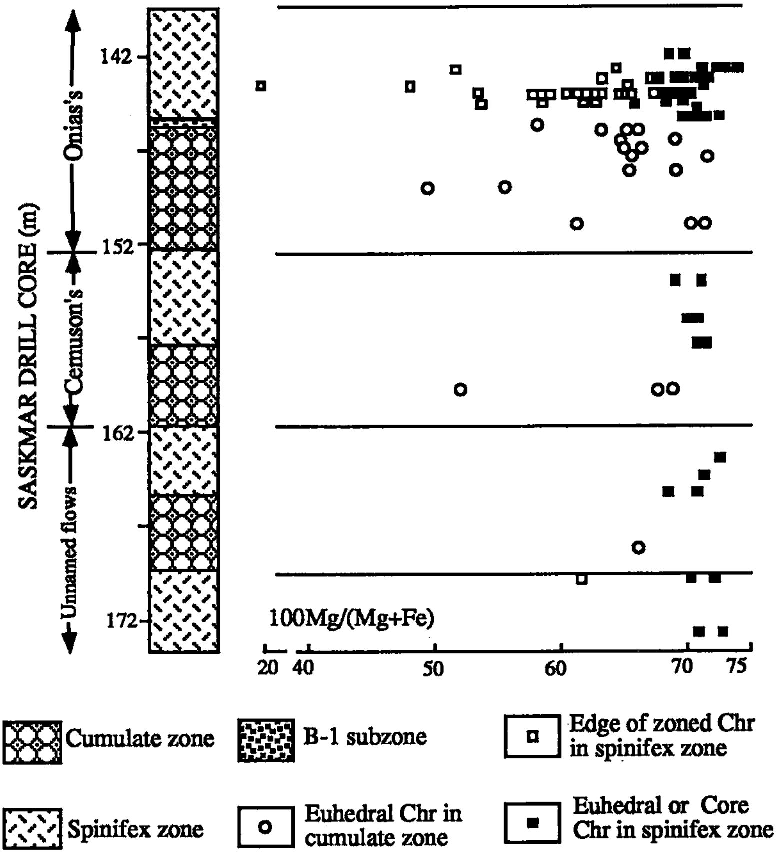


FIG. 2. Stratigraphic section and variations of 100Mg/(Mg + Fe) in chromite (Chr) through the SASKMAR drill core from 142 to 172 m, including three flows, of which the uppermost flow is best developed and contains the random olivine spinifex and platy olivine spinifex (A), hopper olivine (B-1) and equant olivine (B2-4) subzones from top to base.

These samples were taken from the 142-172-m depth interval, and come from three flows, including Onias's and Cemuson's (Fig. 1B), each of which contains spinifex-A and cumulate-B zones (Fig. 2). Onias's flow has all subzones normally associated with komatiitic flows (Donaldson 1982), and contains random spinifex and platy olivine spinifex subzones in zone A, and an uppermost B-1 subzone in zone B (Fig. 2).

The groundmass of the rocks from the spinifex zone has been devitrified to a variable extent and has been partly replaced by greenschist-facies assemblages, as have some olivine crystals, which show a euhedral or skeletal habit. The matrix of the spinifex zone also contains minor clinopyroxene and feathery tremolite. Some of the hopper crystals include pigeonite, and typically have a lantern or, rarely, a chain habit and a hollow core (Nisbet *et al.* 1987). Equant solid olivine phenocrysts in the cumulate zone are mostly pristine, although some serpentine and magnetite occurs along fractures. The cumulate zone also contains matrix together with minor skeletal olivine.

OCCURRENCE AND MORPHOLOGY OF CHROMITE

Chromite is ubiquitous as an accessory mineral throughout the spinifex and cumulate zones of these flows. Distinct morphological varieties of chromite have been identified in the spinifex and cumulate zones (Fig. 3). Their distribution is systematically related to position in each of the three flows studied. Most of the chromite in the cumulate zones and some in the spinifex zones occurs as euhedral, octahedral or subhedral crystals, 15 to 100 μm in diameter, either disseminated in the matrix or concentrated along the margin of olivine crystals. Some euhedral chromite crystals

