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Platinum-Group Minerals and Other Solid Inclusions in Chromite of Ophiolitic Complexes: Occurrence and Petrological Significance

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With 3 Figures

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Summary

Platinum-group mineral, silicate and other solid and fluid inclusions occur in disseminated and massive chromite in a variety of lithologies from ophiolitic and other mafic-ultramafic complex-types. The inclusions are small (< 250 microns) and randomly distributed throughout their host. Silicate inclusions are modally more abundant than the other inclusion types. Platinum-group mineral phases are ruthenium-rich sulphides and PGE alloys are osmium-rich. Mafic silicates (olivine, pyroxenes, pargasitic-amphiboles, micas) are magnesium-, titanium-, and alkali-rich and felsic silicates are sodium-rich (albite, nepheline).

The intimate association of these inclusions with chromite suggests that their origin must be considered within a chromite crystallization model. A hypothesis of origin is suggested wherein the platinum-group minerals and silicates are trapped as discrete, crystalline euhedral phases and silicate liquid during the precipitation of chromite. The similarity of physical characteristics, modal mineralogy and chemical compositions indicates that this model may be applicable to all mafic-ultramafic complex-types.

Zusammenfassung

Minerale der Platin-Gruppe und andere feste Einschlüsse in Chromiten aus Ophiolit-Komplexen: Vorkommen und petrologische Bedeutung

Minerale der Platin-Gruppe, Silikate und andere feste und flüssige Einschlüsse kommen in disseminierten und massiven Chromiten in einer Vielzahl von Gesteinen in ophiolitischen und anderen mafisch-ultramafischen Komplexen vor. Die Einschlüsse sind klein (< 250 microns) und unregelmäßig im Chromit verteilt. Silikat-Einschlüsse sind modal weiter verbreitet als andere Arten von Einschlüssen. Minerale der Platin-Gruppe sind durch Ruthenium-reiche Sulfide und Osmium-reiche Legierungen vertreten. Mafische Silikate (Olivin, Pyroxen, pargasitische Amphibole, Glimmer) sind Magnesium-, Titan- und Alkali-reich; felsische Silikate sind Natrium-reich (Albit, Nephelin).

Die ausgeprägte Assoziation dieser Einschlüsse mit Chromit weist darauf hin, daß ihre Herkunft im Zusammenhang mit einem Kristallisations-Modell für Chromit zu sehen ist. Ein genetisches Konzept wird vorgelegt, wobei die Platin-Gruppen-Minerale als gut ausgebildete, idiomorphe kristalline Phasen, und die Silikate als Silikatschmelze während des Ausfallens des Chromites eingeschlossen werden. Die Ähnlichkeit der physikalischen Eigenschaften, der modalen mineralogischen Zusammensetzung und der chemischen Zusammensetzung weisen darauf hin, daß dieses Modell auf alle mafisch-ultramafischen Komplexe anzuwenden ist.

Introduction

Platinum-group minerals (PGM), silicate (e.g., olivine, pyroxenes, albite, hydrous silicates and others) and other solid and fluid inclusions in chromite are present in ophiolites (e.g., *Johan* and *Lebel*, 1978; *Constantinides* et al., 1980; *Talkington*, 1981; *Prichard* et al., 1981) as well as stratiform (*McDonald*, 1965; *Page* and *Jackson*, 1967; *Hiemstra*, 1979; *Talkington* et al., 1983) and Alaskan-type complexes (*Talkington* et al., 1984). Most of these studies have reported descriptive and chemical composition data for these small (< 40 microns for PGM and < 250 microns for silicate and opaque) though easily recognized inclusions.

All hypotheses of origin for the inclusions require the active participation of chromite during inclusion formation. Two fundamentally different roles for chromite have been advanced. One hypothesis requires that chromite accept the platinum-group elements (PGE) into structural sites during magmatic crystallization and later expel them during subsolidus equilibration (*Gijbels* et al., 1974). The second hypothesis intimates that chromite traps PGM and PGE-alloys as discrete, euhedral phases during all periods of chromite precipitation (*Johan* and *Lebel*, 1978; *Constantinides* et al., 1980; *Talkington* et al., 1983).

Silicate inclusions are suggested to have been trapped either as silicate liquid enriched in Mg, alkalis, Ti and later crystallize as single or composite inclusions or as discrete, often euhedral, crystals.

The purpose of this paper is to present new data for ophiolitic solid inclusions and review and discuss existing hypothesis of origin for PGM and silicate inclusions in chromite from ophiolitic, stratiform and Alaskan-type complexes. Sulphide and fluid inclusions studies are in progress.

