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Full Name of Author — Nom complet de l'auteur

Peter James Whittaker

Date of Birth — Date de naissance

March 28, 1953

Country of Birth — Lieu de naissance

Canada

Permanent Address — Résidence fixe

Department of Geology
University of Regina
Regina, Saskatchewan

S4S 0A2

Title of Thesis — Titre de la thèse

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Name of Supervisor — Nom du directeur de thèse

D.H. Watkinson

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GEOLOGY AND PETROGENESIS OF CHROMITE AND
CHROME SPINEL IN ALPINE-TYPE PERIDOTITES
OF THE CACHE CREEK GROUP, BRITISH
COLUMBIA

by

© Peter J. Whittaker, M.Sc.

A thesis submitted to the Faculty of Graduate
Studies and Research in partial fulfillment
of the requirements for the degree of

Doctor of Philosophy

Department of Geology

Carleton University

Ottawa, Ontario.

Summer, 1983

The undersigned hereby recommend to the Faculty of Graduate
Studies and Research acceptance of the thesis, submitted by
Peter J. Whittaker, M.Sc., in partial fulfillment for the
degree of Doctor of Philosophy.

External Examiner

Thesis Supervisor

Chairman of Department

Carleton University

Summer, 1983

FRONTISPIECE

Incised ridge and cirque topography of the Mitchell Range

ultramafic alloch^hthon

(Scale: 1 in - 1 mi)

Abstract:

Alpine-type peridotites from southern to central British Columbia, mostly in Cache Creek Group rocks, were mapped to determine the extent and style of chromite and chromitite mineralization.

Alpine-type peridotites in Permian aged Cache Creek Group metasedimentary rocks are upper mantle parts of a dismembered ophiolite succession. Tectonism during the latest Triassic or earliest Jurassic emplaced alpine-type peridotites, which were further dissected and displaced by strike-slip faulting during the late Cretaceous or early Tertiary.

Fault bounded alpine-type peridotites from southern to central B.C. consist predominantly of harzburgite with lesser amounts of dunite and minor orthopyroxenite. These units all contain a penetrative foliation of mantle origin defined by elongate orthopyroxene porphyroclasts and elongate patches of finely recrystallized olivine neoblasts. Mylonitic textures and en echelon breccia zones also reflect mantle origins.

Chromite, chromitite and Cr-spinel occur in harzburgite and dunite in alpine-type complexes with chromitite also forming a dyke-like intrusion in metacarbonate rocks of the Anarchist Series in southern B.C.. Chromite forms a disseminated accessory phase throughout harzburgite and dunite and accumulations of chromitite are sparsely distributed. Chromitite forms podiform and layered structures which are deformed by mantle shearing. Chromitite has various textures which include massive, highly disseminated, and nodular. In chromitite from harzburgite a thin dunitic selvage may be present. Many occurrences, however, are in contact with harzburgite. Cr-spinel is most common from dunite layers and is usually associated with a chlorite-serpentine alteration rim. In dunite layers Cr-spinel form centrally-concordant, narrow and highly-disseminated

seams, rarely with some chromite. Cr-spinel with alteration rims changes outwards from Cr-spinel to Cr-magnetite, ferritchromit and magnetite.

Chromite from podiform and layered chromitite occurrences carries fluid and solid inclusions unaltered by serpentinization. Fluids form pseudo-secondary inclusion trains, patches and swarms with isolated primary fluid inclusions rarely observed. Solid inclusions are mostly olivine with minor chlorite and pargasitic-amphibole. Platinum group minerals (laurite) occur in layered and podiform chromitite.

Field relationships and chromite compositions suggest a magma or partial melt related origin for the "Normal" chromite of layered and podiform chromitites. High Al^{+3} Cr-spinel which is confined to occurrences as thin seams in dunite layers is attributed to a solution related origin.

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CHAPTER 1: INTRODUCTION

Introduction:

Ultramafic rocks which contain chromite and Cr-spinel of this study are "Alpine-type" bodies. This term is used in compliance with the description given by Irvine & Findlay (1972) for alpine-type peridotites. In B.C., alpine-type peridotites are the mantle component of a dismembered ophiolite. Field geology describes features of B.C. alpine-type peridotites and these are discussed in terms of existing genetic interpretations where compatible. Consequently some subjective terminology is used.

The purpose of this thesis is to examine in detail, the occurrences, distribution and variability of chromite in B.C. alpine-type complexes. A detailed examination of chromite in Cache Creek Group hosted alpine-type peridotites from southern to central B.C. is lacking and this thesis attempts to describe and compare chromite in this area.

From detailed mapping and chromite analyses it is possible to correlate the type of alpine-type ultramafic with the type of chromite to be expected. Essentially two types of alpine-peridotite occur, one is almost completely harzburgite with chromitite layers and pods, some of which may have thin dunitic rims. The second is also primarily harzburgite but with extensive dunite layering and dunite pods. In these massifs chromite is sparse but Cr-spinel commonly occurs in dunite layers. Harzburgite massifs contain almost exclusively high Cr-chromite whereas harzburgite - dunite massifs have high Al-chromite or Cr-spinel.

Two further features of economic interest related to chromite and Cr-spinel are the occurrences of Platinum Group Minerals (PGM) and Ni-Fe minerals. PGMs are described from podiform chromitite where they occur as inclusion phases in chromitite in harzburgite massifs. In harzburgite - dunite massifs, Ni-Fe sulphides and Ni-Fe alloy occur in association with

Cr-spinel in dunite layers. These associations, although described in other ultramafic rocks, have not previously been described from B.C. alpine-type peridotites.

A feature which is also newly described in this thesis is the relationship of Cr-spinel and Ni-Fe minerals in centrally located seams in dunite layers, best developed at Mt. Sydney-Williams. Development or later refinement of dunitic layers to monomineralic dunite layers by aqueous solution desilicification has resulted in monomineralic dunite layers. In conjunction with aqueous solution flow is the precipitation of Cr-spinel seams in the central zones of dunite layers. Two generations of Cr-spinel seams, one deformed and one planar, reflect spinel precipitation before and after ductile deformation. The association of low S Ni-Fe sulphides (heazlewoodite and pentlandite) and Ni-Fe alloy (awaruite) with Cr-spinel seams indicate final solution flow occurred along these seams as low temperature serpentinization proceeded. Cr-spinel seams, because of their heavily disseminated texture, acted as final zones of fluid flow and became nucleation zones for Ni-Fe sulphides and alloys.

For economic considerations, two generalizations can be made. First, high Cr-chromite can be expected from predominantly harzburgite massifs in southern to central B.C. in the form of chromitite masses which may also include PGMs. Secondly, in harzburgite - dunite massifs dunite layers will likely host Cr-spinel seams with associated Ni rich mineralization.

Eight areas were mapped in detail from southern to central British Columbia (Fig. 1-1) during the field seasons of 1980 (Whittaker & Watkinson, 1981), 1981 (Whittaker, 1982) and 1982 (Whittaker & Watkinson, 1983). In southern B.C. alpine-type peridotites of the Bridon, Nicola

and Scottie Creek deposits were examined. In addition, the Anarchist deposit, in meta-carbonate rocks of the Anarchist Series was also mapped. Most time and mapping was concentrated in central B.C. at Murray Ridge, Pinchi Mt. and primarily at the Mitchell Range and Mt. Sydney-Williams. Chromite and Cr-spinel occurrences were most numerous in the latter two areas and so provided most of the data for this thesis. Analytical work was done primarily by electron microprobe (Cambridge MKV; Carleton University; JEOL; Memorial University; CAMEBAX; BRGM-CNRS, Orléans, France). Major and minor element analyses was provided by the Ministry of Energy, Mines and Petroleum Resources of British Columbia. In addition fire assay neutron activation analyses of platinum group mineral bearing chromitites were done by X-ray Assay Laboratories, Don Mills, Ontario.

Access to all areas except Pinchi Mt., Mt. Sydney-Williams and the Mitchell Range is by road and to the three mentioned exceptions, by helicopter. Previous work has predominantly been done by geologists of the Geological Survey of Canada. In central B.C. alpine-type peridotites were included by Armstrong (1949) in his regional map and accompanying report. In Armstrong's (1949) memoir, ultramafic massifs are grouped as the "Trembleur intrusion" in the Stuart Lake Belt. Paterson (1973) worked on the geology of the Pinchi Lake area and later published a paper (Paterson, 1977) on the evolution of the Pinchi Fault Zone at Pinchi Lake. This work established a Permo-Triassic date for subduction-related faulting of 211 - 218 Ma from blueschist-facies fragments at Pinchi Lake. Petrographic studies by Ross (1977) at Murray Ridge, near Pinchi Mt., suggests two mantle deformation fabrics and a third related to obduction. In southern B.C. the smaller and more scattered ultramafic bodies were

Fig.1-1. Location of chromite occurrences examined
in British Columbia

mapped by Cockfield (1935), Skerl (1957), James (1958) and von Rosen (1977) for government surveys and companies. An early description of Cordilleran geology along the forty-ninth parallel which includes the Osoyoos - Anarchist area was given by Daly (1912).

The Cache Creek Group:

Apart from the Anarchist deposit all chromite, chromitite and Cr-spinel occurrences are in alpine-type peridotites within the Cache Creek Group. The Cache Creek Group occupies the easternmost part of the Intermontane Belt throughout B.C. (Monger et al., 1978; Monger & Price, 1979) and extends into southwestern Yukon (Templeman-Kluit, 1979). Areas occupied by Cache Creek Group rocks are also termed "Hinterland Belt" by Monger et al. (Fig. 1-2; 1978) and are characterized by fold and fault structures reflecting westward transport.

The Cache Creek Group was divided into lower, middle and upper sections by Armstrong (1949). Conodont dating studies show that the Cache Creek Group extends to Upper Triassic time (Monger & Price, 1979). Most of the Cache Creek Group is a marine sedimentary succession recording deep water conditions with massive limestones which have scattered chert nodules. Marginal basin sediments are in the upper middle and upper sections of the Cache Creek Group and include interbedded carbonates, shales and island-arc-type volcanics (Monger & Price, 1979). The Cache Creek Group is thought to consist of numerous transported oceanic crustal blocks not assembled until Mesozoic time (Monger & Price, 1979). Within the carbonate assemblage are contrasting fusulinid and ammonoid faunas. Cold water (Boreal) fauna, dominantly brachiopods and bryozoans, with some fusulinids are adjacent to warmer water faunas. Warm water faunas consist of diverse verbeekiniid fusulinids of tropical origin which are similar to coeval faunas in Japan, south China

Fig.1-2. The Stuart Lake Belt and Pinchi Fault
Zone of the Cache Creek Group, and its
position in the Hinterland Belt (after
Monger et al., 1978)

and Permian Tethys (Monger & Price, 1979). Juxtaposition of warm and cold water faunas is related to northwest movement of Permian oceanic crustal blocks along a northwest trending transform fault system in Late Triassic and Early Jurassic time (Paterson, 1977).

Emplacement of alpine-type peridotites:

Paterson (1977) offered a tectonic model (Fig. 1-3) which incorporates emplacement of alpine-type peridotites for central B.C. In the Prince George area a northerly dipping subduction zone is intersected by a northwest trending transform fault with right lateral movement. At this intersection ultramafic mantle material and blueschists were obducted at 211 and 218 Ma (K - Ar; Paterson & Harakal, 1974). Paterson (1977) also related the elongate form and proximal position of the Hogem Batholith to the Pinchi Fault to melting of the downgoing subducted crust to the south. The Hogem Batholith is dated at 189 ± 6 Ma (K - Ar) by Garnett (1974) while Stock (1974) gives an age of 203 Ma for a southern part of the Batholith. If active subduction continued to 218 Ma, partial melting could have produced liquids of appropriate age for the Hogem Batholith. The transform (Pinchi) fault would then be a suitable zone of weakness for intrusion giving rise to the elongate form of the Batholith (Paterson, 1977). A minimum limit on the age of the alpine ultramafics can be placed at earliest Cretaceous time since Cretaceous conglomerates adjacent to Murray Ridge ultramafic rocks at Pinchi Lake contain serpentized peridotite clasts and detrital chromite (Paterson, 1977).

Northward movement of obducted ultramafic and blueschist-facies rocks along the Pinchi Fault Zone from the Prince George area accounts for alpine-type ultramafics in the Pinchi Lake area and for Mt. Sydney-Williams and the Mitchell Range to the north. Further separation of rocks

Fig.1-3. Tectonic setting of the Prince George to
Stuart Lake area with distribution of
major Alpine-type peridotites (after
Paterson, 1977)

from Mt. Sydney-Williams and the Mitchell Range would have developed by displacement along splay faults associated with the Pinchi Fault Zone and by later strike-slip movement during final faulting in Late Cretaceous or Early Jurassic time (Monger & Price, 1978). As an example, Fig. 1-4 illustrates the relationship of the Mitchell Range to the Pinchi Fault Zone based on field data and from Monger et al. (1978) for the area east of the blueschist-facies rocks.

During Triassic time the western continental margin of North America was characterized by subduction and by right lateral transform fault movement parallel to the continental edge. This thesis is concerned with chromite occurrences associated with alpine-type massifs formed from obduction of mantle peridotites at intersecting subduction - transform fault systems.

Fig.1-4. Cross section of the Cache Creek Group to
Takla Group through the Mitchell Range,
blueschist zone and eastwards (after
Monger et al., 1978)

Cross Section

Cache Creek Group to Takla Group

CHAPTER 2: CHROMITE IN SMALL SCALE ALPINE-TYPE
PERIDOTITES FROM SOUTHERN TO CENTRAL
B.C.

Introduction:

Alpine-type peridotite of the Cache Creek Group occurs from southern to central B.C. and hosts the Nicola and Scottie Creek chromite deposits. Near Osoyoos the Anarchist and Bridon chromite deposits occur in Anarchist Series rocks of equivalent age to the Cache Creek Group. These alpine-type bodies range from several hundred metres to several kilometres in length. One of the larger peridotite massifs, Murray Ridge, lacks chromite deposits and has only disseminated chromite. It is included to give examples of alpine-type peridotite features not found in smaller ultramafic bodies.

This chapter deals with field relationships of the smaller alpine-type peridotites and their chromite occurrences. The atypical Anarchist chromite deposit with its limestone host rocks is described first, followed by the Bridon, Nicola and Scottie Creek deposits and lastly, Murray Ridge.

Anarchist Chromite Deposit:

The Anarchist deposit is located 3.2 km west of Bridesville, British Columbia, and is 0.4 km north of highway 3 (Fig. 2-1). Chromite occurs in rocks of the Anarchist Series (Daly, 1912; James, 1958) which locally consist of metasedimentary and metavolcanic rocks with vertical to westerly overturned dips. Lithologies adjacent to the chromite occurrence include limestone, silty limestone, and calcareous siltstone. Two lenses of amphibolitized siltstone 1 to 2 m long and up to 20 cm thick, occur in the limestone (Fig. 2-1; unit 4). Carbonate rocks weather pale grey to bone white and amphibolite weathers black.

Chromite:

Chromite occurs as aphanitic to very fine-grained chromitite forming a dyke intruding the carbonate rocks (Fig. 2-2a). Veins of chromite range in thickness from 1 m along the main chromite zone, to 1 mm in irregular anastomosing fractures. The anastomosing fractures occur in the same silty limestone unit as the main chromite dyke, but are 31 m removed. Adjacent to the main chromite dyke the silty limestone is brecciated and angular to subrounded, 1 to 3 cm sized, fragments are included within the dyke (Fig. 2-2b). In the central zone of the dyke inclusions are absent and it is cut by 1 to 4 mm thick calcite veins. Larger fragments of silty limestone, 20 to 30 cm in size, have been completely or partially stopped from the dyke walls (Fig. 2-2c). These fragments remain within 2 to 5 cm of their original positions and yet are not highly angular. Lobate embayments (indicated by arrows, Fig. 2-2c) into carbonate fragments suggest that small (2 to 30 cm) scale cusate fracturing of the limestone occurred during dyke emplacement. Remobilized carbonate could then form the numerous calcite veins observed cutting

Fig.2-1. Geology of the Anarchist chromite deposit
near Osoyoos.

Fig.2-2a, Lobate contact between massive chromitite dyke and metacarbonate rocks of the Anarchist Series; 2b, Autobrecciated fragments of limestone in chromitite; 2c, Cuspate fracturing (arrows) in carbonate wallrock and in a stoped off fragment.

the chromite dyke and country rocks (Fig. 2-2c). Stopping and inclusion of limestone fragments probably took place during intrusion. A late brittle deformational event led to intense brecciation of the chromite dyke and to autobrecciation of included limestone fragments. In Fig. 2-2c (above arrow) the main carbonate fragment exhibits a serrated fracture which has opened only 3 mm.

The Anarchist Chromite deposit lacks the usual association with ultramafic host rocks, instead, chromite forms a body which was apparently injected into limestone. The nearest area of ultramafic rocks is the Bridon Deposit, 30 km to the northeast (Cockfield, 1935).

Bridon Chromite Deposit:

The Bridon Chromite Deposit is located 10 km north of Bridesville, B.C., on highway 3. Serpentinized ultramafic rocks which host the chromite deposit are adjacent to metasedimentary rocks of the Anarchist Series (Cockfield, 1935) and crystalline rocks of the Shuswap Complex (Fig. 2-3). Anarchist Series rocks are metaquartzites with finely interbedded metasilstone laminae. These metasedimentary rocks strike northwest with a vertical dip and are strongly foliated parallel to bedding. Rocks of the Shuswap Complex in contact to the west are porphyritic granodiorite with 3 to 15 mm euhedral tabular plagioclase phenocrysts. Plagioclase phenocrysts form about 25 percent of the rock, weather chalky white, and are set in a fine-grained dioritic matrix. Amphibole is the mafic constituent.

The ultramafic body forms a northwest-trending ridge which was mapped in general by Cockfield (1935) and was later described by James (1958). Detailed mapping (Fig. 2-4, in map pocket) shows the northwest trending ultramafic body to be cut and offset by north-trending faults. A porphyritic

Fig.2-3. General geology surrounding the Bridon Claim Group and location of detailed geological map, Fig.2-4.

Fig.2-4. Detailed geology and sample locations of the Bridon Chromite Deposit, in map pocket.

15' 10' 119° 05'

LEGEND

1 Anarchist Series

2 Serpentinite

3 Oliver Granite

4 Granelorite

SCALE

gabbro dyke, possibly related to granodiorite of the Shuswap Complex, trends northwards across the southwest part of the ultramafic body. The dyke is 2 m wide, medium-grained, and is in sharp contact with the serpentinite (Fig. 2.4). Dunite underlies the ridge and is very fine-grained weathering brown with greenish-black fresh surfaces. A northwest-trending shear foliation penetrates the ultramafic outcrop and has a steep southerly dip in the southeastern block, a steep northeasterly dip in the central block, and a steep southwesterly dip in the northwestern block.

Chromite forms 3 to 4 percent of the harzburgite and is fine to medium-grained with sub^{hedral} to euhedral habit. Cumulate chromite in some instances forms intermittent chain-like layers 2 to 3 mm thick which can be traced for 10 to 20 cm (Fig. 2-5a). Thicker layers of fine- to medium-grained chromite constitute wispy chromite layers from 0.5 to 4 cm thick, usually with 20 percent disseminated chromite. Wispy chromite layers are usually proximal to thicker chromitite layers.

Chromitite layers constitute the most extensive form of chromite mineralization (Fig. 2-5b, c) and vary from fine- to medium-grained heavily disseminated chromitite. In all areas examined, the south side of the chromitite layers was medium-grained and graded to fine-grained on the north side of east-west trending chromitite layers. Grain-size sorting such as this would indicate a possible origin by gravitational settling for these chromitite layers with tops to the north. The chromitite layers pinch and swell from 10 cm to 8 cm and bifurcate along strike. Folding of chromitite layers has led to thinning along fold limbs and thickening in hinges (Fig. 2-5c). Folds are broad and open in thicker chromitite layers and become tighter in thinner layers. The regional foliation is reflected by chromitite layers and their

boudins which parallel the foliation elsewhere in the dunite.

Apart from the main chromitite layers, discontinuous chromitite boudins also occur (Fig. 2-5b). These range from 10 cm to 2 m in length and consist of fine to medium-grained subhedral to euhedral chromite. Chromitite boudins may be related to primary chromitite layers deformed by shearing.

Serpentinization has resulted in penetrative alteration of the dunite to lizardite and talc with cross-cutting aphanitic serpentine veins 2 mm to 3 cm in width. Talc is developed throughout the ultramafic body and forms 0.5 cm thick whitish-green layers. Isolated irregularly shaped patches up to 3 cm by 15 cm of white talc are randomly distributed throughout the ultramafic outcrop area.

Fig.2-5a. Disseminated " Wispy " chromite layers
in harzburgite; 5b, Massive deformed -
boudinaged chromitite layers in harzburgite;
5c, Openly folded chromitite layer with
hinge zone thickening and thinning of limbs.

Table 2-1. Fire assays of channel samples from the Bridon claim group, from Skerl, 1957.

Layer	Cr	Cr ₂ O ₃ %	Fe %	Cr/Fe ratio
A	21.4	31.16	11.2	1.90
B	20.8	30.67	10.50	1.98
C	18.0	26.30	10.80	1.66
D	18.3	26.93	10.60	1.74
E	--	--	--	--
F	20.6	30.08	11.20	1.84
G	19.8	29.00	11.20	1.77
Mean composition	19.8	29.00	11.00	1.80
Composite sample	19.6	28.73	10.07	1.84
Concentrate of composite sample	28.0	41.20	15.10	1.88

Nicola (Cameo L.) Chromite Deposit:

The Nicola Chromite Deposit is located 30 km northwest of Kelowna, B.C. Chromite bearing ultramafic rocks are at the contact of silty metasedimentary rocks of the Chapperon Group which are overlain by Cache Creek Group Limestones. Both the ultramafic body and the two groups of metasedimentary rocks trend northwest and dip steeply to the east. Quartz diorite of the Coast Range Batholith outcrops half a kilometre west of the ultramafic body forming the western intrusive contact with the Chapperon Group. (Fig. 2-6; Fig. 2-7, sample location map, in map pocket).

Chapperon Group metasedimentary rocks consist of interbedded siltstone and argillite. Both siltstone and argillite beds range from 0.5 to 3.0 cm and contain 2 to 3 percent fine-grained disseminated pyrite. Weathered outcrops exhibit well developed orange-brown iron staining.

Calcareous rocks of the Cache Creek Group are pale grey silty limestone, calcareous siltstone and brecciated limestone. The carbonate succession has been re-crystallized to medium-grained equigranular texture.

Harzburgite:

The ultramafic body is a fault bounded sliver of harzburgite with an intense shear foliation developed at its contacts. The fault slice is conformable with the Chapperon and Cache Creek Groups by which it is flanked. Harzburgite forms 99 percent of the exposed outcrop with a 3 m long lens of orthopyroxenite (Fig. 2-8) occurring at the Cameo L. showing. The orthopyroxenite lens is in sharp contact with the harzburgite and is very coarse-grained. Smaller orthopyroxenite lenses of 0.5 m size occur irregularly along strike to the northwest for 15 m.

Fig.2-6. Detailed geology of the chromitiferous
ultramafic rocks of the Nicola Deposit.

Fig.2-7. Sample location map, Nicola Deposit, in
map pocket.

Fig.2-8a, Contact between lense of orthopyroxenite
in harzburgite near Cameo Lake; 8b,
Chromitite layering, disseminated chromite
layers and chromitite nodule from a deformed
layer. Both a and b at Nicola deposit.

Chromite:

Chromite occurs as cumulate grains forming fine- to medium-grained aggregate chromitite layers and nodules. Fine-grained disseminated chromite is an accessory phase throughout the body. (Fig. 2-8). It is more abundant in the western part of the body (3 to 5 percent) and decreases to less than 1 percent in the eastern part of the body. Chromite grain size also decreases from west to east, from medium-grained (1.5 mm) to fine-grained (0.5 mm). This may suggest pre-obduction intrusion of a semi-solid slab while still in an ocean floor position.

Wispy chromite layers occur in the western part of the body and consist of fine to medium-grained disseminated chromite (Fig. 2-9). The layers are up to 0.5 cm thick and are of irregular lengths up to 10 cm. and are defined by concentrations of 30 to 40% chromite. Intermixed with wispy chromite layers are irregularly shaped chromitite layers and pods. Chromitite layers are formed of medium-grained sub to euhedral chromite and range from 10 cm to 1.5 m in length and 2 to 8 cm in thickness. These layers are discontinuous and are gently folded and reflect the northwesterly strike and steep easterly dip of the area. Chromitite pods are similarly formed of medium-grained sub to euhedral chromite. Pods are roughly lenticular to ovoid in shape, 10 to 15 cm long and 3 to 5 cm wide.

The Alócin chromite showing (Fig. 2-6) 1.8 km to the north northwest exhibits similar forms of chromite mineralization concentrated to the western side. This pattern of stratigraphic zoning of chromite may also suggest a sufficient degree of partial melting to permit some gravity sorting.

Fig. 2-9 . East - west section based on outcrop thicknesses at Cameo L., B.C. Chromite rich zone occurs at west side of ultramafic sequence.

Table 2.2. Cr assays from the Alocin and Cameo L. showings (after von Rosen, 1977).

Assay	Location	Chromite texture	FeO (total)	Cr ₂ O ₃
1	Alocin	massive	26.37	38.54
2	"	nodular	24.18	35.13
3	"	asbestos?	23.18	34.14
4	"	1 m E. of contact	2.23	3.26
5	"	1 m in crt zone	29.36	42.91
6	"	1 m W. of contact	0.53	0.77
7	"	lens	16.15	23.60
8	"	lens	17.52	25.60
9	"	lens	21.07	30.80
10	Cameo	disseminated	0.80	1.17
11	Cameo	massive vein	27.04	39.52
12	"	disseminated	0.85	1.24

Assays 4 to 6 are from lightly disseminated 1 to 2 cm layers in a 5 m wide layered zone with approximately 20 percent layers. Assays 7 to 9 are heavily disseminated but scattered lenses of chromite, 20 to 50 cm in length.

Scottie Creek Deposit:

Scattered small bodies of serpentized dunite and peridotite occur east of Highway 97, 16 km north of Cache Creek, British Columbia.

The Scottie Creek chromite deposit occurs in sheared, serpentized dunitic harzburgite with minor harzburgite lenses, 5 to 10 m in size and irregularly shaped. The harzburgite lenses contain 15-20% opx which is medium-grained and subhedral. A 3 to 4 m cap of Tertiary flow banded vesicular rhyodacite overlies the serpentinite outcrop. (Fig. 2-10).

Dunitic harzburgite:

Dunitic harzburgite is fine to medium-grained and equigranular with a pale greenish-brown weathered surface and a dark green fresh surface. Olivine grains remain distinguishable as granular anhedral which crumble from the friable weathered surface whereas orthopyroxene is more resistant.

Shearing is penetrative with a curved fracture pattern. Later jointing is subplanar crosscutting the irregular foliation and multiple quartz-carbonate veins up to 2 cm wide. Intense deformation and later carbonate alteration has resulted in a pock-marked weathered surface over entire outcrop areas. Small cave-like depressions in both vertical and sub-horizontal outcrops range from 4 cm to 1 m in depth and diameter.

Dunitic harzburgite in the northeast corner of the outcrop area has been brecciated in an east-west trending zone up to 3 m wide. Opalescent quartz veins form the breccia matrix which holds 2 to 10 cm subangular dunitic harzburgite fragments.

Chromite:

Chromite is concentrated in the southwesterly part of the ultramafic outcrop area. In the northern part of the area chromite occurs only in trace amounts and is mostly fine-grained and sub^{hedra} to euhedral. At the main chromite showing two adits have been driven, one about 15 m in length and the second about 3 m in length. Chromite at the adits occurs in disseminated and layered forms. Disseminated chromite forms 5 to 8 percent dunitic harzburgite and the chromite is medium-grained and subhedral. In some cases disseminated chromite forms nodules which have been deformed into irregular lensoid to slightly sigmoidal shapes. Several nodules may occur in line defining a crude layering. Nodules are generally 0.5 to 2 cm in size. Wispy chromite layers are most common and range from 1 to 2 cm thick and 10 to 20 cm long. These are usually defined by 25 to 35 percent subhedral chromite with sharp borders against enclosing dunitic harzburgite. Zones of parallel wispy chromite layers define a disrupted primary layering.

The main chromite layer is defined by a 1 m thick zone with 50 to 60 percent medium-grained sub hedral to euhedral chromite. The main layer thins to 15 cm and is terminated by a shear zone. The overall exposed length of the main chromite zone is 2 m. Wispy chromite layers occur adjacent and perpendicular to it. This juxtaposition exemplifies the deformed nature of this ultramafic block.

Scattered distribution and variable orientation of chromitite and wispy chromite layers in the Scottie Creek Deposit suggest discontinuous and structurally disrupted chromite mineralization.

Fig.2-10. Geology and sample locations, Scottie
Creek Deposit.

Chromite at Murray Ridge:

Murray Ridge is 10 km northeast of Fort St. James in central British Columbia (Fig. 2-11, 12; in map pocket). A road suitable for four-wheel-drive vehicles branches from the Fort St. James to Germansen Landing road 15 km east of Fort St. James and provides access to the southeast end of Murray Ridge.

Murray Ridge was included in a reconnaissance map sheet by Armstrong (1949) and was studied in greater detail by Paterson (1973, 1977). The ultramafic rocks were the subject of a structural study by Ross (1977) who concluded that internal structures showed two mantle-transport fabrics and a third fabric related to high-level emplacement.

The predominant structural feature in the Murray Ridge area is the Pinchi Fault Zone which trends northwest and separates Late Paleozoic Cache Creek Group rocks to the west from Early Mesozoic Takla Group rocks to the east. The Pinchi Fault Zone may represent a southward extension of the Teslin Suture described by Templeman-Kluit, (1979).

Ultramafic Rocks:

Murray Ridge consists of a fault-bounded alpine-type peridotite body with dunite occupying 2 percent of the outcrop area. The ultramafic body is considered to have been emplaced into the Cache Creek Group (Armstrong, 1949; Paterson, 1977), which includes biomicritic limestone, minor chert, thin siltstone beds, and volcanic rocks, prior to deposition of Upper Triassic Takla Group sediments. The Murray Ridge peridotite plus ultramafic rocks on the north flank of Mount Pope 6 km to the west, and those which underlie Pinchi Mountain 20 km to the northeast, belong to the southernmost extension of the Trembleur Intrusions (Armstrong, 1949).

Harzburgite:

Murray Ridge (Fig. 2-11) is underlain by massive coarse-grained harzburgite which forms 97 percent of the exposed outcrop. Weathered surfaces are buff-brown with a coarse hackly appearance caused by resistant, medium to coarse-grained pale-weathering orthopyroxene phenocrysts; fresh surfaces are dark brownish green. Subhedral to anhedral orthopyroxene, up to 1.5 cm in size forms 15 to 20 percent of the harzburgite.

Penetrative serpentinization has left 25 to 30 percent of the primary olivine and orthopyroxene unaltered. A second, later stage of serpentinization is restricted to randomly oriented polygonal joints which are developed at 1 to 3 cm spacings in harzburgite (Fig. 2-14). The apparently random polygonal joint pattern would suggest development under dilational pressure conditions related to tensional strain (Laurent, 1980). Increased permeability in the preserpentinized rock would allow extensive aqueous solution penetration along these joints resulting in complete serpentinization. In this way Murray Ridge peridotites reflect 2 stages of serpentinization. The first penetrative stage may have developed in an oceanic upper-mantle environment and the second, polygonal stage, developed during initial obduction or detachment from a ridge-mantle environment. This has been suggested for similar stages of serpentinization at Thetford Mines, Quebec (Laurent, 1980).

Dunite:

Harzburgite on the southwest flank of Murray Ridge contains layered dunite zones which trend subparallel to the strike of the ridge. Layered dunite zones are approximately 200 m thick (Fig. 2-13) and dip steeply to the north. Individual dunite layers range in thickness from 10 cm to

Fig.2-11. Geology of Murray Ridge, in map pocket.

Fig.2-12. Murray Ridge sample location map, in map pocket.

Fig.2-13. Vertical section through the main dunite zone, Murray Ridge.

1.5 m and may be traced along strike for up to 30 m. Zones are offset and slightly rotated by minor faults which crosscut Murray Ridge at an acute angle. Dunite weathers pale buff-brown and has a smooth surface relative to harzburgite. On a fresh surface it is black-green with a pale brown weathering rind 1 to 1.5 cm thick.

Dunite layers are massive and contain approximately 5 percent disseminated chromite (Fig. 2-14b). Chains of chromite grains are aligned subparallel and parallel to dunite-harzburgite contacts. These contacts are sharp and exhibit sedimentary type flame structures (Fig. 2-14b). Narrow 4 to 8 cm wide mylonite zones intersect dunite layers and result in chip-textured weathered grooves. In Fig. 2-14b a fragment of dunite is isolated where a mylonite zone bifurcates around it.