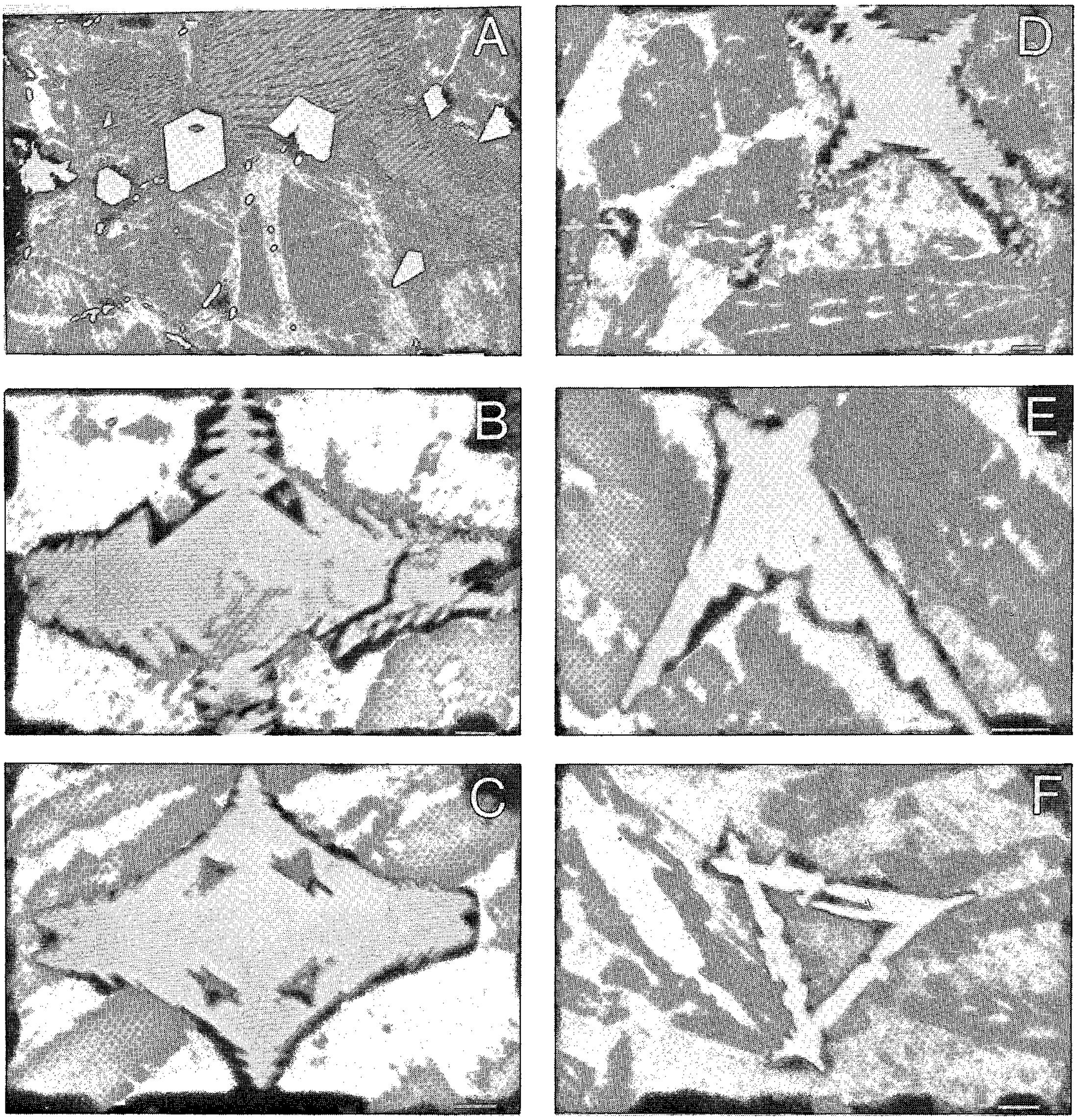


FIG. 3. Back-scattered electron images of chromite in Onias's komatiitic flow from the SASKMAR drill core: (A) euhedral grain in the cumulate zone, with inclusions; (B), (C) cruciform or double cruciform (euhedral core and snowflake-like overgrowths; note the zone of inclusions); (D) double cruciform and lantern chain; (E) swallow tail-like; (F) skeleton (triangle). B to F are from the spinifex zone. The length of each scale bar is 10 μm.

within the cumulate zone contain glass inclusions (Fig. 3A).

Chromite crystals with complex dendritic, skeletal, or hopper-like morphological forms (Fig. 3B–F) are restricted to the spinifex zones, and are particularly prominent in Onias's flow. Such skeletal crystals consist of two parts: core and rim (overgrowth). The core is apparently an early euhedral crystal, which has been surrounded by the later, presumably rapidly crystallized overgrowth (Fig. 3C).

The skeletal crystals of chromite exhibit systematic compositional zonation, which supports the suggestion that they formed in two stages: a stage of slow growth (core) and a stage of rapid growth (overgrowth). A silicate phase is sporadically present at the boundary between core and rim as a concentric zone of inclusions (Fig. 3C). Rapid crystallization during the second stage obscures the original boundary but leaves this zone of "inclusions" intact.

TABLE 1. REPRESENTATIVE COMPOSITIONS OF CHROMITE FROM SASKMAR DRILL CORE

Sample	1	2	3	4	5	6	7
Depth(m)	142.2	142.20	142.38	142.70	143.23	144.05	144.05
	Edge	Centre	Eu	Eu	Edge	Centre	Edge
SiO_2	0.15	0.14	0.12	0.12	0.16	0.13	0.10
TiO_2	n.d.	n.d.	0.30	0.39	0.42	0.42	0.42
Al_2O_3	11.82	10.65	10.45	12.79	11.90	12.12	11.93
Fe_2O_3	9.30	5.02	6.62	6.19	11.08	6.33	9.71
FeO	12.02	9.26	10.06	11.53	13.12	11.18	12.48
MgO	12.40	14.29	14.06	13.51	10.26	14.39	12.33
MnO	0.35	0.20	0.26	0.27	0.28	0.21	0.31
CaO	0.06	0.01	0.09	0.06	0.11	0.03	0.10
Cr_2O_3	52.82	58.90	56.66	53.10	52.11	53.10	50.55
V_2O_5	n.d.	n.d.	0.28	0.22	n.d.	0.32	0.22
NiO	0.14	0.30	0.15	0.17	0.15	0.18	0.17
Total	99.06	98.76	99.05	98.35	99.59	98.41	98.31
Based on 4-oxygen atoms							
Ti^{4+}	n.d.	n.d.	0.008	0.010	0.012	0.01	0.011
Mn^{2+}	0.010	0.006	0.007	0.008	0.009	0.006	0.009
Ni^{2+}	0.004	0.009	0.004	0.005	0.005	0.005	0.005
Al^{3+}	0.481	0.426	0.414	0.499	0.526	0.458	0.481
Cr^{3+}	1.277	1.446	1.409	1.334	1.147	1.376	1.256
Mg^{2+}	0.638	0.723	0.704	0.667	0.573	0.688	0.628
Fe^{2+}	0.347	0.263	0.283	0.319	0.412	0.300	0.357
Fe^{3+}	0.242	0.128	0.168	0.154	0.313	0.153	0.250
Mg#	64.77	73.34	71.34	67.62	58.21	69.63	63.78
Cr#	72.62	77.23	77.28	72.76	68.55	75.01	72.32

Sample	8	9	10	11	12	13	14
Depth(m)	144.10	144.10	144.10	144.10	145.70	149.50	151.20
	Centre	Edge	Centre	Centre	Eu	Eu	Eu
SiO_2	0.11	0.14	0.13	0.14	0.11	0.12	0.14
TiO_2	0.36	0.40	0.44	0.30	0.25	0.32	n.d.
Al_2O_3	11.96	12.14	12.81	10.06	11.23	10.81	9.79
Fe_2O_3	6.41	13.06	7.27	7.50	7.29	8.68	12.14
FeO	11.06	14.20	12.21	10.19	10.89	11.38	11.96
MgO	13.81	9.42	13.4	13.27	11.41	12.24	8.29
MnO	0.22	0.36	0.17	0.23	0.22	0.15	0.33
CaO	0.04	0.30	0.06	0.03	0.07	0.10	0.00
Cr_2O_3	53.28	48.19	51.36	56.34	55.45	55.14	55.61
V_2O_5	0.85	0.66	0.27	1.42	0.17	n.d.	n.d.
NiO	0.19	0.04	0.11	0.17	0.19	0.13	0.07
Total	98.29	98.92	98.23	99.65	97.28	99.07	98.33
Based on 4-oxygen atoms							
Ti^{4+}	0.009	0.011	0.011	0.008	0.007	0.009	n.d.
Mn^{2+}	0.006	0.012	0.005	0.007	0.007	0.005	0.012
Ni^{2+}	0.005	0.001	0.003	0.005	0.006	0.004	0.003
Al^{3+}	0.467	0.544	0.496	0.414	0.500	0.455	0.509
Cr^{3+}	1.362	1.068	1.311	1.380	1.284	1.302	1.089
Mg^{2+}	0.681	0.534	0.656	0.690	0.642	0.651	0.544
Fe^{2+}	0.306	0.452	0.335	0.297	0.344	0.339	0.440
Fe^{3+}	0.160	0.374	0.180	0.197	0.207	0.233	0.403
Mg#	68.99	54.16	66.16	69.88	65.12	65.71	55.27
Cr#	74.49	66.24	72.56	76.93	71.98	74.11	68.16

Notes: Samples 1 to 11 are from spinifex zones, 12 to 14 from cumulate zones. Abbreviations: Eu=Euhedral grain, n.d.=not detected, Mg#=100Mg/(Mg+Fe^{2+}), Cr#=100Cr/(Cr+Al).