Occurrences, Physical Characteristics and Compositions of Solid Inclusions in Chromite

Platinum-group mineral and silicate inclusions (olivine, orthopyroxene, clinopyroxene, nepheline, albite, amphibole, phlogopite) occur in massive chromite accumulations such as seams, clots and pods in dunite, harzburgite and orthopyroxenite. They are rare in disseminated chromite. In our examination of solid inclusions from ophiolitic, stratiform and Alaskan-type complexes, we have not found a stratigraphic control for their distribution. Massive and disseminated chromite is euhedral to subhedral and generally less than 6 mm in size. The modal abundance of solid inclusions varies greatly from specimen to specimen. However, silicate inclusions are more common than the other varieties. All inclusions are randomly distributed throughout the host chromite (Plate 1a), but occasionally

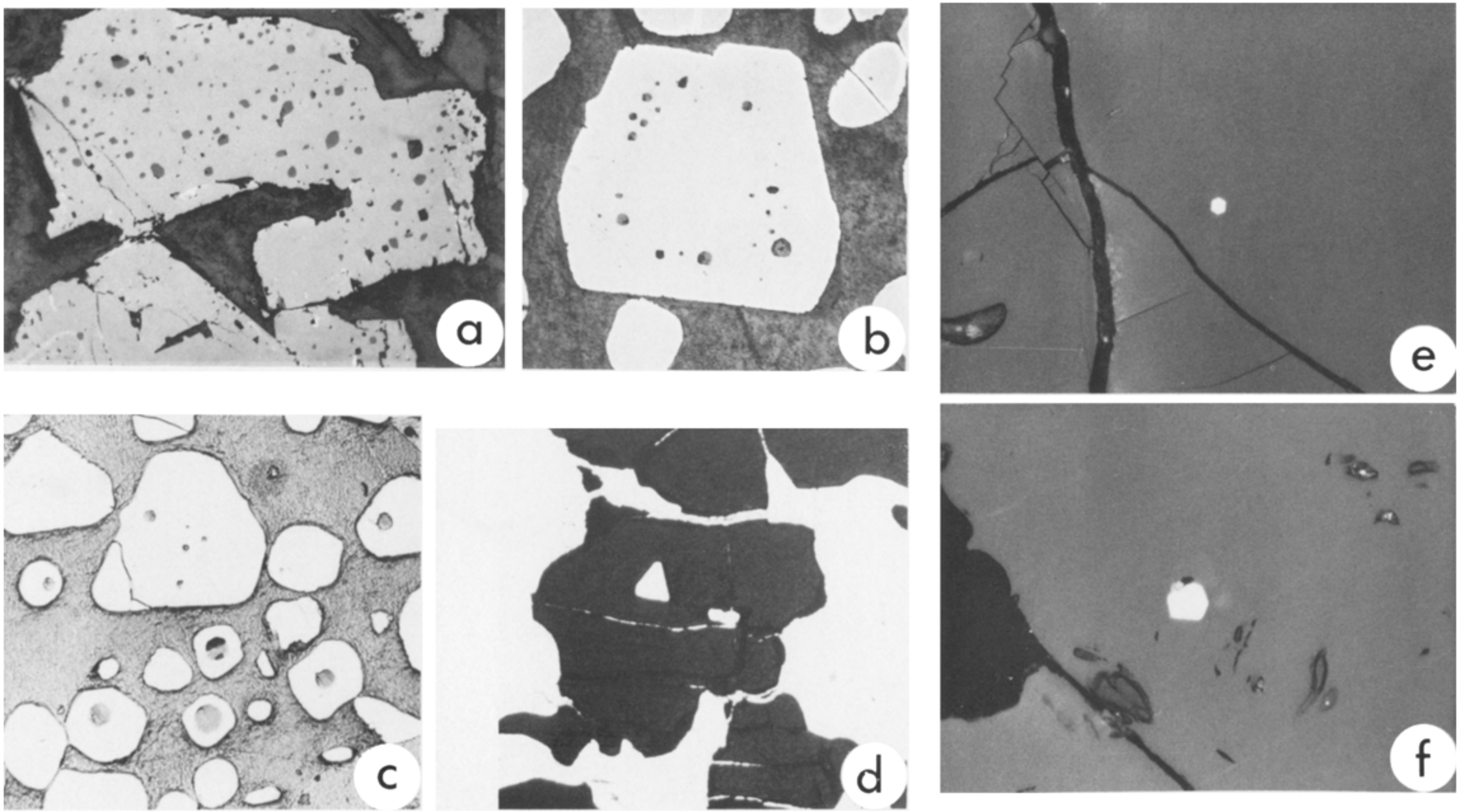

Plate 1. a) Random distribution of silicate (pargasitic amphibole) inclusions in chromite, Montreal Pit, Thetford Ophiolite Complex, Quebec. Plane polarized reflected light. Sample W79-166. Field of view is 0.65 mm. b) Silicate inclusions distributed approximately parallel to chromite crystal faces, Bird River Sill, Manitoba. Plane polarized reflected light. Sample Bird 5. Field of view is 0.4 mm. c) Large, centrally located silicate inclusions in chromite, Bird River Sill, Manitoba. Sample BRS.MASS.CHRM-27. Plane polarized reflected light. Field of view is 0.4 mm. d) Primary, triangular olivine inclusion in chromite, Thetford Ophiolite Complex, Quebec. Sample W79-165. Plane polarized transmitted light. Field of view is 1.4 mm. e) Hexagonal habit to laurite inclusion in chromite, White Hills Peridotite, Newfoundland. Sample 78119-7. Plane polarized reflected light. Field of view is 70 microns. f) Euhedral laurite inclusion with unidentified, attached sulphide (?) phase in chromite, White Hills Peridotite. Sample 78122X-6. Plane polarized reflected light. Field of view is 70 microns