Orthopyroxenite:

A third and volumetrically minor unit is orthopyroxenite which has two distinct generations. The early generation of orthopyroxenite forms layers in harzburgite which range in thickness from 3 cm to 10 cm, are very coarse-grained, and occur singly or in zones of several layers. Layers are folded and exhibit open to isoclinal structure possibly reflecting early internal deformation related to a period of mantle transport as described by Ross (1977). Later generations of orthopyroxenite layers are undeformed, planar, and cut both early orthopyroxenite layers and enclosing harzburgite (Fig. 2-14c). The later layers range in thickness from 3 cm to 1 m and occur individually or in groups.

Contacts between orthopyroxenite and harzburgite are sharp with sparsely distributed slab-shaped xenoliths of harzburgite, up to 0.5 m, in orthopyroxenite veins. Closely spaced jointing is developed in orthopyroxenite layers and is perpendicular to the contacts. Individual

orthopyroxene crystals have crystallized with their c-axes parallel to the joint direction and grain boundaries and cleavage directions would be responsible for the joints. This defines a comb texture (Spry, 1969) developed by crystal growth beginning at the contact and progressing inwards. This texture suggests a linear opening in the harzburgite filled by slow moving or static liquid which also precipitated up to 2 percent very fine-grained disseminated chromite. A tensional or dilational environment produced suitable fractures for orthopyroxenite vein intrusion.

Two generations of orthopyroxenite layers represent first; an early dilational stage which during later compression ^{and} mantle transport, was deformed. This was followed by a second tensional period which produced planar crosscutting orthopyroxenite veins.

Fig.2-14a, Two stages of serpentinization shown by polygonal serpentine filled expansion fractures in previously serpentinized harzburgite; 14b, Part of a dunite layer in harzburgite with disseminated chromite and cut by a narrow mylonitic shear zone; 14c, Coarse-grained orthopyroxenite vein cutting harzburgite.

CHAPTER 3: CHROMITE IN ALPINE-TYPE PERIDOTITE
OF THE MITCHELL RANGE

Mitchell Range introduction:

The Mitchell Range, 240 km northwest of Prince George, British Columbia, is within the Stuart Lake Belt of the Permian Cache Creek Group (Fig. 3-1; Fig. 3-2 in map pocket; Armstrong, 1949; Monger et al., 1978; Monger & Price, 1979). Its southernmost range consists of an alpine-type peridotite massif consisting predominantly of serpentized harzburgite and associated chromitite occurrences (Fig. 3-3; Armstrong, 1949).

Harzburgite forms about 80 percent of the massif (Table 3-1) with lesser amounts of dunite and chromitite. Gabbro dykes and rodingitic dykes also occur as part of the mantle succession, all of which has a strongly developed tectonite foliation. Incorporated in the ultramafic succession are norite dykes which are thought to have intruded at a spreading ridge - transform fault intersection prior to obduction of the ultramafic massif. Fault-block xenoliths of Cache Creek Group marine metasediments are included within the ultramafic massif. These are primarily recrystallized cherty limestones and black pyritic shales which could represent the sedimentary part of a less deformed, more complete ophiolite.

Fig.3-1. Detailed geology of the Mitchell Range,
in map pocket.

Fig.3-2. Sample location map of the Mitchell
Range, in map pocket.

Fig.3-3. General geology of the Mitchell Range
showing locations of chromitite occurrences,
marked as " X " with numbers corresponding
to those in Table 3-2 and Fig.3-16.

LITHOLOGIES	ESTIMATED AREAL PERCENTAGE OF ULTRA- MAFIC & MAFIC ROCKS	PERCENT TOTAL AREA
Harzburgite	94.5	80.2
Dunite and dunite pods	3.0	2.6
Gabbro	1.0	0.9
Norite	1.0	0.9
Rodingite dykes	0.5	0.4
Total (of ultramafic & mafic rocks)	100.0	
Metasedimentary Xenoliths		
Laminated chert-siltstone		8.0
Limestone		5.0
Slate		2.0
Total		100.0

Table 3-1. Estimated areal extent of lithologies in the
Mitchell Range Allochthon.

Harzburgite:

Tectonitized harzburgite in the Mitchell Range consists predominantly of medium- to coarse-grained olivine (60 percent) and orthopyroxene (38 percent). Fine-grained chromite is an accessory phase (2 percent) and is evenly distributed. Weathered surfaces are dark brown to greyish brown and fresh surfaces are blackish-green, both are vaguely mottled by colour and differential weathering.

Primary textures and structures are rarely preserved within tectonitized harzburgite except where untectonized blocks are incorporated. Untectonized blocks, up to 60 m in size, retain primary massive structure and medium- to coarse-grained equigranular texture observed elsewhere in peridotites. Untectonized harzburgite occurs in the central part of the massif as a block 200 to 300 m in extent, and again as smaller, 50 to 60 m elongate zones in northeast ridge. In northeast ridge primary texture is defined by coarse-grained equigranular harzburgite (Fig. 3-4a). It exhibits very hackly weathered surfaces formed by resistant orthopyroxenes adjacent to deeply weathered olivine. Also in northeast ridge are areas with very coarse-grained poikiloclastic textures which grade from massive to foliated (Fig. 3-4b). Poikiloclastic texture is defined by poikiloclasts of anhedral orthopyroxene enclosing 2 to 10 mm subhedral olivine grains. Poikiloclastic textures are ascribed to cumulate processes in zones of advanced partial melting where poikilitic textures have undergone ductile shear. Zones of primary cumulate poikiloclastic harzburgite are massive at their centres and become poikiloclastic over widths of 20 to 30 cm.

Fig.3-4a, Primary coarse-grained untectonized harzburgite, dark grains are olivine in finer-grained talcose matrix after orthopyroxene;
4b, Foliated very coarse-grained harzburgite with talcose orthopyroxene (pale grey) porphyroclasts poikilitically enclosing finer-grained olivine (dark grey).

Apart from scattered areas with primary magmatic features, the tectonitized harzburgite is moderately to intensely foliated. Moderately foliated tectonite harzburgite exhibits stretched and flattened orthopyroxene porphyroclasts which define the foliation and are usually altered to pale tan weathering talc. Extensive foliation has been achieved by ductile shear deformation from reduction in orthopyroxene and olivine grain size (Raleigh, 1968, Nicolas et al., 1980). Much of the tectonite harzburgite is thus mylonitic in texture. Fine to medium-grained tectonite harzburgite in places exhibits a ribbonary foliation. This is formed by orthopyroxene rich layers, 0.5 to 2 cm thick, intertwined with olivine rich layers of similar thickness. During ductile shear (mylonitization) brittle orthopyroxene is mechanically separated from olivine which deforms in a ductile manner by slip and glide dislocations (Raleigh, 1968). Bands intertwine over lengths of 0.5 to 1 m and differential weathering leaves orthopyroxene ridges with up to 1.5 cm of relief over olivine rich runnels resulting in a braided rippled surface. Extreme examples of mylonitic mechanical sorting occurs in some areas where strongly foliated zones, predominantly of olivine, contain sparse porphyroclasts, up to 7 cm, of orthopyroxene. These porphyroclasts show brittle fracturing and are associated with orthopyroxene fragment trains. In some outcrop areas fracturing along foliation planes has produced closely spaced rock cleavage which is accentuated by frost wedging.

Dunite:

Dunite is sparsely distributed throughout the tectonite harzburgite and exhibits a finer, more closely spaced (0.5 mm) foliation than that in harzburgite. Dunite is fine- to medium-grained, equigranular and contains as much as 3 percent accessory chromite. Dunite may also have up to 10 percent medium-grained orthopyroxene. Dunite weathers a waxy orange-brown with rounded exfoliation and smooth surfaces. Contacts with tectonite harzburgite are sharp and may exhibit flame-like structures where dunite has penetrated harzburgite (Fig. 3-5a). Similarly sharp contacts and flame-like structures occur in the Murray Ridge peridotite (Whittaker & Watkinson, 1981). A single dunite body occurs as a large irregularly shaped pod 200 to 300 m in size in an area south of north cirque (Fig. 3-1). This pod consists of very fine-grained equigranular anhedral olivine. Olivine forms 90 percent of the dunite pod, accessory disseminated chromite as much as 5 percent and there is 5 percent medium-grained subhedral orthopyroxene. Chromite is fine-grained to sub hedral to euhedral.

Tabular vein-like dunite occurs at northeast ridge (Fig. 3-1) with sharp contacts against harzburgite. It is up to 30 cm wide, 15 m long and subparallel to the foliation with a northwesterly strike and dip of 52 degrees southwest. This tabular dunite body contains 98 percent very fine-grained olivine and 2 percent disseminated accessory chromite. Chromite is a fine- to medium-grained and sub to euhedral. Multiple quartz-carbonate alteration veinlets with symmetrical alteration envelopes occur both in and centre and the edge of the body (Fig. 3-5a). These veinlets are up to 1.5 cm thick, weather up to 5 mm above the dunite and are concordant to the dunite body. Multiple veinlets such

Fig.3-5a, Alteration veins in tabular dunite body
hosted by harzburgite; 5b, Orbicular
structure defined by orthopyroxene in same
dunite body.

as these suggest several stages of alteration within the dunite body.

Alteration would have occurred after formation of the dunite body since the lateral alteration vein cuts across the base of the dunite flame structure rather than precisely following the contact (Fig. 3-5a).

Orbicular texture within the dunite body is developed by a ring of dark green orthopyroxene, 0.5 to 2.0 mm thick and 2 cm in diameter (Fig. 3-5b). The orbicule encloses very fine-grained equigranular dunite, similar to that which encloses the orbicule itself. Diffusion of silica, similar to diffusion processes involved in formation of Liesegang rings (Liesegang, 1913), could result in an orthopyroxene ring enclosing a dunite core.

Gabbro dykes:

Gabbro dykes define the "Gabbro-harzburgite" area which occupies the central and southwestern parts of the ultramafic massif (Fig. 3-1, map pocket). The southwest flank of Chrome Peak and the col between Chrome Peak and south ridge are underlain by as much as 15 percent gabbro dykes. These gabbros have variable steep to shallow dips, trend to the north and constitute a roughly defined dyke swarm. Contacts with harzburgite are sharp, gabbro is serpentinized and chloritic with finely foliated texture which parallels that in harzburgite. Dykes are deformed showing pinch and swell structures and are often sheared into boudins or into en echelon segments separated by 1 to 2 m of foliated harzburgite. Further details are discussed under "Structure".

Alteration of gabbro dykes and dyke segments has proceeded to various degrees. Core areas of boudins and dykes are usually most highly altered with apple-green epidotized and bone-white to pale buff-brown rodingitized zones. In other places alteration is complete with only deformation structures preserved.

Rodingite Dykes:

In the northwest ridge and central areas of the ultramafic massif deformed rodingite dykes occur. They range in thickness from 10 cm to 1 m and consist of pinch and swell structures and boudins. Rodingites are resistant to weathering and in some cases form 1 m high ridges above surrounding harzburgite (Fig. 3-6a). On weathered surfaces rodingite dykes are bone-white to pastel shades of pink or buff-brown and may have vaguely-defined angular brecciated fragments. In all observed cases rodingite dykes had 1 to 3 cm thick black-green

chloritic late alteration selvages. These are in sharp contact with rodingite to the inside and with harzburgite to the outside (Fig. 3-6b).

Gabbro dykes may be similarly deformed and exhibit partial rodingitization. The core areas of gabbro dykes partially separated by pinch and swell structures or completely detached as boudins show from 10% to complete rodingitization. One such boudin exhibits a rodingitic core, chlorite rich gabbro shell still 20 cm thick and fractures in adjacent harzburgite filled with microcrystalline quartz-carbonate. (Fig. 3-6c).

Development of rodingite dykes is initially the result of intense Ca - Si metasomatism. This would be achieved by passage of hydrothermal solutions through gabbro dykes which acted as permeable conduits. Metasomatism in this manner would allow alteration of gabbro dykes previously deformed in the upper mantle. Ensuing serpentinization and associated Fe - Mg metasomatism would develop chloritic selvages as final solutions continued to permeate original dyke contacts. Two stages of metasomatism are recorded by rodingite dykes. Ca - Si metasomatism could occur in the upper mantle at higher temperature and Fe - Mg metasomatism could occur during obduction at lower temperature.

Texturally rodingite dykes are aphanitic with very fine saccharoidal fresh surfaces. In this section rodingite is aphanitic with turbid appearance. X-ray diffraction patterns give the following assemblage, characteristic of rodingite:

Grossularite + Wollastonite + Quartz + Feldspar

Anorthositic Gabbro:

A rootless anorthositic gabbro dyke outcrops along northeast ridge, south of the ridge summit (Fig. 3-1. - map pocket). The anorthositic

Fig.3-6a, Positive relief of a rodingite dyke in harzburgite, ice axe for scale; 6b, Detail of rodingite dyke showing 2 to 3 cm chlorite selvage at harzburgite, ice axe for scale; 6c, Lobate contact between deformed gabbro and harzburgite with irregular quartz - carbonate veinlets in a zone adjacent to the gabbro, pencil for scale. A, b and c are sketches from photographs.

A

B

C

gabbro is medium-grained and equigranular with 0.5 to 1.0 cm thick chill margins sometimes evident. The dyke, 1 to 2 m thick, weathers pale grey and outlines a detached recumbent fold, the upper limb of which is missing. Ductile deformation has occurred in a hot shear environment in the upper mantle. The presence of anorthositic gabbro would suggest proximity to a magma chamber. Fractional crystallization to produce anorthositic magma must have occurred in the magma chamber prior to intrusion. This relationship has been described at the Leka Ophiolite, Norway (Prestvik, 1980) where melagabbro, leucogabbro and meta-anorthosite occur in proximity to the ultramafic succession.

Plagioclase (An_{52}) forms 75 percent of the dyke rock and commonly exhibits dusty saussuritic alteration in internal patches and along cleavage planes. Mafic minerals are actinolite (17 percent) and pale brown biotite (8 percent). Opaques form an accessory phase (2 percent). Actinolite forms euhedral acicular radiating clusters and are closely associated with adjacent biotite. Accessory opaques are similarly associated with actinolite - biotite. This texture and mineralogy results from progressive hydration of original pyroxene in the anorthositic gabbro.

Meta-Norite:

Meta-norite dykes occur in north cirque, and in the central and southern parts of the ultramafic massif (Fig. 3-1, map pocket). These dykes are up to 10 m thick and in north cirque form a "Y" shaped intrusion several hundred metres long. The west fork of the "Y", near the point of divergence has horizontal upper and lower contacts, is 5 m thick and approximately 20 m wide (Fig. 3-7a). Northward (downvalley),

the contact becomes nearly vertical dipping 75 degrees east (Fig. 3-7b). Meta-norite is medium to coarse-grained and shows sub-ophitic texture. Pyroxenes are black-green on both weathered and fresh surfaces with plagioclase having a mottled greyish white appearance. Internal structure is massive other than a few scattered feldspathic clots and a poorly defined chill margin. Serpentinization is absent as is the foliation, characteristic of the enclosing harzburgite. The dykes, along strike, are planar with parallel contacts because they have not been subject to the deformation shown by gabbro dykes.

Essential minerals are plagioclase (45 percent), ortho and clinopyroxene (53 percent) and accessory opaques (2 percent). Plagioclase is An_{15-20} , and commonly shows some saussuritization. Twin lamellae are bent and some grains have very fine polygonal recrystallization texture with vague twin lamellae still visible. Elsewhere alteration has resulted in cloudy patches resulting from saussuritization.

Approximately 20 percent of the orthopyroxene exhibits poikilitic texture. This is defined by highly birefringent inclusions of anhedral round and colourless olivine. In some grains there is 15 percent olivine. Orthopyroxene and minor clinopyroxene show alteration to actinolite and finely disseminated opaques, probably magnetite - ilmenite.

Emplacement of meta-norite dykes is suggested to occur during displacement of the ultramafic massif along a transform fault or at a ridge - transform intersection. The nearest transform fault is the Pinchi Fault (Paterson, 1977) the west side of which has been displaced northwards. The absence of mantle fabric and deformation structures implies emplacement after cooling of the peridotite block with transport away from a spreading ridge. Meta-norite dykes are confined to the

Fig.3-7a, Meta-norite sill in harzburgite, dashed line
is the contact, circled ice axe for scale;
7b, Same meta-norite, 1/2 km along strike
and with near vertical dip, ice axe for
scale.

ultramafic massif and do not extend into adjacent country rocks nor have they been described from surrounding Cache Creek Group rocks. This indicates emplacement prior to arrival of the ultramafic massif into its present position, sometime during its movement along a transform fault. A mechanism of mafic intrusion, initially at a spreading ridge - transform fault intersection, or later during displacement along the transform has been suggested for ophiolite suites in western Newfoundland (Fig. 3-8); Malpas & Strong, 1979). This model can be applied to meta-norite dykes in the Mitchell Range ultramafic massif.

Also of significance is the lack of serpentinization of meta-norite. This implies that serpentinization of the host harzburgite took place while still in the upper mantle, probably adjacent to an active spreading ridge. During obduction no further serpentinization occurred nor did it proceed after obduction while the massif was in its present position.

Nephrite:

Nephrite, otherwise known as "B.C. Jade", underlies the east spur of northeast ridge, east central and southeast ridges of the Mitchell Range (Fig. 3-1, map pocket). Nephrite weathers from bright apple-green to black-green, and paler varieties are mottled with black patches. Black patches are very fine to fine-grained accessory chromite and magnetite anhedral, often with serrated borders. Well developed weathered surfaces are rare. A strongly developed curvi-planar foliation results in rapid exfoliation of curved plates of nephrite from outcrop surfaces. Freshly exposed nephrite is highly lustrous, apple-green and often has slickensides.

Fig.3-8. Model for intrusion of high level mafic
magmas at transform fault - spreading
ridge intersections (after Malpas and
Strong, 1979)

Structural Geology:

The Mitchell Range ultramafic allochthon is bounded by north-northeast and east-trending strike-slip and normal faults on the northern and western borders. The southern and eastern borders are steeply dipping thrust or reverse faults. Rocks of the Cache Creek Group occur to the south and east, Takla Group rocks (Upper Triassic) outcrop to the north and the Mitchell Batholith (Upper Jurassic to Lower Cretaceous) is to the west. The easterly dipping tectonic breccia zone, in places up to 0.75 km wide (Fig. 3-3) is a southerly extension of east dipping thrust - reverse faults described by Monger et al., (1978) in the northern part of the Stuart Lake Belt. Movement along this fault system occurred in the Late Triassic to Early Jurassic and involved obduction of the Mitchell Range massif. Later strike-slip movement on transform faults, locally the Pinchi and Ingenika faults, in Late Jurassic to Early Cretaceous time transported obducted terranes west of the transform faults northward (Monger & Price, 1979; Paterson, 1977). Smaller displacements on splay faults such as the Takla, Finlay and Vital faults could produce rotation of the obducted blocks into their present positions.

Foliation:

Harzburgite of the ultramafic massif exhibits a penetrative north-northeast foliation produced by ductile shear (Fig. 3-9; Fig. 3-10). Ductile shear produces mylonitic texture by glide and slip dislocations in olivine and pyroxene (Nicolas, 1971). In the Mitchell Range ductile shear has produced a foliation defined by mechanical separation and concentration of olivine and orthopyroxene into braided layers. Olivine-rich layers are up to 0.5 to 1 cm wide and weather

Fig.3-9. Contour plot of poles to foliation planes in the Mitchell Range, 135 poles at a contour interval of 2% per 1% area. Triangles are poles to deformed gabbro dykes.

2

Fig.3-10. Composite stereographic projection of poles to ,
foliation planes used in Fig.3-9..

low against orthopyroxenite layers. Orthopyroxenite layers have a similar range in thickness but weather as much as 1.5 cm above olivine layers. The discontinuous form of these layers develops a ribbon foliation (Fig. 3-11a) throughout the harzburgite massif. In areas of intense ductile shear or mylonitization, clots of orthopyroxene up to 5 cm in size are surrounded by mylonitic dunite (Fig. 3-11b).

Olivine in such a groundmass exhibits a very fine-grained anhedral-polygonal poeblastic texture. This is developed by recrystallization and grain size reduction in a solid-state high-strain environment (Calon, 1973) such as would be found in the upper mantle adjacent to spreading ocean ridge (Nicolas, et al., 1982). The coarse orthopyroxene porphyroclasts are ovoid and also show brittle fracturing.

Further evidence of mylonitic flow deformation is shown in Fig. 3-12 where harzburgite fragments are plastically deformed in a matrix of very fine-grained recrystallized olivine. The harzburgite fragments have been altered to pale silvery-brown weathering talc.

Ultramafic Breccia:

The term ultramafic breccia is used here to describe a breccia zone of country rock blocks in a harzburgite matrix and which was formed during emplacement of the ultramafic massif. Obduction of the Mitchell Range ultramafic massif has incorporated blocks of Cache Creek Group metasedimentary rocks several hundred metres in size. The northeast ridge of the Mitchell Range (Fig. 3-3), in addition to Chrome Peak and the south central area, has slabs of metasediment enclosed in foliated harzburgite (Fig. 3-13). The summit area of northeast ridge is formed of coarse tectonic breccia, the contact of which dips steeply eastwards. The ridge summit area also hosts

Fig.3-11a, Ribbony tectonite foliation in harzburgite.

Ridges are predominantly medium-grained orthopyroxene, grooves are finely recrystallized olivine, ice axe for scale; 11b, Large, 8 to 10 cm orthopyroxene porphyroclasts in mylonitic olivine rich shear zone; 11c, Coarse tectonic breccia with angular to rounded harzburgite blocks (pale grey) in finely comminuted serpentine matrix (dark grey), dashed line is contact with unbracciated harzburgite, ice axe for scale.

Fig.3-12. Ductile deformation of harzburgite fragments
(dashed pattern) in shear zone (white) in
harzburgite (lined pattern), sketch from
photograph.

schlieren of disseminated chromitite of the Bob Deposit (Armstrong, 1949) and a folded anorthositic gabbro dyke. Incorporated fault blocks or slabs consist of medium to coarse-grained marble and interbedded ferruginous shale - argillite. The carbonate rocks have been recrystallized to equigranular texture and have 1 to 2% aphanitic grey and black chert nodules up to 12 cm in size. Microcrystalline quartz veins, 1 to 4 mm thick, fill anastomosing fractures in the carbonate blocks and often originate from chert nodules. Shale and argillite are thinly bedded to laminated and are ferruginous resulting in friable black limonitic weathered surfaces. Black shale has 1% anhedral pyritic clots up to 2 cm in diameter. Blocks of carbonate are distributed throughout the shale and argillite (Fig. 3-13) and primary bedding and lamination in both is highly contorted. Combined slabs of carbonate and pelitic metasedimentary rocks in NE ridge are exposed for up to 350 m with thicknesses up to 125 m. Incorporation of country-rock blocks of this size into harzburgite would require extensive ductile flow. The ultramafic massif, during obduction, must have remained hot enough to allow ductile flow. This could have been maintained by frictional heat generated during faulting as has been described at the base of the St. Anthony Complex, Newfoundland (Talkington & Jamieson, 1979).

Tectonic Breccia:

The eastern flank of the ultramafic massif is underlain by coarse tectonic breccia (Fig. 3-3) reflecting a stage of brittle deformation restricted to the outer margin of the massif. This breccia zone strikes north northeast and its contact dips up to 60 degrees east. The breccia consists of 90% fragments, up to 2 m in size, in a matrix

Fig.3-13. Ultramafic mélange, 100 to 200 m blocks of Cache Creek Group metasediments in tectonite harzburgite of northeast ridge, sketch from photograph.

of finely comminuted, serpentized harzburgite (Fig. 3-11c). Larger blocks over 0.5 m, are sub-angular with smaller blocks being well rounded and angular 1 to 5 cm fragments. Angular blocks have aspect ratios (length:width) of 3:2 with major axes sub-parallel to the foliation.

Tension-Gash Breccia:

Augen-shaped breccia zones with 5 to 30 cm well-rounded fragments are developed in the north and south-central parts of the ultramafic massif (Fig. 3-11d). These elliptically shaped breccia zones may be in echelon where two occur together and are oriented with their long axes to the north northeast. Breccia-zone contacts with harzburgite are sharply defined and are subparallel to the foliation of the harzburgite. Individual breccia lenses are up to 9 m in length and 3 m in width (Fig. 3-11d). Harzburgite forms the only fragment-type and they are ovoid with a pre-existing foliation. Fragments are sub-parallel to each other and to the breccia zone. They form 60 to 70% of the breccia with the matrix being very fine-grained serpentized harzburgite.

The well-rounded form of fragments and the augen-shaped in echelon structure of these zones suggests formation under hot and ductile conditions. This has resulted in the passive failure of harzburgite into tension gash-like breccia zones. These zones would also have formed during initial detachment and emplacement of the ultramafic massif.

Deformed Orthopyroxenite:

Orthopyroxenite veins are rare in the Mitchell Range. Where observed they occur as 5 - 7 cm thick veins consisting of medium to

coarse-grained sub to anhedral orthopyroxene. Weathering produces a hackly grey-white surface cut by fractures oriented perpendicularly to vein walls. Orthopyroxenite predates ductile deformation and has subsequently been ptgmatically folded, and then with continued shearing, pulled apart (Fig. 3-14a). No examples of post-deformation undeformed veins, as seen at Murray Ridge and Mt. Sydney-Williams, were observed.

Deformed Gabbro Dykes:

Deformed gabbro dykes are dark green, have very fine-grained schistose texture and are chloritic. They exhibit sharp contacts with enclosing harzburgite and lack chill margins. Strikes and dips of these dykes fall within the same contoured area outlined by the foliation (Fig. 3-9); open triangles). This also indicates that they were deformed by the same strain environment which generated the foliation. Gabbro dykes have pinch and swell structures (Fig. 3-14b) and some are separated into elliptical boudins. Some boudins show the sense of rotation induced by shear (Fig. 3-14c).

Fig.3-14a, Highly deformed "Ptygmatic" first generation orthopyroxene veins (lined pattern) in tectonite harzburgite; 14b, Pinche and swell structure in deformed gabbro dyke (dashed pattern) in harzburgite; 14c, Boudins of deformed gabbro (dashed pattern) in harzburgite. Heavy black line denotes long axis and arrows the sense of rotation. Hammer for scale in a, b and c, all are sketches from photographs.

Chromite Occurrences:

Chromite occurrences are illustrated with tracings from photographs in Fig. 3-15, X_1 to X_{17} . Occurrences denoted by "X" correspond to localities given on Fig. 3-3. They also correspond to a descriptive summary in Table 3-2 and to a list of sample numbers in Table 3-3. In Fig. 3-15, X_1 to X_{17} , solid black represents massive chromitite and stippling, disseminated chromite or chromitite. Double-headed arrows indicate foliation in the harzburgite which forms the host rock unless otherwise indicated in the descriptions.

General Features:

Chromitite is defined here as requiring modal (volume) concentrations of 90% or more chromite (Greenbaun, 1977). Throughout a central north-northeast trending zone in the ultramafic massif (Fig. 3-1, map pocket & Fig. 3-3) are chromitite occurrences with both layered and podiform structures. In most cases ductile shear has deformed them producing in some, schlieren structure. Both layers and pods have massive and highly disseminated or "Net-textured silicate" textures. Examples of nodular chromitite, also known as "Grape-ore", occur at locality X_8 .

In outcrop massive chromitite is dull coal black and disseminated chromite gives a mottled charcoal grey surface to the rock. On fresh exposures massive chromite has a hackly surface with sub-metallic black to blue-black lustre. Chromite is non-magnetic but often gives a weak magnetic response. This usually indicates the presence of magnetite filling fractures in chromitite or forming rims on chromite grains.

Fig.3-b5. Sketches from photographs of chromitite occurrences, X_1 to X_{17} , shown on geological map Fig.3-3 and listed in Table 3-2.

Table 3-2
Chromite occurrences in the Mitchell Range, British Columbia

Chromite Occurrence	Form	Texture	Trend	Dimensions (cm)	Host Rock
X ₁	nodule	a.c.	027	8 x 4	H.
X ₂	nodules (4)	a.c.	in loose talus blocks	6 x 3	H.
X ₃	nodules (3)	a.c.	145	4 x 3	H.
				6 x 4	H.
				7 (diameter)	H.
	schlieren	d.c. (50%)	145/45NE	300 x 15	H.
X ₄	nodules (2)	a.c.	010	12 x 3	H.
				6 x 4	H.
X ₅	layers	a.c.	—	30 x 1-3	D.
X ₆	layers	a.c.	155/45SW	200 x 2	H.
				15 x 1.5	H.
	nodules	m.c.	"	30 (diameter)	H.
				20 "	H.
X ₇	nodules	a.c.	025	50 x 20	H.
		m.c.		40 x 20	H.
				10 x 6	H.
				50 (diameter)	H.
				30 "	H.
X ₈	layer	m.c.	122/33N	150 x 40	H. (breccia)
X ₉	layer	m.c.	151/66NE	200 x 75	H.
X ₁₀	nodules	m.c. & a.c.	073	10 x 3	H.
				10 x 2	H.
				5 x 2	H.
				4 x 1	H.
				12 (diameter)	H.
X ₁₁	nodule	d.c. rim on m.c. core	—	130 x 100	H.
X ₁₂	nodule	a.c.	121	7 x 3	H.
X ₁₃	nodule	a.c.	126	4 x 2	H.
X ₁₄	nodules	a.c. & m.c.	012	50 x 10	H.
			038	40 x 15	H.
			155	40 x 10	H.
			—	8 x 3	H.
X ₁₅	nodule	a.c.	—	10 x 4	H.
X ₁₆	layers (2)	d.c.	015/V	300 x 2-25	H.
			022/66E	100 x 3	H.
X ₁₇	layer	a.c.	103/47N	25 x 4	H.
	nodules (2)	a.c.	—	5 (diameter) 4 "	H. H.

Abbreviations:

a.c. - aggregate chromitite.	D. - dunite (serpentinized).
d.c. - disseminated chromite.	cm - centimetres.
m.c. - massive chromitite.	X - location of chromite occurrence
H. - harzburgite (serpentinized).	on Figure 37.1.

Individual occurrences of chromite:

X_1 is the most northerly chromite occurrence described for the Mitchell Range ultramafic massif and is in the general area of the Irish Deposit described by Armstrong (1949). The chromite pod is deformed with pinch and swell structure in foliated harzburgite (027/44 E). The pod consists of fine- to medium-grained highly disseminated and massive chromitite. The foliation (parallel to pencil in Figures 3-15, $X_1 - X_{16}$) is sub-parallel to the long axis of the pod.

Pods at locality X_2 are highly deformed and are predominantly massive chromitite. They enclose 1 to 1.5 cm clots of fine-grained disseminated chromite (approximately 60%). Foliated harzburgite hosts the pods.

Chromitite at X_3 occurs as disseminated schlieren layers and as massive chromitite pods, 5 to 10 cm in size, constituting the "Bob Deposit" described by Armstrong (1949). Schlieren chromitite layers consist of 90% fine to medium-grained sub- to anhedral chromite. Brittle fracturing of large chromite grains is evident in hand specimen and results in angular fragments. An alignment of chromite grain fragments concordant to the foliation can be observed in thin section. Foliated harzburgite forms the host rock.

Also from the Bob deposit, X_3 , are massive chromitite pods from 5 to 10 cm in size and in the form of irregular oblate spheroids. The pod illustrated in Fig. 3-15 (X_3) is massive in texture with its long axis subparallel to the harzburgite foliation (145/45 NE).

The chromitite pod at X_4 exhibits pinch and swell structure in the larger boundaries. The train of chromite pods parallels the harzburgite foliation (051/64 NW) and are stretched apart over 36 cm with

some boudins up to 4 cm wide. Contacts are sharply defined with trains of finely granulated chromite between the pods.

At the X_5 locality (Fig. 3-3) a chromitite layer is isoclinally folded and is enveloped by very fine to fine-grained equigranular dunite. The folded chromitite layer has highly disseminated texture with 90% or more sub- to euhedral chromite. Contacts with dunite are sharply defined and the layer is 30 cm long and 1 to 3 cm wide with pinch and swell structure.

The chromite locality at X_6 consists of multiple chromitite layers and chromitite pods. The overall chromitiferous zone with layers and pods extends for 20 m along strike and averages 3 m in thickness. The attitude is 155/26 SW for the southern part of the occurrence and 090/80 S for the southern part (Fig. 3-16). Illustrations of deformed layers are given in Fig. 16- X_6 . Individual chromitite layers range from 0.5 to 10.0 cm thick and extend for 15 to 200 cm. Chromite is fine-grained, sub to anhedral and forms both single and multiple or bifurcating layers. One bifurcating layer (Fig. 15- X_6) has isolated a 20 cm block of country rock harzburgite. Parallel chromitite layers are separated by 1 to 3 cm of medium-grained harzburgite and have sharply defined contacts. Chromite which forms individual layers is massive with neither grain-size nor modal gradation. Deformation, particularly at the ends of chromitite-layer segments is ductile with pinch and swell structure and boudins. Layer fragments form trains extending away from the layer terminations and are sub-angular to rounded. Fragments derived from pulled-apart chromitite layers form chromitite pods similar to those described elsewhere but with no immediately adjacent layers.