ANALYTICAL METHODS

Chromite grains from the top downward to the base of the flows were analyzed using a JEOL JXA-8600 Superprobe in the Department of Geological Sciences, University of Saskatchewan. Analytical conditions were: accelerating voltage 15 kV, and beam current 10 nA. We made use of a range of natural oxide and synthetic standards, of which pure vanadium and pentlandite were used for V and Ni, respectively, and the manufacturer's ZAF correction program. Elements determined include Si, Ti, Al, Fe, Mn, Mg, Ca, Cr, Ni, V, Na and K. Zinc was sought but found to be below detection limits. Iron was determined as total iron (FeOt), and Fe^{2+} and Fe^{3+} were distributed by assuming an $R^{2+}R^{3+}{}_2O_4$ formula and balancing $RO{:}R_2O_3 = 1$ for the chromite (*e.g.*, Michailidis 1990). In each grain, two or three points were analyzed; an average value is reported where interpoint variations were found to be insignificant. Representative compositions are listed in Table 1. Olivine grains in cumulate zones and the silicate inclusions in chromite were analyzed under the same conditions, but using silicate (olivine, clinopyroxene and plagioclase) standards.

RESULTS

Interflow compositional variations

Chromite from the three flows is characterized by total ranges in composition as follows: 9.79–12.94 wt% Al_2O_3, 13.62–34.08 wt% FeOt, 3.53–15.24 wt% MgO, and 43.03–58.90 wt% Cr_2O_3. Compositional variations are related to position within the flows and thus to the morphology of the chromite (Fig. 2); euhedral grains and the core area of skeletal chromite in the spinifex zones are characterized by higher Cr and Mg contents, but lower Fe contents than the euhedral chromite in the cumulate zones (Figs. 4, 5). Chromite inclusions in olivine from the cumulate zones have the same composition as euhedral chromite in the same zones. Generally, from the top to the base of each flow, Mn, Ti and Fe contents of euhedral chromite increase, whereas Mg and Cr decrease. These relationships are illustrated by correlation coefficients of the oxides in Table 2.

For all varieties of chromite, variations of Al contents from the spinifex to the cumulate zones are small, and show a weak negative correlation with Cr, although Al contents of euhedral chromite in cumulate zones are slightly less than those of

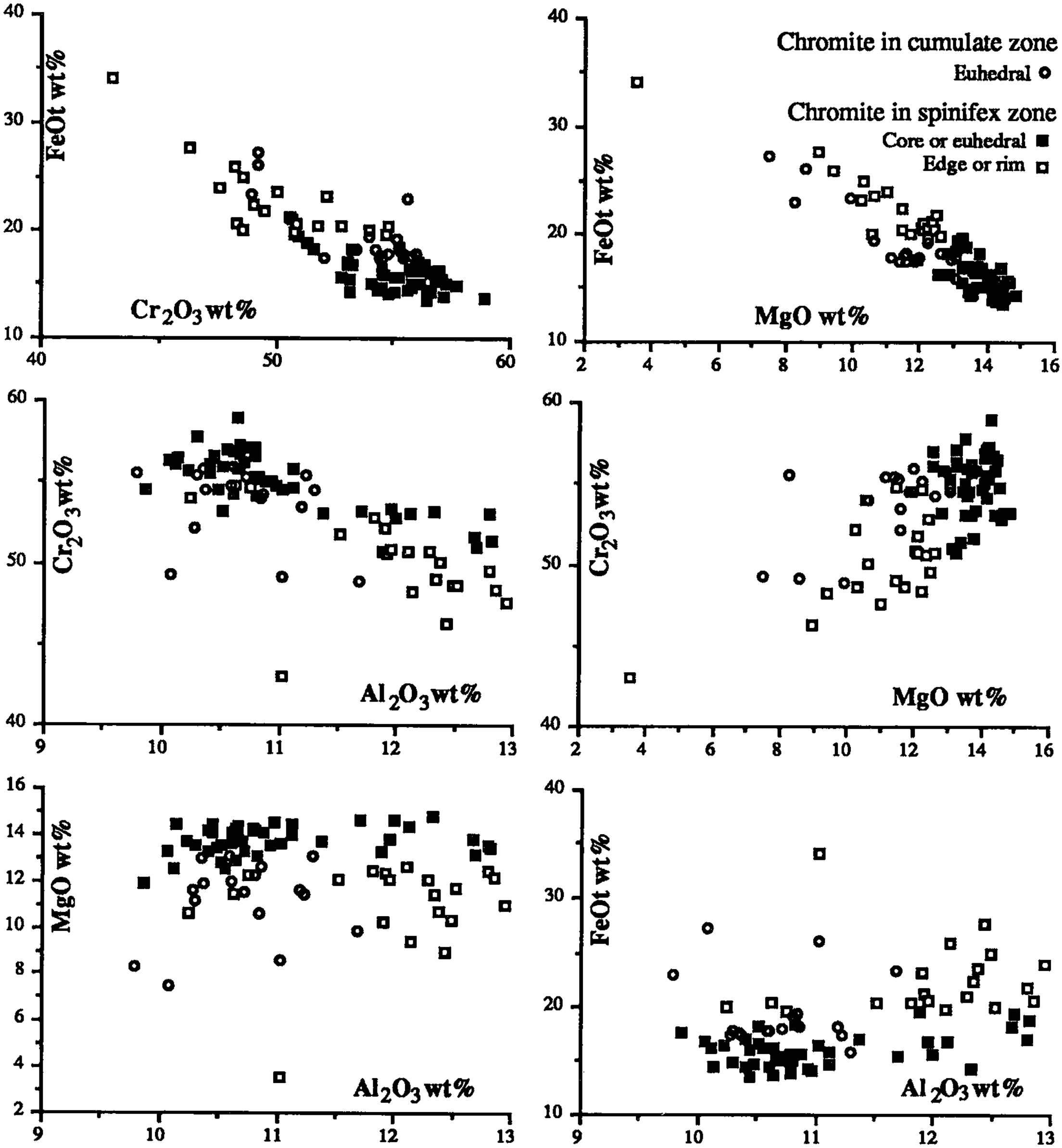


FIG. 4. Inter-element relationships in chromite from komatiites in the SASKMAR drill core: see explanations in the text for detail.

chromite in spinifex zones (Fig. 4). Cr and Mg are negatively correlated with Fe, but Cr and Mg display a positive covariation (Fig. 4). With respect to the less abundant oxides, total compositional ranges for all grains of chromite analyzed are: 0.19–0.50 wt% TiO_2, 0.12–0.74 wt% MnO, 0.86–1.42 wt% V_2O_5, and 0.04–0.30 wt% NiO. The relationships between these and the major elements are plotted in Figure 5. Mn exhibits a positive correlation with Fe; Ti exhibits a positive correlation with Al and Fe and a negative correlation with Cr. Generally, Mn and Ti contents increase from spinifex to cumulate zones. Variations of V and Ni contents in the chromite seem irregular.