either parallel crystal faces (Plate 1b), concentrate in the host core (Plate 1c) or near a crystal face.

The association of solid inclusions in chromite is varied. For example, within a single specimen PGM inclusions may occur in an individual chromite grain as a solitary phase or associated with various silicate and sulphide phases. In addition to these associations, laurite (RuS_2) and PGE alloys occur in the same specimen, but not in the same chromite grain. Other associations include PGM inclusions with an attached small, anhedral silicate phase. This may be similar to the wetting effect described by *Hiemstra* (1979) for some Bushveld Complex, South Africa samples and the laurite-silicate association described by *Stockman* (ms.) for the Josephine Peridotite, Oregon. Composite solid inclusions that contain two or more silicate phases or PGM and a Cu-Ni-Fe sulphide are rare. Where found each phase is in sharp contact and for the PGM-sulphide composite inclusion they have smooth and arcuate grain boundaries with no visible evidence of unmixing.

Physical characteristics of the solid inclusions in ophiolitic chromites are listed in Table 1. We have attempted to limit the data of Table 1, where possible, to solid inclusions in nonfractured chromite grains. The inclusions are similar in size, habit and variety of mineral phases for all ophiolite occurrences and complex-types (cf. *Talkington* et al., 1984). The silicate inclusions are commonly the largest and predominantly subhedral to spherical (see Plates 1b, c), though hexagonal outlines and euhedral olivine grains (Plate 1d) have been observed. Cu-Ni-Fe sulphides are anhedral, whereas the PGM and PGE alloys are euhedral (e.g., triangle, square, rectangle, hexagon and combinations of these habits) (Plates 1e, f); round apices and corners of original polyhedra are rare.

Other alloys (e.g., Cu-Zn and Ni-Fe) and native elements (e.g., Cu and Ag) occur in negative crystal cavities, fractures in chromite and in the serpentinized groundmass. We consider these phases to post-date the formation of the PGM, PGE alloy and silicate inclusions and further suggest that the Cu-Zn alloy and native Cu may represent tap water contaminants introduced during sample preparation (cf. *Stockman* ms.).

Fluid inclusions have been identified in all complex-types but have been analyzed only for the Al Ays Ophiolite, Saudi Arabia by *Johan* and *Lebel* (1978) (see Table 1). The Al Ays inclusion is more NaCl-rich than fluid inclusions in quartz (3.2 ± .05 equivalent wt.%) from the volcanogenic sulphide ore deposits of the Troodos Complex, Cyprus (*Spooner* and *Gale*, 1982).

Mineral analyses for PGM, PGE alloy and silicate inclusions in chromite for all complex-types have been published elsewhere (*Talkington* et al., 1984) and are presented here in diagram form.

Olivines have been identified in the Newfoundland and Quebec ophiolites. For these occurrences, olivine has high forsterite (Fo_{96}) and nickel contents (up to 0.78 wt.%). *Legendre* (1982) and *Johan* and *Lebel* (1978) have reported similar olivine compositions (up to Fo_{98} and NiO $\sim$ 2 wt.%) from the New Caledonian and Saudi Arabian ophiolites.

Orthopyroxene and clinopyroxene analyses have been plotted on Fig. 1 for all complex-types. Orthopyroxene has a high *En* content for all complexes, though somewhat lower for the Crystal Lake Gabbro, Ontario and Bushveld