Fig.3-16. Distribution of chromitite at locality
 X_6 on west-central ridge.

Chromitite pods at X_6 are up to 30 cm in size (Fig. 3-16) and are oriented with long axes parallel to the foliation in harzburgite. They consist of massive chromitite in sharp contact with harzburgite; brittle fracturing has resulted in angular fragment clusters.

Locality X_7 is a zone containing several chromitite pods. These are:

1. 30 cm long ovoid pod with its long axis parallel to the foliation in harzburgite, 028/64 N.
2. 5 m northward is a 40 cm diameter pod fractured in half; the outer half lies in the talus.
3. 1 m away in the same outcrop is an 8 cm diameter pod.
4. 10 m northward again is a 50 cm long augen-shaped pod adjacent to a 20 cm wide shear zone of friable harzburgite trending 025/64 NW.

Chromite in all of the pods forms massive chromitite with small, 1 to 4 cm, patches of 70% disseminated chromite. The patches are irregularly shaped and consist of fine to medium-grained sub to euhedral chromite in a matrix of pale green amorphous serpentine. Contacts between disseminated patches and massive chromitite are lobate but sharply defined. Patches of disseminated chromite form up to 5% of the pods with many pods being entirely massive chromitite. Deformation of pods has resulted in elongation and brittle fracturing which has produced clusters of angular fragments (Fig. 15 - X_7). The second illustration for X_7 has a slight sigmoidal form suggesting early ductile deformation and rotation followed by brittle deformation.

Occurrence X_8 occurs in highly sheared harzburgite with blocky and spheroidal weathering. The occurrence has both massive and nodular textures forming a chromitite layer. The layer is 3 to 40 cm thick and is exposed over a length of 1.5 m at 122/33 N (Fig. 3-1, in map pocket). The lower harzburgite contact, the dashed line in Fig. 16 - X_8 ,

is an assumed contact.

Massive chromitite forming 95% of the layer and is in sharp contact with 10 to 15 cm ovoid patches of nodular textured chromitite. Individual nodules are up to 1 cm in size, ovoid and closely packed to form 80% of the patch. Their matrix is pale green to blue-grey serpentine. Nodular textured patches in the layer segment form about 5% of the layer.

Occurrence X_9 occurs in unshered but foliated harzburgite below the shear zone which hosts X_8 , and 100 m to the east. This layer segment parallels the foliation at 151/66 NE and is in sharp contact with harzburgite.

The layer consists entirely of massive chromitite and is exposed over a width of 75 cm and a length of 2 m. Its limits are not located because of overburden. Part of the east contact of the layer exhibits localized shearing with 1 to 4 cm fragments of angular chromitite set in pale green serpentine. The dashed line (Fig. 15 - X_9) defines the assumed contact.

Chromite at X_{10} forms a succession of small rounded ovoid pods, individually up to 8 cm, which define a train of pods 40 cm long. Adjacent harzburgite is foliated at 028/45 NW, the enclosed chromitite pods showing sub-parallel alignment.

Massive and highly disseminated chromitite occur in the pods (Fig. 15 - X_{10}) and in the fragment train beside the largest pod, fragments of entirely disseminated or massive chromitite occur. The largest pod illustrated, approximately 20 cm minimum, is about 50% highly disseminated chromite which itself contains 2 to 3 cm patches of massive chromitite. The second illustration from area X_{10} shows

development of a fragment-train aligned sub-parallel to the harzburgite foliation. Angular to sub-angular blocky to tabular fragments are derived from the brittle fracture of larger parent pods.

Chromite at area X_{11} defines a compound pod, consisting of a massive chromitite core which forms 80 to 85% of the exposed surface area, and a highly disseminated discontinuous chromitite rim (Fig. 15 - X_{11}). The long axis is 1.3 m and it is up to 60 cm wide. The pod is deformed with horn-like projections into foliated harzburgite (121/33 NE). Foliation in the harzburgite warps around the brittle chromitite pod. Contacts of both harzburgite against massive and disseminated chromitite and disseminated chromitite against massive chromitite are sharply defined. The outer harzburgite - disseminated chromitite rim is slightly undulatory and the inner massive - disseminated chromitite contact is smooth and curvilinear.

Deformed gabbro dykes also occur at area X_{11} (flecked pattern) and one abuts against the compound pod. Gabbro dyke segments are up to 1 m long, 30 cm wide and are concordant with the harzburgite foliation. The chromitite - gabbro contact is also sharply defined.

A highly disseminated chromitite pod occurs at X_{12} in foliated medium-grained harzburgite. Chromite forms 90% of the pod and is fine to medium-grained and sub to euhedral. The main pod has a tensional "pull-apart" break sub-parallel to the foliation. The outer borders of the pod segments display an irregular lobate form and in adjacent harzburgite there are sub-angular blocky to tabular fragments. These fragments are derived from the break-up of the larger pod during ductile shear and account for the lobate borders.

At locality X_{13} a fragment of a compound chromitite layer or pod has been further deformed by ductile shear (Fig. 15 - X_{13}). Later brittle fracture has resulted in angular corners and the development of a fragment train beside and between the two segments of the dismembered pod. The pod segments have both massive and heavily disseminated chromitite texture. A localized schlieren texture has developed with finely fragmented chromitite forming trains parallel to the foliation immediately between the two larger pod fragments.

Area X_{14} corresponds to the "Simpson deposit" described by Armstrong (1949). It is located on a ledge formed by a sub-horizontal joint surface on the south ridge of Chrome Peak (Fig. 3-1, map pocket and Fig. 3-3). A sketch (Fig. 3-17) shows distribution of various chromitite pods and details of two of the pods are sketched in Fig. 15 - X_{14} . The host rock generally is medium-grained harzburgite foliated at 010/75 W but locally a 1 to 2 cm thick selvage surrounds the pods. Dunite weathers into friable chips, 1 to 3 cm wide and 4 to 6 mm thick. Dunite is a distinctive orange-brown with a waxy smooth very fine-grained equigranular texture.

Chromitite pods have major axes or diameters that range from 20 to 50 cm and are 2 to 5 cm thick forming disc-like pods. The pods are aligned parallel to the plane of the thin dunite sheet which dips from 56 degrees southeast to 40 degrees southwest. Some pods have shallower dips of 23 degrees.

Massive chromitite, in all pods, forms 90% or more of the pod with the remainder consisting of highly disseminated chromitite (Fig. 15 - X_{14} , second illustration). Chromite in the irregularly shaped disseminated patches is anhedral and fine to medium-grained. Highly

disseminated chromite also forms discontinuous patches in pod rims up to 5 cm thick and 15 cm long. Contacts between chromite textural types and between chromitite and harzburgite are sharp, although undulatory to lobate. Pinch and swell and pull-apart structures are shown by the chromitite pods indicating initial deformation in ductile shear environment followed by a phase of brittle deformation.

Some of the larger pods from locality X_{14} are sketched and have the following dimensions;

South pod - 40 X 15 cms (038/56 SE),

Central pod - 50 X 10 cms (012/23 E),

North pod - 40 X 10 cms (038/56 SE).

Chromite layers at X_{15} extend for 3 m and are subparallel to the foliation in host harzburgite (Fig. 15 - X_{15}). The layer trends 015/ V and the foliation is at 176/ 64 W. The chromite is fine to medium-grained, sub- to anhedral and forms 60% of the layer. Grain size distribution is homogenous and both contacts with harzburgite are gradational over 1 to 2 cm. The layer shows boudins and pinch and swell structures which range from 3 cm to 25 cm thick. Fragments detached from the main layer show both massive chromitite and 60% disseminated fine to medium-grained texture.

At area X_{16} layers are up to 1 m long and range from 4 to 20 cm thick (Fig. 15 - X_{16}). Layers show both pinch and swell and boudin structures formed by deformation in a ductile shear environment. The layers consist of highly disseminated chromite to chromitite which is medium-grained and sub to anhedral. Grain size distribution is homogenous and both contacts are gradational over 1 to 2 cm with foliated harzburgite which itself contains 2 to 3% disseminated accessory chromite. The layers are oriented subparallel to the foliation with layers at 022/ 66 SE and the foliation at 172/43 W.

Fig.3-17. Sketch from photograph of chromitite pod
distribution at the Simpson Deposit, locality
X₁₄.

At locality X₁₇ (Not illustrated; Fig. 3-3) a compound pod is formed from predominantly massive chromitite and highly disseminated chromite. Massive chromitite forms 90% of the pod and heavily disseminated chromite, 10%. The pod is 25 cm long, up to 4 cm wide and is pulled apart into boudins. Chromite in the disseminated portion is medium-grained and sub to anhedral. Contacts between the two chromitite textural areas sharply defined by lobate borders and the contact with enclosing harzburgite is similarly sharp. The pod is oriented at 103/47 NE.

One metre below the podiform chromitite are three 2 to 4 cm patches of disseminated chromitite with 75 to 80% chromite. The chromite in these patches is sub- to anhedral and medium-grained.

CHAPTER 4: Mt. SYDNEY-WILLIAMS

Introduction:

Mt. Sydney-Williams (MSW) is located 92 km northwest of Fort St. James, British Columbia, and rises to an elevation of 1,877 m. (Fig. 4-1, in map pocket; Fig. 4-1A). The MSW area is 44 km SSE of the Mitchell Range ultramafic massif (Whittaker, 1980), and is underlain by tectonized harzburgite and minor dunite. The MSW massif has been obducted into Permian Cache Creek Group metasedimentary rocks (Armstrong, 1949). Adjacent to the ultramafic massif, Cache Creek Group rocks consist of metamorphosed schistose argillites and andesitic volcanics (Little, 1947). Much of the ultramafic massif is covered by overburden; consequently mapping was restricted to the peak, ridges and cirques. Features outlined by mapping include; a mantle tectonite fabric throughout the massif, layered dunite + harzburgite + orthopyroxenite + disseminated Cr-spinel layers and layered zones some of which are folded, deformed dunite pods and a cross-fibre asbestos occurrence. Chromite (Cr-spinel) mineralization is restricted to the layered zones and forms discontinuous disseminated layers within some dunite layers.

Cache Creek Group metasedimentary and metavolcanic rocks are folded into open anticlines and synclines with northwest-trending axial planes. The Pinchi Fault, 30 km to the east and also striking northwest, separates the Cache Creek Group from Upper Triassic Takla Group metasedimentary and metavolcanic rocks. The Cache Creek Group and enclosed ultramafic rocks have undergone regional metamorphism to upper greenschist facies.

This section describes the geology of these features at the Mt. Sydney-Williams massif with emphasis on Cr-spinel mineralization in dunite layers. Detailed maps of Insets a, b and c of Fig. 4 - 1A are given in Figs. 4-2, 3 and 4.

Fig.4-1. Geology of the Mt. Sydney-Williams alpine-type peridotite, in map pocket.

Fig.4-1a. General geology of the Mt. Sydney-Williams alpine-type peridotite.

Fig.4-2. Detail of geology at Middle River Ridge,
inset A of Fig.4-1,-1a.

Fig.4-3. Detail of geology at Baptiste Spur, inset B
of Fig.4-1, -1a.

Fig.4-4. Detail of central dunite zone with Cr-spinel, inset C of Fig.4-1, -1a.

Harzburgite:

Tectonite harzburgite forms 85 to 90% of the outcrop area at the Mt. Sydney-Williams massif (Fig. 4-1, 1A). It is penetratively foliated with several planar to ribbonary foliations. On weathered surfaces harzburgite is dark brown to grey brown and has a hackly surface produced by resistant orthopyroxenes. On fresh surfaces it is black-green. Orthopyroxene is coarse-grained, anhedral and has been elongated and forms 40 to 50% of the rock. Olivine constitutes the other 50 to 60% and forms elongate patches or clots. These clots are of recrystallized olivine which exhibits a very fine-grained recrystallized polygonal texture. Such textures are formed during solid state flow in high strain environments (Nicolas and Le Pichon, 1980; Calon, 1973). Elongation of olivine clots parallels that of orthopyroxene porphyroclasts and together they define the tectonite fabric, developed at or near an active spreading ocean ridge while still in the upper mantle (Nicolas et al., 1980; Nicolas et al., 1982). In general harzburgite in the MSW massif is more olivine rich than harzburgite of the Mitchell Range ultramafic massif which has 50 to 60% orthopyroxene. The development of tectonite fabric however, is much stronger in the Mitchell Range. The higher proportion of olivine in the MSW massif would suggest a greater degree of partial melting and perhaps then a deeper level in the upper mantle relative to the Mitchell Range ultramafic massif.

Dunite:

Dunite occurs throughout the MSW massif in two major forms and is 85% or more serpentinized to lizardite. The first dunite type consists of irregularly shaped deformed dunite pods (Fig. 4-1, 1A;

Fig 4-5a). The second type is of dunite layers. These may be as single layers which crosscut layered zones or as the main component of dunite + harzburgite layered zones (Fig. 4-2, 3, 4, 5a).

Dunite pods range in size from 2 to 500 m (Fig. 4-2) and were mapped on both MSW and on Pinchi Mt. (Fig. 4-8). Pods can be ovoid, kidney shaped or have sigmoidal form, probably reflecting ductile shear. Deformed dunite pods are formed of very fine-grained recrystallized olivine which has mosaic or polygonal texture. Weathered surfaces are smooth orange-brown while fresh surfaces are black-green. Pods are monomineralic olivine with the exception of accessory sub to euhedral Cr-spinel which is fine to medium-grained. Tectonite fabric (foliation) is only weakly developed in monomineralic dunite pods. This may be due to extensive recrystallization and grain size reduction as olivine underwent strain. Brittle shear zones, up to 10 cm wide, have sharp boundaries within dunite and develop deeply weathered (5 to 7 cm) trenches with friable - platy texture. In larger dunite pods (greater than 10 m) zones of brittle shear can be up to 2.5 m wide and within these foliations can be highly variable. This variable foliation, which can be curvilinear, tends to isolate spheres of less intensely foliated dunite and result in outcrops with spheroidal weathering structures. Individual spheres are 10 to 25 cm in diameter and may also be ovoid. Contacts between dunite pods and enclosing harzburgite are sharply defined and accentuated by the recessive weathering of dunite. Foliation planes are abruptly refracted by these sharp contacts with deflections of up to 24 degrees measured.

7 Fig.4-5a, Dunite layers cutting harzburgite of the east
cirque headwall; 5b, Harzburgite xenoliths (dark grey) in dunite (pale grey). Dashed
line traces contact and outlines xenoliths.

Dunite in Layered Zones:

Dunite in layered zones (Fig. 4-2, 3, 4) exhibit textures similar to those in dunite pods. It is very fine-grained polygonal olivine which has recrystallized in the formation of monomineralic dunite layers. Dunite layers range in thickness from 3 - 5 cm up to 25 - 30 cm and are separated by layers of harzburgite of variable thickness (Fig. 6a, 7). Layered zones are generally planar with sharp and gradational contacts with harzburgite or they may be folded as at Baptiste Spur (Fig. 4-3).

Layered zones both at Pinchi Mt. and at MSW are usually subconcordant with the tectonite foliation. Gradational contacts are developed over 1 to 2 cm and have serrated to lobate texture. In some cases flame-like structures are defined by tongues of dunite penetrating harzburgite, as also seen at Murray Ridge (Whittaker & Watkinson, 1980). Orthopyroxene phenocrysts may become incorporated in dunite layers as shown in Fig. 4-6b, and exhibit embayed resorption textures. Dunite layers in layered zones of the MSW massif host disseminated Cr-spinel (Fig. 4-3, 4). It can occur as either accessory disseminated grains or as single-grain thick, chain like laminae usually discontinuous but traceable for the length of the dunite layer.

Dunite Dyke-Like Structures:

In the southeastern part of the MSW massif (Fig. 4-1a) and on Pinchi Mt. (Fig. 4-8) crosscutting dyke-like structures of dunite were mapped. These tend to have strikes parallel or sub-parallel to the tectonite fabric, between NE and NW, but have variable dip directions in the 45 degree to vertical range. On both Pinchi Mt. and MSW the roots of dunite dyke-like structures begin from the zones of irregular irregularly shaped dunite pods, usually 50 m or larger. At MSW the headwall the east cirque gives a vertical section showing a parental dunite pod with

Fig.4-6a, Planar and parallel dunite layers in harzburgite;
6b, Detail of dunite - harzburgite contacts
where dunite embays harzburgite with mottled
texture.

Fig.4-7. Representative section, true thickness, of
a dunite layered zone on Middle River
Ridge.

with numerous dunite dyke-structures emanating from it (Fig. 5a). These dunite dyke structures range in thickness from 1 to 4 m, most are near vertical but some have 45 degree dips. These two dyke structure sets appear to be contemporaneous, no dunite crosscutting features were noted, and form 10 to 15 m stockworks.

Textures within dunite structures are similar to those described in previous dunites. The texture is uniformly very fine-grained and equigranular across the width of these structures. Chill margins are absent. In some cases detached and openly folded apophyses of dyke structures can also be traced to the same parental dunite pod indicating that these features are pre and synkinematic. Dunite dyke structures represent a process that was continuous throughout mantle deformation and for a short while post dates mantle deformation.

Within some dunite dyke structures harzburgite forms xenoliths stoped from the wallrock (Fig. 4-5b). There appears to have been only minor displacement, 1 to 10 cm, individual xenoliths are 2 to 10 cm in size and are subrounded. In some cases larger xenoliths are auto-brecciated with component fragments also subrounded. The development of subrounded xenoliths and fragments could be accounted for using a process of metasomatism of in situ xenoliths. Long dimensions of harzburgite xenoliths are aligned parallel to the foliation in adjacent wallrock harzburgite which is also parallel to the strike of the dyke structures.

Orthopyroxenite:

Coarse-grained orthopyroxenite layers occur individually or in layered zones in conjunction with dunite + harzburgite layering. In dunite layered zones orthopyroxenite may form a layer within the central part of the dunite layer. In some areas a layered zone will be formed

Fig.4-8. Distribution of dunite layers and pods in
the summit area of Pinchi Mt.

entirely of orthopyroxenite layers as at Pinchi Mt. (Fig. 4-9a). The layered zone in Fig. 4-9a consists of 2 to 4 cm thick coarse-grained and equigranular orthopyroxene with prominent crystal fracture - cleavages developed perpendicular to layer walls. Repeated layers are regularly spaced at approximately 1 m intervals and form a layered zone 10 m wide with near vertical dip.

In contrast to this layering, and within 200 m of it, is a single orthopyroxenite layer with near horizontal dip (Fig. 4-9b). Single layers are up to 10 to 15 cm thick and develop similar perpendicular fracture - cleavage patterns. Orthopyroxenite layers, both in layered zones and as single layers may be continuous for tens of metres, or they may pinch and swell and terminate within 2 to 5 m. Deformed orthopyroxenite layers also occur, and can be adjacent to planar layers or they can define crosscutting relationships where planar orthopyroxenite layers cut folded ones as was observed at Murray Ridge (Whittaker and Watkinson, 1980).

Orthopyroxenite usually forms monomineralic layers with accessory disseminated Cr-spinel. On weathered surfaces it is pale grey-white and weathers recessively against harzburgite, particularly at layer contacts. Contacts are always sharply defined. At Pinchi Mt. (Fig. 4-8) bottle-green weathering diopside (Cr diopside) forms patchy anhedral crystals within some larger (10 cm) orthopyroxenite layers and form about 1% of the layer as websteritic patches. Both orthopyroxenite and diopside are very coarse-grained with well defined cleavage (Fig. 4-9c). In well weathered patches the coarse cleavage pattern takes a woody - fibrous appearance.

At MSW folded orthopyroxenite was sparsely developed and planar layers most common. These are entirely monomineralic with an absence of green diopside.

Fig.4-9a, Planar undeformed orthopyroxenite veins
with regular 1 m spacing in harzburgite;
9b, Undeformed and thicker orthopyroxenite
vein with near horizontal dip; 9c,
Websteritic patch in orthopyroxenite vein
, clinopyroxene (outlined) with ortho-
pyroxene, both are very coarse-grained.

Chromite (Cr-spinel):

Occurrences of Cr-spinel at MSW are unlike the generally podiform chromite-chromitite described from the Mitchell Range ultramafic massif (Whittaker, 1981). At MSW Cr-spinel forms an accessory phase throughout the tectonic harzburgite where it is fine-grained and sub to euhedral. Concentrations of Cr-spinel which form disseminated and massive net-textured laminae occur only within dunite layers which are part of larger layered zones. In the mineralized dunite layers (Fig. 4-4) disseminated Cr-spinel forms 45 to 95% of individual laminae which pinch and swell from 0.5 to 2.0 cm thick. These laminae can be discontinuous, are usually concordant with layering and are also centrally located in the dunite layer (Fig. 4-10a). In the plane of the dunite layer the generally medium-grained sub to euhedral Cr-spinel forms tabular patches. Patches are from 1 to 15 cm in size and are aligned parallel to the dunite layer (Fig. 4-10b).

Two instances of discordant disseminated Cr-spinel occur, one at Pinchi Mt. (Fig. 4-8) and a second at Middle River Ridge on the MSW massif (Fig. 4-2). At Pinchi Mt. disseminated Cr-spinel is medium-grained and forms 95% of a 2 m long gently folded layer. The layer varies from 1 to 3 cm thick and is oriented at an acute angle to the tectonite fabric and layered zones (Fig. 4-8). Disseminated Cr-spinel at Middle River Ridge (MRR) has developed in fractures which are acute to a more prominent and central fracture (Fig. 4-2). Cr-spinel is medium-grained and sub to euhedral. In both cases the development of Cr-spinel in discordant planar orientations suggests the movement of late (post-kinematic) mineralizing solutions.

At Baptiste Spur evidence exists for two distinct generations of Cr-spinel development. The earliest Cr-spinel generation has been folded within the nose of a folded dunite layer and so predates ductile deformation (Fig. 4-11a). The later generation has developed in the axial plane foliation of the fold structure, but only within the dunite layer. This would be syn or post-deformational mineralization (Fig. 4-11b).

Extensive development of Cr-spinel reaction rims and multi-stage Cr-spinel mineralization, always in dunite, strongly suggests that dunite bodies were zones of long-lived solution migration. Rounded xenoliths of harzburgite in dunite dyke structures would be additional evidence in favour of solution migration - metasomatism. Direct evidence for late hydrous solution migration is found at west cirque. Cross-fibre asbestos mineralization is well developed in 1 to 3 cm wide brittle fractures that strike east - west (Fig. 4-1). These were described by Armstrong (1949) and additional field work has shown them to be restricted to west cirque.

Later Intrusions - Norite Dykes:

Norite dykes cut the MSW massif in an ENE trend with vertical dips (Little, 1947). They range in width from 1 to 4 m and are medium-grained and equigranular. Grey-white subhedral plagioclase laths form about 40% of the dykes with the remaining 60% being partially amphibolitized orthopyroxene. Orthopyroxene is sub to anhedral and equant in form. Norite dykes are planar, undeformed and unserpentinized. These characteristics would suggest post-obduction emplacement into the ultramafic massif.

Fig.4-10a, Highly disseminated Cr-spinel seam with pale coloured chlorite - lizardite alteration rims in central part of dunite layer; 10b, Vertical section of Cr-spinel seam showing patchy distribution of Cr-spinel; 10c & d, Detail of alteration rims on Cr-spinel.

Fig.4-11a, Folded first generation Cr-spinel in hinge area
of folded host dunite layer; 11b, Planar second
generation Cr-spinel in foliation plane in dunite
only, oriented obliquely to limbs of folded
dunite.

West Peak Area:

In fault contact with the MSW massif and to the west is a norite intrusion from which the norite dykes are suggested to have originated. This body is 1.2 km long and 0.6 km wide and is roughly ovoid in shape (Fig. 4-1). The southern and lower part of the ridge formed by the intrusion is massive norite which grades into irregularly layered norite + anorthositic norite. Individual layer segments are up to 1 m in length and from one outcrop to another attitudes are highly variable, a result of magmatic soft sediment style deformation. The norite body is weakly foliated in the same direction as the enclosing Cache Creek Group rocks, to the northwest. This does not reflect the mantle tectonite fabric of the MSW massif.

On the south side of the norite intrusion is a narrow (50 m wide) zone of ultramafic rocks which extend westwards for 3.5 km (Fig. 4-1). Adjacent to MSW and the right lateral strike-slip fault which separates the two areas is a zone of angular to subangular breccia developed in dunitic harzburgite. The breccia zone consists of 80% fragments, 3 to 15 cm in size, and bound together by a finely comminuted serpentinite groundmass. The actual norite - breccia zone contact is covered. The breccia zone is 10 to 15 m wide and is in contact with strongly foliated dunitic harzburgite. Dunitic harzburgite outcrops appear in westerly progressions and end at a ridge of highly sheared, friable green nephrite. These outcrops carry accessory Cr-spinel which is fine-grained and sub to euhedral. Orthopyroxene forms about 10 to 15% of the rock and is coarse-grained and elongated parallel to the foliation. Olivine has recrystallized into very fine-grained polygonal mosaics which are also elongated parallel to the northwesterly foliation.

In the immediate West Peak area dunitic schlieren are incorporated within highly schistose andesitic metavolcanic rocks described by Little (1947). The dunitic schlieren are 1 to 2 m wide and are traceable for 10 to 30 m parallel to the northwest foliation. The dunite itself is highly schistose and friable breaking into a "Poker-chip" orange-brown weathered surface. In some instances competent bedrock does not exist, but only a felsenmeer of dunitic chips.

Fault displacement of a zone of talcose highly sheared harzburgite of the MSW massif has been transported in a right-lateral sense along the fault separating the MSW massif from the West Peak area (Fig. 4-1). Displacement in strike-slip movement along this fault has been approximately 0.5 km, the vertical component is unknown. Between the offset talcose harzburgite zones are outcrops of dark green densely jointed and foliated nephrite.

Structural Geology:

Harzburgite and dunite throughout the MSW massif exhibit a mantle fabric. This consists of a penetrative foliation which is defined by stretched orthopyroxene phenocrysts and elongate clots of finely recrystallized olivine. The foliation has a steep dip and strikes between northeast and northwest. In many outcrops the foliation has a ribbon structure and highly variable orientation. This may be related to folding of the foliated ultramafic rocks while still in the upper mantle (Nicolas and Le Pichon, 1980). Oriented parallel and subparallel to the mantle foliation, are layered zones consisting predominantly of dunite layers separated by harzburgite layers. Orthopyroxenite and disseminated Cr-spinel layers are less common.

The MSW massif retains an early, F_1 , fold structure with an axial plane trend which is acute to the northwest trending folds in enclosing Cache Creek Group rocks. F_1 fold structures at MSW are defined by primary igneous layering. Layers occur individually, or more commonly in layered zones up to 10 m wide. Layers consisting of dunite in harzburgite with minor orthopyroxenite and Cr-spinel layers are, on outcrop scale, planar and have no internal deformation. Lower hemisphere projections of poles to layers in layered zones from four localities in the ultramafic massif define four separate structural domains (Fig. 4-1, 1a, 12) Van Decar Creek (VDC), Middle River Ridge (MRR), Baptiste Spur (BS) and Mt. Sydney-Williams (MSW). In the northern part of the area, domains VDC and MRR outline an F_1 antiformal structure with domains BS and MSW defining a synformal structure to the south. This juxtaposition is brought about by strike-slip movement on the MRR fault which has been projected through an outcrop of angular breccia (Fig. 4-1, 1a). The MRR fault is subparallel to the Pinchi Fault, a regional strike-slip structure 30 km to the east. F_1 fold structures at MSW consist of a northeast trending antiform - synform system with a wavelength of about 3 km. More recent strike-slip faulting, as late as post-Paleocene (Armstrong, 1949) has offset segments of this structure by possible left lateral movement.

Second order, F_2 , and third order, F_3 , structures were mapped at Baptiste Spur (BS) on the southeast flank of MSW (Fig. 4-3). A 30 cm wide layered zone (dunite + orthopyroxenite + Cr-spinel) in harzburgite has been plastically folded into a doubly plunging synform. A pre-folding Cr-spinel layer within the layered zone has developed F_3 box folds in the nose of the larger F_2 structure (Fig. 4-11a). The axial plane foliation of the F_2 synformal structure, which is parallel to the mantle foliation in the enclosing harzburgite, cuts the synform limbs at an oblique angle.

Fig.4-12. Stereographic projection of poles to dunite layers
with domains for each of four areas outlined.

Late stage Cr-spinel mineralization has developed along the axial plane foliation, only where the foliation cuts the dunite layer (Fig. 4-11b). This suggests that Cr-spinel mineralization was active during mantle deformation and development of tectonite fabric in harzburgite. A proposed site for this process is adjacent to a spreading ocean ridge and magma chamber which is a site of ductile shear deformation and folding (Nicolas et al., 1980). In this environment circulating seawater brines would provide the necessary hydro-thermal environment for remobilization of such elements as Cr, Al, Mg etc. The restriction of secondary Cr-spinel mineralization to the dunite layer also suggests that the dunite layer acted as a curvilinear conduit for mineralizing solutions both during and after mantle deformation.

Petrography - Silicates:

Serpentinization is ubiquitous and 75% or more complete in harzburgite and 85% or more complete in dunite. Only relict olivine and orthopyroxene crystal cores and crystal fragment cores remain and these are enveloped by lizardite.

Lizardite is pale green in plane transmitted light with low first order birefringence. Mesh texture is well developed and consists of lizardite bastite pseudomorphs after both olivine and orthopyroxene (Wicks & Whittaker, 1977a,b). In some cases, oxides formed from liberation of Fe in olivine and orthopyroxene form sparse very finely disseminated rims around the original silicates. Individual mesh textural units are outlined by ribbony lizardite which generally parallels the foliation (Fig. 4-13). Individual segments of ribbony lizardite have a symmetric structure where lamellar fabric is developed perpendicular to ribbon borders, and meet at a central seam which also parallels the ribbon

segment (Fig. 4-13).

Fig. 4-13. Segment of ribbon lizardite defining part of a mesh textural unit, each unit with an olivine core.

Ribbon lizardite, in part, defines or accentuates the tectonite fabric and may then represent a period of pervasive serpentinization within the upper mantle prior to obduction.

Olivine is colourless in plane light and occurs as anhedral remnants of crystal or crystal fragment cores. In all cases olivine is very fine-grained and enclosed by lizardite. Microprobe analyses of groundmass olivine give compositions consistently of Fe_{92} . Some olivine grains have opaque acicular inclusions which are randomly oriented. These are likely to be rutile.

Orthopyroxene occurs as coarse-grained fractured and anhedral crystals. Serpentinization has totally surrounded orthopyroxene and is developed along cleavage planes and fractures. Where it is un-serpentinized orthopyroxene is pale green and weakly to non-pleochroic. Some grains (5 - 10%) exhibit exsolution lamellae of more highly birefringent clinopyroxene with average extinction angles of 31 degrees. These are likely diopside, possible Cr-diopside.

Spinel and Sulphides:

Cr-spinel is the predominant spinel phase and occurs in dunite layers as medium-grained disseminations and often forming 0.5 to 2.5 cm thick laminae. In harzburgite tectonite Cr-spinel forms only an accessory phase of fine to medium-grained sub to euhedral grains. In only one area, on

the south side of the ridge at west cirque (Fig. 4-1), were nodules observed. Two elongated nodules, 2 and 3 cm long respectively, consist of anhedral fine to medium-grained net textured chromitite and parallel the foliation.

Cr-spinel described in layered zones from MSW (Fig. 4-3,4) occur as both single grains and as constituents in massive net textured laminae. In all cases observed reaction rims which surround single chromite grains and net textured aggregates consist of serpentine (lizardite) and chlorite. Most grains are completely altered but some spinels retain primary Cr-spinel cores. Grains that are completely and partially altered retain their original subhedral to euhedral form.

Cr-spinel cores can form up to 25% of the total grain and are not always left at the true grain centre (Fig. 4-14a). Original cores are irregularly shaped and have serrated borders with the surrounding altered spinel. Compared to altered spinel areas the cores have few or no silicate inclusions. Where present, primary anhedral silicate inclusions are larger, rounded and more smoothly bordered (Fig. 4-14b). In reflected light unaltered cores are smoothly textured and a constant shade of pale grey. Transmitted light shows dark reddish-brown to pale brown body colour with moderate translucency. Cores become opaque only at their contacts with the surrounding altered spinel rims.

Partial and complete alteration of Cr-spinels leads to development of dendritic-skeletal textures (Fig. 4-14a, b). Silicate inclusions are numerous and form up to 50% of the altered areas. In reflected light altered skeletal-dendritic spinel often reflects a mottled pale-grey and white surface. Initial microprobe analyses give higher Fe in white areas than in the pale-grey patches. This is in accordance with results obtained by Stumpfl & Rucklidge (1982) for altered spinels in dunite pipes of the

Fig.4-14a, Skeletal alteration of Cr-spinel with smooth-textured unaltered core; 14b, Skeletal altered Cr-spinel with remnant serpentized anhedral silicate (probably olivine) inclusions. Scale bars in a & b are 200 microns.