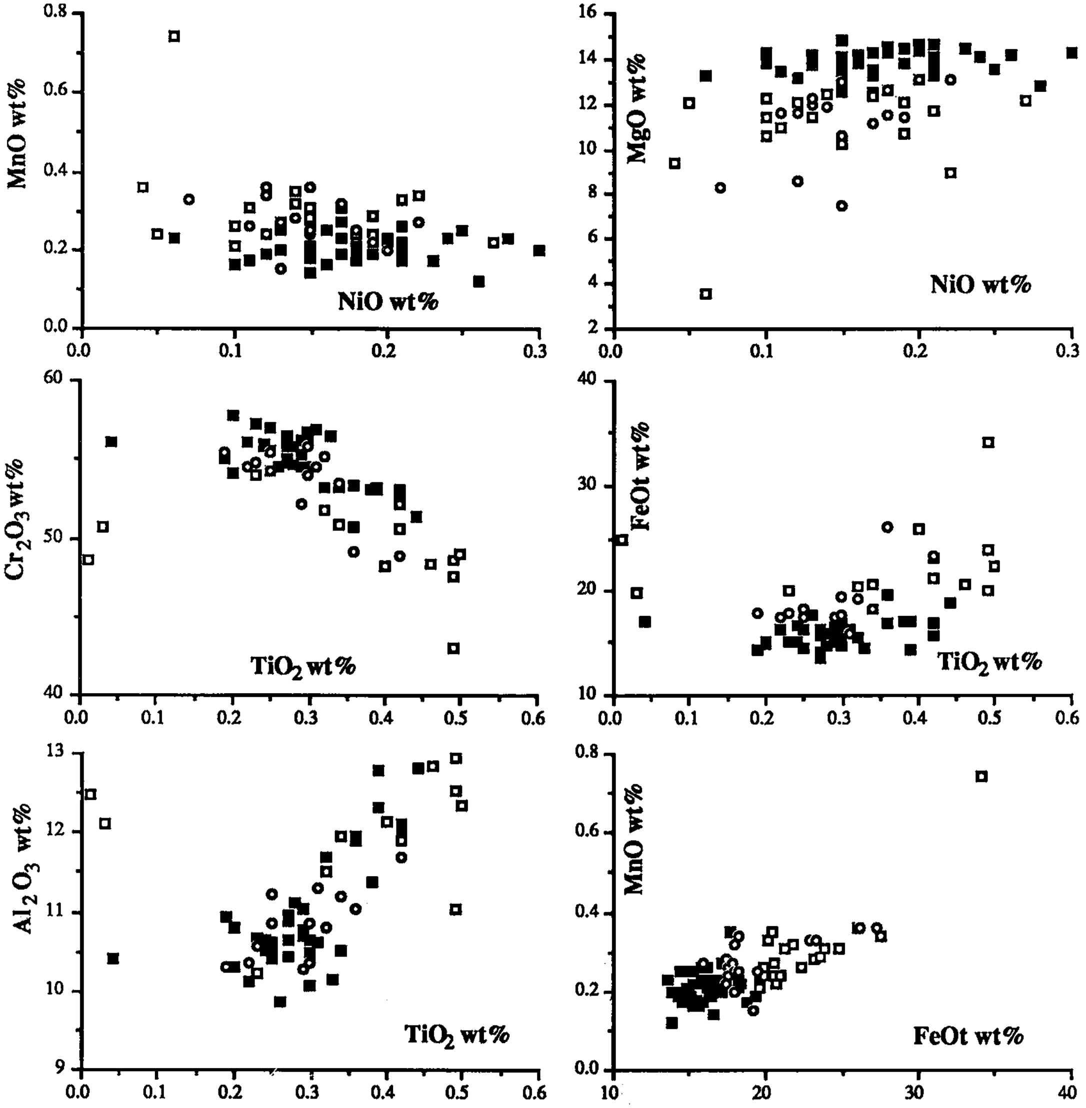


FIG. 5. Variations of major and trace elements in chromite from komatiites sampled in the SASKMAR drill-core. Legend as in Figure 2.

Compositional variations of Ti-free spinel have generally been represented on bivariate plots of 100Cr/(Cr + Al) *versus* 100Fe/(Fe + Mg) or 100Mg/(Mg + Fe) (Irvine 1965, 1967, Dick & Bullen 1984). On such diagrams, it is not possible to discriminate between chromite from komatiites and chromite from layered intrusions, although the former plots in a different field from chromite in Alpine ultramafic rocks and in kimberlites (Fig. 6). In an "Al-Cr-Fe^{3+}" triangular diagram, points representing chromite from komatiites are located in an area of overlap between the fields of chromite from Alpine ultramafic rocks and from layered intrusive rocks. These points display a clear trend on the diagram from euhedral cores in the spinifex zone to euhedral grains in the cumulate zones (Fig. 7).

Intragrain compositional variations

Euhedral chromite crystals generally have uniform compositions, whereas those with a

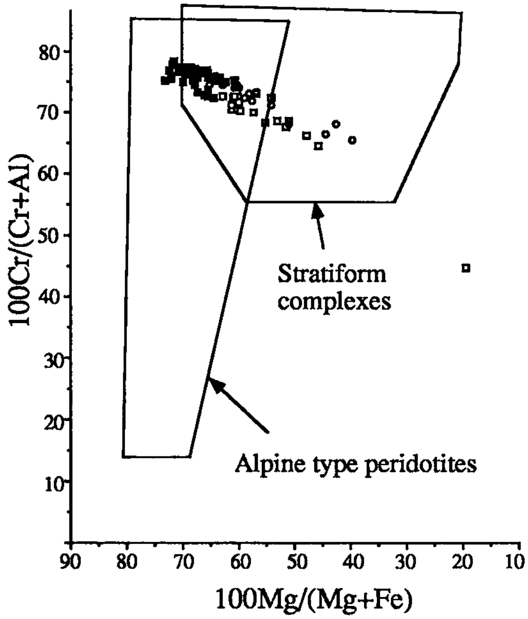
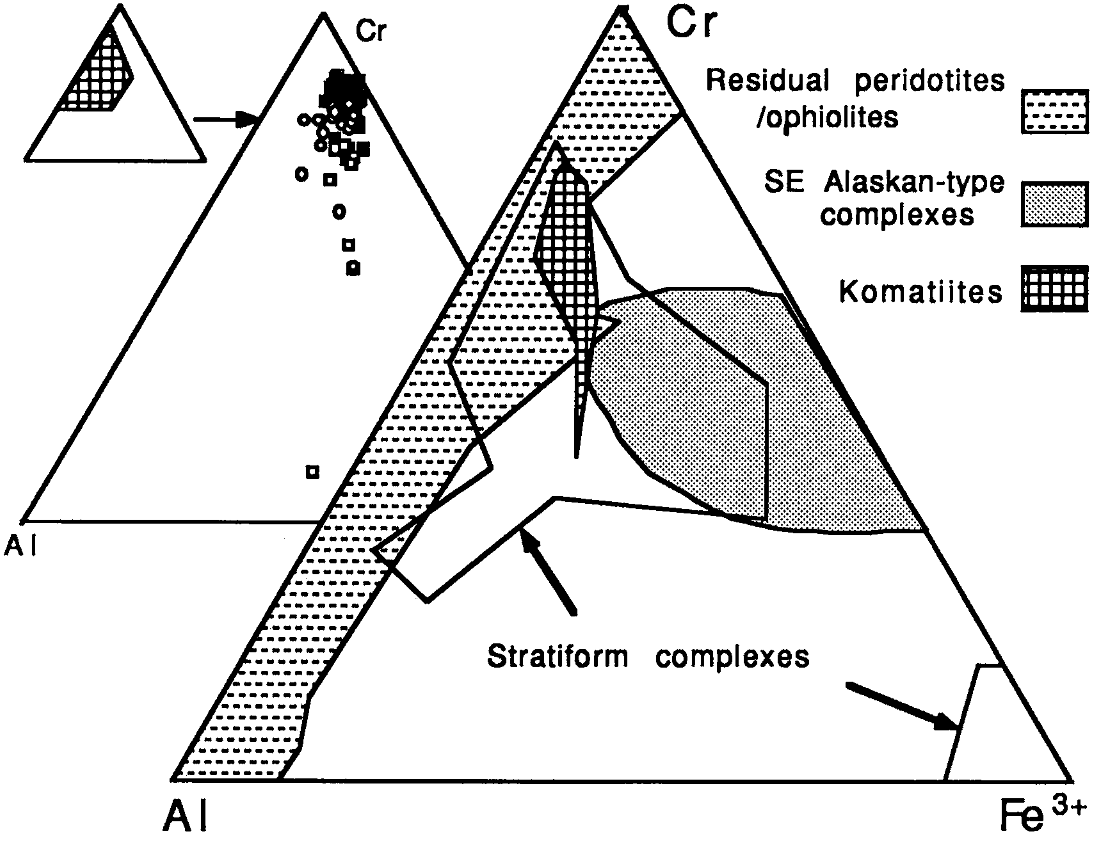