Table 1. *Solid and Fluid Inclusions in Chromite*

Location and Host Rock	Type of S.I.*-F.I.* and Composition	Size (μm)	Crystal Habit	Reference
Newfoundland				
1) White Hills Peridotite				
"websterite" to peridotite	a) laurite	$\leqslant 20$	euhedral to	*Talkington* (1981) and this study
	b) silicates	–	various shapes	
	c) fluid inclusions	< 10	spherical	
	d) sulphide			
	(1) – (NiS)	< 35	spherical	
	(2) – (NiCu, Fe, S)	"	spherical	
	(3) – (Ni, FeS)	"	spherical	
	e) alloy (Cu-Zn)	< 10	anhedral	
2) Bay of Islands Complex				
dunite	a) native silver	< 15	anhedral	this study
	b) silicates		spherical to	
	(1) pargasite	< 100	ovoid	
	(2) Na-mica (or clays)	"	"	
	(3) chlorite	"	"	
	(4) biotite	"	"	
	(5) olivine	"	"	
	(6) clinopyroxene	"	"	
	(7) orthopyroxene	"	"	
	c) fluid inclusions	< 40	spherical to tubular	
3) Pipestone Pond				
dunite	a) silicates	< 50	euhedral to anhedral	this study
	b) fluid inclusions	< 10	spherical to polyhedron	
Quebec				
1) Thetford Ophiolite				
peridotite	a) olivine	< 160	euhedral	*Watkinson* and *Mainwaring* (1980, 1982)
	b) pargasite	< 20	ovoid	
	c) Na-mica	< 40	–	
	d) fluid inclusions	–	–	
British Columbia				
1) Murray Ridge				
chromitite in dunite and harzburgite	a) fluid inclusions	< 10	spherical to tubular	*Whittaker* and *Watkinson* (1981) *Whittaker* (1982)
	b) silicate	$\leqslant 20$	subhedral	
	c) sulphide	~ 5	euhedral to anhedral	

Table 1 (continued)

Location and Host Rock	Type of S.I.*-F.I.* and Composition	Size (μm)	Crystal Habit	Reference
Greece 1) Vourinos Complex (Xerolivados Mine)				
dunite	a) native silver	~ 5	anhedral	this study
harzburgite	b) magnetite	~ 5	spherical	
	c) silicate	< 100	round and polyhedron	
chromitite	a) sulphide			
	(1) pyrite	~ 5	anhedral	
	b) fluid inclusions	< 40	polyhedron	
	c) silicate	< 50	polyhedron some hexagons	
Cuba 1) Camaguey district (Guillermina Mine)				
troctolite	a) pyroxene	minute	polyhedron	*Thayer* (1969)
	b) amphibole	"	polyhedron	
	c) mica	"	polyhedron	
Cyprus 1) Kokkinorotsos Chrome Mine				
dunite in harzburgite	a) laurite	5–15	euhedral-anhedral	*Constantinides* et al. (1980)
	b) erlichmanite	"		
	c) silicate	< 100	–	this study
	d) pyrite	5–15	spherical	
	e) pyrrhotite	"	"	
	f) chalcopyrite	"	"	
	g) fluid inclusions	< 30	spherical-polyhedron	
2) Limassol Forest				
dunite (serpentinite) in harzburgite	a) serpentine	2–250	spherical	*Panayiotou* (1978)
Cyprus 3) Hjipalou Mine				
dunite	a) fluid inclusions	< 30	spherical-polyhedron	this study
	b) silicate	< 200	rounded	
	c) sulphide	< 30	various shapes	

Table 1 (continued)

Location and Host Rock	Type of S.I.*-F.I.* and Composition	Size (μm)	Crystal Habit	Reference
Saudi Arabia 1) Al Ays				
olivine and clinopyroxene cumulates	a) olivine ($Fo_{94.0-97.7}$, mol.%) 1) up to 0.6 wt.% Cr_2O_3 2) up to 1 wt.% NiO 3) 0–0.2 wt.% MnO	–	subhedral	*Johan* and *Le Bel* (1978)
	b) amphibole (Cr-rich pargasite) 1) up to 3.4 wt.% Cr_2O_3	–	–	
	c) clinopyroxene (rare) 1) $En_{46.7-50.2}$ $Wo_{51.2-47.6}Fs_{2.1-2.3}$ 2) 1–1.2 wt.% Cr_2O_3	–	–	
	d) fluid inclusions (fill negative crystal cavities) 1) 5 equiv. wt.% NaCl 2) minor CO_2, CH_4 and heavier hydrocarbons ($\rho = 0.68$ g/cm^3) 3) homogenization temperatures 337.5–357.5 °C	–	–	
Oman Semail				
dunite in peridotite	a) olivine	–	–	*Peters* and *Kramers* (1974)
	b) clinopyroxene (very rare)	–	–	
	c) heazlewoodite (Ni_3S_2)			
Brazil Tocantins Complex GOIAS				
dunite (serpentine) and olivine-rich peridotite	a) ilmenite (with hematite exsolution)	"tiny"	round	*White* et al. (1971)
United Kingdom 1) Unst Ophiolite, Shetland Isles				
chromitite	a) laurite	< 12	subhedral to oval-shaped	*Prichard* et al. (1981)
	b) iridosmine	2		
	c) nickel sulphide	–		
New Caledonia 1) Massif du Sud				
chromitite	a) rutheniridosmine	–	–	*Legendre* and *Johan* (1981)
2) Massif de Tiébaghi				
chromitite	a) laurite	–	–	
	b) $(Cu, Ni)(Ir, Rh)_2S_5$	–	–	"

Table 1 (continued)

Location and Host Rock	Type of S.I.*-F.I.* and Composition	Size (μm)	Crystal Habit	Reference
3) New Caledonia (inclusive)				
chromitite	a) silicates			*Legendre* (1982)
	(1) olivine (*Fo_{96}*)	–	–	
	(2) clinopyroxene (*En_{50}*; *Wo_{47}*)	”	”	
	(3) orthopyroxene (*En_{96}*)	”	”	
	(4) pargasitic hornblende	”	”	
	(5) nepheline	”	”	
	b) fluid inclusions	”	”	
	c) platinum-group minerals (see 1 and 2)	”	”	

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* S.I. = solid inclusion; F.I. = fluid inclusion.

samples. The clinopyroxenes are diopside-rich and contain variable Al_2O_3 contents (0.55 to 4.43 wt.%).