Bushveld Complex. Accurate analyses are difficult to obtain because of the intimate development of silicate inclusions. In transmitted light altered areas are always opaque and this indicates an increase in Fe. Opaque areas can be directly correlated to areas of high reflectivity and the formation of ferritchromit and magnetite.

Sulphides and Ni-Fe alloys are usually always present with altered spinels from monomierallic dunité layers and form secondary phases. They occupy fractures in original spinels and occur at the junction of 2 or more grains (Fig. 4-15a, b). Secondary sulphide inclusions (those in fractures in spinel) and groundmass sulphides are present both as mono and polyphase sulphides. Polyphase sulphides occur as anhedral porphyroblasts both in fractures in spinel and the groundmass (Fig. 4-15b). In some grains up to 3 co-existing sulphide phases occur. The most abundant phase is the Ni-Fe alloy, awaruite. Awaruite forms the host for smaller anhedral sulphide inclusions, usually of pentlandite and heazlewoodite. They are usually angular to sub-angular blebs and may be either creamy-white, and difficult to distinguish from the white host Ni-Fe alloys or they are slightly brownish bronze. A more detailed discussion is presented in the petrography section. In one section from Baptiste Spur (Fig. 4-3) disseminated secondary sulphides form approximately 3 to 5 modal percent of the rock with approximately 1 to 2 modal percent being Ni-Fe alloy.

Secondary sulphides in the groundmass are concentrated adjacent to altered Cr-spinel grains and become sparser away from them. Also, secondary sulphides are largest adjacent to altered Cr-spinel grains. This density and size distribution may be linked to several possible processes. First, primary sulphides may have been concentrated around Cr-spinel grains as is documented in stratiform intrusions

Fig.4-15a, Secondary Ni-Fe alloy, awaruite (white) occupying fracture in altered Cr-spinel; 15b, Ni-Fe alloy (white) and heazlewoodite (pale grey) between two altered Cr-spinels. Matrix in a & b is serpentized dunite, scale bars are 200 microns.

(Hiemstra, 1979). Secondly, secondary sulphides were formed from diffusion of elements originally in solid solution in Cr-spinel (Stumpfl & Tarkian, 1976) and silicates. A third and favoured process involves the remobilization of the cations now in secondary sulphides from discrete sulphide inclusions in Cr-spinel, examples of which are described from unaltered chromitite (Whittaker & Watkinson, 1982). An increase in sulfur fugacity during alteration, i.e. mantle serpentinization, would stabilize the observed secondary sulphides.

Summary of Spinel and Sulphide Petrography:

1. Cr-spinels are subhedral to euhedral and sometimes have unaltered translucent reddish-brown cores.
2. Alteration has formed dendritic to skeletal textures with numerous very fine silicate inclusions.
3. Altered spinel commonly has mottled pale-grey and white texture with higher Fe associated with areas of high reflectance.
4. Inclusions are secondary sulphides, filling fractures in Cr-spinel and occurring at the junctions of two or more spinels.
5. Secondary sulphides are most concentrated and largest adjacent to Cr-spinel grains as are Ni-Fe alloy.
6. Larger anhedral (70%) are monophase brilliant white Ni-Fe alloy.
7. Approximately 30% are polyphase sulphides (2 and 3 phase) with white sulphide (heazlewoodite) hosting angular to sub-angular blebs of creamy white or brownish-bronze sulphides (pentlandite).

Discussion:

Spinel and sulphide textures indicate an environment within monomineralic dunite layers where solutions were reactive and mobile during mantle deformation. Initial alteration of Cr-spinel must

have been associated with later Fe - rich solutions to form opaque (Fe rich) replacement ferritchromite and magnetite. If the original Cr-spinels had only a few silicate inclusions (about 5 modal percent) then a substantial amount of primary Cr-spinel has been removed and transported elsewhere. This is indicated by the abundance (25 to 30%) of fine silicate inclusions occupying interstices left by development of dendritic or skeletal texture in Cr-spinel pseudomorphs. Continued element mobility or metasomatism is suggested by the growth of anhedral sulphide porphyroblasts within the groundmass and in fractures in Cr-spinel. The environment must also have been one of increasing sulphur fugacity to stabilize the sulphide phases. It appears that Cr-spinel grains may have caused localized "Grain-size" pockets of higher sulfur fugacity which resulted in concentration of sulphide phases adjacent to altered Cr-spinels. This may have developed by Cr-spinel supplying the cations and sulphur from dissolved sulphide and alloy inclusions during alteration. In unaltered chromite, euhedral to subhedral discrete inclusions of Ni - Fe - S, Ni - Fe alloy, PGM sulphides and PGM alloys have been described (Talkington et al., 1982, Whittaker & Watkinson, 1982 and Pritchard et al., 1981). This in addition to Ni, Fe and other cations from altered silicate groundmass minerals could generate the observed secondary sulphide texture where most of the sulphides and the largest grains are adjacent to the altered Cr-spinel.

Cr-spinels from MSW dunite layers, whether planar or folded and whether they are pre or post-deformation (occupying axial plane foliations) are altered. This strongly suggests a period of mantle metasomatism which was pre-, syn-, and post-deformational and which was most intense and continuous within what are now monomineralic dunite layers, both planar and folded.

In further support of intense metasomatic processes which can alter spinels, sulphides and silicates, and in particular produce monomineralic dunite layers are the dunite pipes in the Bushveld Complex, South Africa. Several workers at the Driekop dunite pipe (Peyerl, 1982 and Schiffries, 1982) and at the Onverwacht and Mooihoek pipes (Stumpfl & Rucklidge, 1982) and earlier (Cameron & Desborough, 1964) suggest processes of post-magmatic metasomatism involving Fe rich, CO_2 and aqueous chloride compound solutions. At MSW direct evidence exists for late Fe rich solutions and as an alpine-type body, the percolation of sea water would be possible to form aqueous chloride compound compounds. In addition CO_2 is known from inclusions in mantle olivine (Roedder, 1965). With these conditions fulfilled in an upper oceanic mantle environment Cr, Ni, Fe and other elements could be transported from altered Cr-spinels to be reprecipitated elsewhere.

CHAPTER 5: FIELD GEOLOGY - INTERPRETATION & DISCUSSION

Field geology: Interpretation and discussion.

Features mapped and described from field work on chromite - chromitite occurrences from southern to central British Columbia are summarized in Table 5-1 and are shown schematically in Fig. 5-1. All processes discussed are considered to occur synchronously amongst the alpine-type peridotites. From the chromite occurrences studied, the Anarchist deposit in metacarbonate rocks of the Anarchist Series remains most enigmatic. Because of its peculiar lithological association it is not included in the interpretation and field model which is discussed for the remaining alpine-type ultramafic massifs and their associated chromite occurrences.

Ultramafic massifs have been grouped according to similarities in field geology, primary lithologies and structures present. Common to all ultramafic massifs is extensive serpentinitization (70% or more in harzburgite and 90% or more in dunite) and a strongly defined tectonite fabric, i.e. mantle foliation. In the Mitchell Range, mylonite zones and porphyroclastic textures as well as a coarse angular tectonic breccia are developed which result from detachment and obduction of the hot upper mantle block.

If synchronous processes can be applied to allochthonous ultramafic blocks in this study together with similarities in geology, they may be assigned to relative stratigraphic levels in the upper mantle (Fig. 5-1). Detailed work on the well preserved Samail Ophiolite in Oman (Boudier & Coleman, 1981; Christensen & Smewing, 1981; Hopson et al., 1981 and Brown, 1980) provides the basis for the stratigraphic column of an ophiolite succession which has been modified to accommodate allochthonous ultramafic rocks, particularly from the central British Columbia Fort St. James to Takla Lake region.

In the upper "Depleted" mantle the areas studied have been assigned to lower, intermediate and upper depleted mantle.

Lower depleted mantle:

The Mitchell Range ultramafic massif is the area considered to represent the lowest depleted mantle level as it is thought to be adjacent to the plane of thrust emplacement.

Although there is no evidence for a basal thermal aureole such as is developed at the base of the Samail Ophiolite or the St. Anthony complex (Ghent & Stout, 1981; Jamieson, 1980), a strongly developed mylonitic shear fabric and coarse angular tectonic breccia do occur. Mylonitic fabric, sometimes concentrated in lenticular breccia zones with well-rounded fragments, and porphyroclastic textures are interpreted to develop in the upper mantle at the time of detachment of the ultramafic block (Nicolas & Le Pichon, 1980; Nicolas, et al., 1980; Nicolas et al., 1982). At higher levels during obduction and consequently at lower temperatures, coarse tectonic breccia would form in response to the increasingly brittle ultramafic block. The Mitchell Range massif with its mylonitic - porphyroclastic textures and coarse angular tectonic breccia is therefore interpreted to be most proximal to the sole of the thrust sheet which was subsequently dismembered to form the array of ultramafic massifs studied, particularly in the Fort St. James to Takla Lake region.

Within this section of lower depleted mantle are deformed intrusive bodies consisting of gabbro and anorthositic-gabbro dykes. The gabbro dykes can represent picritic tholeiitic partial melt in tensional fractures in the vicinity of an upper mantle magma chamber such as would occur beneath a spreading ocean ridge (Pallister & Hopson,

1981; Malpas, 1978). Fractionated liquid from a nearby magma chamber could be laterally or vertically injected to form the anorthositic-gabbro dykes. The high strain ductile environment in which they were emplaced would account for their deformed structures. These fracture zones could subsequently become zones of later Ca-Si and Mg metasomatism forming rodingite dykes with chlorite rich selvages during later serpentinization by aqueous brines.

Chromite in the highly strained upper mantle environment could form in layer-like zones parallel or sub-parallel to the tectonite fabric or as augen-shaped pods in tensional openings (Cassard et al., 1981). Both augen-shaped and layered chromitite, either massive or highly disseminated depending upon the availability of Cr could then concentrate. Continued strain in a ductile environment would then pull apart brittle chromitite layers to form additional augen-shaped chromitite pods with attendant fragment trains. Podiform chromitite may also exhibit a sigmoidal form from rotation during ductile shear. Chromite crystallized in lower depleted mantle, away from zones of brittle fracturing, is unaltered and when not massive is sub to euhedral. Nodular-textured chromitite is very coarse-grained and is similarly unaltered. Weak development of ferritchromite rims can be related to serpentinization and lower greenschist facies metamorphism. The absence of alteration textures associated with chromite grains suggests that the Mitchell Range ultramafic massif represents a deeper level of mantle where chromite rich areas escaped the effects of later hydrothermal alteration. Alteration was concentrated in areas of gabbro dykes, some of which became rodingites.

Intermediate depleted mantle:

Massifs assigned to this level are in the Bridon, Nicola and Scottie Creek areas. Features in these massifs indicate a transitional level between lower, less depleted mantle with sparse dunite layers and no dunite pods, and upper depleted mantle with abundant dunite layers and pods. Deformation of dunite layers, concordant to the tectonic fabric in harzburgite form open folds with axial planes parallel and subparallel to the mantle foliation. Primary unaltered chromite forms thin disseminated seams within and concordant to dunite layers and in highly deformed areas such as Scottie Creek, chromitite pods also occur. Chromite in dunite at this intermediate mantle level may be both unaltered and altered and is weakly to strongly fractured.

Upper depleted mantle:

Three ultramafic massifs, Mt. Sydney-Williams, Murray Ridge and Pinchi Mt., may be assigned to the upper depleted mantle level. Upper depleted mantle is the level from which as much as 23% partial melting has occurred (Malpas, 1978) to produce picritic tholeiitic liquid. This partial melt has been able to segregate and completely leave the residual harzburgite for extrusion or higher level magma chambers. In the lower depleted mantle this partial melt was, in part, trapped and formed pre-obduction gabbro dykes. The channelways and source areas for the partial melt may be left as refractory olivine rich residues which are the dunite layers and pods. Zones of magma migration, in which disseminated chromite could be formed, could later act as zones for hydrothermal fluid movement. At both Pinchi Mt. and Mt. Sydney-Williams dunite layer-structures originate from root zones which are dunite pods. Ductile deformation is well developed in the upper

depleted mantle and at Mt. Sydney-Williams an antiform - synform pair is defined by widely separated layered dunite zones. On an outcrop scale dunite zones are planar to curvi-planar. Folds, at Baptiste Spur record localized but still ductile deformation. These features indicate a mantle strain environment of ductile shear which has also developed a strong foliation.

Dunite layers, interpreted to be residual planar conduits record zones along which later aqueous alteration and mineralizing fluids moved. Strong evidence at Mt. Sydney-Williams suggests that some dunite layers were active conduits for sustained periods of time. Contacts with harzburgite in places are gradational over 1 to 2 cm and are lobate. Embayed orthopyroxene clots also occur isolated within dunite layers. Cr-spinel has formed disseminated seams defining two separate periods of mantle deformation and mineralization. The earliest pre-dates mantle deformation and is folded within the nose of its folded host dunite layer. A second generation of Cr-spinel defines the axial plane foliation, which parallels the tectonite fabric, but is confined to the dunite layer. The following features; embayed contacts between dunite and harzburgite and two distinct periods of Cr-spinel mineralization suggest that dunite-layer structures acted as conduits for partial melts and for later alteration and mineralizing solutions.

Field evidence from Pinchi Mt. and Mt. Sydney-Williams suggest a position in the upper depleted mantle that was a zone of hydrothermal alteration and considerable depletion with respect to picritic tholeiitic partial melt.

Table 5-1. Summary of field geology.

Area	Anarchist Deposit	Bridon Claim Group
Host Rocks	meta-carbonates - Anarchist Series.	harzburgite, minor dunite.
Chromite	massive chromitite dyke.	highly disseminated chromitite and chromite layers.
Deformation	closely spaced angular fracturing.	openly folded layers with pinch & swell and boudin structures.
Xenoliths		
Intrusions		dyke of Shuswap complex granodiorite.

Table 5-1. Continued.

Area	Nicola Deposit	Scottie Creek Deposit
Host Rocks	harzburgite, minor dunite, dunite and orthopyroxenite.	harzburgite and dunite.
Chromite	disseminated chromite layers and nodules.	podiform massive chromitite and disseminated chromite.
Deformation	angular fracturing of some chromite grains.	intensely fractured and sheared pods, schlieren patches.
Xenoliths		
Intrusions		

Table 5-1. Continued.

Area	Murray Ridge	Pinchi Mt.
Host Rocks	harzburgite, minor dunite and orthopyroxenite.	harzburgite, dunite pods and layers, orthopyroxenite layers.
Chromite	disseminated chromite & chromite stringers in dunite layers	disseminated chromite & highly disseminated chromitite layer in dunite pod.
Deformation	early mantle deformation shown by folded orthopy- roxenite layers & some dunite layers. Well defined mantle foliation, i.e. tectonfabric.	highly folded dunite & orthopyroxenite layers, strong tectonite fabric.
Xenoliths		

Table 5-1. Continued.

Area	Mitchell Range	Mt. Sydney-Williams
Host Rocks	harzburgite, minor dunite & orthopyroxenite	harzburgite, abundant dunite, minor orthopyroxenite.
Chromite	massive chromitite pods & highly disseminated chromitite layers & pods, nodular chromitite in some layers.	disseminated Cr-spinel stringers in some dunite layers.
Deformation	chromitite layers & pods have pinch & swell and boudin structures - some pods derived from pulled apart layers, in harzburgite - coarse angular tectonic breccia & mylonitic shear zones, widespread porphyroclastic texture defined by orthopyroxene clots.	broad synform - antiform defined by dunite layers and smaller outcrop size isoclinally folded dunite & orthopyroxenite layers, recent faulting shown by angular breccia zones.
Xenoliths	km scale to m scale blocks of Cache Creek Group metasedimentary rocks.	
Intrusions	pre-obduction gabbro dykes, some altered to rodingite dykes. anorthositic gabbro dykes - pre or syn-obduction - undeformed, but offset.	meta-norite dykes, syn-obduction, unfolded but offset by small scale displacements on faults.

Fig.5-1. Reconstruction of mantle sequence represented by ultramafic allochthonous rocks from southern to central British Columbia.

CHAPTER 6: PETROGRAPHY

Petrography - introduction:

The petrography chapter summarizes features of silicate, spinel and sulphide minerals in transmitted and reflected light. Petrographic characteristics described apply to all alpine-type peridotites previously described and to their associated chromite and Cr-spinel occurrences. Features of special note are described separately and are related to the areas in which they occur. The first part of each section is descriptive and is followed by a discussion of mineral compositions. The sulphide and alloy assemblage is related to fO_2 and fS_2 conditions. Chromite and Cr-spinel compositional variations are in a separate chapter for detailed discussion.

Petrography of silicate minerals:

Olivine and orthopyroxene are the primary silicate phases associated with chromite from harzburgites and dunites. In all areas primary textures are obscured by tectonite fabric. Serpentinization has formed mesh textures defined by interlocking lizardite (Wicks & Whittaker, 1977a, b) where orthopyroxene has been preferentially altered to talc + serpentine along cleavage planes. Textures in serpentinized olivine show remnant unserpentinized cores or fragments and neoblasts were observed as very fine-grained aggregates. Tectonite fabric occurs as a foliation defined by stretched and fractured orthopyroxene porphyroclasts and stretched finely recrystallized olivine. Grain boundaries and fractures parallel to foliation have the most extensive serpentinization. Groundmass olivine and orthopyroxene retain 10 to 15 percent unserpentinized cores and from these, primary features and compositions are described.

Olivine from harzburgite:

Olivine formed, on average, 80 percent of tectonite harzburgite; it is fine-grained, sub to anhedral, and recrystallized into elongated aggregates which in part define the foliation. Serpentinization of olivine is usually 80 percent or more complete, resulting in flattened mesh textural units.

Olivine from dunite:

Olivine from dunite layers and pods may occur with up to 5 percent Cr-spinel and orthopyroxene. Serpentinization is more complete than in harzburgite, generally 90 percent or more. Unserpentinized olivine cores at centres of mesh textural units are similar to olivine from harzburgite. One contrasting feature is the occurrence of pale brown

Cr-spinel exsolution crystals (Fig. 6-1a, b). Exsolved Cr or Cr-Al spinels are approximately 10 microns in size. A skeletal texture (Fig. 6-1a) is most common although more massive "Blebby" forms also occur in the same section (Fig. 6-1b). This represents exsolution of excess Cr and Al from olivine, similar to exsolved Cr-spinel, also with pale brown colour, from the Elephants Head Dyke, South Africa (Eales & Snowdon, 1979). These Cr or Cr-Al spinels are in parallel alignment along olivine (001) planes, identical to their orientation in Elephants Head olivine. Exsolved spinel has not been observed from olivine in harzburgite but Talkington (1981) reported it from harzburgite at the White Hills Peridotite in western Newfoundland.

Chemical composition of Olivine:

Table 6-1 and Fig. 6-2 show the ranges and average Fo contents of olivines from this study. The overall range in Fo, 94.48 to 89.21, is also the range for olivine from harzburgite. Dunitic olivine is more restricted in range, 92.16 to 91.76, and has an average Fo content slightly less than that of olivine in harzburgite. The smaller number of olivine analyses from dunite may be responsible, in part, for this more restricted range.

Olivine from harzburgite and dunite show a similar to slightly wider range of Fo content compared to the White Hills Peridotite (90.4 - 91.3, harzburgite; 88.8 - 91.6, dunite: Talkington, 1981). In dunite the range is more restricted, 92.16 - 91.75, than dunite from the Bay of Islands ophiolite (87.50 - 91.30; Malpas, 1976) and the Vulcan Peak Peridotite in Oregon (89.9 - 91.9, Himmelberg & Loney, 1973).

Fig. 6-1 Exsolution of Cr or Cr-Al spinel with skeletal (a) and "Blebby" form in olivine from dunite (b). Cr or Cr-Al spinel - black; Olivine white. Scale bar in a & b: 50 microns.

Olivine inclusions in chromite occur in both harzburgite- and dunite-hosted chromite. A distinct difference exists between olivine inclusions from chromites of different host rocks. Average Fo in olivine inclusions from dunitic is 93.72 whereas for olivine inclusions from harzburgitic hosted chromite it is 89.91 (Table 6-1). The greater availability of Mg in dunitic olivine is indicative of its more refractory nature. If unserpentinized olivine inclusions in chromite are assumed to represent equilibrium compositions then inclusion olivine from dunite hosted chromite has higher Fo than adjacent groundmass olivine, 93.72 in inclusions and 91.93 in groundmass. This could suggest a loss of Mg from chromite to olivine before or during serpentinization. Similarly high Fo contents for inclusion olivines occurs from Thetford Mines area chromite, Eastern Townships, Quebec (D.H. Watkinson, pers. comm., 1983)

Table 6-1 *Fo in olivines from alpine-type ultramafics, B.C.

<u>Olivine</u>	<u>n</u>	<u>$\bar{X}$</u>	<u>Max.</u>	<u>Fo</u>	<u>Min.</u>
Overall range	29	92.04	94.5		89.2
In harzburgite	21	92.1	94.5		89.2
In dunite	3	91.9	92.2		91.8
In chromite, harz.	1		--	89.8	--
In chromite, dunite	4	93.7	93.9		93.5

* See Appendix A5 for complete analyses.

Geothermometry of B.C. alpine-type ultramafics:

A discussion on the development and application of geothermometry for olivine and spinel is given in Appendix A-13. Three possible geothermometers can be applied to Cr-spinel and olivine pairs, these are Jacksons' (1969) expression, the updated version of Roeder et al, (1979) and the equation of Fabries (1979). Fabries (1979) geothermometer may not give realistic temperatures since it ignores Fe^{+3} which is present in unaltered spinels and should influence Fe^{+2} - Mg equilibrium. Uncertainty surrounding Al in high Al spinels from inaccurate G^0 values will result in higher than expected temperatures of equilibration.

Temperatures are given for B.C. chromite and Cr-spinel with olivine for all three geothermometers and these are shown in Table 6-2. The following limitations must be kept in mind when calculating such temperatures.

1. Some degree of nonideal Fe^{+2} - Mg solid solution between olivine and spinel probably exists.
2. Incomplete solid solution between spinel end members likely occurs.
3. Errors in thermodynamic data.
4. Errors in microprobe analysis of Fe^{+2} , Fe^{+3} , Cr, Al and Mg.
5. Effects of minor elements on Fe^{+2} - Mg equilibrium.
6. Effects of serpentinization on primary compositions.

3

Table 6-2. Calculated olivine-spinel equilibrium temperatures.

Sample # and description N = # of analyses; T = °C	Jackson (1969) T	Roeder et al (1979) T	Fabries (1979) T
W82-47A: Cr-spinel and ol. inclusion, dunite N-5 - Cr-spinel; n=4 - ol.	1511	1092	1254
W82-193: Chromite and ol. inclusion, harzburgite n=5 - chromite; n=1 - ol.	1851	1291	1393
W81-77: Groundmass ol. and chromite, harzburgite. n=4 - chromite; n=4 - ol.	1453	1088	1218
W81-163: Groundmass ol. and chromite, harzburgite n=1 - chromite; n=4 - ol.	1361	1007	1197
W82-MCB: Groundmass ol: and chromite, dunite. n=1 - chromite; n=2 - ol.	1033	792	1079

Two pyroxene geothermometer:

Two temperatures from co-existing orthopyroxene and clinopyroxene in a websteritic patch from an orthopyroxenite vein were determined using geothermometers from Wood & Banno (1973) and from Wells (1977). Temperatures from the Wells geothermometer are about 100 degrees C lower than temperatures from Wood & Banno (1973). The temperature range defined by the two pyroxene pairs is 899 to 941 degrees C. Results are listed in appendix A13.

Olivine - spinel geothermometry from B.C. alpine-type ultramafics give a range of equilibrium temperatures from three variations on olivine - spinel equilibrium (Table 6-2). The Jackson (1969) equation gives the highest range of temperatures which results from Fabries (1979) are lower and those from the Roeder et al (1979) equation are lowest. Roeder et al (1979) temperatures range from 792 degrees to 1291 degrees C and support their experimental heating results on natural samples for Fe^{+2} - Mg sub-solidus equilibration below 1200 degrees C. Temperatures from Fabries (1979) equation which ignores ferric iron, are also reasonable but are 100 to 200 degrees higher. Results using the Jackson geothermometer are 300 degrees or more higher and are not considered realistic.

From Table 6-2, one conclusion is that temperatures from chromite and olivine inclusion pairs are higher than for groundmass olivine and chromite. This trend is apparent regardless of which olivine - spinel geothermometer is used. Higher temperatures from inclusion olivine may reflect, more closely, a trapping temperature of the inclusion. This is true only if there has been less subsolidus equilibration with inclusion olivine than with groundmass olivine and available chromite or Cr-spinel.

Orthopyroxene

Two pyroxene geothermometer:

Pyroxene analyses are listed in appendix A6. Orthopyroxene forms 20 to 30 percent of tectonite harzburgite which underlies 95 percent or more of B.C. Alpine-type ultramafic terranes. Orthopyroxene has porphyroclastic texture and deformed grains are elongated parallel to tectonite fabric. Most grains are 75 percent or more serpentinized with preferential development of serpentine, in the form of interlocking lizardite, along fractures and cleavage planes. Two nearly perpendicular

cleavage directions are often well-defined and low order interference colours are typical.

Clinopyroxene occurs as sparsely distributed exsolution lamellae in some orthopyroxene grains and rarely occurs in harzburgite groundmass. In orthopyroxenite veins sparse websterite patches are formed by very coarse-grained clinopyroxene and orthopyroxene. These two pyroxenes have heteradcumulate texture and smoothly lobate boundaries. Orthopyroxene from veins also shows abundant clinopyroxene lamellae from exsolution.

Clinopyroxene composition:

Clinopyroxene has withstood serpentinization with less alteration than orthopyroxene. Clinopyroxene analyses come from a websterite patch in an orthopyroxenite vein at Pinchi Mt. Analyses are listed in appendix A6 and are shown in Fig. 6-2. FeO is given as total Fe (Fe_t) as determined by electron microprobe.

Experimental and field investigations have shown that clinopyroxene is influenced by the composition of the liquid.

Fluid inclusions in chromite:

Fluid inclusions in upper mantle rocks can be considered equivalent in their distribution to those from high grade metamorphic rocks such as migmatites and granulites (Touret, 1981). In migmatites and granulites fluid inclusions are concentrated in minerals from the "Mobilisate" fraction (Touret, 1981) and this would correspond to partial melt in mantle peridotites. From such a partial melt, cumulate chromite may precipitate trapping volatiles from the partial melt or if chromite precipitates from a fluid phase, more likely at mantle pressures, it traps some of the fluid. Touret (1971, 1974) noted that fluid inclusions associated with anatectic

Fig.6-2. Ternary Mg - Ca - Fe_t plot of Pinchi Mt.

clinopyroxene analyses (solid circles) from a weathered orthopyroxenite vein. Orthopyroxene analyses are shown by solid triangles.

Hachured areas correspond to co-existing orthopyroxene and clinopyroxene from harzburgites of three areas:

- White Hills Peridotite; Talkington, 1981.
- Bay of Islands Complex; Malpas, 1976.
- Group 1 harzburgite xenoliths, San Carlos, Arizona; Frey and Printz, 1981.

Stippled areas represent co-existing clinopyroxene and orthopyroxene from orthopyroxenite veins of the White Hills Peridotite (Talkington, 1981).

Tie line joins co-existing orthopyroxene and clinopyroxene from Pinchi Mt.

melts are enriched in CO_2 whereas inclusions in lower-grade metamorphic rocks are usually H_2O and hydrocarbon (CH_4) rich (Mullis, 1979).

Existing analyses of the contents of fluid inclusions from upper mantle ophiolite-suite peridotites are sparse. Those that exist show that CO_2 is a minor phase, together with H_2O (Johan & LeBel, 1978) and in this respect they are similar to fluid inclusions from low or medium grade metamorphic rocks. Johan & LeBel (1978), in addition to CO_2 and H_2O report up to 5 wt. percent NaCl, anomalous for upper mantle rocks.

Roedder (1979) groups fluid inclusions into primary, pseudo-secondary and secondary groups. Primary inclusions are individual inclusions free from intersecting fractures and which retain their entrapment compositions and densities. Pseudo-secondary inclusions occur in trains or planar arrays and originally were related to fluid migration along a fracture which has since healed. Secondary inclusions are localized about an existing fracture or break in the host mineral. In upper mantle peridotites conditions remain at high temperatures for long periods of time (slow plate spreading rates) which allows fractures to anneal. Fluid inclusions in chromite are most commonly arranged in linear trains or planar swarms (Fig. 6-3a, b, c). A linear inclusion train is usually a normal section to a planar swarm. These constitute pseudo-secondary inclusions in chromite. Because partial melt compositions are likely to be constant over the period in which chromite precipitates (chromite in individual occurrences has uniform composition), fluids in annealed fractures probably approximate compositions in primary fluid inclusions. Inclusion trains or swarms with numerous small round to ovoid inclusions are considered younger since with time inclusions migrate, coalesce and become larger and less numerous (Touret, 1981). This relationship is apparent in Fig. 6-3a, b where in Fig. 6-3a inclusions are abundant, small and ovoid. In Fig. 6-3b

inclusions occupy relatively large negative crystal cavities (empty in Fig. 6-3b) with subhedral form. Remnant, smaller and irregularly shaped fluid inclusions surround negative crystal cavities, decreasing in abundance outwards away from what was a fracture.

In some cases larger fluid inclusions may be connected to a fracture or annealed fracture by a tube (Fig. 6-3c, d). With cooling and changing strain, necking of fluid inclusions occurs (Roedder; 1981, 1979) and this is well illustrated in Fig. 6-3d. Daughter minerals crystallized from fluids in fluid inclusions represent saturation of the fluid with respect to the elements in the mineral. An unknown, apparently cubic and opaque daughter mineral occurs in Fig. 6-3d.

Most important is the observation that abundant fluid inclusions, often with 2 visible phases (Fig. 6-3a, arrow); liquid + gas (bubble) occur in chromite. Some chromites contain as much as 10 modal percent fluid inclusions (W81-74, Scottie Ck.) and indicate volatile-rich conditions in an otherwise anhydrous mantle.

Pargasitic amphibole:

Highly disseminated chromitite from a 3 to 5 cm thick layer has sparsely distributed amphibole inclusions in chromite grains. Complete chemical analyses are given in Appendix A7. Several inclusions occur in a single grain from one sample and are subhedral, tabular in form with moderate second order interference colours. They are randomly oriented in host chromite and randomly dispersed.

Pargasitic amphibole inclusions with 3.0 to 3.2 wt percent Na_2O average 3.1 wt percent (four analyses). Fe/Mg ratios (cation basis) range from 0.05 to 0.06, averaging 0.06. These amphiboles are Cr-rich and contain up to 2.2 wt percent Cr_2O_3 and average 2.1 wt percent.

Fig.6-3a, Fluid inclusion train in chromite, arrow points to bubble in a two phase inclusion; 6b, Inclusion clusters around negative crystal cavities in chromite, now empty of fluid; 6c, Single primary fluid inclusion with pinched stem (arrow); 6d, Primary fluid inclusion with opaque cubic daughter mineral (arrow) and necked stem. A, b, c and d are all oil immersion photos, scale bar in each is 50 microns.

In the Al Ays ophiolite of Saudi Arabia (Neary, 1974) Johan & LeBel (1978) describe similar inclusions of pargasitic amphibole in chromitite. Maximum chromium content is as high as 3.4 wt percent; other compositional data are not given. Pargasitic amphibole also occurs in chromite from mafic-ultramafic complexes in eastern Canada and Ontario and have similar Na_2O contents (Talkington et al., 1982; Watkinson and Mainwaring, 1982). Johan & LeBel (1978) invoke a process of incongruent melting to form chromite from Cr-rich pargasitic amphibole by the reaction: $\text{Pa} = \text{Crt} + \text{Ol} + \text{Liq} + \text{Fl}$. This reaction may occur on a localized scale but is not considered appropriate, due to the paucity of pargasite, as a major chromitite-forming mechanism. Legendre (1982) gives data for pargasite and pargasitic amphibole inclusions in chromitite from New Caledonia (Fig. 6-4, hachured areas from Legendre, 1982). Amphibole inclusions from Mitchell Range chromitite (Fig. 6-4, solid circles) are strongly pargasitic, generally more so than those from New Caledonia. The combined data give a linear trend for increasing Na + K with increasing Al.

In the Mitchell Range Cr-bearing pargasite co-exists with unserpentinized olivine inclusions in a disseminated chromite grain. Pargasitic amphibole is thus considered to be similarly unaltered with primary composition. Sub-solidus equilibration with hosting chromite, or liquid - solid equilibration at the time of precipitation would account for Cr in the amphibole.

The presence of Na_2O concentrated to 3.19 wt percent is anomalous as is the entrapment of a hydrous silicate phase as a primary inclusion in chromite in an essentially anhydrous mantle. A possible source of H_2O and Na_2O would be interaction of mantle and brines of marine origin.