FIG. 6. Plot of 100Cr/(Cr + Al) *versus* 100Mg/(Fe + Mg) in chromite from komatiites in the SASKMAR drill core. The majority of chromite compositions from komatiites plot in the layered intrusion field, but have a different evolutionary trend, compared to that of Irvine (1967) and Dick & Bullen (1984). Legend as in Figure 2.

TABLE 2. CORRELATION COEFFICIENTS OF OXIDES IN THE CHROMITE

	Al_2O_3	FeOt	MgO	Cr_2O_3	MnO	TiO_2	NiO
Al_2O_3	1.000						
FeOt	0.142	1.000					
MgO	0.006	-0.832	1.000				
Cr_2O_3	-0.440	-0.693	0.400	1.000			
MnO	0.010	0.598	-0.640	-0.420	1.000		
TiO_2	0.639	0.373	-0.135	-0.574	0.145	1.000	
NiO	0.002	0.188	-0.175	0.105	0.099	-0.056	1.000

FIG. 7. Plot of Cr–Al–Fe^{3+} of chromite from komatiites in the SASKMAR drill core, compared with fields of other associations [after Jan and Windley (1990)]. Legend as in Figure 2.



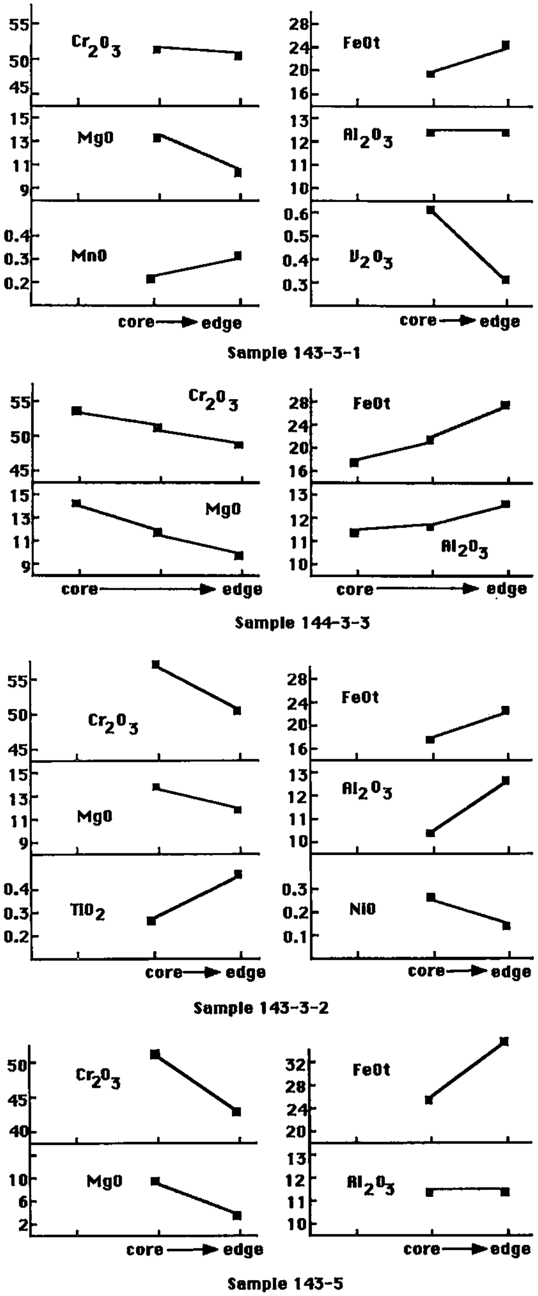


FIG. 8. Core-to-rim compositional variations of zoned grains of chromite in komatiites from the SASKMAR drill core.

TABLE 3. CHEMICAL COMPOSITIONS OF INCLUSIONS IN THE CHROMITE

	1	2	3
SiO_2	65.22	66.27	63.61
TiO_2	0.27	0.10	0.89
Al_2O_3	16.92	20.47	19.24
FeOt	4.33	1.53	3.05
MgO	1.20	1.02	0.67
MnO	0.00	0.03	0.03
CaO	4.96	1.36	5.17
Cr_2O_3	0.00	0.54	0.02
NiO	0.00	0.04	0.49
K_2O	0.00	0.02	0.00
Na_2O	7.79	9.52	8.21
Total	100.76	100.90	101.37

skeletal morphology exhibit wide compositional ranges and are chemically zoned. Analytical results from the center to the edge of representative grains are plotted in Figure 8. Cores are compositionally uniform, with relatively high Cr, Mg and Ni contents, whereas in the overgrowths, or toward their margins, Fe, Mn and Ti contents progressively increase. Al contents are relatively uniform, or may increase slightly toward their rims, with the exception of one outlier with 3 wt% increase from core to rim (Fig. 8).

The chromite crystals contain variable proportions of silicate inclusions. Many of the skeletal grains of chromite contain ovoid to circular felsic inclusions, 1–10 μm in diameter, concentrated at the boundary between the core and rim. In two dimensions, they appear to be droplets of trapped liquid. Electron-microprobe analyses indicate that some of the inclusions contain 64 wt% SiO_2, 19 wt% Al_2O_3 and 8 wt% Na_2O, and up to 0.54 wt% Cr_2O_3 (Table 3).