Amphiboles are Mg-rich and contain variable TiO_2 contents. Ophiolitic amphiboles are TiO_2-poor (< 1.00 wt.%) and stratiform amphiboles are TiO_2-rich (> 1.00 wt.%). We have no data for Alaskan-type complexes. When tetrahedral aluminum is plotted against (Na + K, at. prop.), two groups are defined for ophiolitic and stratiform, though there is some overlap (Fig. 2). The ophiolitic amphiboles are lower in sodium and potassium and are hornblende-rich, whereas the stratiform amphiboles are more sodium- and potassium-rich and plot between edenite and pargasite.

No attempt has been made to classify the sheet silicates, but three analyses from the Stillwater Complex, Montana and Tulameen Complex, British Columbia are of phlogopitic mica.

Platinum-group mineral analyses are plotted on Fig. 3. Laurite analyses from the Bird River Sill, Manitoba, Stillwater Complex, and Big Trout Lake Complex, Ontario group near the ruthenium apex. Those from the White Hills Peridotite, Newfoundland and Josephine Peridotite, Oregon plot away from the ruthenium apex toward osmium-rich compositions. Although separate groups for PGM compositions are defined, PGM inclusions from the Troodos Complex, Cyprus define a trend from laurite to erlichmanite (*Constantinides* et al., 1980).

A subhedral PGM inclusion with serrated borders and spongy texture occurs in an altered fractured chromite from the Alpine-type ultramafic (= ophiolitic) tectonic slices in the Cache Creek Group, British Columbia (*Whittaker*, 1982). An energy dispersive spectra (EDS) of the altered chromite and PGM indicates that the PGM inclusion is arsenic-bearing and zoned from rim (high) to core (low).

No arsenic is present in the chromite host. The presence and distribution of arsenic for this example is analogous to arsenic rims and alteration zones in PGM grains described by *Stumpfl* and *Tarkian* (1976).

No PGE alloys have been identified for the ophiolites we have examined, but they have been identified from the Bird River Sill. According to the classification of *Harris* and *Cabri* (1973) they are rutheniridosmine. These inclusions are similar to osmium-iridium-ruthenium alloy inclusions reported by *Legendre* and *Johan* (1981) and *Legendre* (1982) for the New Caledonian ophiolites, but more ruthenium-rich than the iridosmine inclusion from the Unst Ophiolite, Shetland Isles (*Prichard* et al., 1981). *Stockman* (ms.) has identified a variety of PGE alloys in unfractured and fractured chromite from the Josephine Peridotite. They include ruthenium-rich alloys [Ru/(Ru+ Ir + Os)> 0.5], platinum-rich alloys with variable amounts of iron, copper, nickel, antimony, and iridium- and osmium- or iridium-rich alloys. In addition, platinum-bearing sulphides and arsenides are associated with laurite.

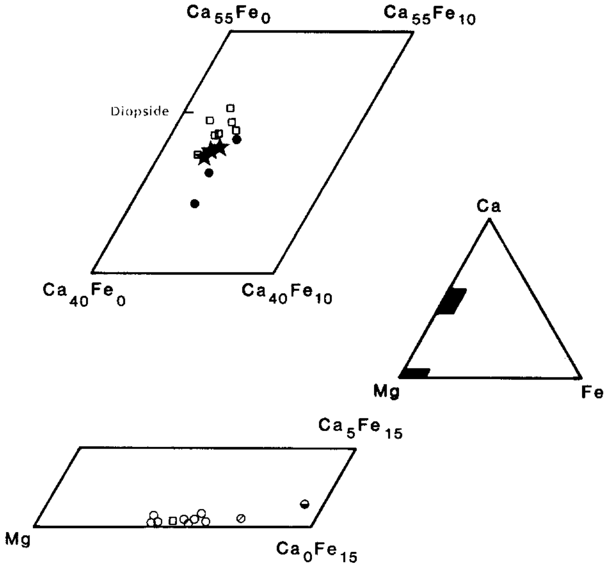

Fig. 1. Electron microprobe analyses of pyroxene inclusion compositions plotted on the Ca-Mg-Fe (atomic proportions) triangle. Symbols: □ Bay of Islands Ophiolite (Springer's Hill), Newfoundland, ○ Stillwater Complex, Montana, ◒ Crystal Lake Gabbro, Ontario, ● Bird River Sill, Manitoba, ⊘ Bushveld Complex, South Africa, ★ Tulameen Complex, British Columbia