Fig.6-4. Pargasitic amphiboles from Mitchell Range chromite
(solid circles) compared to those from New
Caledonia (hachured areas, after Legendre,
1982).

Abbreviations: Ts - Tschermakite, Pa - Pargasite, Hb - Hornblende, Ed - Edenite (Deer, Howie & Zussman, 1966).

Chlorite:

Chromite forming highly disseminated and massive chromitite from the Mitchell Range, B.C., contains a small number of chlorite inclusions. Analyses of 8 chlorite inclusions are given in appendix A8. Chlorite inclusions co-exist with unserpentinized olivine in both disseminated chromite (forming chromitite) and in massive chromitite. Chlorite inclusions are randomly oriented, platy and have low birefringence.

Chlorite inclusions contain as much as 2.56 wt percent Cr_2O_3 and are Cr-rich chlorites. Cr_2O_3 averages 2.14 wt percent and is variable to as low as 1.03 wt percent. Fe/Mg ratios are similarly variable and range from 0.014 to 0.042 and average 0.027. Enrichment of Cr in chlorite inclusions probably occurred in part by sub-solidus re-equilibration but may be primary. Variability of Fe/Mg ratios suggests lack of equilibrium between chlorite and host chromite.

The presence of a strongly hydrous inclusion, such as chlorite, in chromite requires the presence of an aqueous phase probably introduced during serpentinization. However, the presence of parasitic amphibole and abundant fluid inclusions all combine to suggest a high volatile content at the time of chromite precipitation. Substantial amounts of Na would occur in aqueous solution of marine origin and could be the source of contamination, especially in a marine crust - mantle environment. In view of isotopic studies (Gregory & Taylor, 1981) which show that seawater contamination occurs ^{down} to the base of cumulate series rocks and the uppermost mantle, further penetration along established magma feeder zones could become possible. Certainly, more extensive work on primary inclusion chemistry, free from effects of serpentinization, and more isotopic work would be needed to substantiate this suggestion.

Platinum group mineral inclusions:

PGM (platinum group mineral) inclusions have been found only in chromite from chromitite occurrences and not in disseminated chromite. Chromitite with PGM inclusions however, are of several textural types which include massive chromitite and disseminated chromite layers, massive podiform chromitite and a massive chromitite nodule (Table 6-3). Individual chromite grains which constitute the various textures carry PGM inclusions which are sub- to euhedral and show hexagonal or cubic habits (Fig. 6-5a to f; 6-6a to f). Laurite (ideally, RuS_2) is the commonly observed PGM sulphide and exhibits a high reflectance and high relief against chromite. The inclusions are in the 5 to 10 μ range with rare examples reaching 15 μ . Grain boundaries between PGM sulphide inclusions and chromite are generally straight planar and angular representing a well equilibrated phase at the time of entrapment by chromite. In some cases PGM inclusions are partially or completely rimmed by a pale yellow sulphide, commonly Fe-Ni sulphide (probably pentlandite) which also exhibits a smooth border with chromite (Fig. 6-6e, f), but anhedral in form. A PGM and pentlandite pair was also observed at the contact between ovoid silicate inclusions and enclosing chromite (Fig. 6-6c, d & e). This could suggest a wetting effect (Hiemstra, 1979) with the subhedral PGM and sulphide grains adhering to a silicate droplet which was then incorporated into the host chromite. Legendre (1982) described similar silicate PGM associations and has identified several silicate grains as clinopyroxene.

In addition to pentlandite adhering to PGM inclusions, larger PGM subhedra exhibit internal exsolution or alteration patches (Fig. 6-5d, e & f).

The position of PGM inclusions in chromite grains is variable, ranging from centrally to peripherally located. One group of PGM inclusions is euhedral single phase sulphides with smooth borders against chromite and

they occur in unfractured chromite (Fig. 6-5a, b & c; Fig. 6-6a to f). Where fractures have developed in chromite, dark to opaque edges occur and in annealed fractures fluid inclusion trains trace the relict fracture. Euhedral PGM inclusions from chromite examined during this work are not spatially related to existing or annealed fractures and are thus considered primary.

A second group of PGM inclusions is sub-hedral to anhedral, has finely serrated borders with chromite and is intersected by fracture zones in chromite (Fig. 6-5d, e & f). In reflected light altered chromite is pale grey and is dark to opaque in transmitted light, typical of ferritchromit formed during serpentinization.

PGM inclusion compositions have been examined using energy and wavelength dispersive spectra on a Cambridge MKV electron microprobe. Complete analyses are given in appendix A3. PGM inclusions were analysed in order to limit interference from adjacent chromite. Osmium-ruthenium rich compositions were observed with lesser amounts of Rh and Ir. These elements suggest compositions intermediate in the solid solution series Laurite (RuS_2) - Erlichmanite (OsS_2). In addition to this a PGM inclusion with spongy texture from an altered chromite (Fig. 6-5d) contained about 4 wt percent As. Adjacent chromite had no detectable As. Consequently As was attributed to the two-phase PGM sulphide, one phase possibly being Osarsite (Snetsinger, 1972). Three points were analysed on the alteration zone inclusions and more As was found at the grain edges with a minor amount in the centre. The presence of As primarily at the grain edges is thought to represent alteration of a primary euhedral Os-Ru PGM inclusion similar to those observed in unfractured areas in chromite. Tables 6-3 and 4 summarizes PGM petrography and compositional variation. The presence and distribution of As here is analogous to As in alteration rims and zones in

PGM grains described by Stumpfl & Tarkian, 1976 from serpentinites and placer deposits. Platinum and Pd sulphides are absent from the sections examined, a trait which is common with chromite from ultramafic rocks of the Appalachian Orogen of western Newfoundland (Talkington & Watkinson, 1983) and with other ophiolite massifs such as the Troodos Ophiolite, Kokkinorotsos mine area (Constantinides et al., 1979).

Hypotheses concerning the genesis of PGM sulphide inclusions in chromite centre around three processes. One maintains that discrete PGM sulphide grains were trapped during precipitation of chromite. The second suggests that PGM sulphide minerals developed by exsolution from chromite (Gijbels et al., 1974). A third process involves the remobilization of PGE and the growth of PGM sulphides during serpentinization (Rucklidge, 1971; Stumpfl & Tarkian, 1976).

The possibility of PGM sulphide inclusions forming as remobilization products during serpentinization would require that A/ Some of the inclusions along chromite fracture zones show alteration textures internally or along rims and fractures and B/ That PGM sulphides be found in the serpentinized groundmass. PGM inclusions in chromite from the ultramafics examined, some of which are fractured, show subhedral form and a 2-phase spongy texture with serrated borders. This is the As-bearing PGM inclusion (Fig. 6-5d). However, PGM elements are absent from groundmass sulphides and from sulphides filling fractures in chromite. This would suggest little mobility of PGE during serpentinization, a condition which may occur in other ophiolites (Constantinides et al., 1979), and argues against this process as a mode of origin for primary PGM inclusions in chromite. In addition, the fresh condition of euhedral PGM inclusion is in favour of a primary origin.

The occurrence of PGE as diadochic elements in base metal sulphides has been documented from the Bushveld Complex in South Africa (Vermaak & Hendriks, 1976) and from low temperature alteration in placer deposits and serpentinized ultramafic rocks (Stumpfl & Tarkian, 1976). Substitution of PGE into chromite followed by exsolution to form PGM inclusions in chromite would be expected to exhibit some form of crystallographic control by the host chromite which is cubic. The apparently random distribution of PGM inclusions in chromite would argue against such control and entrapment at various stages of chromite growth is the preferred hypothesis.

Later fracturing of chromite with some fractures intersecting the PGM inclusions allowed alteration during serpentinization. This would produce the serrated borders and subhedral observed. This alteration is shown by the presence of As only with PGM inclusions in fractures in chromite.

Table 6-3. PGM inclusion - host chromite texture, and relation to massive or fractured chromite.

Habit: Euhedral (E) or Subhedral (S)	Host chromite texture	In unfractured chromite (U) or in Fracture zone (F)
E	Disseminated chromite layer.	U
E	Massive podiform chromitite.	U
E	Massive podiform chromitite.	U
E	Massive chromitite nodule.	U
S	Massive chromitite layer.	F
S	Disseminate chromitite layer.	F

Table 6-4. Distribution of As and PGE's from a subhedral PGM inclusion in fractured chromite (Fig. 6-9d).

Analysis	Position	Elements	As, relative intensity
1.	Edge	S-Fe-Ni-Os-Ru-Ir	As - moderate
2.	Centre	S-Ni-Os-Ru-Ir	As - weak
3.	Edge	S-Os-Ru-Ir	As - strong

7

Fig.6-5a, b & c, Euhedral PGM inclusions in unfractured areas in chromite grains; 5d, e & f, Subhedral PGM inclusions in chromite intersected by fractures. Serrated borders with chromite accompany subhedral form and higher than usual As in 5d. Reflected light, oil immersion, scale bar is 50 microns.

A

B

C

D

E

F

Fig.6-6a & b, Euhedral PGM inclusions in chromite; 6c, d & e, PGM inclusion with attached silicate (clino-
pyroxene ?) inclusion in chromite and a second
Ni-Fe sulphide in 6d & e; 6f, Small PGM inclusion
adhering to larger Ni-Fe sulphide in chromite.
Reflected light, oil immersion, scale bars are
50 microns.

Composition of Platinum Group Mineral inclusions:

From previous descriptions of PGM in chromite it was concluded from textural evidence that PGM inclusions were randomly trapped by chromite precipitating at high temperature. This environment is compatible with pressure and temperature conditions for which phase equilibria data on PGE (Skinner et al., 1976) has been compiled.

Appendix A9 provides electron microprobe analyses of PGM inclusions in chromite from the Mitchell Range, B.C. Fig. 6-7 shows variation of the three major PGE's, Os, Ru and Ir. The main variation reflects the laurite (RuS_2) - erlichianite (OsS_2) solid solution whereas IrS_2 content remains relatively constant. Limited data suggest the cores are more osmium-rich than the grain rims (Fig. 6-7). Compared to laurite inclusions in chromitite from other ophiolites (Legendre, 1982; Constantinides, et al., 1979) Mitchell Range laurites are less Ru rich and higher in Os while Ir is similar (Fig. 6-7). Sulphur contents average 32.0 wt percent, Os 15.0, Ru 36.9 and Ir 9.6 wt percent. Platinum and palladium are both very low, less than 2 and 1 wt percent respectively. The PGM is laurite with lower than average Ru and Os but slightly higher than average Ir (Cabri, 1981 - Table 8.5). Sample W81-86B contains an As-rich PGM intersected by a fracture in host chromite. The As-rich PGM has a mottled surface and has slightly lower reflectance than white PGM without As. This mottled texture may be an exsolution - alteration texture from appearance of the As phase. In several PGM grains intersected by fractures, As is predominant at the inclusion rim and decreases inwards (Fig. 6-5d). The rim effect suggests that As was supplied from alteration fluids during serpentinization or metamorphism.

Fig.6-7. Ternary Os- Ir - Ru plot showing Ru rich compositions of laurites, dashed line is composite PGM inclusion field from other ophiolites (after Legendre, 1982).

Secondary sulphides and alloys:

Secondary sulphides and alloys related to serpentinization, occur in dunite layers (Fig. 6-8a to f). At Mt. Sydney-Williams dunite layers with chromitite seams host secondary nickeliferous sulphides and the Ni-Fe alloy, awaruite.

Ni-sulphides and alloys are concentrated in chromitite seams in dunite layers and are sparsely distributed in dunite away from chromitite. Grain size is strongly correlated with proximity to seams where the largest sulphide and alloy grains occur between individual chromite grains or occupy fractures cutting them. Most sulphides and alloys are irregularly shaped with serrated borders and consist of single and multiple phases. Pentlandite and heazlewoodite usually form anhedral blebs enclosed by awaruite (Fig. 6-8a, b, c & e) plus magnetite rims (Fig. 6-8a, c, d, e & f). Awaruite also occurs as isolated anhedral grains (Fig. 6-8f). Magnetite may form in awaruite as blebs in addition to forming discontinuous rims (Fig. 6-8c). Secondary sulphides and alloy consist of: Pentlandite + Heazlewoodite + Awaruite + Magnetite: 6-1. The predominantly nickeliferous assemblage, with secondary texture, is considered to reflect Ni released during serpentinization of olivine.

Texturally and compositionally, assemblage 6-1 corresponds to sulphide - alloy mineralogy described by Eckstrand (1975) for altered ultramafic rocks. He similarly involves remobilized silicate (olivine) Ni to form Ni-sulphides and alloys. Reaction 6-1 implies a loss of S and addition of oxygen during later stages of serpentinization. Assemblage 6-1 is

a low sulphur assemblage, particularly with awaruite, and corresponds to extremely low fS_2 during initial serpentinization. Possible oxidizing conditions may be reflected in the appearance of magnetite rims although awaruite and magnetite often form together.

The system Ni - Fe - S:

In the low temperature Fe - Ni - S system (Misra & Fleet, 1973) the assemblage pentlandite - awaruite - heazlewoodite reflects low fS_2 conditions (Fig. 6-9). Mt. Sydney-Williams samples are shown in Fig. 6-9 as solid circles. At the low temperatures involved with serpentinization the fS_2 vs fO_2 diagram at 127 degrees C (Holland, 1959) is used where solid lines are based on reliable data and dashed lines on uncertain data (Fig. 6-10). The dominant assemblage from Mt. Sydney-Williams indicates extremely low fS_2 , less than 10^{-30} . Magnetite replacement indicates a shift to slightly oxidizing conditions accompanied by a drop in fS_2 (Fig. 6-10; Holland, 1959).

From the Ni sulphide - awaruite - magnetite assemblage low temperature serpentinization is interpreted to operate under extremely low fS_2 conditions. Under these conditions it is possible to concentrate silicate Ni as suggested by Eckstrand (1975). It is apparent that similar conditions prevailed during serpentinization of Mt. Sydney-Williams alpine-type peridotite and dunite. At Mt. Sydney-Williams, concentrated fluid flow along dunite layers was able to concentrate silicate Ni as sulphide and alloy phases. Chromitite seams have the coarsest and most concentrated Ni phases.

Fig.6-8a to f, Secondary Ni-Fe sulphides and alloy ⁺
magnetite related to serpentinization in dunite
layers. Abbreviations; Aw - awaruite, Pn -
pentlandite, Hz - heazlewoodite, Mt - magnetite,
Py - pyrite. Reflected light, oil immersion,
field of view in a to f is 0.18 mm.

Fig. 6-9. The system Fe-Ni-S, after Misra & Fleet (1973). "X's" are Pentlandite and Ni-Fe alloy analyses from Mt. Sydney-Williams.

Fig. 6-10. fS_2 vs fO_2 diagram for part of the system Fe-Ni-S-O, after Holland (1959), 127 °C.

CHAPTER 7: MAJOR-ELEMENT COMPOSITION OF ULTRAMAFIC
AND RELATED ROCKS

Major-element composition of ultramafic and related rocks:

Major element chemistry of ultramafic rocks is complicated by their alteration from original compositions during serpentinization. Interaction of aqueous solutions capable of removing some elements, particularly Ca, by various degrees renders establishment of primary concentrations difficult.

A study of chemical changes related to serpentinization at Burro Mountain, California (Coleman & Keith, 1971) found that Ca was the element most affected. It was significantly lower in the more serpentinized harzburgites. In conjunction with this is the composition of spring water associated with various ultramafic bodies. At Burro Mountain (Barnes & O'Neill, 1979) and in Oman (Barnes et al., 1978) spring waters are Ca^{2+} OH^- types and reflect on-going serpentinization at low temperature (less than 50 C) by meteoric water.

Although many elements are mobile during serpentinization it has become evident that relative amounts of SiO_2 , Al_2O_3 , total Fe, MgO , Cr_2O_3 and Ni remain essentially constant (Coleman & Keith, 1971). On this premise SiO_2 , Al_2O_3 and FeO were plotted against MgO for Mitchell Range harzburgite and a pre-obduction gabbro and compared to similar rock types from the Samail ophiolite, Oman (Boudier & Coleman, 1981). In addition CaO was plotted against MgO to examine the effect of alteration suffered by some gabbro dykes to form rodingite dykes.

Fig. 7-1a & b, and Fig. 7-2a & b show variations of major element oxides against MgO using data from Table 7-1. There are 12 harzburgite analyses from samples throughout the Mitchell Range, one of deformed gabbro and 3 of rodingite. Hachured fields represent equivalent rock types from the structurally complete Samail ophiolite, Oman (Boudier & Coleman, 1971) and are given for comparative purposes.

Al_2O_3 in harzburgite, gabbro and rodingitized gabbro is equivalent to and slightly higher than that of harzburgite (THZD) and gabbro (PL) from Oman (Fig. 7-1a). In addition MgO and FeO values are slightly lower (Fig. 7-1a & b). SiO_2 for both harzburgite groups is similar while gabbro and rodingite from the Mitchell Range are significantly lower (Fig. 7-2a & b). ^{in silica} CaO in Mitchell Range harzburgites (Fig. 7-2b) is equivalent to that from Oman but ranges to higher upper values of 6 wt percent. Gabbro from the Mitchell Range is low in CaO while rodingites are extremely enriched in CaO.

From this comparison with well-documented data from Oman it is evident from slightly higher ranges of Al_2O_3 and SiO_2 that these rocks are equivalent to upper levels of Oman mantle. The lower range of $\text{FeO}_{(\text{total})}$ in rodingites represents an overall Fe loss with rodingitization. CaO enrichment in rodingites relative to less altered picritic gabbro suggests that some pre-obduction gabbro dykes acted as planar conduits for Ca-rich aqueous solution and apparently accepted Ca liberated from harzburgite during serpentinization.

In summary Mitchell Range major element chemical data show depleted harzburgite to be less magnesian and ferroan than Oman equivalents. The occurrence of trapped partial melt, as pre-obduction dykes, has Fe and Mg contents close to that of parental harzburgite and higher Al than Oman gabbros. This feature suggests negligible fractionation of the partial melt and an initially more Al-rich liquid. This melt has been trapped in situ and was perhaps derived from garnet lherzolite. The initial melting trend from harzburgite to gabbro has been affected by alteration resulting primarily in strong Ca enrichment and formation of rodingite.

Fig.7-1. Al_2O_3 and FeO vs MgO for harzburgite, deformed
gabbro and rodingite from the Mitchell Range
compared to Oman data (after Boudier and
Coleman, 1981).

Fig.7-2. SiO_2 and CaO vs MgO , symbols as in Fig.7-1,
arrows indicate compositional evolutionary
trends.

SAMPLE NUMBER	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂
1	44.47	1.15	7.24	39.24	0.11	0.07	0.02	0.02
2	34.88	15.15	10.57	6.32	27.38	0.07	0.02	2.08
3	42.69	1.76	6.96	39.21	0.32	0.07	0.02	0.02
4	45.54	2.25	8.18	38.54	0.02	0.07	0.02	0.03
5	31.50	8.52	7.84	30.43	0.66	0.07	0.02	0.03
6	37.41	14.23	8.41	12.99	21.51	0.07	0.02	0.14
7	40.62	14.69	7.46	7.98	26.75	0.07	0.02	0.06
8	44.89	1.95	6.30	34.11	5.86	0.07	0.02	0.03
9	42.85	1.43	6.54	35.88	0.62	0.07	0.02	0.04
10	46.91	2.88	7.17	34.91	2.23	0.09	0.02	0.04
11	36.27	0.17	10.56	41.81	0.16	0.07	0.02	0.02
12	42.34	1.27	8.38	42.01	0.15	0.07	0.02	0.02
13	43.51	3.53	6.93	38.89	0.40	0.07	0.02	0.05
14	42.12	1.91	6.58	36.72	4.07	0.07	0.02	0.03
15	39.49	3.49	7.62	31.99	4.08	0.07	0.02	0.27
16	43.68	0.98	7.96	40.16	0.23	0.07	0.02	0.02

Table 7-1. Major and minor whole rock chemistry of Mitchell Range ultramafic and associated rocks.

S.N.	MNO	+H ₂ O	-H ₂ O	CO ₂	P ₂ O ₅	S	FeO	Fe ₂ O ₃	TOTAL
1	0.14	6.44	0.38	0.48	0.00	0.05	4.62	2.11	99.28
2	0.23	2.63	0.17	0.33	0.00	0.02	2.33	7.98	99.60
3	0.10	7.81	0.47	0.40	0.00	0.02	3.89	2.63	99.43
4	0.11	4.22	0.28	0.11	0.00	0.03	6.54	0.91	98.65
5	0.10	11.70	0.26	0.59	0.00	0.01	6.39	0.74	98.86
6	0.16	5.29	0.49	0.66	0.00	0.01	3.39	4.65	101.00
7	0.19	2.03	0.09	0.55	0.00	0.01	0.94	6.41	100.34
8	0.85	5.70	0.38	0.40	0.00	0.01	2.32	3.72	99.47
9	0.10	9.30	0.30	1.61	0.00	0.08	4.93	1.06	98.19
10	0.13	5.19	0.51	0.26	0.00	0.01	4.92	1.71	99.79
11	0.12	7.69	0.35	0.66	0.00	0.02	3.80	6.34	97.42
12	0.14	3.54	0.08	1.36	0.00	0.05	6.42	1.25	98.63
13	0.10	5.59	0.35	0.26	0.00	0.01	5.09	1.27	99.03
14	0.08	6.41	0.43	0.55	0.00	0.01	4.07	2.05	98.55
15	0.10	8.90	1.04	1.39	0.00	0.02	2.68	4.65	98.10
16	0.11	3.82	0.14	0.40	0.00	0.30	6.46	0.78	97.09

Table 7-2. Sample numbers and rock names for analyses in Table 7-1.

<u>Sample Number from Table</u>	<u>Field Sample Number</u>
1	W81-97
2	-98
3	-99
4	-105
5	-109
6	-110
7	-112
8	-113
9	-207
10	-161
11	-132
12	-191
13	-22
14	-33
15	-40
16	-53

Sample Description: 1; Harzburgite. 2; Rodingite. 3; Harzburgite.
 4; Harzburgite (Adjacent to chromitite pods). 5; Pre-obduction gabbro.
 6; Rodingite. 7; Rodingite. 8; Harzburgite (Adjacent to previous sample,
 7). 9; Harzburgite. 10; Harzburgite. 11; Dunitic harzburgite.
 12; Harzburgite. 13; Harzburgite. 14; Harzburgite. 15; Harzburgite.
 16; Harzburgite.

CHAPTER 8: PLATINUM GROUP ELEMENTS

Platinum Group Elements; introduction:

The platinum group elements (PGE) occur with decreasing abundance from ultramafic to felsic rocks. Highest average abundances are in chondritic meteorites. Work on the geochemical nature of PGE in rocks, meteorites, and on their siderophilic and chalcophilic nature has been reviewed by Crocket (1969, 1981). Physico-chemical properties of PGE are taken from tables in Mertie (1969) and from Shannon & Prewitt (1969). Subsequent plots of PGE^{from this thesis} are arranged, left to right, in order of decreasing fusion temperature.

PGE concentrations in chromitite were obtained by fire-assay neutron activation with detection limits in the 1 ppb range for Ph, Re; 3 ppb for Os and 5 ppb for Ru, Pt and Pd. Ir has a detection limit of 0.10 ppb. Since most values from chromitites are above the 1 ppb level radiochemical neutron activation analysis (Crocket, 1981) was not required. Data are presented in parts per billion and then as chondrite normalized plots which reduce variability of chondrite PGE values and allows for comparison of chromitite PGE with chondritic PGE values (Naldrett et al., 1979). The chondritic values of McBryde (1972) are used for this purpose. Table 8-1 gives analyses of PGE abundances in chondrites and these are plotted in Fig. 8-1. From these data chondritic PGE values plot in the range of 10^2 to 10^3 ppb and each set of data reflect the coherent geochemical nature of the platinum group elements.

PGE analyses are from selected chromitites from the Mitchell Range and represent three textural types; massive podiform, nodular and massive layered chromitite. They contain as much as 3 modal percent interstitial serpentine, primarily between nodules. Silicate inclusions are present in small amounts, less than 1 percent, and are usually serpentine.

Fig.8-1. Plot of chondrite PGE values from sources
in Table 8-1.

The chromitites selected were observed in polished thin section to contain one or more, up to 6, individual sub to euhedral PGM inclusions trapped with chromitite.

Table 8-1. PGE values from chondrites.

	Os	Ir	Ru	Rh	Pt	Pd
Janssens et al., 1977	757	771				617
McBryde, 1972	700	500	1000	200	1500	1200
Nadkarni & Morrison, 1974	970	830	840		1020	1660
Wasson, 1974	720	800	1900	300	1200	1300

PGE in Mitchell Range chromitites:

Chromitites from the Mitchell Range generally have PGE values and ratios much lower than those for carbonaceous chondrites (Fig. 8-1; 8-2). In samples 1 and 3 Table 8-2) the Pd/Ir ratio is higher than for chondrites - sample 1 is podiform chromitite and 3 is nodular chromitite from a layer. This indicates that a range of PGE values to give these variable ratios exists between different textural types of chromitite. In addition a range of values exists in chromitite of similar textural type from the same occurrence. Samples 1, 5 and 6 are podiform chromitite from across the Mitchell Range. This suggests that local heterogeneities occur with respect to the distribution of PGE in chromitite-forming environments.

Consistently higher PGE levels are shown for one sample with 850 ppm Ru, 440 ppm Os and 450 ppm Ir. This corresponds to a massive chromitite pod which measures 6 cm X 2.5 cm. Several polished thin sections cut from this pod all contain 3 to 6 discrete sub to euhedral PGM sulphide inclusions up to 20 microns in size and averaging 5 to 10 microns. Other samples showed 1 or 2 PGM inclusions or none at all. This direct

Fig. 8-2. Three cycle log plot of podiform, nodular and layered chromitite PGE analyses from the Mitchell Range.

correlation with composition favours control of PGE values by concentration of discrete PGM sulphide inclusions rather than a sampling problem. This role for chromite as a PGE collector by entrapment of PGM sulphide inclusions has also been shown for layered stratiform intrusions such as the Stillwater (Page, 1971) and Bushveld (Hiemstra, 1979; Hendriks & Peyerl, 1971) complexes. Gijbels et al. (1974) noted from mineral separates from the eastern Bushveld that Os, Ru and Ir contents, in constant proportions at the same stratigraphic level, showed steadily decreasing trends upwards. This was interpreted to result from solid solution mechanisms for the various minerals; consequently processes other than entrapment of PGM sulphides can affect overall PGE levels.

Table 8-2. Platinum group element composition of selected chromites from the Mitchell Range.

Sample	Au	Cr ₂ O ₃ (wt%)	Ru	Rh	Pt	Re	Os	Ir	Pd	Pd/Ir	Pt/Ir
1	11	36.3	70	11	< 5	< 1	4	4	< 5		
2	10	37.0	30	5	< 5	< 1	8	11	< 5		
3	8	43.7	55	8	< 5	2	12	15	30	2.00	
4	8	42.9	65	7	< 5	< 1	21	19	< 5		
5	3	47.2	100	9	< 5	< 1	43	36	< 5		
6	4	28.9	850	55	80	< 1	440	450	110	0.24	0.18

All concentrations other than Cr are in ppb.

1. Simpson deposit; massive podiform chromitite.
2. W81-171; nodular chromitite from layer.
3. W81-176; nodular chromitite from layer.
4. W81-CT; massive chromitite from layer.
5. W81-107; massive podiform chromitite.
6. W81-86; massive podiform chromitite.

Cr₂O₃ by XRF and all other elements by neutron activation; X-Assay Laboratories, Don Mills, Ontario.

PGE in Chromitite compared to PGE in mafic and ultramafic rocks:

PGE values in Mitchell Range chromitites are generally higher than for ultramafic and mafic rocks (Fig. 8-3, after Crocket, 1979; Table 8-3). Ru, Os and Ir are more concentrated ($Ru > Os > Ir$), in some cases by an order of magnitude, than in ultramafic rocks. This has similarly been noted in other alpine-type ultramafics in the Urals (Fominykh & Khvostova, 1970) and in the Mt. Albert body, Quebec (Crocket & Chyi, 1972). Chromitites are interpreted, on the basis of PGE content, to represent concentrated mantle residue derived from garnet lherzolite primitive mantle.

Fig.8-3. Three cycle log plot of PGE values (ppb) for
ultramafic and mafic rocks compared to chromitites
of the Mitchell Range (after Crocket, 1981).

Ophiolitic Harzburgite	Os	Ir	Ru	Rh	Pt	Pd	
Mt. Albert	6.7	2.4				7.6	Crocket & Chyi, 1972
Troodos	3.8	4.8				9.6	Becker & Agioritis, 1978
Thetford Mines		3.6			9.5	4.4	Crocket & Oshin, 1981
Alaskan Intrusions							
Donbas-Azov	3.9	8.5	0.65	4	82	30	Crocket, 1979
Peridotites - Komatiites							
Pike's Hill		1.1			14	8	Crocket, 1979
Fred's Flow		0.37			10	11	"
Theo's Flow		0.39			15.5	11	"
Mt. Clifford		2.4				8	"
Forrestannia		7.7				8	"
						4.7	"
Stratiform Complexes							
Skaergaard		0.26				17.5	Naldrett et al., 1979
Stillwater	6	0.25		< 5		55	"
Ocean Basalts							
Atlantic 36°N		.025				.69	Crocket & Teruta, 1977
Troodos	.006	.022				.45	Becker & Agioritis, 1978

Table 8-3. PGE from mafic and ultramafic rocks of different tectonic environments

(after Legendre, 1982).

PGE values from Mitchell Range and other ophiolitic chromitites:

Légendre (1982) provides PGE data from chromitites of several world localities; New Caledonia, Cyprus, Oman and Saudi Arabia. These values are used as a basis for comparison with PGE values from Mitchell Range chromitites (Table 8-4; Fig. 8-4).

With the exceptions of Oman and Cyprus trends the Mitchell Range PGE values are similar to trends from New Caledonia and Saudi Arabia and closest to Saudi Arabian chromitites. These values show a characteristic increase in Os, Ir and Ru levels, a strong drop through Rh and especially in Pt. A slight increase in Pd is characteristic of almost all PGE patterns. From this comparison of PGE values, Mitchell Range chromitites conform to PGE distributions from ophiolites elsewhere in the world.

Using the data in Table 8-4, $(Os + Ir + Ru) \times 100 / PGE$ ratios were plotted against $(Pt + Pd) \times 100 / PGE$ ratios in Fig. 8-5. In addition points for chondrites, komatiites and stratiform complexes were plotted for comparison against ratios from Mitchell Range chromitite and ophiolites. This shows the relative enrichment in Os + Ir + Ru against chondrites and fractionated mafic magmas, including komatiites. Chromitites and ophiolites in general are enriched in residual elements (Os, Ir, Ru) while Pt and Pd are fractionated into ultramafic and mafic magmas.

	number of samples	n	Os	Ir	Ru	Rh	Pt	Pd
New Caledonia; Legendre, 1982		3	327	227	100	7	5	5
Cyprus	"	3	24	14	123	7	17	27
Oman	"	2	11	6	28	3	10	5
Saudi Arabia	"	2	93	85	133	7	22	45
Mitchell Range, British Columbia		6	88	89	195	16	17	27
Chondrites; McBryde, 1972		700	500	1000	200	1500	1200	
New Caledonia		.47	.45	.10	.04	.003	.004	
Cyprus		.03	.03	.12	.04	.011	.023	
Oman		.02	.01	.03	.02	.007	.004	
Saudi Arabia		.13	.17	.13	.04	.015	.036	
Mitchell Range, British Columbia		.12	.18	.20	.08	.011	.023	

Table 8-4. Average chondrite normalized PGE values from the Mitchell Range, B.C. and other ophiolitic chromitites (after Legendre, 1982).

chondrite

Fig.8-4. Chondrite normalized PGE contents of Mitchell Range chromitites (solid circles) compared to contents from New Caledonia (hexagons), Cyprus (open circles), Oman (triangles) and Saudi Arabia (squares), after Legendre, 1982).

Fig.8-5. Plot of $(Os + Ir + Ru) \times 100 / (Os + Ir + Ru + Rh + Pt + Pd)$ vs $(Pt + Pd) \times 100 / (Os + Ir + Ru + Rh + Pt + Pd)$ for Mitchell Range chromitites compared to values from chromitite in other environments (after Legendre, 1982).

Conclusions from PGE chemical composition:

Mitchell Range chromitites show "Normal" PGE distributions and have comparable PGE concentrations to other world ophiolites. Os, Ir, and Ru levels are above those of mafic and ultramafic rocks such as komatiites and gabbros which represent various degrees of partial melting from peridotitic mantle. This relationship reflects fractionation trends where Ir, Os, and Ru are left in depleted mantle (Harzburgite) and Pt + Pd are partitioned into derived partial melts. Chromitite PGE values are consequently interpreted to represent refractory residues from partial melting of primitive mantle (Lherzolite).