Estimate of conditions of crystallization of the cumulate zones

In the cumulate zone, most of the chromite occurs as euhedral or subhedral crystals, either isolated or in small clusters between the larger cumulus grains of olivine. The small euhedral chromite crystals that were trapped in growing olivine crystals imply that the two minerals coprecipitated.

The temperature of crystallization of komatiitic magmas at eruption or emplacement may be estimated on the basis of the partitioning of Fe and Mg between olivine and chromite (Jackson 1969, Roeder *et al.* 1979, Lehmann 1983). Lehmann's equation, which was established from the diffusion between olivine and chromite, is used to calculate the temperatures.

Compositions obtained from pairs of contiguous or adjacent unzoned olivine and chromite grains avoid the possibility of disequilibrium. Calculated results are listed in Table 4. All samples are from the cumulate zones. It is clear that the calculated values, extending from 1090° to 1250°C, which represent the temperature of last equilibration between olivine and chromite, are lower than those obtained from liquid temperatures estimated from the MgO contents (Nisbet 1982), but are similar to temperatures (1055° to 1141°C) found for rocks from the cumulate zone of komatiites from Western Australia, based on two-pyroxene thermometry (Gole *et al.* 1990).

Calculated absolute temperatures using olivine and chromite compositions are known to be suspect because of uncertainties in the thermodynamic data. The relative scale of temperatures, however, may be correct.

TABLE 4. CALCULATED TEMPERATURES FROM OLIVINE-CHROMITE PAIRS

Sample	1	2	3	4	5	6	7	8	9
Depth(m)	144.7	144.7	144.8	145.7	147.1	149.3	149.3	149.5	149.5
Chromite (based on 4 oxygen atoms)									
Al^{3+}	0.419	0.424	0.430	0.496	0.466	0.459	0.423	0.455	0.429
Cr^{3+}	1.423	1.415	1.412	1.230	1.361	1.310	1.441	1.302	1.355
Fe^{3+}	0.148	0.152	0.150	0.262	0.163	0.221	0.127	0.233	0.206
Fe^{2+}	0.276	0.284	0.284	0.370	0.304	0.332	0.268	0.340	0.310
Mg^{2+}	0.712	0.707	0.706	0.615	0.681	0.655	0.720	0.651	0.678
Olivine (based on 4 oxygen atoms)									
Si^{4+}	0.991	1.000	0.991	0.999	0.995	0.984	1.002	0.997	1.005
Fe^{2+}	0.179	0.173	0.154	0.156	0.159	0.168	0.162	0.184	0.183
Mg^{2+}	1.813	1.797	1.808	1.817	1.823	1.837	1.810	1.776	1.785
Mn^{2+}	0.002	0.004	0.003	0.002	0.003	0.004	0.003	0.003	0.003
Cr^{3+}	0.003	0.004	0.003	0.005	0.003	0.004	0.002	0.003	0.002
Ni^{2+}	0.008	0.008	0.007	0.010	0.010	0.009	0.008	0.007	0.007
T(K)	1243	1221	1154	1085	1126	1137	1195	1210	1240

Sample	10	11	12	13	14	15	16	17	18
Depth(m)	156.5	156.5	157.7	158.2	158.2	162.7	163.9	164.9	166.2
Chromite (based on 4 oxygen atoms)									
Al^{3+}	0.451	0.451	0.446	0.423	0.418	0.415	0.434	0.435	0.457
Cr^{3+}	1.405	1.356	1.409	1.425	1.403	1.453	1.424	1.325	1.318
Fe^{3+}	0.138	0.184	0.136	0.146	0.169	0.124	0.133	0.231	0.217
Fe^{2+}	0.282	0.310	0.283	0.277	0.284	0.260	0.276	0.321	0.327
Mg^{2+}	0.703	0.678	0.704	0.712	0.702	0.726	0.712	0.663	0.659
Olivine (based on 4 oxygen atoms)									
Si^{4+}	1.002	0.994	0.989	0.998	1.000	0.996	0.992	0.995	1.000
Fe^{2+}	0.164	0.149	0.171	0.163	0.154	0.140	0.155	0.143	0.147
Mg^{2+}	1.804	1.837	1.823	1.799	1.819	1.842	1.834	1.842	1.825
Mn^{2+}	0.003	0.001	0.003	0.004	0.002	0.001	0.003	0.003	0.003
Cr^{3+}	0.003	0.003	0.005	0.003	0.004	0.003	0.004	0.004	0.005
Ni^{2+}	0.009	0.010	0.009	0.008	0.010	0.008	0.009	0.008	0.009
T(K)	1178	1097	1185	1198	1160	1117	1142	1090	1092

Note:The temperatures were calculated according to Lehmann's thermometer (1983). Compositions of chromite and olivine were recalculated from electron-microprobe results. All samples come from cumulate zones in the komatiites.

DISCUSSION

Origin of chemical variations in the chromite

Compositional zonation of chromite from komatiites has not previously been reported in detail. Chemically zoned primary chromite from layered intrusions or Alpine ultramafic rocks is rare. On the basis of data accumulated to date, magmatic chromite can be described as being relatively homogeneous; it occupies distinct compositional fields, and follows distinct compositional trends depending on geodynamic setting. Where it occurs in strongly altered or metamorphosed rocks, chromite crystals show a dark homogeneous core surrounded by a lighter Al- and Mg-poor zone of "ferritchromit" that changes gradually in composition toward magnetite at the margin (Bliss & MacLean 1975, Evans & Frost 1975, Zakrzewski 1989, Michailidis 1990). Altered chromite may be surrounded by or intergrown with "ferritchromit" having a chlorite or antigorite association (Bliss & MacLean 1975).

Breakdown of chromite to form "ferritchromit", magnetite and chlorite requires temperatures above those at which serpentinization takes place (Bliss & MacLean 1975). The chlorite typically forms a rim around the altered chromite grains, and is stable during subsequent conversion of olivine to lizardite, but is replaced by antigorite during metamorphism (Thayer 1966).

For chromite from the Belingwe komatiites, we believe that the zonation is primary and thus quite different from chromite zonation or rims having a metamorphic origin. Systematic chemical variations in chromite from the spinifex to the cumulate zones, and from core to rim of crystals (Fig. 8) differ from those attributed to alteration as described above. For example, Al contents are relatively uniform or increase slightly from the core to the rim (Fig. 8). Moreover, chemical variations from core to rim of crystals are similar to those exhibited by euhedral chromite crystals from the top to the base of a flow; these features may imply that euhedral cores of the skeletal chromite and the euhedral chromite in the upper part of a flow formed earlier than euhedral chromite in the lower part of the same flow.