In summary, the solid inclusions in chromite commonly occur in massive chromite accumulations and exhibit a full-range in size (< 10 microns to 250 microns), shape, variety and are randomly distributed throughout their host. The PGE-bearing phases are smallest and modally least abundant and are predominantly ruthenium-rich sulphides and alloys. The silicate inclusions are

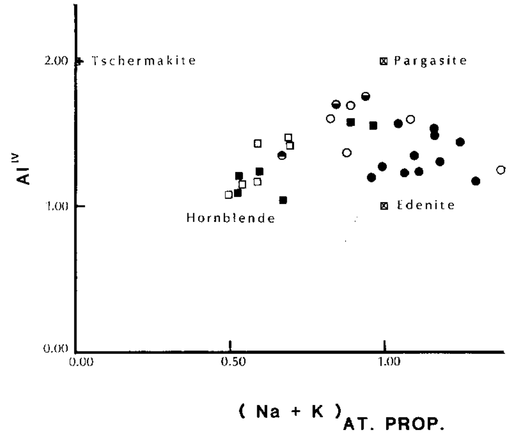

Fig. 2. Al^{iv} plotted against (Na + K) (atomic proportions) for amphibole inclusions in chromite. Symbols as for Fig. 1. Additional symbols: ■ Thetford Ophiolite Complex, Quebec; ◓ Big Trout Lake Complex, Ontario

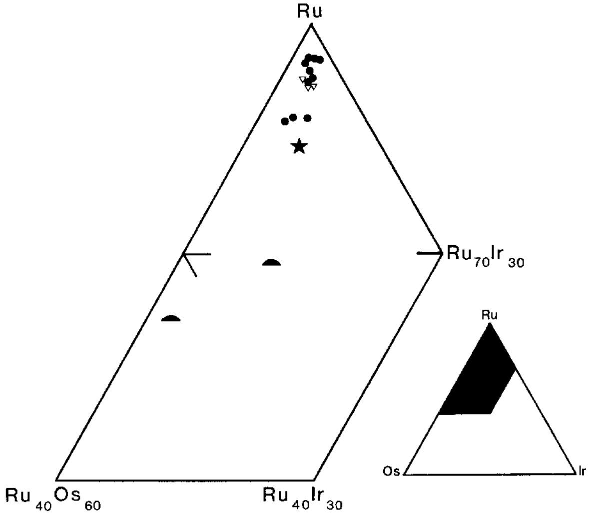

Fig. 3. Projection of microprobe analyses (atomic proportions) of laurites onto part of the Ru-Ir-Os triangle. Symbols: ▲ White Hills Peridotite, Newfoundland, ▽ Stillwater Complex, Montana, ★ Big Trout Lake Complex, Ontario, ● Bird River Sill, Manitoba

usually magnesium-, nickel- and alkali-rich and are richer in these elements than associated groundmass phases (cf. *Talkington* et al., 1984). There are no significant differences in the physical characteristics and mineral compositions among the complex-types, though the composition of a silicate phase does appear to reflect whole rock chemistry. For example, the orthopyroxene inclusions in chromite from the Bay of Islands Ophiolite Complex, Newfoundland and Stillwater Complex are $En_{92.5}$ and $En_{\sim 91}$, respectively and occur in a dunite host, whereas those for the Crystal Lake Gabbro ($En_{84.8}$) and Bushveld Complex ($En_{88.4}$) occur in a gabbroic host. Quantitative data are not yet available for fluid inclusions.

Parageneses of the Solid Inclusions in Chromite

Several fundamentally different hypotheses of origin for PGE and/or silicate inclusions in chromite have been proposed. None of these hypotheses has attempted to completely explain the formation of all inclusion types, though many agree that most inclusions are magmatically derived. The hypotheses for PGE-bearing inclusions are:

i) exsolution of PGE from chromite
ii) PGE sulphide and alloy inclusions trapped as discrete phases during chromite precipitation

and for silicate inclusions:

i) incongruent melting of chrome-rich pargasite
ii) trapping of silicate inclusions
    a) trapped contaminated silicate liquid and crystals
    b) separation of a silicate liquid from a chrome-rich immiscible liquid
    c) entrapment of silicate liquid and crystals during chromite precipitation initiated by changing fO_2.

Early interpretations of PGE-bearing sulphide inclusion formation have speculated that because cumulus chromite is commonly associated with PGE concentrations (e.g., *Gijbels* et al., 1974; *Page* et al., 1976; *Crocket* et al., 1976; *Agiorgitis* and *Wolf*, 1978), the PGE are probably collected by chromite at magmatic temperatures and later expelled during subsolidus cooling (*Gijbels* et al., 1974).