Individual chromitite PGE values indicate some heterogeneity in Mitchell Range podiform chromitites. This suggests unequal distribution of PGE or sulphur, necessary to precipitate PGM sulphide inclusions in chromitite. From polished thin section studies the range of PGE values is directly correlated to variations in abundance of discrete PGM sulphide inclusions. For these occurrences in harzburgite hosted chromitite a process of entrapment of PGM sulphides in precipitating chromite is favoured over PGE solid solution.

CHAPTER 9: CHROMITE AND Cr-SPINEL

Introduction:

Chromite occurs most commonly as an accessory mineral in mafic and ultramafic rocks and under appropriate circumstances it becomes concentrated to form ore grade mineralization. Chromite belongs to the spinel solid solution series and one of the main substitutions is Al^{+3} for Cr^{+3} in octahedral sites. The octahedral radius of Cr^{+3} is $0.615\text{\AA}$ (Shannon and Prewitt, 1969) and is similar to the octahedral radii of Al^{+3} ($0.53\text{\AA}$), Fe^{+3} ($0.645\text{\AA}$), Ti^{+4} ($0.68\text{\AA}$), and Mg^{+2} ($0.72\text{\AA}$) (Burns and Burns, 1975). Consequently Cr^{+3} can be substituted into the octahedral sites of several silicate minerals apart from occupancy of octahedral sites by Cr^{+3} in the spinel-magnesiochromite solid solution series. The capability for these elements to substitute into the spinel lattice reflects the compositional variations in the precipitation environment of chromite and Cr-spinel. The stability of chromite relative to silicate minerals during serpentinization and metamorphism further enhances chromite's value as a petrogenetic indicator. Finally, since chromite is usually one of the first phases to precipitate from a basaltic liquid, and since Cr-spinel is an equilibrium phase in the mantle, it provides a good petrogenetic tracer reflecting the composition of its protolith.

In this section a data base of 358 electron microprobe chemical analyses of chromite is used to characterize and examine chromite types and to evaluate the effects of various inclusion phases. The main data file and the Bio-Medical-Data-Processing (BMDP) command programmes written to examine the data are given in appendices A3 and A12. A basic statistical description of the data file presents data by individual localities (Fig. 1-1) and is in appendix A2 while a description of electron microprobe operating conditions is in appendix A11.

Analytical Method:

The data file, compiled during 1981-1983 contains analyses of chromite and Cr-spinel from widely separated occurrences in the Cache Creek Group, with the exception of the Anarchist deposit which is in Anarchist-Series metasedimentary rocks. From the different areas are representative chromite samples of various textural types, and from different host rocks. Individual chromite grains themselves are variable, some with silicate and/or sulphide inclusions or some with fluid inclusions. Many chromite grain rims show partial alteration to ferrit-chromit and some are severely altered with only skeletal chrome-bearing material remaining. Following a discussion of the factors controlling chromite composition, variation diagrams are used to illustrate the above-mentioned factors and comparisons to other appropriate chromite compositions are presented where useful.

Refractory chromite and chromite from partial melt:

In primary mantle undergoing partial melting chromite can form in two ways. It can precipitate from a partial melt as a cumulus mineral or it can be left behind as part of the refractory residue after extraction of the partial melt. As a refractory residue, pods or layers containing chromitite thus formed should be in equilibrium with the host rock and with the magma being extracted. They would become increasingly Cr-rich as more Al was fractionated into the magma. Cr-rich spinels encountered in this study are from harzburgites which are thought to be residues from partial melting. This would require depletion of clinopyroxene and orthopyroxene providing Al to the partial melt and leaving residual harzburgite bearing chromite with high Cr and Mg. Chromite precipitating from a partial melt should experience the same type of constraints as did chromite from

stratiform layered intrusions such as the Muskox Intrusion (Irvine, 1965, 1967, 1975, 1977) or the Bushveld Complex (Cameron, 1978, 1980).

During partial melting of mantle the silicate phase which contributes most Cr to the magma is Cr-diopside along with some Cr from orthopyroxene. Dickey et al., (1971) have shown in the 5 component system:

that diopside, which can contain over 0.9 wt% Cr_2O_3 , will melt incongruently to Cr-spinel plus liquid at 1 atm pressure. However, above 10 kb diopside will melt congruently (Dickey, 1975). For pressures less than 10 kb, appropriate for the upper mantle, partial melting could produce Cr-spinel from diopside. The paucity of clinopyroxene in the harzburgites studied is compatible with nearly complete depletion in lherzolite mantle with precipitation of chromite beginning near the end of depletion. In this manner olivine and co-existing Cr-spinel in a picritic tholeiitic liquid could generate the poikilitic texture where predominantly olivine forms inclusions in chromite.

Based on inclusion studies which document pargasitic amphibole in chromite grains (Johan & LeBel, 1978) a second example of incongruent melting may form some chromite. Similar pargasitic amphibole inclusions in B.C. chromite may also give evidence for the incongruent melting reaction:

With increased partial melting residual harzburgite acquires an increasing Mg/Fe^{+2} ratio and the refractory spinel Cr/Al ratio increases. The increasing Cr/Al ratio in spinel is a result of Cr and to a greater extent Al preferentially going into liquid (Kurat et al., 1980). Once in the liquid Cr favours entry into the spinel phase. This occurs due to the following:

$D_{\text{liquid-rock}}^{\text{Al}} > D_{\text{liquid-rock}}^{\text{Cr}}$ and also because

$D_{\text{spinel-liquid}}^{\text{Cr}}$ increases with increasing Cr content of the spinel (Dickey & Yoder, 1972; Kurat et al., 1980). For Al-spinel $D_{\text{spinel-liquid}}^{\text{Cr}}$ is about 20 (Kurat et al., 1980) and in chromite it is about 100 (Hill & Roedder, 1974).

To summarize the above controls, chromite with lower Cr/Al ratios represent Cr-spinel left behind as refractory minerals while chromites with higher Cr/Al ratios originated by fractional crystallization from a picritic tholeiitic melt or by equilibration of refractory accumulations with magma.

Equilibration with adjacent silicates and liquids:

The range of $\text{Mg}/(\text{Mg} + \text{Fe}^{+2})$ for chromite from B.C. alpine-type ultramafics is similar to that of ophiolites in general (Irvine & Findlay, 1972) but with a slightly wider range of Cr/Al ratios (Fig. 9-1). A method for controlling spinel compositions suggested by some authors (Thayer, 1946; Irvine, 1965, 1967; Jackson, 1969; Loney et al., 1971; Sigurdsson & Schilling, 1976; Sinton, 1977; Frey & Prinz, 1978; Fisk & Bence, 1980 and Talkington & Malpas, 1980a,b) is by equilibration of spinel and its co-existing silicates. These controls result because 1/ spinel is an early phase precipitating from liquids where fractional crystallization occurs and should be most directly tied to the initial composition of its host rock and early melt; 2/ during subsolidus cooling where Cr-spinel is exsolved from mantle silicates it should retain some chemical traits of its host mineral, and; 3/ if cognate xenoliths alter the chemistry of the liquid from which Cr-spinel crystallized, then the Cr-spinel should reflect the altered liquid chemistry.

Spinel in ophiolite complexes exhibit Cr/Al ratios which are independent of Mg/Fe^{+2} , a feature in contrast to spinel chemistry from stratiform complexes. Irvine (1967) maintains that the Mg/Fe^{+2} ratio of co-existing spinel and silicate, when in equilibrium, is closely linked. The major variable component is Al_2O_3 which produces widely variable Cr/Al ratios with nearly constant Mg/Fe^{+2} . The variability of Al_2O_3 has been documented in alpine peridotites (Loney et al., 1971; Sinton, 1977), in mid-Atlantic Ridge basalts (Sigurdsson & Schilling, 1976; Fisk & Bence, 1980), in ultramafic xenoliths (Basu & McGregor, 1975; Frey & Prinz, 1978) in stratiform intrusions (Jackson, 1969) and in ophiolites (Talkington & Malpas, 1980a, b). From this evidence it is apparent that the composition of spinels are strongly influenced, particularly with respect to Al_2O_3 , by the composition of the liquid from which they crystallize.

Subsolidus equilibration:

An additional mode of occurrence for Cr-spinel is that of subsolidus exsolution from diopside to form disseminated spinel. Cr-spinel formed in this manner occurs as finely disseminated subhedral, often embayed, grains at the edges of orthopyroxene and/or olivine. If fO_2 is low and constant (Irvine, 1967) then variations in temperature and pressure are the two major controls on the formation of spinel by exsolution. McGregor (1974) has examined sub-solidus equilibration in the 3 component system:

and demonstrated a temperature dependence for Al_2O_3 solubility in enstatite for the reaction:

Similar experimental work by Anastasiou & Seifert (1972) and Boyd & England (1964) has also shown, at constant pressure, that increasing amounts of Al_2O_3 are stable in En at high temperatures. Pressure controls on this reaction were studied by Obata (1976) who found that with increasing pressure more Al_2O_3 was stable in En. On this basis, equation 9-1 will proceed to the right, in favour of Al-enstatite with both increasing temperature and pressure. The reverse is also true so that with decreasing temperature and pressure En will exsolve Al_2O_3 to form Al-spinel. This process appears valid for pressures up to 10 kb, anhydrous (Anastasiou & Seifert, 1972). However, most authors agree that the solubility of Al_2O_3 in En is primarily temperature dependant (Boyd & England, 1964; Anastasiou & Seifert, 1972 and Obata, 1976).

In the four component system $\text{CaO} - \text{MgO} - \text{Al}_2\text{O}_3 - \text{SiO}_2$, CaO represents the presence of clinopyroxene which is perhaps more applicable to mantle. Green (1964) applies this system to the Lizard, Cornwall, where a coarse-grained primary peridotite core is surrounded by a finely foliated recrystallized peridotite rim. Contrasting Al_2O_3 contents are described from pyroxenes of the core and recrystallized rim. At the core Al-En and Al-Diop co-exist with green Al-spinel, and reflect crystallization at high pressure. The rim peridotite, recrystallized at lower pressure has En and Diop with normal Al_2O_3 contents. This difference in Al is shown by the reaction:

and is held to be pressure dependant. The appearance of a spinel phase and control of its composition in peridotite can thus be achieved by both decreasing pressure or temperature. In the setting of rising mantle diapirs and obduction for ophiolites and alpine-type peridotites it would seem that both decreasing pressure and temperature would provide favourable

conditions for the exsolution of disseminated spinel. However, recent work on spinels from crustal and mantle environments show no dependence on pressure for the content of Al in spinels.

Summary of mantle processes controlling chromite petrogenesis:

1. Partial melting; high temperature at constant high pressure...

- Refractory Cr-spinel will have lower Cr/Al ratios because;

$$D_{\text{liquid} - \text{rock}}^{\text{Cr}} > 1$$

(i.e. Cr preferentially goes to liquid as rock melts)

- Chromite precipitated from a partial melt will have higher Cr/Al ratios because;

$$D_{\text{liquid} - \text{rock}}^{\text{Al}} > D_{\text{liquid} - \text{rock}}^{\text{Cr}}$$

but with increasing Cr content in spinel;

$$D_{\text{spinel} - \text{liquid}}^{\text{Cr}} \text{ increases rapidly.}$$

2. Subsolidus equilibration, variable temperature and pressure.

- Cr/Al ratio of spinel from most environments is directly tied to Al content of co-existing silicates, and the availability of that Al is controlled primarily by temperature - greater at low T and less available at high T.

3. Direct exsolution, low temperature and pressure.

- Because of decreasing solubility of Al in enstatite at lower temperature it exsolves Al_2O_3 to form Cr-spinel disseminated in depleted mantle.

Comparison of B.C. chromite to chromite from other complexes:

Fig. 9-1 shows an extensive overlap of the range in chromite compositions from B.C. with compositions from other complexes (after Irvine and Findlay, 1972). The range of XMg is slightly lower in the main part of Fig. 9-1. An anomalous trend is strongly shown by high CRT values, which correspond to the lowest XMg values. It is also notable that in the main part of

Fig. 9-1, the lower XMg area between CRT 65 and 82 overlaps best with the field for stratiform chromite.

The data distribution on which Fig. 9-1 and the outline of the B.C. chromite field is based is shown in Fig. 9-2. Fig. 9-2 is a BMDP plot of all analyses from the B.C. chromite data file. Individual points represent between 1 and 20 analyses, asterisks indicate a point with more than 20 analyses.

The remainder of this chapter first describes compositional variations with individual chromite grains, massive chromitite pods and compound pods. This serves as a basis upon which to compare compositional variations in chromite based on texture, host rock type and from one area to another.

Compositional zoning in chromite grains:

Individual chromite grains from a highly disseminated chromitite layer were examined for compositional zoning by five point microprobe traverses across each grain. Data are shown in Figs. 9-3; 9-4 and Table 9-1; 192B and 173. Compositional differences between the two separate grains for their averaged compositions are all less than one weight percent with the exception of FeO (1.38 wt%). This suggests that chemically homogenous conditions prevailed in the environment from which chromite of this layer precipitated.

Zoning within each grain from 192B is slight and where developed is similar (Fig. 9-3). The pattern of zoning is assymetric with increases or decreases developed only toward one edge of each grain. There is an increase in FeO (15-21%) and MnO, although weak for MnO. For this change in FeO, Fe_2O_3 remains constant and shows constant to slightly decreasing oxidation ratio. Serpentinization has had little effect on grain edges

Fig.9-1. Plot of $100 \text{ Cr} / (\text{Cr} + \text{Al})$, hereafter CRT, vs $100 \text{ Mg} / (\text{Mg} + \text{Fe})$, hereafter XMg, showing the compositional ranges of B.C. alpine-type chromite and those of chromite from stratiform complexes and other alpine-type areas (after Irvine and Findlay, 1972).

Fig.9-2. CRT vs XMg plot showing all data points on which boundaries for the field of B.C. chromite is based. Asterisks indicate over 20 points, plot is from BMDP data processing package (see appendix A12).

1PAGE 6 RATIO PLOTS - CHROMITE FROM DIFFERENT HOST ROCKS

	MEAN	ST. DEV.	REGRESSION LINE	RES. MS.
X	.52035	.16329	$X = -.55092*Y + .89010$	.01933
Y	.67115	.15692	$Y = -.50298*X + .93288$	.01765

in these grains. The increase in FeO can be related to primary compositional variation by equilibration with changing FeO in magma or by later sub-solidus equilibration. This offsets a decrease in Cr_2O_3 where Al_2O_3 remains constant (Fig. 9-3). These grains also show a decreasing Cr/Fe ratio towards one edge. Sub-solidus equilibration with trapped interstitial partial melt would reflect decreasing Cr/Fe as restricted fractionation of pore liquid proceeded. In support of this process is an increasing Fe/Mg ratio towards grain edges. A peculiar feature of these grains is assymmetric zoning, which may be explained by an environment where chromite equilibrates with pore liquid. Interstitial pore liquid would not necessarily be evenly distributed around chromite grains, but instead could be in contact with only one side of individual grains. Sub-solidus equilibration between chromite and liquid would be restricted to the chromite edge in contact with liquid resulting in asymmetric zoning.

Chromite from a nodular part of a chromitite layer was similarly examined for compositional zoning (Fig. 9-4; Table 9-1; -173). The averaged composition of the chromitite sample has higher Al_2O_3 , MnO and MgO whereas Cr_2O_3 is similar to averaged disseminated grain compositions (Table 9-1). FeO and Fe_2O_3 are both lower.

Zoning from one edge to the other of the grain from chromitite is negligible with only slight increase in FeO decrease in MgO at grain edges. Cr_2O_3 shows a vague decrease towards the grain centre with corresponding increase in Al_2O_3 , the difference in contents are, however, low and less than 1 weight percent, FeO and MgO show the greatest difference, 1.58 and 1.57 weight percent respectively, from grain edge to centre (Table 9-1). Zoning in this chromitite sample is very weak although more symmetric than for disseminated chromite grains (Fig. 9-4 vs. Fig. 9-3).

Fig.9-3. Analyses from a single disseminated and unaltered chromite grain to examine zoning in W81-192B.

192 B: ● grain 1 ; ▲ grain 2 .

Fig.9-4. Analyses from a single unaltered fragment of massive chromite to examine zoning in W81-I73.

Table 9-1. Variation in chromite compositions for microprobe traverses across two grains in one sample.

wt %	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	Fe ₂ O ₃	FeO	MnO	NiO	Total	
192B	0.16	14.64	52.66	5.79	14.36	0.23	13.19	101.03	Edge
grain 1	0.13	14.98	52.72	5.46	14.92	0.21	12.92	101.35	
	0.16	15.00	52.50	5.44	15.44	0.31	12.55	101.41	Centre
	0.09	14.99	50.71	4.50	21.55	0.27	8.36	101.47	
	0.14	15.44	48.84	6.22	22.58	0.32	7.92	101.46	Edge
n=5; $\bar{X}$	0.14	15.01	51.49	5.48	17.77	0.27	10.99	101.15	
192B	0.16	14.92	52.16	5.07	15.26	0.30	12.44	100.31	Edge
grain 2	0.17	14.95	52.81	5.02	15.22	0.27	12.66	101.10	
	0.15	15.19	52.74	5.17	15.43	0.29	12.63	101.60	Centre
	0.12	14.67	52.92	5.30	15.43	0.26	12.49	101.19	
	0.13	13.99	51.61	4.87	20.60	0.31	8.86	100.37	Edge
n=5; $\bar{X}$	0.15	14.74	52.45	5.09	16.39	0.29	11.82	100.93	
173	0.16	16.87	51.63	4.00	12.95	1.18	13.60	100.39	Edge
grain 1	0.16	16.59	51.28	6.79	11.71	1.10	14.84	102.47	
	0.16	17.29	51.08	4.17	12.87	1.19	13.70	100.46	Centre
	0.16	16.52	51.46	4.40	12.89	1.11	13.59	100.13	
	0.18	16.91	51.55	3.47	13.29	1.21	13.27	99.89	Edge
n=5; $\bar{X}$	0.16	16.84	51.40	4.57	12.74	1.16	13.80	100.67	

Compositional variation of Cr-spinels from dunite layers:

Cr-spinels hosted by dunite layer structures are usually altered to opaque rims. Microprobe analyses of a completely altered grain and a rare unaltered Cr-spinel are listed in Table 9-2 and shown in Fig. 9-5. Contrasts in composition are extreme between altered and unaltered spinel ^{which} averages 40.52 weight percent. Cr_2O_3 and MgO similarly are lower in altered spinel while TiO_2 , MnO , FeO and Fe_2O_3 are all higher (Fig. 9-5; Table 9-2). The completely altered spinel composition is considered to originally have been a Cr-spinel.

Chemical transition from unaltered Cr-spinel cores to Cr-magnetite, and magnetite rims, is shown in Fig. 9-6 with averaged analyses from Table 9-2; W82-41; -44. Core and rim analyses for these two separate samples show the same alteration trends between each other and totally altered spinel. TiO_2 and Cr_2O_3 are an exception. In -44, compositional differences between core and rim are less extreme (Fig. 9-6) and reflect less complete alteration. The contrasting trends for TiO_2 and Cr_2O_3 in -41 and -44 (Fig. 9-6) suggests that Ti has been enriched and Cr depleted by interaction with solutions causing alteration of -41. For all other elements in totally unaltered and altered grains and between unaltered cores and altered rims alteration trends are similar and differ only in degree of alteration (Fig. 9-5; Fig. 9-6). It is concluded from these similarities in alteration trends that completely altered Cr-magnetite grains were initially Cr-spinels of composition similar to those in Table 9-2 for unaltered grains or parts thereof.

Fig.9-5. Comparison of composition between unaltered and altered Cr-spinel.

Fig.9-6. Comparison of compositional variation between
unaltered chromite cores and altered ferritchromite
rims.

Table 9-2. Compositions of altered and unaltered Cr-spinel from dunite-layer hosted spinel seams.

wt %	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	Total
-44 unaltered grain	0.12	40.73	28.31	1.63	12.80	0.27	16.67	100.52
	0.11	40.30	28.35	2.06	12.57	0.31	16.86	100.56
	0.10	40.53	28.52	1.81	12.77	0.29	16.82	100.84
	0.10	40.50	28.30	1.82	13.23	0.29	16.49	100.73
n-4; $\bar{X}$	0.11	40.52	28.37	1.83	12.84	0.29	16.71	100.67
-19 altered grain	0.18	0.25	17.38	52.59	23.51	0.71	4.57	99.19
	0.23	0.35	20.36	48.56	24.19	0.91	3.94	98.54
	0.22	0.20	23.38	46.11	28.03	0.87	1.92	100.73
n-3; $\bar{X}$	0.21	0.27	20.37	49.09	25.24	0.83	3.48	99.49
-41 n-6; $\bar{X}$ unaltered core	0.11	34.68	35.07	1.24	13.59	0.30	15.02	100.01
-41 n-5; $\bar{X}$ altered rim	0.13	1.15	21.46	46.15	29.58	0.58	1.00	100.05
-44 n-2; $\bar{X}$ unaltered core	0.11	39.73	28.48	2.44	13.05	0.32	16.49	100.62
-44 n-2; $\bar{X}$ altered rim	0.10	31.96	33.98	4.36	15.97	0.40	13.67	100.44

Compositional variation in olivine bearing chromite:

Fig. 9-7 and Table 9-3 present analyses from a single chromite grain in nodular chromitite. This grain contains several unaltered olivine inclusions and altered inclusions which are now serpentine. Detailed microprobe analyses were done to examine chromite adjacent to and away from olivine inclusions to test for chemical gradients between chromite and olivine. From Fig. 9-7 and Table 9-3 it is evident that compositions from areas adjacent to and away from olivine inclusions are very similar. Differences in composition are all less than 0.25 wt% and apart from showing that chromite composition here is unaffected by olivine inclusions it shows that inclusion-bearing chromite is homogeneous on the single-grain scale.

Fig.9-7. Analyses from a single chromite grain with
olivine inclusions.

-174 A,B; same grain.

● A; away from olivine inclusions.

▲ B; adjacent to olivine inclusions.

Table 9-3. Compositional variation of chromite adjacent to and away from olivine inclusions in chromite. n=analyses. W81-174A, B.

wt %	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	Total
-174A								
n=5	0.11	11.45	55.25	5.42	15.28	0.95	11.55	100.01
in chromite								
max.	0.13	11.64	55.79	5.83	16.00	1.04	11.68	
min.	0.06	11.36	55.10	4.72	14.79	0.86	11.20	
range.	0.07	0.28	0.69	1.11	1.21	0.18	0.48	
-174B								
n=5	0.13	11.67	55.00	5.36	15.48	0.97	11.46	100.05
adjacent to olivine								
max.	0.14	11.76	55.35	5.94	15.88	1.03	11.64	
min.	0.11	11.62	54.80	4.99	15.16	0.89	11.18	
range.	0.03	0.13	0.55	0.95	0.78	0.14	0.46	

W81-174A, B are the same grain.

A: points away from olivine inclusions, 150 microns.
B: points adjacent to olivine inclusions, 20 microns.

Compound chromitite pods:

Variation in chromite composition from single compound chromitite pods are shown in Fig. 9-8 and in Fig. 9-9; Table 9-4. Fig. 9-8 shows variation for a compound pod consisting of a highly disseminated chromitite rim enclosing massive chromitite at the centre. A second type of compound pod has heavily disseminated chromitite patches enclosed by massive chromitite (Fig. 9-9; 9-10; Table 9-4; 9-5). Contacts between heavily disseminated patches and massive chromitite are sharply defined and smoothly lobate. Groundmass in heavily disseminated patches consists of pale grey-green serpentine.

Variation in rim and core:

Differences in composition between highly disseminated chromitite from the rim of the pod and massive chromitite from the core (Fig. 9-8) are negligible. All variations are less than one weight percent and indicate well-equilibrated chromite regardless of texture or position. The one variation of significance is that of Fe^{+2} and Fe^{+3} between chromitite from the rim of the pod and the core. Rim chromitite has lower Fe^{+2} but higher Fe^{+3} , i.e. higher oxidation ratio, than massive chromitite from the core of the pod. This would be likely since core chromitite, massive in texture, is protected from contact with serpentinizing solutions whereas highly disseminated chromitite from the rim of the pod is in a position to be oxidized. Apart from this contrast in oxidation ratios (rim; 0.09; core; 0.07), primary compositions are very similar between disseminated and massive chromitite.

Variation between disseminated chromitite patches and massive chromitite:

Variations in composition between different disseminated chromitite patches within the massive pod are low (Fig. 9-9, 9-10; Table 9-4, 9-5). Differences for all element oxides from disseminated chromitite patches are less than two weight percent and oxidation ratios are very similar (0.090, 0.094) and are also similar to oxidation ratios for disseminated rim chromitite. It is apparent from this relationship that textural control over oxidation is less well defined since for massive chromitite ratios are 0.12 and 0.98. The ratio 0.12 for massive chromitite is relatively high compared to massive chromitite from both compound pods and may reflect localized more extreme oxidation.

Massive chromitite (Fig. 9-9a, b & Table 9-4a, b) is less homogenous with greatest variation in FeO and MgO. There is negligible variation in Fe_2O_3 (0.05 wt%) while FeO increases by 4.31 wt% and MgO decreases by 3.17 wt%. This sympathetic variation is the main heterogeneity and is a primary compositional variation. In general there is a slightly larger variation between averaged massive and disseminated chromitite compositions for patches (1.33 wt% maximum difference for Al_2O_3 ; Fig. 9-9; Table 9-4) compared to disseminated rim and massive core chromitite (Fig. 9-8). Subsolidus re-equilibration is thought to be the main process for homogenizing chromitite compositions from these different textural types and in the case of rim and core chromitite it has proceeded further. However, for the patchy and massive chromitite pod, chemical variations are still small and are considered to represent near equilibration. In general, there are only minor chemical differences between chromitite of different textural type and position in compound pods. In addition to subsolidus re-equilibration this could also indicate similar starting compositions.

Fig.9-8. Chromite analyses from rim and core areas of a compound chromitite pod.

W81-153; rim sample from compound pod, heavily

▲ disseminated chromitite.

● -154; massive chromitite, interior of same pod.

Fig.9-9. Chromitite analyses from massive and highly disseminated chromitite patches in a compound pod.

Fig.9-10. Sketch of W81-108, a compound chromitite pod.

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Table 9-4. Averaged chromite analyses of four samples from a compound chromitite pod.

n=analyses	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	Total
W81-108A n=7	0.09	11.38	56.47	4.48	14.38	0.85	12.14	99.79
W81-108B n=5	0.09	10.32	55.61	4.53	18.69	1.08	8.97	99.29
W81-108C n=4	0.09	12.73	54.99	3.79	17.16	0.97	10.49	100.22
W81-108D n=8	0.05	11.63	56.65	3.87	16.70	0.87	10.79	100.56

Table 9-5. Analyses from four points of a sample (W81-107) of massive podiform chromitite.
n=analyses.

wt % n-4	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	Total
max.	0.19	11.60	60.05	3.30	16.44	0.89	13.61	
min.	0.18	10.99	58.74	2.17	12.66	0.64	11.10	
range.	0.01	0.61	1.31	1.13	3.78	0.25	2.51	

Variation within a massive chromitite pod:

Compositional variation within massive podiform chromitite is shown in Table 9-5. All variations of major element oxides, particularly for Cr and Al, are small with analyses from four separate points on a polished thin section. With the exception of FeO and MgO variations are less than 1.5 weight percent. FeO and MgO show sympathetic variation with increasing FeO corresponding to decreasing MgO. This represents lack of sub-solidus equilibration and thus would reflect a primary heterogeneity with respect to FeO and MgO. Other elements are essentially constant. Oxidation ratios vary from 0.06 to 0.11 and reflect variance in alteration of Fe^{+2} , probably during serpentinization.

Variation of composition within a massive and nodular chromitite layer:

For most of the oxides, with the exception of Fe_2O_3 and MnO, the composition of the massive stratigraphically lower part of the layer is within the compositional range of the middle to upper middle parts (Fig. 9-11; Table 9-6). The difference for Fe_2O_3 results from a difference in degree of oxidation since FeO for the massive basal part is within the FeO range for the middle parts.

The greatest variation exists for analyses from within the middle part of the layer where the texture is predominantly medium to coarse-nodular. TiO_2 shows a marked increase to 0.40 wt% (Fig. 9-11; Table 9-6) in the upper middle section. This could imply cumulate affinity involving precipitation from magma. Al_2O_3 is variable and highest in the upper middle section (17.76 wt%). In conjunction with the Al variation Cr_2O_3 varies in opposite sense and is lowest in the upper middle section. This again suggests a cumulate origin for nodular chromitite. However, Cr_2O_3 in nodular chromitite is about equal to Cr

content in massive basal chromitite. FeO and MgO show a well defined sympathetic variation with FeO lowest and MgO highest in the upper middle section. This is indicative of origin as refractory chromitite. MnO is low in all middle section analyses and is surprisingly high (1.16 wt%) in massive chromitite from the lowest stratigraphic level of the layer.

Compositional variation trends show scattered values and give conflicting evidence for any one single mode of origin for chromitite. Generally increasing TiO_2 and Al_2O_3 with decreasing Cr_2O_3 would suggest accumulation from magma while strongly decreasing FeO and increasing MgO do not support this. Some samples have distinctly refractory compositions primarily with high Cr and low Al. High Mg and low Fe also suggest refractory origins rather than cumulate.

This variability in chromitite composition suggests a complex origin for layered chromitite, particularly where more than one texture is involved. A process incorporating both refractory and cumulate chromite is required to fit the compositional variations in Fig. 9-11 and Table 9-6. Chemical heterogeneity persists due to a lack of sub-solidus equilibration.

Fig.9-11. Comparison of chromitite analyses from the bottom, middle and upper parts of a chromitite layer with nodular patches.

Table 9-6. Analyses from a massive chromitite layer with nodular textured patches in middle part of layer. n=analyses, W81-171, 173, 174 & 175.

wt %	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	Total
-171 n=4 nodular	0.40	17.76	50.19	3.87	11.98	0.65	14.63	99.48
-174 n=5 nodular	0.15	8.17	61.39	2.71	14.06	0.75	12.03	99.26
-175 n=5 nodular	0.26	14.57	54.93	1.77	15.75	0.59	11.86	99.73
-173 n=5	0.16	16.84	51.40	4.57	12.74	1.16	13.80	100.67

-173; bottom of layer with massive texture.

-171, 174 & 175; middle of layer with patchy - nodular texture,
171 is from the upper middle section.

Variation in chromite composition from different host rocks:

Host rock types in which chromite occurs in B.C. alpine ultramafics are harzburgite, dunite and orthopyroxenite. The Anarchist deposit is hosted by metacarbonate rocks and is shown to have chromite with similar composition to ultramafic hosted chromite (Fig. 9-12). The ranges of XMg for all rock types overlap and thus show no distinctions based on host rock. Of more interest is the wide range in CRT ratio which is shown most extensively by dunite, and in part by orthopyroxenite hosted chromite (Fig. 9-12). Generally most of the dunite and the orthopyroxenite-hosted chromites have CRT ratios lower than harzburgite-hosted chromite.

Dunite hosts chromite with high CRT ratios, 87 to 98, which correspond to low XMg values of 10 to 22. These analyses are from Mt. Sydney-Williams (Fig. 9-12). In contrast to this extreme upper range are dunite-hosted chromites with more normal low CRT values, 10 to 44, and higher XMg ratios, 48 to 80 (Fig. 9-12; 9-13). These dunites come from Murray Ridge in addition to Mt. Sydney-Williams. Associated with dunite-bearing lower CRT - higher XMg chromites are two chromite analyses from an orthopyroxenite vein from Mt. Sydney-Williams. This orthopyroxenite with disseminated chromite is contained concordantly within a chromitiferous dunite layer, and their respective chemistries are similar for CRT and XMg. In addition to dunitic chromite occupying extreme ends of the B.C. chromite field their compositions also range throughout the central part of the alpine complex compositional field. The most atypical being dunite-hosted chromite from some of the Mt. Sydney-Williams dunite layers.

Dunite and orthopyroxenite hosted chromite with lower Cr/Al and higher Mg/Fe ratios represent crystallization products from a partial

melt. The second group of Mt. Sydney-Williams dunite-hosted chromite have however, a much more refractory nature with high CRT. These should, by their refractory nature also have a high XMg ratio, reflecting the refractory host dunite and harzburgite. The anomalously low XMg ratio is attributed to formation of the chromite principally by late iron-rich solutions confined to the dunite layers.

(see p. 211)
The distribution of various host rock-types using FRT and XMg (Fig. 9-13) shows a strong grouping of dunite hosted chromite in the upper FRT range, from .25 to .80. One point, essentially pure magnetite, plotted with FRT at .98 and XMg at .02. These again are some of the Mt. Sydney-Williams chromites and have high total iron combined with extreme oxidation to occupy this upper range. The low Mg/Fe ratio for this group indicates high total iron which is felt to be a primary, pre-oxidation feature.