In zoned chromite crystals, silicate inclusions that have high SiO_2, Al_2O_3 and Na_2O contents (Table 3) were trapped by the chromite crystals at the point at which their growth rate started to accelerate. The silicate inclusions may be droplets of a granitic liquid formed by contamination from wall rocks (*e.g.*, Irvine 1975). Alternatively, the silica-rich inclusions may represent late liquids, or a silica-rich residual liquid resulting from local consumption of Fe, Mg, and Cr by rapid growth of chromite. Silica-rich inclusions in chromite are remarkably similar in composition to ocellar units described from the top of komatiitic flows at Kambalda. Frost & Groves (1989) interpreted them to represent an immiscible liquid generated by contamination of the ultramafic magma. The silicate inclusions documented in this study may have formed either by immiscibility, or by one of the processes listed above.

Johan *et al.* (1983) described silicate inclusions, notably jadeite, in ore-forming chromite from ophiolites. They reflect volatile-rich conditions. The inclusions in chromite documented in this study are not directly comparable to those described by Johan *et al.* (1983), inasmuch as the former occur in accessory chromite within komatiites, whereas the latter are in chromite deposits.

Euhedral chromite, and euhedral cores of skeletal chromite crystals in spinifex zones, might be phenocrysts transported with the komatiite liquid, that grew prior to the onset of olivine nucleation. As the magma cooled rapidly, skeletal chromite crystallized on nuclei of pre-existing euhedral crystals (phenocrysts) in equilibrium with small volumes of evolved residual liquids. Residual liquids would be relatively depleted in Mg and Cr; this may account for the lower Mg and Cr contents of the skeletal mantles relative to the cores.

Chromite in the cumulate zone may originally have had the same composition as euhedral chromite or chromite cores in the spinifex zone. Euhedral chromite in the cumulate zones may have re-equilibrated with residual liquids and olivine during slower cooling, to acquire the same composition as the skeletal variety.

The presence of two stages of compositionally distinct chromite in the spinifex zone may result from a change in conditions of crystallization or in liquid compositions. For example, the euhedral grains of chromite may have grown in equilibrium with a large volume of magma that had not undergone significant evolution, whereas the skeletal variety grew rapidly from small volumes of evolved liquid trapped between spinifex olivine crystals. The evolved liquid would trend toward relatively depleted Mg and Cr contents, and this trend is reflected in the skeletal chromite. The change of composition from core to skeletal rim also may result in part from a change of oxygen fugacity during the emplacement of the komatiitic magma. Oxygen fugacity could influence the compositions of coprecipitating chromite and silicate minerals. Systematic decreases of Mg and Cr contents from the euhedral to skeletal outer portions of the zoned chromite could be explained by diminished oxygen fugacity and temperature decrease after magma emplacement (Haggerty 1976, Murck & Campbell 1986).

Comparisons of chromite compositions from various geodynamic settings

In ophiolites, chromite occurs in cumulate complexes, tectonized peridotites and podiform chromitites (*e.g.*, Bai & Zhou 1988). Chemical compositions of chromite from tectonized peridotites were influenced by the partial melting of the mantle, with concomitant separation of chromite from pyroxene as a result of incongruent and multistage melting (Paktunc 1990). During progressive melting of the upper mantle, there will be corresponding variations in the compositions and textures of residual minerals. Their modification and reformation are characterized by two parallel evolutionary trends: 1) progressive increase of $100\text{Mg}/(\text{Mg}+\text{Fe})$ values, and 2) a corresponding increase in the $100\text{Cr}/(\text{Cr}+\text{Al})$ ratio of the accessory spinel (Fig. 6). During this process, there is a progressive enrichment of Mg and Cr in chromite at approximately uniform Fe contents (Figs. 6, 7, 9).

Chromite in ophiolitic cumulates, as an accessory or ore-forming mineral, displays a clear magmatic evolutionary trend with progressive enrichment in Al and Fe, coupled with depletion in Cr (*e.g.*, Laurent & Kacira 1987) (Fig. 9).

Chromite from layered intrusions within continental settings, and chromite from cumulate complexes of ophiolites, share the same chemical trends (Fig. 9). The former has a relatively greater degree of enrichment in Al than the latter. This difference can be explained by differences in compositions and conditions of crystallization. Ophiolitic complexes, which represent parts of ancient oceanic crust and which contain troctolites, would seem to have formed at lower pressures, whereas layered intrusions, such as the Stillwater, Bushveld and the Great Dyke, which contain orthopyroxene, formed at higher pressures (*e.g.*, Campbell 1985, Bai & Zhou 1989).

Relative to chromite from plutonic igneous rocks derived from relatively evolved basaltic liquids, chromite from mantle peridotites and chromitite from ophiolites, from xenoliths in kimberlites and continental basalts, or as inclusions in diamonds, has higher Al contents and relatively uniform Fe contents. This feature stems from the fact that multistage melting, or compositional changes of melt, would not influence iron contents of the chromite, and the magmas would be buffered by large volumes of residual mafic silicates.

In chromite from high-pressure environments, Cr/Al values would be expected to diminish with decreasing temperature, because the chromite would be progressively depleted in Cr and enriched in Al. The Fe/Mg values of the chromite vary little

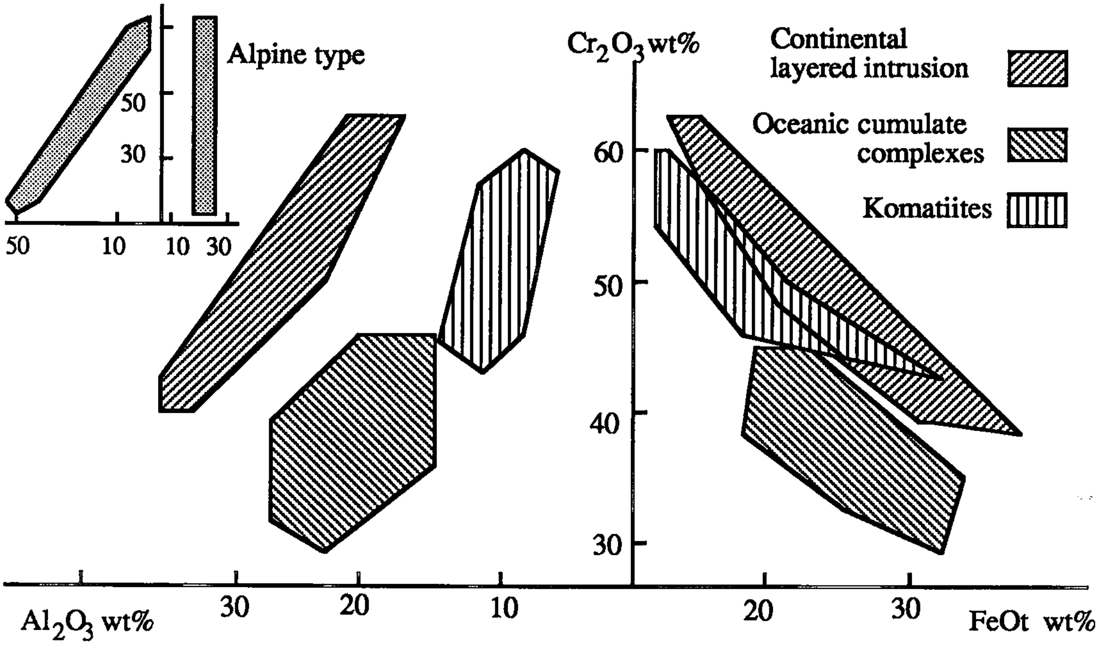


FIG. 9. Discrimination diagrams for chromite composition, plotted in terms of Cr_2O_3 *versus* Al_2O_3 and Cr_2O_3 *versus* FeOt. The upper left inset plots trends of chromite composition from Alpine type ultramafic rocks. Modified from a four-component diagram of Bai & Zhou (1988).

because of the buffering effect of residual mafic silicates.