We are not aware of any experimental partition studies for PGE-chromite pairs to test the validity of the exsolution hypothesis. However, PGE analyses of chromite separates and whole rock chromitite are available from the literature. These data (*Agiorgitis* and *Wolf*, 1978; *Becker* and *Agiorgitis*, 1979; *Watkinson* and *Talkington*, 1982; *Talkington* and *Watkinson*, unpublished data) indicate a weak relationship between chromite composition (Cr^{3+}, Cr/Cr+Al) and the PGE. There is, however, a good correlation among osmium, iridium and ruthenium and a poor correlation among platinum, palladium, rhodium vs. osmium, iridium, ruthenium. The presence of osmium, iridium and ruthenium-bearing sulphide and alloy inclusions in chromite convincingly argues that these PGE relationships are caused by their presence and does not necessarily favour exsolution. The random (non-crystallographic) distribution, euhedral habit for the PGM and the diversity of the inclusions indicates that an origin by exsolution cannot adequately account for their formation.

Many investigators (e.g., *Constantinides* et al., 1980; *Legendre* and *Johan*, 1981; *Talkington* et al., 1983; *Stockman* ms.) favour an origin for PGE sulphide and alloy inclusions whereby either; i) an immiscible PGE alloy is trapped during chromite precipitation and converted to a PGM sulphide by sulphurization; or

ii) an immiscible PGE bearing sulphide and/or alloy and silicate liquid are trapped during chromite precipitation.

Legendre and *Johan* (1981) prefer mechanism i) where a PGE alloy is trapped by chromite and later converted to PGE-bearing sulphides. Although sulphurization (i.e., S, As, Sb, Bi) may be applicable in some cases such as for fractured chromite grains, we do not believe that it is a viable process for unfractured chromite because of the general paucity of primary sulphides and therefore sulphur associated with ophiolitic chromite deposits.

Constantinides et al. (1980), *Talkington* et al. (1983), *Stockman* (ms.) and others favour mechanism ii) where a PGM and/or PGE alloy and silicate liquid are trapped as discrete, though occasionally as composite, inclusions. We suggest that the high melting temperatures of the native PGE and a PGE alloy indicate that they may exist as a discrete euhedral phase in the silicate melt (cf. *Bird* and *Bassett*, 1980). *Talkington* et al. (1983) have suggested that the nature of the PGE-phase (i.e., sulphide or alloy) may be related to physio-chemical factors that control chromite precipitation from a magma. They assume that a likely mechanism to initiate chromite precipitation is by a change (increase) in the oxygen fugacity (f_{O_2}) of the magma caused by an increase of volatiles, expecially H_2O. Chromite precipitation, as indicated by *Buchanan* and *Nolan* (1979) and *Haughton* et al. (1974), may produce a local increase of sulphur due to Fe^{2+} extraction from the magma. This increase of sulphur may be sufficient to convert the complete PGE alloy or only certain PGE's to PGE-bearing sulphides depending upon temperature, sulphur fugacity (f_{S_2}) and mineral equilibria (cf. *Talkington* et al., 1983, Fig. 5). Hence, PGE-bearing sulphides and alloys can coexist in a cumulus chromite.

Silicate inclusions are hypothesized to form either from the incongruent melting of chrome-rich pargasite or by the trapping of silicate liquid by chromite at magmatic temperatures.

Johan and *Lebel* (1978) have suggested that chromitite layers and solid inclusions could be formed by the incongruent melting of a chrome-rich pargasite by the reaction:

cr-pargasite = chromite + olivine + liquid + vapour (1)

Because equilibrium is not achieved all phases coexist in the chromite host, thus accounting for the presence of pargasite, olivine and fluid inclusions. No pressure or temperature conditions were given by *Johan* and *Lebel* (1978) for reaction (1).

Boyd (1959) has determined the maximum stability of pargasite as 1045 °C @ low pressure (~ 1 kb $P_{total} = P_{fluid}$) for the reaction:

pargasite = diopside + forsterite + spinel + nepheline + anorthite + fluid (2)

Holloway (1973) later showed that pargasite is stable up to 1053 °C and 7 kb with the maximum stability temperature of pargasite changing only slightly for variable $X^{fluid}_{H_2O, CO_2}$ and pressure up to 8 kb.

According to reaction (1) chrome-pargasite is modal or liquidus phase that later must incongruently melt. This may occur on a finite scale within a magma chamber, but probably not on a large-scale so as to result in extensive inclusion-bearing chromitite deposits.