Variation in chromite composition with texture:

Chemical variation in chromite on the basis of textural type shows a distinction between disseminated chromite from both harzburgite and dunite and podiform to layered chromite.

Disseminated chromite includes analyses of chromite from harzburgite and from disseminated laminae in dunite layers, particularly from Mt. Sydney-Williams. The range of CRT values defined by most of the disseminated chromite is from 10 to 67 (Fig. 9-14). With values for disseminated chromite in the middle and upper CRT range (Fig. 9-14) intersecting the field for harzburgite (Fig. 9-12), it is apparent that harzburgitic disseminated chromite has higher Al. This would suggest a lower temperature origin by exsolution as Al was increasingly exsolved from pyroxenes. Disseminated chromite from seams in some dunite

Fig.9-12. Plot of CRT vs XMg based on different host rock types.

Fig.9-13. Plot of $\bar{\text{Fe}}^{+3} / (\text{Fe}^{+3} + \text{Cr} + \text{Al})$, hereafter
FRT, vs XMg. for the rock types in Fig.9-12.

layers from Mt. Sydney-Williams has high CRT - low XMg ratios, atypical for normal alpine complex CRT ranges. This chromite has highly altered textures and suggests that these are altered compositions.

Podiform chromite (Fig. 9-14) exhibits evolving cumulate nature with high CRT ratios, 70 to 85, and low to moderate XMg ratios, 15 to 45. These relationships suggest an increasingly evolved composition of chromite forming pods as partial melting progresses. Some podiform chromite chemistry extends to the upper range of XMg, about 80 with CRT at 88 and suggests equilibrium with later more Mg - Cr rich liquids. Thus the development of podiform chromite begins with early partial melting with precipitation from Al - Fe rich liquids (low CRT and XMg) and continues to the end of melting where residual harzburgite has higher Mg and lower Al (Fig. 9-14; 9-15). The final liquids produced are thus high CRT and XMg melts reflected by the chemistry of the last chromite pods to develop. Podiform chromite development is shown by the arrow in the podiform field (Fig. 9-14; 9-15).

Chromite forming layers has a composition which falls predominantly in the field for harzburgite hosted chromite (Fig. 9-14; 9-15) although thin, 1 to 2 cm dunitic selvages are often associated as with chromite pods. A distinct trend exists for layered chromite which is more indicative of precipitation from a liquid. This field (L) also includes a scattering of data from other textural types and is thus not characterized by exclusive occupancy. CRT ratios in the lower range, around 63, correspond to a low range for XMg of about 15, as CRT increases so does Mg/Fe to upper values of 88 (CRT) and 80 (XMg). Relatively less Al and Fe is available from the increasingly refractory mantle, thus Cr and Mg are concentrated in later partial melts and this defines a trend of increasing CRT and XMg ratios. This trend for layered

chromite is shown by an arrow in the field for layered chromite in Fig. 9-14.

The chemical trends for podiform and layered chromite, shown by arrows in their respective fields, are essentially parallel and reflect similar crystallization environments. As their CRT and XMg trends increase refractory disseminated chromite follows a trend of decreasing CRT opposite that of cumulate layers and pods and with steeper slope. The trend for refractory chromite is similarly indicated by an arrow in the disseminated chromite field (Fig. 9-14).

In a plot of FRT against XMg for chromite of different textural types one major distinction exists (Fig. 9-15). For most chromites, regardless of textural type FRT is low, less than .12, and the same distinctions as in Fig. 9-14 can be made for XMg ratios. A distinction of interest is made on the basis of FRT for disseminated chromite which forms disseminated seams in dunite layers (Fig. 4-10a) from Mt. Sydney-Williams (Fig. 9-15). Chromite with disseminated texture, and thus greatest surface area available for alteration, reflects the greatest range of oxidation ratios, from .12 to .75. In addition to their propensity for oxidation they are initially higher in Fe^{+2} as shown by the low range of XMg, .02 to .38. The other textural types, not associated with dunite layers, are more massive in texture and structure and will be less liable to alteration. Dunite layers are also thought to channel solutions increasing the intensity of alteration for enclosed chromite.

Variation in chromite rim and core composition:

Chromite from various textural types and host rocks were analyzed primarily at their cores to avoid possible peripheral alteration effects.

Fig.9-14. Plot of CRT vs XMg based on chromitite textural types.

Fig.9-15. Plot FRT vs XMg for the same textural types
as in Fig.9-14.

In Fig. 9-16 CRT is plotted against XMg and the overall field (C) is that of chromite core analyses. Two smaller fields within field C are those of rim analyses (R). The larger of the two rim fields reflects the trend of core data for normal alpine-type chromite. It shows a restricted range of XMg from 48 to 70 and wider variation in CRT from 52 to 80. Rim XMg values are in the upper half of the range outlined by B.C. chromites meaning that the rims trend towards higher Mg. If chromite grains are precipitating from or equilibrating with increasingly refractory liquids, then increasing XMg should be expected. However, rim analyses in this upper XMg range overlap fully with core analyses.

The second and smaller field for rim data occurs at the lower limit of XMg, 5 to 10, and near the upper limit for CRT, 86 to 89. This field corresponds to rims on altered, skeletal textured Cr-magnetite occurring as disseminated grains in Cr-spinel laminae from dunite layers at Mt. Sydney-Williams. These are possibly highly altered Cr-spinels or formed from late Fe rich solutions confined to the dunite layers.

The link between XMg for rims and cores of both groups, high and low, indicates a lack of zoning within respective groups. A generally homogenous chemistry is then attributed to B.C. alpine-type chromites.

Fig. 9-17 FRT vs. XMg again shows the upper range of XMg for most chromite rim analyses. In this plot, the rim analyses for low XMg grains from dunites show extremely high FRT values, 95 to 98, which reflects both initially high total iron and high oxidation. These analyses, as stated earlier, correspond to white rims on mottled grey - white chromian magnetite. The rims are magnetite, probably formed during serpentinization and are themselves unaltered.

Fig.9-16. Plot of CRT vs. XMg for chromite rim and core analyses.

Fig.9-17. Plot of FRT vs XMg for chromite rims and cores.

Variation in chromite composition related to solid inclusion phases:

Solid inclusions in chromite grains are grouped generally as silicate and sulphide inclusions. Silicate inclusions are almost exclusively olivine (Fo_{91-92}) with minor amounts of mica and amphibole.

Sulphide inclusions occurring as primary inclusions are Fe-Ni sulphides and platinum group minerals (PGM) and these two species are shown separately.

In Fig. 9-18 CRT is plotted against XMg and shows a complete range of ratios for silicate and non-silicate bearing chromite. Sulphide inclusions (thought to be primary) occupying fields S and PGM (Fig. 9-18) show an affinity for chromite with moderate to moderately high CRT values at about 75. These form two groups with one group adjacent to the PGM field. Both are at the lower end of the XMg range, 15 to 32. This suggests an early appearance of sulphides, particularly PGM, in early higher Fe partial melts which produced chromite with XMg. In general, there is a complete overlap in the fields of solid inclusion bearing and solid inclusion free chromite chemistry.

A plot of FRT and XMg (Fig. 9-19) shows the same distribution for XMg as in Fig. 9-18 with 95% of the data points falling below 0.10 for FRT. No distinction between solid inclusion bearing and solid inclusion free chromite exists on the basis of FRT.

Variation in chromite composition related to fluid inclusions:

Fluid inclusions occur in chromite in several forms which include planar swarms, trains, irregular patches and more rarely single isolated inclusions. They are not equally distributed amongst chromite and from petrographic studies are restricted to chromitites as opposed to sparsely disseminated chromite. For the purpose of this section, samples were

Fig.9-18. Plot of CRT vs XMg for inclusion bearing chromite.

Fig.9-19. Plot of FRT vs XMg for inclusion bearing chromite.

considered to qualify for the fluid inclusion bearing category if one or more grains were observed to carry one or more of the above-mentioned fluid inclusion types.

Both Fig. 9-20 and Fig. 9-21 show a complete overlap of ranges for CRT, FRT and XMg for chromite with and without fluid inclusions. The field for predominantly disseminated chromite is included in this range since these fields include chromite forming thin, 1 to 3 mm, discontinuous seams in dunite layers. Other analyses of more typical disseminated chromite from harzburgite are normal in the sense of being fluid inclusion free and have fully overlapping composition. All other chromite textures from various host rocks and locations have similar ranges in chemistry regardless of fluid inclusion content. This implies a similar crystallization environment for layered and podiform chromitites with one important exception. The variability in fluid inclusion content reflects a variable partial pressure of volatiles or a variable solubility of volatiles in partial melts. Chromite precipitated from partial melts with or without a separate volatile phase has similar compositional ranges. In this way, volatiles are not seen to influence chromite compositions.

Major element variation in B.C. chromite:

Four major element oxides involved in chromite compositional variation outline well defined linear zones reflecting good solid solution. Cr-Al in Fig. 9-22 and Fe^{+2} - Mg in Fig. 9-23 outline the range in composition for alpine-type B.C. chromite and Cr-spinel. Data for Anarchist deposit chromite, although hosted by meta-carbonate rocks, is similar and is included in the composite fields (Fig. 9-22; 9-23).

Fig.9-20. Plot of CRT vs XMg for chromite with and without fluid inclusions.

Fig.9-21. Plot of FRT vs XMg for chromite with and without fluid inclusions.

For Cr vs. Al (at.%) the main field contains 95% of B.C. data and inclusions analyses from all eight areas considered in this study. A well-defined linear relationship exists between decreasing Cr_2O_3 and increasing Al_2O_3 . In field L (Fig. 9-22) are the other 5% of analyses which come exclusively from dunite-layer hosted Cr-spinels and Cr-magnetites at Mt. Sydney-Williams. Values with extremely low Cr - Al are magnetites. Field L (Fig. 9-22) represents a deviation in chemistry and mineralogy from usual alpine-type chromite compositions. This reflects in part alteration products from serpentinization effecting Cr-spinel and Fe^{+2} rich spinels and magnetite formed during serpentinization (Bliss & MacLean, 1974, 1975; Malpas & Strong, 1975).

Variation of FeO vs. MgO for other areas:

Fig. 9-22 shows Fe and Mg (at.%) which similarly define a strongly linear relationship between decreasing Fe and increasing Mg from approximately 23% to 0%. Field C (Fig. 9-23) contains 100% of B.C. chromite and Cr-spinel analyses and is more tightly grouped than the equivalent composite plot for Cr and Al (Fig. 9-22). This tighter grouping of FeO and MgO in Fig. 9-23, relative to field L in Fig. 9-22, is because of a more restricted primary range for these elements.

Both composite plots (Figs. 9-22 & 9-23) and particularly Cr - Al show well defined 1:1 linear relationships with almost 45 degree slopes. Since each of these four elements have similar ionic radii and that of Cr^{+3} is midway in the range (0.615 Å, octahedral; Shannon & Prewitt, 1969) there is good substitution of Cr^{+3} for Al^{+3} , Fe^{+2} , Mg and Ti. These substitutions occur in octahedral sites in chromite, Cr-spinel and other silicates. The dominant substitution is between Al^{+3} and Cr^{+3} and is shown the tight linear grouping for field C (Fig. 9-22). For the same reasons the slope for Fe^{+2} - Mg substitution (Fig. 9-23)

is close to 45 degrees but is more restricted and implies more limited substitution. Fig. 9-22 and Fig. 9-22 between them also indicate linear 1:1 substitution for $\text{Cr}^{+3} - \text{Fe}^{+2}$ and for $\text{Cr}^{+3} - \text{Mg}^{+2}$, however, these also will have more limited substitution.

Variation of Cr_2O_3 vs. Al_2O_3 for other areas:

The widest range of element substitution in chromite is between Cr and Al; Fe - Mg substitution is relatively restricted. For further discussion Cr_2O_3 vs. Al_2O_3 diagrams have been selected because they best reflect differences in chromite or Cr-spinel petrogenesis.

At Murray Ridge Cr-spinel almost exclusively occurs as disseminated grains forming 2 - 3% of harzburgite and dunite. Medium-grained aggregates, up to 1 cm, are sparsely distributed in dunite layers. Compositionally, disseminated chromite from harzburgite is high Cr - low Al whereas from dunite layers it is low Cr - high Al (Fig. 9-24). High Cr disseminated chromite from harzburgite is anhedral with irregular lobate form and often has olivine inclusions. This texture and high Cr content suggests a highly refractory origin for this chromite by the incongruent melting of Cr-diopside. Cr-spinel in dunite layers, in contrast, has lower Cr and higher Al and forms sub to euhedral grains. A few samples of dunite hosted chromite plot in the harzburgite field (Fig. 9-24) and defined a range of composition suggesting a transition towards more abundant high Al Cr-spinel. This degree of Al enrichment is found in Cr-spinels exsolved from pyroxenes as they increasingly expel Al_2O_3 with falling temperature.

At the Mitchell Range, chromite is predominantly hosted by tectonite harzburgite rather than occurring in well-defined dunite layers. In some cases thin, 1 to 3 cm, dunitic selvages may enclose individual chromite occurrences. Chromite forms ovoid to rounded chromitite pods

Fig.9-22. Plot of $100 \cdot \text{Cr}$ vs $100 \cdot \text{Al}$ for all B.C. chromites.

Fig.9-23. Plot of $100 \cdot \text{Fe}^{+2}$ vs $\cdot 100 \text{ Mg}$ for all B.C. chromites.

Fig.9-24. Plot of Cr_2O_3 vs Al_2O_3 based on host rock type
from Murray Ridge.

with massive or ocluded silicate texture. It is almost exclusively high Cr - low Al chromite with three exceptions (Fig. 9-25). These exceptions, all with low Al, show lower Cr. In addition to chromitite pods are chromitite layers with massive, nodular and heavily disseminated textures. These all have high Cr - low Al chromite compositions similar to those for podiform chromitite and all plot in the field shown on Fig. 9-14.

Compositionally Mitchell Range chromite - chromitite is of the higher CRT type and texturally shows larger accumulations forming pods and layers. This results from some of the chromite precipitating from initial partial melts. Since very low concentrations of Cr in a liquid will cause precipitation of chromite (Keith, 1954) small accumulations can collect from small volumes of partial melt and equilibrate with refractory chromite at subsolidus temperatures. With this sort of process, combined refractory - cumulate chromite, pods and layers could form in partially melted mantle. Later deformation produced the deformed pods and broken layers mapped in the Mitchell Range.

The Anarchist deposit, hosted by meta-carbonate rocks with no proximal ultramafic rocks, consists of high Cr - low Al chromite (Fig. 9-26). At the Anarchist deposit chromite forms a massive chromitite dyke intruding Anarchist Series met-carbonates. Serpentine forms about 2% of the dyke and is a fracture-filling material within chromitite. Samples collected from the dyke walls, centre and along strike give similar compositions which correspond with textural homogeneity in thin section. No carbonate alteration of the wallrock is evident, fragments of wallrock form sub-angular xenoliths in chromitite. Chromitite, chemically and optically, shows no zonation towards dyke walls or along strike. These characteristics make it unlikely that

Fig.9-25. Plot of Cr_2O_3 vs Al_2O_3 based on host rock type from the Mitchell Range.

chromitite was intruded as a high temperature melt or was part of a silicate melt. A low-temperature Cr saturated aqueous solution is thought to be the carrier and agent for precipitation of massive chromitite.

Chromite from the Bridon deposit (Fig. 9-27), the Nicola deposit (Fig. 9-28) and from Scottie Creek (Fig. 9-29) all have similar ~~chrome~~ ^{contents}. In each case, with the exception of Scottie Creek, chromite forms highly disseminated to sometimes massive chromitite layers. Harzburgite and olivine rich harzburgite form the host rocks and represent highly depleted mantle. Substantial partial melting could form in these areas with enough liquid for layering to form by crystal settling from partial melts and by accumulation of refractory chromite. At Scottie Creek (Fig. 9-29) chromitite is compositionally similar but shearing is more extreme than at Bridon or Nicola. This has formed schlieren - like chromitite layers and highly fractured and fragmented podiform chromitite. This deformation has not changed chromitite compositions.

At Mt. Sydney-Williams, Cr-spinel concentrations are hosted in dunite layers as highly disseminated but thin, 0.5 to 2 cm, seams. At Baptiste Spur (Fig. 4-3) Cr-spinel occurs in two generations, both are chemically similar based on core analyses. Dunite hosted Cr-spinel occupies two separated fields in Fig. 9-30. Both types have lower Cr_2O_3 than harzburgitic chromite from other massifs. The field representing primary compositions, D^1 , was derived from analyses of cores which are translucent amber whereas altered spinel rims or entire grains define field D^2 . Grains and rims in D^2 are opaque. Where Al_2O_3 is low with constant Cr_2O_3 , $\text{FeO} + \text{Fe}_2\text{O}_3$ primarily replace Al_2O_3 (Fig. 9-30).

Fig.9-26. Plot of Cr_2O_3 vs Al_2O_3 from Anarchist chromite.

Fig.9-27. Plot of Cr_2O_3 vs Al_2O_3 from the Bridon Deposit.

Fig.9-28. Plot of Cr_2O_3 vs Al_2O_3 from the Nicola Deposit.

Fig.9-29. Plot of Cr_2O_3 vs Al_2O_3 from the Scottie Creek Deposit.

Primary compositions, in D^1 , from unaltered cores represent medium-Cr and high-Al spinels. Compositionally they are intermediate to dunite hosted spinels from Murray Ridge (Fig. 9-24). A process by which exsolved spinel, at low temperature, can be transported and reprecipitated in concordant seams in dunite layers is favoured. Dunite on either side of Cr-spinel seams is depleted in accessory Cr-spinel with respect to accessory spinel in harzburgite. Cr-spinel forming laminae may in part be remobilized Cr-spinel from the volume of the present dunite layers. A possible process for transport of Cr-spinel involves the movement of Al and Cr in aqueous solutions within the confines of the dunite layers. Transport of solution will be greatest near the dunite layer centre and thus will concentrate Cr + Al in this zone to be precipitated as Cr-spinel. This forms centrally concordant disseminated Cr-spinel seams. Original refractory-type chromite with higher Cr and lower Al constitutes a few grains also within dunite layers and is thought to represent earlier chromite possibly associated with a magma. Only partial re-equilibration of this early chromite was achieved.

The second dunite hosted Cr-spinel field, D^2 (Fig. 9-30), has extremely low Al^{+3} which is balanced by increased Fe^{+3} . This corresponds to opaque grains and rims on translucent cores. Opaque grains and rims with low Al are from mottled - skeletal areas on these grains. It is these grains with alteration textures which exhibit chlorite + serpentine (Lizardite) rims formed during serpentinization. Rimmed Cr-spinels are confined to dunite layers showing that serpentinizing solutions were most concentrated in dunite layers. Al necessary to form chlorite was taken from Cr-spinel thus localizing chlorite-rich rims around spinels (c.f. Watkinson and Mainwaring, 1982). As Al^{+3} was removed Fe^{+2} and Fe^{+3} substituted into spinel from increasingly Fe-rich serpentinizing

solutions. Outer rims of Cr-spinel became Cr-Fe rich and with loss of Al and falling temperature unmixed to form Cr-magnetite + magnetite intergrowths. These two phases, Cr-magnetite + magnetite, with different reflectivities, form mottled and skeletal textures. In some cases euhedral Cr-spinel pseudomorphs remain as totally altered grains. Irregularly lobate Cr-spinel cores, unaltered, remain in diffuse contact with encroaching opaque alteration rims.

After formation of Cr-spinel and with alteration during serpentinization the major exchange is a loss of Al^{+3} and an influx of Fe^{+3} . A suggested reaction for this exchange which produces chloritic rims is:

In this reaction unaltered Cr-spinel is the source for Al required for chlorite. Additional Fe and Mg for both chlorite and lizardite are supplied by serpentinizing solutions. Fe also substitutes into spinel to fill empty Al sites resulting in Cr-magnetite and magnetite intergrowths. This Fe is similarly supplied by serpentinizing solutions.

Variation of chromite composition by area:

Chromite from all B.C. alpine-type ultramafics except area F, Scottie Creek, show a range of XMg from 15 to 75 (Fig. 9-31). Scottie Creek (F) chromitite analyses are tightly grouped with moderate CRT ratios between 55 and 60 (Fig. 9-31). This represents a highly refractory

Fig.9-30. Plot of Cr_2O_3 vs Al_2O_3 from dunite and harzburgite at Mt. Sydney-Williams.

host and is also likely a function of restricted sample size; all chromite is from one adit.

Distribution of CRT is more variable than XMg and ranges from 10 to 98, the higher values being atypical for ophiolite related chromite (Fig. 9-31). The extreme ends of the B.C. chromite field (Fig. 9-31) are defined by exclusive occupancy of area MR (Murray Ridge) at the lower end and by area MSW (Mt. Sydney-Williams) at the upper end. Areas MR and MSW also have analyses throughout the central part of the B.C. chromite field and thus show the widest range of CRT for any B.C. ultramafic massifs studied. It is also areas MR and MSW (Murray Ridge & Mt. Sydney-Williams) that have extensive dunite-layered zones and pods. Although Pinchi Mt. (area PMT) also has substantial dunite, its chromite analyses are within the main chromite field (Fig. 9-31). The Anarchist deposit (area A) which consists of massive chromitite intrusive into Anarchist Series meta-carbonate rocks has CRT and XMg ratios within the normal Alpine-type complex field. Although no ultramafic rocks form nearby outcrops, chromite composition is similar to that of an ultramafic host. The ultramafic source, in this peculiar occurrence is then, somewhere at depth?

The distribution of FRT from various areas shows that for area MR and some from MSW have low FRT ratios in accordance with those from other areas (Fig. 9-32). Area SC shows again a consistently tight grouping and area PMT is also normal. This low FRT range indicates low total iron and lack of oxidation which corresponds close to texturally unaltered chromite. The high range of FRT for 42% of the analyses from area MSW (Mt. Sydney-Williams) signifies both an increase in total iron and intense oxidation for corresponding samples with CRT ratio. Alteration textures are well developed in these chromites. For these samples there

is a fundamental difference in composition; higher total Fe, Cr and lower Al are present than in other chromites.

Chromite composition; Summary:

Chromite compositional variations presented in this chapter have been related primarily to differences in texture and type of host rock, mainly peridotite or dunite. Most chromite compositions are typical for alpine-type complexes (Irvine, 1967; Talkington, 1981) and ophiolite suites. The Mt. Sydney-Williams massif, with abundant dunite layer structures however, has Cr-spinel, different to most other B.C. chromite. Primary compositions here are much more Al rich than from other ultramafic massifs in B.C. (Fig. 9-33; Fig. 9-34). Chromite and Cr-spinel from B.C. ultramafics display compositional variations which, together with different host rock and textural associations represent a complex petrogenesis. No one single process is adequate.

Chromite from harzburgite:

Chromite occurrences hosted by harzburgite, with the exception of thin dunitic selvages, constitute the most abundant type of occurrence on the basis of host rock association. Predominant compositional characteristics include high Cr/Al and low to high Mg/Fe ratios. Chromite of all textural types; massive disseminated and nodular, which forms chromitite layers, pods and schlieren are, in most cases unaltered. They appear as translucent brownish-red grains, fractured and sometimes with ferritchromite rims which indicate only peripheral alteration.

Chromite from dunite:

Chromite from dunite is mostly Cr-spinel with abundant Al_2O_3 , greater than 30 weight percent. In some cases, as at Pinchi Mt., high

Fig.9-31. Plot of CRT vs XMg showing compositional variation
from various alpine-type peridotites in B.C.

Fig.9-32, Plot of FRT vs XMg for the same alpine-type peridotites as in Fig.9-31.

CRT also occurs in dunite pods and is unaltered in contrast to all other spinels from dunites. Most Cr-spinel from dunite layers forms discontinuous highly disseminated lamellae or irregular patches all concordant to and centrally located in dunite layers.

Compositionally these Cr-spinels are distinct from all other chromite or layered and podiform association from harzburgite. Dunite related Cr-spinels have low CRT and medium to high XMg. Mostly they are altered grains with remnant translucent cores grading outwards to opaque altered zones or are totally altered. Compositionally this is shown as a gradient of strongly decreasing Al, less strongly decreasing Cr and Mg, and increasingly Fe_{total} , TiO_2 and MnO.

Summary of chromite compositional features:

1. Most B.C. chromite analyses plot within the field for chromite of alpine-type complexes. Two areas, Mt. Sydney-Williams and Murray Ridge, have analyses with extreme values for CRT. High CRT values come from altered spinels in dunite layers at both Mt. Sydney-Williams and Murray Ridge.
2. Harzburgite and dunite have the most dissimilar chromite compositions. No difference exists between dunite and orthopyroxenite hosted Cr-spinel. Dunite and orthopyroxenite hosted Cr-spinel have lower Cr/Al ratios than harzburgite hosted chromite, although some overlap exists.
3. Texturally related variations in composition shows widest variation between disseminated and chromite both harzburgite and dunite vs. podiform - layered chromitite from harzburgite. Disseminated chromite from harzburgite is more aluminous and similar to dunite hosted Cr-spinels. Disseminated chromite - Cr-spinel has low Cr/Al.

4. Variation in rim to core compositions of unaltered chromite, or chromite with weak ferritchromite rims is negligible. In some cases symmetric or asymmetric zoning occurs in individual grains. Greatest variation exists for altered disseminated Cr-spinel forming discontinuous seams in dunite layers. Extreme loss of Al occurs outward from core areas with less extensive loss of Cr and Mg. The other elements show variable degrees of enrichment relative to core compositions (Fig. 9-33; 9-34) and pseudomorphic textures suggest constant volume reactions.

5. No variations in chromite composition are related to the presence of silicate and fluid inclusions. The latter occur to various extents in all types of chromite and Cr-spinel examined with the exception of accessory disseminated chromite in harzburgite.

6. Sulphide inclusions are mostly associated with chromite containing higher CRT - lower XMg and of more massive texture. This is particularly so for PGM inclusions which typically are anhedral to subhedral. A cumulate origin is favoured to account for PGM anhedra in chromitites. A Cr-bearing, high Fe liquid such as an early stage partial melt would be required.

7. Individual chromite grains are usually homogenous as are most chromites in chromitite occurrences at the scale of the occurrence. Zoning in chromite does occur and in unaltered chromites is weakly

developed and can be either symmetric or asymmetric from core to rim.

TiO₂, Cr₂O₃ and MgO either decrease or increase towards grain edges while FeO, Fe₂O₃ and MnO show slight trends in the opposite senses. Altered Cr-spinel shows most extreme zoning from unaltered cores to altered rims and between rare unaltered grains (from dunites) and totally altered grains. Zoning is predominantly shown by decreasing Al, Cr and Mg from core to rim with accompanying increases in Ti, Fe_{total} and MnO.

Spinel prism:

The spinel prism (Stevens, 1944; Irvine, 1965) gives a three dimensional view of the interaction of the six end member components in the spinel series. These are:

FeCr_2O_4 - chromite

MgCr_2O_4 - picrochromite

FeAl_2O_4 - hercynite

MgAl_2O_4 - spinel

Fe_3O_4 - magnetite

MgFe_2O_4 - magnesioferrite

In the spinel prism (Fig. 9-33) the length corresponds to relative amounts of MgO and FeO, the triangular cross section to Cr_2O_3 , Al_2O_3 and Fe_2O_3 and each corner corresponds to one of the above end members.

In Fig. 9-33 most chromite analyses from unaltered chromitites plot near the base of the prism with low Al and negligible Fe^{+3} . Mitchell Range chromites are most representative (solid circle) while chromite from other massifs shows more Fe^{+3} (various other open circles). Unaltered Cr-spinel from Mt. Sydney-Williams (open triangles) dunite layers show more Al and negligible Fe^{+3} . However, with alteration affecting either rims or entire grains from dunite layers Fe^{+3} strongly increases while Al and Mg decrease (open hexagons). The spinel prism serves to show the difference between chromite from massive chromitite layers and pods and Cr-spinels from dunite layers. The progression toward Fe^{+3} enrichment of Cr-spinels is similarly well illustrated.

Fig.9-33. Projection of averaged B.C. alpine-type chromite
and Cr-spinel analyses onto the spinel prism
(after Stevens, 1944). *Symbols defined on*
Fig. 9-34.

Fig.9-34. Ternary plot of Fe^{+3} - Al - Cr (cation basis)
showing the field of B.C. alpine-type chromite
and Cr-spinel with the Cr-spinel alteration
path.

CHAPTER 10: PETROGENESIS

Petrogenesis of chromite from harzburgite:

Harzburgite hosts chromite which forms several types of occurrences. These are layered and podiform types with massive, nodular, and highly disseminated texture. In terms of CRT and XMg ratios chromite is in the alpine-type field (Fig. 9-1; Irvine & Findlay, 1972) and are similar to chromite from other alpine-type complexes (Talkington, 1981; Greenbaum, 1977).

Podiform chromitite:

Although small in volume, podiform chromitite forms the most abundant single type of occurrence, the largest being 1.3 m long. There is a wide overlap in composition of podiform and layered chromitite. This overlap together with fracturing and shearing of pre-existing chromitite layers suggests that many podiform structures result from tectonic fragmentation.

Chromite forming podiform chromitite is the result of two processes, refractory accumulation and cumulate chromite. Later sub-solidus equilibration may have occurred leaving individual chromitite occurrences in a homogenous state, but this is not thought to be a major process since minor symmetric and asymmetric zoning remains in some grains.

Refractory chromite:

Chromite from refractory processes results primarily from incongruent melting of Cr-diopside from primitive mantle and above 10 kb (Dickey, 1975) it melts congruently. Experimental work by Dickey et al. (1971) and by Dickey & Yoder (1972) showed that up to pressures of 10 kb in the system $\text{CaO} - \text{MgO} - \text{Al}_2\text{O}_3 - \text{SiO}_2 - \text{Cr}_2\text{O}_3$ Cr-diopside melts incongruently to Cr-spinel + liquid. Spinel formed in this manner undergoes further changes by equilibration between Cr-spinel and liquid since:

$$D_{\text{spinel-liquid}}^{\text{Cr}} > 1 \text{ and } D_{\text{liquid rock}}^{\text{Al}} > D_{\text{spinel-liquid}}^{\text{Cr}}$$

(Dickey & Yoder, 1972). Al prefers liquid and Cr from the same liquid prefers entry into Cr-spinel. This increases the Cr/Al ratio of refractory spinel where it is in contact with liquid and can render it similar to cumulate chromite. Since only small amounts of Cr in a liquid are required to produce Cr-spinel at low pressures (Fig. 10-1, Keith, 1954), and since $D_{\text{liquid-lherzolite}}^{\text{Cr}} > 1$, (Kurat et al., 1980) initial (first stage) partial melt from spinel lherzolite should be enriched in chromium, about 350 ppm. From Fig. 10-1 (Keith, 1954) the small amount of Cr necessary to form Cr-spinel is shown by proximity of the cotectic to the $\text{MgO} - \text{SiO}_2$ join of the $\text{Cr}_2\text{O}_3 - \text{MgO} - \text{SiO}_2$ triangular diagram.

These relationships for incongruent melting of Cr-diopside and equilibration of initially low Cr/Al spinel and partial melt to raise Cr/Al ratios suggest that some, at least, of the high Cr/Al chromitite has formed from post-precipitation equilibration with the melt. At liquidus temperatures to sub-solidus temperatures down to 1200°C Fe^{+2} and Mg also exchange (Roeder, et al., 1979). These Cr-spinels should also reflect high Fe^{+2} of the early partial melt and thus give low X_{Mg} values. Much podiform chromitite does have low X_{Mg} to support association and equilibration with early liquids.

Accumulation of initially disseminated refractory chromite into massive or heavily disseminated chromitite proceeds by continued partial melting reaching sufficient percentages to allow refractory chromite to accumulate in pods and or layers. Refractory chromite is

formed from incongruent melting of an anhydrous phase, Cr-diopside.

Refractory chromite is not likely to have trapped fluid inclusions nor sulphide inclusions. Observed minerals included are olivine and serpentized equivalents.

Characteristics of refractory chromite:

1. High Cr/Al and low Mg/Fe.
2. Forms chromitite if sufficient partial melting allowed accumulation of otherwise disseminated chromite.
3. Only anhydrous silicate inclusions, if any.
4. Absence of fluid and sulphide inclusions since this chromite derived from a solid anhydrous phase with no sulphur.

Cumulate chromite:

Partial melting in the upper mantle will in places become complete enough to allow cumulate processes to proceed. In this environment precipitating chromite should be in equilibrium with partial melt and thus reflect its composition in a way similar to which stratiform chromite reflects liquid compositions (Roeder & Emslie, 1970; Cameron, 1975 and Eales & Marsh, 1983). Chromite of this origin could also reflect changes in pressure on the partial melt (Cameron, 1978, 1980) but mantle rocks are considered to be under isotropic conditions at depth.