The Al content of chromite depends both on the Al contents of the melt and on the pressure of crystallization (Dick & Bullen 1984, Augé 1987). Compositions of spinifex zones are quite different from those of cumulate zones (Nisbet *et al.* 1987, Renner *et al.* 1992), but the similar Al contents of chromite may indicate that the Al contents of the liquids from which chromite crystallized were probably similar.

The uniform Al contents of chromite from the komatiites indicate low-pressure crystallization upon eruption. Pressure will affect Cr partitioning on chromite composition, leading to less chromian chromite at high pressure (Dick & Bullen 1984). Low pressures would lead to a less aluminous chromite. Changes in composition or oxygen fugacity after komatiite eruption presumably led to changes in the proportion of Mg and Fe, as these are similar to those for chromite from layered intrusions. Because Al contents are relatively uniform, increases of Fe^{3+} require a corresponding decrease of Cr^{3+}. Thus, the compositional field of chromite from komatiites is distinct in Figure 9.

For purposes of comparison, chemical compositions of chromite from komatiites at Pyke Hill, Ontario (Arndt *et al.* 1977), and from Suomussalmi, Finland, which have been suggested to be closest to a possible primary composition (Blais & Auvray 1990), also are plotted in this diagram. The results indicate that they share the same chemical characteristics with those of komatiites from the Belingwe greenstone belt. Compositional ranges of relict chromite from komatiites in Western Australia also are similar to the Abitibi, Belingwe and Finnish examples (Donaldson *et al.* 1986); this similarity corroborates the view that this compositional field of chromite is representative of komatiites, and accordingly the discrimination diagrams are valid.

Nickel contents of chromite from the Belingwe komatiites are low, similar to those of chromite in ultramafic intrusions, *i.e.*, on average 0.15 wt% NiO for podiform chromite deposits, 0.09 wt% NiO for Alpine ultramafic rocks, and 0.9-1.7 wt% NiO for the Great Dyke. Ni contents in the outer rim of "ferritchromit" from central Manitoba samples reach as high as 2.8 wt% NiO (Bliss & MacLean 1975). This is attributed to the release of Ni from silicates during serpentinization and incorporation of the Ni in magnetite, serpentine and sulfides.

A distinction can be made between chromite from stratiform and podiform deposits on the basis of Ti concentration (Herbert 1982). The latter

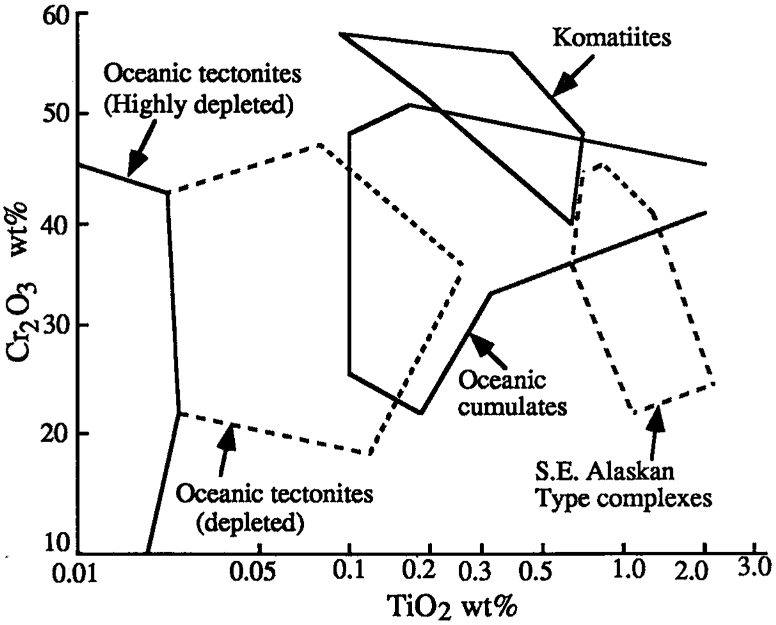


FIG. 10. Cr_2O_3 *versus* TiO_2 diagram for chromite, illustrating distinctions between chromite compositions from different types of ultramafic rocks (Herbert 1982, Jan & Windley 1990).

generally contain less than 0.3 wt% TiO_2, whereas the former typically have in excess of 0.3 wt% TiO_2, because Ti is strongly partitioned into the liquid during partial melting in the upper mantle. Thus chromite in komatiites is similar to counterparts in layered intrusions in terms of TiO_2 contents (Fig. 10).

SEM investigations of some chromite crystals by Leblanc (1980) show significant morphological differences between chromite from stratiform complexes and that from podiform deposits. Chromite from mafic–ultramafic layered complexes is euhedral and displays large, smooth and bright faces with sharp edges. Podiform examples, on the other hand, feature disseminated crystals with rounded habit and numerous surface-pits or cavities, which are interpreted as stemming from dissolution. Some chromite crystals in komatiites are morphologically similar to those in layered intrusions, but skeletal crystals also are present in the former.

CONCLUSIONS

The principal conclusions of this study are as follows:

1. Skeletal and dendritic chromite grains from komatiites sampled from the SASKMAR drill core have diverse morphologies, and are present in spinifex zones. They are different from chromite grains in Alpine and stratiform ultramafic rocks. They may contain euhedral cores, which may represent phenocrysts transported with the komatiitic liquid, and skeletal overgrowths, that formed during rapid crystallization in equilibrium with evolved residual liquid. The euhedral chromite in cumulate zones could have re-equilibrated with residual liquids and olivine after the komatiitic liquid erupted, to acquire the same composition as the skeletal variety.
2. From top to base of flows, the euhedral chromite is enriched in Fe, Ti and Mn, but is depleted in Mg and Cr. This trend parallels core-to-rim variations of zoned chromite in spinifex zones. Al contents are relatively uniform for all varieties of chromite and are consistent with low-pressure crystallization.
3. Calculated temperatures (1090° to 1250°C) based on olivine-chromite pairs provide an estimate for the ambient conditions of last equilibrium crystallization in komatiitic cumulates.
4. Chemical compositions of chromite provide an important means of distinguishing komatiites from ultramafic rocks in other geodynamic settings; Al_2O_3 *versus* Cr_2O_3 and FeOt *versus* Cr_2O_3 diagrams separate komatiites from Alpine and intrusive mafic–ultramafic rocks.

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