Irvine (1975) has suggested that the silicate inclusions (orthopyroxene, Cr, Ti – phlogopite, and its sodium analogue, sodic plagioclase, pyrrhotite, chalcopyrite, rutile, "granitic", and probably potassium feldspar and quartz) in chromite from chromite-rich layers of the Muskox Intrusion, Northwest Territories represent both contaminated salic material that resulted from the incomplete mixing of the Muskox basaltic magma with the assimilated granitic country rock and trapped crystalline silicates (e.g., olivine, orthopyroxene). The compositions of some of these salic inclusions have not yet been reported for ophiolitic or Alaskan-type complexes and do not appear to be likely equilibrium phases in the early differentiation history of a basaltic melt. Therefore, these inclusion-types may be incompletely digested xenoliths in chromite as suggested by *Irvine* and are thus far unique to the Muskox.

McDonald (1965) has identified and described the characteristics of silicate (predominantly orthopyroxene, clinopyroxene, biotite and plagioclase) and fluid inclusions in chromite from the critical zone, Farm Ruighoek, Bushveld Complex. He postulated that the inclusions represent crystallization products from a chrome-rich immiscible liquid. The presence of several randomly distributed inclusions may be due to the "rate and uniformity of nucleation on the surface, or distortion of the (immiscible) droplets during settling". Although this process envisages the trapping of silicate liquid during chromite formation, *Jackson* (1966) has argued that an immiscible chrome-rich liquid is unlikely to form from a basaltic magma.

Watkinson and *Mainwaring* (1980) have suggested an origin for silicate inclusions and chromite deposits by invoking hydrothermal circulation of seawater that passes through a magma chamber in the case of ophiolites, to form metal-brine complexes and hydrates that are eventually transported to the upper part of the chamber. Rapid chromite precipitation may be initiated by a rapid change in P_{H_2O} and f_{O_2} during possibly, the fracturing of the roof of the magma chamber. This sudden change in fluid pressure and f_{O_2} may destabilize the hydrates and breakdown the metal-brine complexes, thereby causing chromite precipitation and the trapping of a contemporaneous silicate liquid.

Johan et al. (1982) have suggested a hypothesis similar to *Watkinson* and *Mainwaring*'s, but further suggest that the magma be strongly enriched in volatiles, alkalis and halides, to account for the composition of the silicate inclusions. Chromite may also form from this magma due to the interaction of chloride-rich reducing fluid with the magma.

Although these hypotheses adequately account for the compositions of the silicate inclusions and presence of fluid inclusions there are no experimentally determined hydrothermal solubility data for the PGE (*Barnes*, 1979). The apparent similarity in composition of the silicate inclusions for all complex-types may indicate that the effect of a seawater-rich (i.e., NaCl-rich solution) hydrothermal system on minerals precipitating from a magma is of limited extent.

In summary, although these studies indicate that the solid inclusions are discrete minerals, alloys or liquid when trapped by contemporaneously precipitating chromite, too few experimental studies are available to adequately define the processes which control their formation. Several questions arise from these hypotheses: i) by what mechanism (e.g., magma mixing, pulsing f_{O_2}, change in P_t) is chromite precipitation initiated and are solid inclusions especially their chemical compositions, a consequence of this event; ii) is the appearance of PGE alloys and PGE sulphides within the same chromitite horizon due to differences in PGE stability (the conversion of alloy to sulphide); iii) are the compositions of the PGM, osmium, iridium-, ruthenium-rich, related to magmatic (i.e., partial melting) processes whereby platinum, palladium, rhodium remain in the source material as an intergranular composite bleb (cf. *Mitchell* and *Keays*, 1981).

We favour the following model for the origin of chromite and solid inclusions. Chromite precipitation is initiated by a change (increase) in the f_{O_2} of the magma, accompanied by an increase of volatiles and locally an increase in the sulphur content of the magma which may be sufficient to convert PGE alloys to PGE sulphides. A contemporaneous precipitation of Mg-Ti- and alkali-rich silicates and trapping of silicate liquid and/or crystals with chromite and accumulation of these phases to form a layer along the base of the magma chamber. We are unsure of the cause for the unusual mineralogy and chemical compositions of some of the silicate inclusions. These processes, with minor variations, are applicable to chromite accumulations from a range of complex-types and geological ages.

Conclusions

The solid inclusions in chromite show the following features:

1) Silicate inclusions are modally most abundant.
2) All inclusions in unfractured massive and disseminated chromite are randomly distributed.
3) PGM and PGE alloy inclusions are smaller (< 40 microns) than silicate inclusions (< 250 microns).
4) PGM and PGE alloy inclusions are euhedral to subhedral and silicate inclusions are commonly spherical, but hexagonal and euhedral habits have been identified.
5) PGM and PGE alloy inclusions are ruthenium-rich and osmium-rich, respectively.
6) Mafic silicate inclusions (olivine, pyroxenes, amphiboles and sheet silicates) are magnesium, titanium, and alkali-rich; plagioclase is albitic.

The favoured hypothesis of origin for the inclusions is suggested to be intimately related to chromite precipitation. All discussed solid inclusions are suggested to have been trapped as discrete crystals or liquid during chromite precipitation. The unusual mineralogy and chemical compositions of some inclusions cannot readily be explained.

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