Compositional variation in chromite thus reflects changes in partial melt composition in an environment which because of the large volumes of homogeneous rock involved would generate melts of slowly changing composition. Compositions of mantle residuum are controlled by the degree of partial melting and show this primarily by XMg values, and by CRT. As partial melting proceeds increasingly depleted refractory mantle develops higher XMg and CRT ratios. Partial melting of depleted mantle produces more Mg, Al bearing liquids from which minor amounts of later

Cr-spinel can precipitate. High CRT and XMg ratios of most B.C. chromitites consequently suggest equilibration with late high Mg, Cr, Fe, low Al liquids. Other phases precipitating in a partial melt of basaltic composition could include PGM sulphides and residual olivine. These would be trapped as primary inclusions in chromite and in some cases are accompanied by the hydrous silicate phase paragonitic amphibole. Volatiles in partial melt are trapped as fluid inclusions although many are secondary fluids trapped along annealed fractures. These would still represent mantle fluids. Single isolated fluid inclusions, unrelated to any annealed fractures, are considered primary and definitely reflect fluid phases from the partial melt. In addition to paragonitic amphibole fluid inclusions have been reported from other ophiolites (Johan & LeBel, 1978) to contain up to 7 equivalent weight percent alkalis. Subhedral to euhedral PGM inclusions require a melt in which to exist prior to entrapment by precipitating chromite. Sources of fluid, $H_2O + CO_2$ (Roedder, 1965) and more importantly of alkalis are not likely to be of mantle origin but rather a contaminant. In the model presented later seawater is discussed as a possible agent. With precipitation cumulate chromite can form layers or pods in areas of sufficient partial melting. This will be contemporaneous then with accumulations of refractory chromite also contributing to layered and podiform structures.

Nodular textures are possibly explained by the trapping of pockets of silicates + liquid + chromite between more massive textured chromitite from more rapid or complete melting. Small silicate + liquid + chromite pockets would then develop highly disseminated texture with normal crystallization. If liquid compositions are supersaturated with respect to chromite (Cr) then rapid precipitation around several nuclei could

develop nodules in silicate liquid patches trapped within massive chromitite and would be similar to nodular textures at Cyprus (Greenbaum, 1977).

Characteristics of cumulate chromite:

1. High Cr/Al and low to high Mg/Fe reflecting partial melts derived from increasingly depleted mantle.
2. With sufficient melting precipitated chromite can have euhedral form resulting in chromitites of heavily disseminated (occluded silicate texture) texture but with individual fine to medium-grained euhedra still discernible.
3. Chromite carries euhedral PGM sulphide inclusions, silicate (+ hydrous silicates) and fluid inclusions. This indicates co-existence with sulphide - vapour bearing melt.

Cr-spinel from dunite:

Petrogenesis of chromite to this point has dealt with chromite related to partial melting in harzburgite. Where dunite is associated with these chromitites it is usually restricted to thin, 2 - 3 cm, selvages around chromitites and represents extremely depleted zones. This section presents petrogenesis of Cr-spinel hosted by distinctive dunite layer structures which crosscut harzburgite. These layers contain a small proportion (2 percent) of chromite with "Normal" high CRT compositions and is considered to be early refractory chromite incorporated into the dunites as they formed.

Chromite from harzburgite has formed from early first stage partial melting in rocks that have since undergone at least one further stage of melting (Duncan & Greene, 1980). First stage melting occurred at depths in the order of 30 to 50 km which would be in a region of isobaric conditions. At these pressures chromitite initially would be from cumulate processes as pressure would be too high (greater than 10 kb) for refractory chromite to contribute to chromitites (Dickey, 1975). Ascent of a mantle block bringing it closer to a hot spreading ridge and associated magma chamber complex (Smewing, 1981) also brings it into a zone of increasing shear stress proximal to a spreading ridge. The

development of dunitic layering in this environment can be initiated mechanically. Shear strain upon a homogenous rock, the mantle peridotite, will tend to segregate minerals with contrasting physical properties into zones or layers of minerals with similar properties (Nicolas & LePichon, 1980). Under plastic mantle conditions solid state creep, particularly in olivines (Calon, 1973), is the predominant mechanism of deformation (Nicolas et al., 1980). Early formed layers can themselves become folded, possibly into pod-like structures and into isoclinally folded structures with axial planes concordant to mantle fabric. Stratigraphically, this environment occurs at the petrologic mocho, possibly beneath a ridge magma chamber which migrates laterally to a position beneath transform-faulted basaltic crust. In this environment, isotopic contamination of cumulate rocks by seawater has been shown (Gregory & Taylor, 1981) from Oman. It is then [possible] that diffusion of aqueous chloride species into uppermost mantle rocks via dunitic zones would be possible.

Evidence from Bushveld Complex dunitic pipes which vertically crosscut nearly horizontal igneous layering suggests that aqueous chloride brines have left residual dunite pipes (Peyerl, 1982; Schiffries, 1982). The dunite pipes were formed by circulation of Fe-rich meteoric solutions which removed pyroxene by desilicification reactions. Remaining olivine forms dunitic pipes which are the conduits through which aqueous solutions passed. Chromite still traces its original stratigraphy as sub-horizontal layers and is the only unaltered phase. In Cr-spinel seams from Mt. Sydney-Williams and from Pinchi Mt. chromite occurs with high CRT composition. This would correspond to early refractory - cumulate chromite unaltered during formation of dunite layers, but chromite in dunite of high CRT composition is sparsely distributed.

Cr-spinel at Mt. Sydney-Williams in dunite layers is intimately associated with features suggestive of long-lived solution migration. These solutions are the final agent in formation of monomineralic dunite layers probably initiated by mechanical separation of olivine from pyroxenes. Evidence of solution activity is indicated by the presence of two generations of Cr-spinel, one folded and one planar, in the same folded dunite layer. Cr-spinel of each generation is of similar composition and consists of highly disseminated seams centrally located within the dunite layer where fluid flow would be greatest and most persistent. Individual disseminated grains are enveloped in a chlorite - lizardite alteration rim. Development of both Cr-spinel generations is confined to the dunite layer where the second planar generation defines the axial plane (and tectonite) foliation only within the dunite. Cr-spinel mineralization is absent on strike immediately into the adjacent harzburgite. These relationships indicate fluid migration restricted to dunite layers and that mineralizing fluids were in motion before, during and possibly after mantle deformation. Alteration of Cr-spinels is variable from unaltered cores to altered rims; more commonly grains are totally altered, and rarely are entirely unaltered grains observed. Alteration from cores to rims is shown by extreme loss of Al, Cr and Mg with Al primarily going to form chlorite - lizardite rims. Pseudomorphs of primary spinels are euhedral and fresh core areas are irregular in shape with diffuse contacts with altered opaque rims. This alteration is related to serpentinization and low temperature aqueous solution migration. Attendant with this are remobilized sulphides concentrated in fractures in spinel and between spinels. These are heazlewoodite and some pentlandite, as well as Fe-Ni alloy, awaruite. This assemblage corresponds well with the low sulphur nickeliferous assemblage described by Eckstrand

(1975), from serpentized ultramafic rocks and is additional evidence of extensive fluid flow in dunites which was most concentrated along centrally located spinel seams in dunites. This Ni assemblage in spinel seams in dunite layers constitutes an example of natural concentrating of Ni during serpentinization.

Compositionally Cr-spinels are distinct from all other harzburgite associated chromitites. Their CRT ratios are low with equally low ratios coming from spinels similarly hosted by dunite layers at Murray Ridge. Low CRT ratios in addition to a range from medium to high XMg values is compatible with low temperature conditions and with fluid migration. This would correspond to mantle rocks at the petrologic moHo which are drifting away from a hot spreading ridge and beginning to cool. With dropping temperature Al becomes less soluble in any remaining pyroxenes in dunitic layers and in adjacent harzburgite. Exsolution of Al thus results in spinel with low CRT ratio (Anastasiou & Seifert, 1972; Obata, 1976) and there is no partial melt available for equilibration which could raise Cr/Al ratios. Because these spinels are exsolving from highly depleted mantle with high Mg/Fe, and since exchange of Fe^{+2} and Mg persists at subsolidus temperatures, to 1200°C (Roeder et al., 1979), the Mg/Fe ratio of these low Cr/Al spinels can range to higher values. Exsolution consequently provides low Cr/Al spinel, which forms some disseminated grains in harzburgite, from any remaining pyroxenes, in dunitic layers. This can be taken into solution by circulating aqueous chloride brines and concentrated or precipitated from a fluid phase in centrally located seams in dunites. In addition to this process, aqueous chloride solutions act as desilicifying agents leaving less soluble Cr and Al behind. Further increases in Cr and Al in this manner contribute to formation of Cr-spinel seams.

Continued fluid circulation along well established diorite conduits continues with lower temperatures and serpentinization with increasingly Fe rich and oxidizing solutions propagates alteration of Cr-spinels towards increasingly Fe rich rims of Cr-Fe spinel, Cr-magnetite and finally magnetite. Al extracted from spinel facilitates growth of chlorite - lizardite envelopes.

Explanation of petrogenetic model:

A petrogenetic model (Fig. 10-2) shows various stages at which chromite and Cr-spinel can precipitate.

1. Starting material is spinel lherzolite which has only accessory disseminated spinel. The strain environment is assumed to be isotropic and corresponds to depth of 50 to 60 km, well below high strain conditions beneath a spreading ridge.
2. Temperature rises in this high pressure environment (20 - 30 kb) and first stage partial melting initiates diapiric upwelling. Tholeiitic basalt partial melt is produced by 20 to 25 percent melting which consumes most of the clinopyroxene. Partial melt is almost completely extracted leaving harzburgitic residuum. Occasional clinopyroxene exsolution lamellae may remain in orthopyroxene. First generation orthopyroxenite veins crosscut harzburgite to be later highly deformed during plastic mantle deformation. Cumulate chromite begins to form layers and pods of disseminated or massive chromitite as partial melt is extracted. With later mantle deformation pods become more rounded, layers are broken into more angular pods, both have associated fragment trains. The rising diapir enters increasingly higher strain conditions as it approaches a hypothetical spreading ridge - magma chamber complex. Strain orientation is in a vertical plane. Development of mantle "Tectonite" fabric or foliation begins by solid state deformation - elongation of olivine and, to a lesser

Fig.10-1. The system $\text{MgO} - \text{SiO}_2 - \text{Cr}_2\text{O}_3$ and phase relations
(after Keith, 1954)

extent, orthopyroxene. Mechanical separation of olivine from orthopyroxene results in coarse mineralogical foliation and crude layering.

3. Diapiric rise brings depleted mantle in proximity to base of a magma chamber associated with a spreading ridge. Pressure is less than 10 kb allowing incongruent melting of remaining Cr-diopside to form small amounts of refractory chromite. Refractory chromite, by equilibration with partial melt has similar ranges of CRT and XMg to cumulate chromite. Further shear deformation deforms chromitites. With high temperatures from a now proximal magma chamber depleted mantle undergoes less extensive, 5 to 10 percent, partial melting, some of which is trapped as high Mg gabbro dykes in harzburgite residuum. These are also deformed with further ductile shear. Combined mechanical separation of olivine from orthopyroxene in tectonite shear zones, and passage of partial melt along these zones leaves residual olivine-rich dunite layers often with scattered and embayed orthopyroxenes or harzburgite forming in situ xenoliths. Depleted mantle begins moving away from the spreading ridge zone and into cooler off-axis zones. Plastic deformation ceases and with this a final generation of orthopyroxenite veins crosscut harzburgite and earlier deformed orthopyroxenite veins and remain relatively undeformed.
4. Influenced by mantle convection and overlying plate movement, the mantle diapir adjoins an end of the magma chamber and can also be in direct contact with the base of basaltic crust. In each setting percolating seawater and associated alkali cations, Cl etc. contaminate mafic magmas or reach uppermost mantle (2 to 3 km). Percolating and diffusing aqueous brines down crustal faults, in cooler off-axis regions, towards hotter ridge centres, and are circulated back to surface (of the crust) where they may form submarine vents.

Availability of aqueous brines at the upper mantle contacts, both petrologic and geophysical mohos, and the influence of convection cause migration of aqueous brines into already established dunitic zones.

Remaining pyroxenes are desilicified leaving residual Cr and Al.

Together with Cr and Al from high Al Cr-spinel formed by exsolution, Cr-spinel is precipitated in zones of highest solution flow, the dunite layer centers. No partial melts exist to facilitate equilibration of Cr-spinel to higher CRT values. Continued migration of aqueous brines and decreasing temperature allow serpentinization to begin. This is associated with development of chlorite - lizardite rims on Cr-spinel from Al loss. Sulfur poor Ni-sulphides and Ni-Fe alloy (awaruite) are also concentrated in Cr-spinel seams within dunite layers and result from serpentinization. In some cases two generations of Cr-spinel mineralization pre- and syn- to post-deformational, are confined to dunite layers along with associated chlorite-lizardite serpentinization rims. This shows that Cr-spinel mineralizing solutions and later serpentinizing fluids were concentrated within dunite layers.

Conclusions:

Obduction of various levels of mantle material equivalent to stages 2 to 3 and stage 4^(Fig. 10-2) produces the ultramafic massifs and associated chromite - chromitite - Cr-spinel occurrences studied in this thesis.

Stage 4, the high level - low temperature and pressure stage with well defined dunite zones and high Al Cr-spinel is represented best by Mt. Sydney-Williams and also by Murray Ridge and Pinchi Mt. Deeper levels where combined cumulate - refractory chromite originate are equivalent to the Mitchell Range ultramafic massif, and to the smaller Scottie Creek, Nicola and Bridon ultramafics.

The area of most importance to this thesis is Mt. Sydney-Williams where field and mineralogical relations show strong evidence for interaction of aqueous brines resulting in Cr-spinel mineralization. Other areas have chromite of refractory - cumulate origin, but at Mt. Sydney-Williams the final influencing process on Cr-spinel has been precipitation of Cr-spinel and its later alteration by continued passage of aqueous brines. Not only are aqueous solutions an important Cr - Al - Ni redistributing agent, but they must penetrate the uppermost mantle via established dunitic zones. Desilicification reduces these harzburgites to zones of monomineralic dunite with Cr-spinel.

Concluding remarks:

In conclusion, petrogenesis of chromite and Cr-spinel from B.C. alpine-type massifs can be summarized as following three separate and divergent trends. These trends are shown using variations in $\text{Cr}/\text{Cr} + \text{Al}$ vs $\text{Mg}/\text{Mg} + \text{Fe}^{+2}$ in Fig. 10-3.

Trend 1 corresponds to cumulate chromite precipitating, initially at high pressure (over 10 kb), before refractory chromite forms. Below 10 kb, refractory chromite joins this trend by equilibration with partial melt. $\text{Cr}/\text{Cr} + \text{Al}$ remains relatively constant while $\text{Mg}/\text{Mg} + \text{Fe}^{+2}$ steadily increases. This increase accompanies partial melting of progressively depleted mantle.

Trend 2 is characterized by decreasing $\text{Cr}/\text{Cr} + \text{Al}$ and similarly increasing $\text{Mg}/\text{Mg} + \text{Fe}^{+2}$. This corresponds to exsolved chromite and Cr-spinel which forms at pressures less than 10 kb and with falling temperature. The most Al rich Cr-spinel are those from spinel seams in dunite layers which represent spinel formed at low temperatures by aqueous fluids migrating through dunite layers. Increasing $\text{Mg}/\text{Mg} + \text{Fe}^{+2}$

Fig.10-2. Petrogenetic model showing various environments for precipitation of chromite and Cr-spinel of the textures and compositions described in B.C. alpine-type peridotites.

again reflects increasingly depleted mantle from which spinels are exsolving and undergoing sub-solidus re-equilibration. Higher Al in disseminated exsolved spinels has also been reported from the White Hills Peridotite, Newfoundland (Talkington, 1981) and by Menzies (1975) from the Othris Ophiolite.

Trend 3 is primarily an alteration trend brought about by fluid migration during serpentinization. The anomalous increase in $\text{Cr} / \text{Cr} + \text{Al}$ results from loss of Al to facilitate growth of enclosing lizardite - chlorite rims during serpentinization. Low $\text{Mg} / \text{Mg} + \text{Fe}^{+2}$ similarly reflects a loss of Mg.

Trends 1 to 3 portray chromite and Cr-spinel petrogenesis from high pressure and partial melting conditions which gives cumulate and then cumulate + refractory chromite (Trend 1) to low pressure - temperature conditions where exsolved disseminated chromite evolves into Cr-spinel (Trend 2). Finally Cr-spinels, primarily from dunite layers, lose Al and some Mg during serpentinization and define an alteration path (Trend 3).

Fig.10-3. Summary petrogenetic diagram in terms of CRT
vs XMg showing the three chromite and Cr-spinel
evolutionary trends.

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APPENDICES

A1: TABLE OF NOMENCLATURE FOR
ULTRAMAFIC ROCKS (after
Streckeisen, 1976)

A2: CHROMITE ANALYSES AVERAGED BY AREA
AND STATISTICS BY AREA

Cr-Spinel Chemistry for Mt Sydney-Williams Dunites

n= number of analyses per sample

	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	TOTAL
W82-2A n=8 Cr-Spinel	0.12	37.51	30.40	3.65	12.08	0.28	17.01	101.06
W82-17A n=3 Cr-Fe Spinel	0.18	10.94	36.87	19.93	27.67	0.96	3.25	99.80
W82-17B n=2 Cr-mgt	0.19	1.32	27.88	39.57	29.52	0.81	1.08	100.37
W82-19 n=3 Cr-mgt	0.21	0.27	20.37	49.09	25.24	0.83	3.48	99.49
W82-45 n=4 Cr-spinel	0.06	39.92	28.26	3.01	12.87	0.25	16.74	101.11
W82-49 n=6 Cr-spinel	0.03	30.40	38.72	2.17	14.93	0.35	14.29	100.89
W82-44 n=1 (rim) Cr-Fe spinel	0.09	24.29	39.70	6.27	18.79	0.48	10.99	100.42
W82-44 n=7 (core) Cr-spinel	0.11	40.16	28.39	2.09	12.94	0.30	16.59	100.58
W82-41 n=2 (rim) Mgt	0.12	0.11	1.46	66.92	30.54	0.13	0.24	99.52
W82-41 n=2 (mottled pale grey, in from rim) Cr-mgt	0.14	2.02	35.04	31.10	28.20	0.93	1.74	99.17
W82-41 n=6 (mottled medium grey, interior) Cr-spinel	0.11	34.68	35.07	1.24	13.59	0.30	15.02	100.01
W82-47A n=5 (in dunite) Cr-spinel	0.13	32.91	35.02	2.76	14.04	0.45	15.00	100.31

	TIO	AL2O3	CR2O3	FE2O3	FeO	MNO	MGO	TOTAL
W02-47A	0.12	34.21	34.46	2.15	12.55	0.41	16.05	99.95
n=5 (in opx)								
Cl-spinel								

MURRAY RIDGE DATA FROM DUNITe & HARZBURGITE:

W80-16,28, 0.03 21.50 46 47 2 33 13 66 0.59 12 40 22 21
37,40 n=8
Harzburgite

W80-38,39 0 04 10.68 58.73 2 88 16.34 0 85 10.91 100 43
n=4
Dunits

WS2-M2,M4 0 02 40 09 19 31 3 50 10 55 0 04 19 10 100 61
n=1
Dunit=

AVERAGED DATA FROM OTHER E.C. CHEMITE LOCALITIES:

Mitchell

Range 0 18 13.04 53.74 4.45 17.20 0.73 10.65 99.99
n=244 Harzburgite, some thin dunitic selvages

Elidon 0.25 15.30 52.49 4.13 16.20 0.42 11.94 100 73
n=13 Harzburgite

Nicola	0.36	167.05	45.94	6.70	23.77	0.29	7.08	100	20
n=17 Harzburgite									

Scottie Cr.	0.26	22.00	45.83	5.01	12.42	0.18	15.32	101.02
na10 Olivine rich harzburgite								

[illegible]

Anarchist	0 00	17 50	52.09	3.05	14.01	0 30	13.58	100.70
n=10								
Meta-carbonate								

1PAGE 11 STATISTICS FOR B.C. CHROMITE

VARIABLE NO. NAME	GROUPING VARIABLE LEVEL	TOTAL FREQUENCY	MEAN	STANDARD DEVIATION	ST. ERR OF MEAN	COEFF. OF VARIATION	S.M.A.L. VALUE	S.M.A.L. Z-SCORE	L.A.R.G.E.S.T. VALUE	L.A.R.G.E.S.T. Z-SCORE	RANGE
1 BDY											
	BDY	358	3.142	2.048	.1083	.65180	1.000	-1.05	8.000	2.37	7.000
	MURR	24	1.000	.000	.0000	.00000	1.000	.00	1.000	.00	.000
	MITR	224	2.000	.000	.0000	.00000	2.000	.00	2.000	.00	.000
	ANAR	10	3.000	.000	.0000	.00000	3.000	.00	3.000	.00	.000
	BRID	13	4.000	.000	.0000	.00000	4.000	.00	4.000	.00	.000
	NICO	17	5.000	.000	.0000	.00000	5.000	.00	5.000	.00	.000
	SCOT	10	6.000	.000	.0000	.00000	6.000	.00	6.000	.00	.000
	MSW	54	7.000	.000	.0000	.00000	7.000	.00	7.000	.00	.000
	PMT	6	8.000	.000	.0000	.00000	8.000	.00	8.000	.00	.000
3 Y102											
	BDY	358	.168	.141	.0074	.83485	.000	-1.20	1.900	12.32	1.900
	MURR	24	.037	.057	.0116	1.53264	.000	-.65	.280	4.27	.280
	MITR	224	.179	.098	.0066	.54830	.000	-1.82	.470	2.95	.470
	ANAR	10	.080	.021	.0067	.26352	.050	-1.42	.110	1.42	.060
	BRID	13	.252	.496	.1377	1.97373	.070	-.37	1.900	3.32	1.830
	NICO	17	.359	.093	.0225	.25755	.180	-1.94	.540	1.95	.360
	SCOT	10	.261	.027	.0085	.10289	.220	-1.53	.310	1.82	.090
	MSW	54	.116	.048	.0065	.40995	.010	-2.23	.230	2.40	.220
	PMT	6	.025	.042	.0171	1.67332	.000	-.60	.100	1.79	.100
4 AL203											
	BDY	358	17.133	9.951	.5259	.58085	.100	-1.71	53.250	3.63	53.150
	MURR	24	31.042	16.939	3.4576	.54567	1.230	-1.76	53.250	1.31	52.020
	MITR	224	13.044	2.921	.1951	.22390	.150	-4.41	18.790	1.97	18.640
	ANAR	10	17.583	1.622	.5130	.09227	14.500	-1.90	18.680	.68	4.180
	BRID	13	15.295	1.185	.3287	.07749	13.680	-1.36	16.850	1.31	3.170
	NICO	17	16.053	6.135	1.4879	.38216	1.410	-2.39	23.730	1.25	22.320
	SCOT	10	22.004	1.233	.3898	.05601	19.040	-2.40	23.180	.95	4.140
	MSW	54	28.366	14.062	1.9136	.49572	.100	-2.01	40.730	.88	40.630
	PMT	6	11.202	.245	.1001	.02190	10.980	-.90	11.640	1.79	.660

VARIABLE NO.	GROUPING	TOTAL FREQUENCY	MEAN	STANDARD DEVIATION	ST. ERR OF MEAN	COEFF. OF VARIATION	S M A L VALUE	L E S T Z-SCORE	L A R G E S T VALUE	Z-SCORE	RANGE
BDY	MURR	358	48.547	10.683	.5646	.22006	-1.170	-4.43	63.490	1.40	62.320
	MTR	24	36.044	16.428	3.3534	.45579	14.430	-1.32	59.860	1.45	45.430
	ANAR	224	53.736	4.163	.2782	.07748	20.900	-7.89	63.490	2.34	42.590
	BRID	10	52.092	2.046	.6470	.03928	50.250	-.90	56.790	2.30	6.540
	NICO	13	52.491	2.488	.6901	.04740	48.820	-1.48	55.200	1.09	6.380
	SCOT	17	45.942	4.753	1.1528	.10346	38.630	-1.54	55.620	2.04	16.990
	MSW	10	45.828	1.232	.3896	.02388	44.540	-1.05	48.880	2.48	4.340
	PMT	54	31.208	7.613	1.0360	.24395	1.170	-3.95	39.700	1.12	38.530
		6	58.305	1.157	.4725	.01985	57.290	-.88	50.140	1.59	2.850
6 FE203	MURR	358	5.429	7.855	.4151	1.44676	.010	-.69	66.940 ^c	7.83	66.930
	MTR	24	3.776	3.595	.7337	.95200	1.720	-.57	20.290	4.59	18.570
	ANAR	224	4.451	3.754	.2508	.84337	1.440	-.80	47.310	11.42	45.870
	BRID	10	3.045	.530	.1676	.17405	2.140	-1.71	3.830	1.48	1.690
	NICO	13	4.128	1.365	.3786	.33061	2.060	-1.52	6.350	1.63	4.290
	SCOT	17	6.895	1.727	.4188	.25790	5.240	-.84	10.340	2.11	5.100
	MSW	10	5.014	.450	.1422	.08968	4.410	-1.34	5.780	1.70	1.370
	PMT	54	10.915	17.625	2.3984	1.61478	.010	-.62	66.940	3.18	65.930
		6	3.088	.716	.2925	.23199	1.780	-1.83	3.760	.94	1.980
7 FEO	MURR	358	16.874	4.906	.2593	.29076	9.480	-1.51	31.430	2.97	21.950
	MTR	24	13.946	4.066	.8299	.29152	9.540	-1.08	28.080	3.48	18.540
	ANAR	224	17.199	4.539	.3033	.26390	9.480	-1.70	31.430	3.14	21.950
	BRID	10	14.008	1.416	.4477	.10107	11.560	-1.73	16.260	1.59	4.700
	NICO	13	16.198	.834	.2312	.05146	14.250	-2.34	18.050	2.22	3.800
	SCOT	17	23.745	1.708	.4143	.07188	21.170	-1.52	27.930	2.44	6.760
	MSW	10	12.418	.825	.2610	.06646	11.200	-1.48	13.860	1.75	2.660
	PMT	54	16.609	6.325	.8607	.38082	11.050	-.98	30.640	2.22	19.590
		6	12.982	.615	.2509	.04734	12.170	-1.32	13.670	1.12	1.500

[illegible]

A3: CHROMITE ANALYSES FROM MASTERFILE; KROBC
WITH SAMPLE AND ANALYSIS NUMBERS

12:12 APR 07 '83 APP1.PJ092914

MURRAY RIDGE		TID2	AL203	CR203	FE203	FEO	MNO	MGO	TOTAL	CRT	MRT	FRT	CRFE
W80-16		001	.03	20.56	46.54	2.98	15.89	.58	12.01	98.59	.60	.56	.04 1.28
1.		002	.03	20.14	47.69	2.54	16.01	.59	11.97	98.97	.61	.55	.03 1.31
W80-28		003	.03	25.23	43.24	2.34	14.56	.52	13.60	99.52	.53	.61	.03 1.31
1.		004	.28	24.70	43.91	1.72	14.87	.53	13.48	99.49	.54	.60	.02 1.33
W80-37		005	.02	21.47	46.96	2.70	16.04	.62	12.29	100.10	.59	.56	.03 1.29
1.		006	.01	20.67	48.02	2.29	16.16	.61	12.08	99.84	.61	.55	.03 1.32
W80-38		007	.01	12.03	57.69	2.89	16.35	.85	11.14	100.96	.76	.53	.04 1.54
1.		008	.01	11.97	57.85	2.86	15.84	.83	11.45	100.81	.76	.55	.03 1.60
W80-39		009	.06	9.58	59.51	2.83	16.90	.87	10.36	100.11	.81	.50	.04 1.55
1.		010	.07	9.13	59.86	2.95	16.26	.86	10.69	99.82	.81	.52	.04 1.61
W80-40		011	.03	20.00	47.27	2.91	16.03	.62	11.87	98.73	.61	.55	.03 1.29
1.		012	.03	19.26	48.13	2.77	15.71	.65	11.92	98.47	.63	.56	.03 1.34
W82-M4		288	.00	47.10	19.99	4.38	10.67	.01	19.04	101.19	.22	.75	.04 .75
1.		289	.00	46.27	20.70	4.55	10.87	.05	18.80	101.24	.23	.74	.05 .76
1.		290	.02	47.33	20.73	3.32	11.07	.00	18.85	101.32	.23	.74	.03 .78
1.		291	.04	47.12	19.86	2.92	10.71	.04	18.60	99.25	.22	.74	.03 .78
1.		292	.05	46.92	19.85	4.61	10.43	.15	19.08	101.09	.22	.75	.05 .75
1.		293	.00	45.67	21.79	3.62	11.11	.05	18.49	100.73	.24	.73	.04 .81
1.		294	.08	45.35	21.66	3.65	10.80	.00	18.62	100.16	.24	.74	.04 .82
1.		295	.05	46.01	22.03	3.70	11.30	.06	18.64	101.79	.24	.73	.04 .80
W82-MCB		296	.05	1.23	45.94	20.29	28.08	.87	1.59	98.05	.96	.09	.29 .58
1.		297	.00	53.25	14.43	2.86	9.54	.00	20.25	100.33	.15	.78	.03 .63
1.		298	.03	52.77	15.40	1.84	9.92	.00	19.88	99.84	.16	.77	.02 .68
1.		299	.00	51.24	16.00	3.10	9.58	.05	19.88	99.85	.17	.77	.03 .69
MITCHELL RANGE													
IRISH		013	.15	17.59	51.87	4.00	11.79	.34	15.07	100.81	.66	.68	.05 1.80
2.		014	.28	7.80	59.19	2.85	17.42	.41	9.78	97.93	.84	.48	.04 1.50
W81-CT		016	.12	15.29	51.87	5.20	16.67	.65	11.51	101.31	.69	.53	.06 1.29
2.		017	.12	17.31	51.38	3.48	16.79	.62	11.70	101.40	.67	.54	.04 1.32
2.		018	.16	17.14	50.99	3.70	16.60	.60	11.74	100.93	.67	.54	.04 1.32
2.		019	.27	16.82	50.73	4.26	17.13	.55	11.53	101.29	.67	.53	.05 1.26

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	W81-184	055	T102	AL203	CR203	FE203	FE0	MNO	MGO	TOTAL	CRT	MRT	FRT	CRFE
			.29	8.15	60.84	3.73	11.50	.49	13.86	98.86	.83	.67	.05	2.18
	2.	056	.29	8.12	61.09	3.31	13.10	.57	12.87	99.35	.83	.62	.04	1.98
	2.	057	.28	8.05	60.06	3.58	14.90	.63	11.58	99.08	.83	.56	.05	1.72
	2.	058	.29	7.93	60.79	3.38	13.08	.56	12.75	98.78	.84	.62	.04	1.97
	2.	059	.29	7.98	60.86	3.70	12.72	.55	13.07	99.17	.84	.63	.05	2.00
	W81-171	060	.40	17.70	50.36	3.82	11.98	.64	14.64	99.54	.66	.67	.05	1.74
	2.	061	.41	17.99	50.04	3.59	12.13	.63	14.54	99.34	.65	.67	.04	1.72
	2.	062	.39	17.68	50.31	3.94	12.00	.65	14.62	99.60	.66	.67	.05	1.73
	2.	063	.40	17.68	50.05	4.11	11.81	.67	14.70	99.42	.65	.67	.05	1.73
	W81-100	064	.41	8.51	50.15	7.88	25.86	1.05	3.96	97.82	.80	.20	.11	.81
	2.	065	.40	11.60	49.47	5.86	26.20	1.02	4.31	98.86	.74	.21	.08	.81
	2.	066	.34	8.98	48.86	10.51	24.43	1.03	5.21	99.36	.78	.26	.14	.79
	2.	067	.39	13.27	47.86	5.64	26.06	1.01	4.56	98.78	.71	.22	.07	.79
	2.	068	.43	12.91	49.60	4.60	26.68	.99	4.32	99.53	.72	.21	.06	.82
	W81-153	069	.35	14.13	51.60	4.93	18.15	1.01	10.11	100.28	.71	.48	.06	1.20
	2.	070	.36	15.73	51.22	4.30	19.83	1.01	9.55	102.00	.69	.44	.05	1.11
	2.	071	.33	15.09	51.62	4.07	18.11	.98	10.30	100.50	.70	.49	.05	1.22
	2.	072	.35	16.24	51.56	3.22	18.75	1.01	10.17	101.29	.68	.47	.04	1.21
	2.	073	.38	16.54	51.18	3.38	18.26	1.05	10.51	101.30	.67	.49	.04	1.22
	W81-154	074	.37	16.25	51.35	3.25	19.61	1.03	9.65	101.52	.68	.45	.04	1.15
	2.	075	.35	16.17	51.05	3.33	19.50	1.03	9.60	101.03	.68	.45	.04	1.15
	2.	076	.39	16.52	50.83	2.99	19.48	1.01	9.66	100.88	.67	.45	.04	1.15
	2.	077	.36	16.49	50.76	3.33	19.56	1.02	9.63	101.15	.67	.45	.04	1.14
	2.	078	.38	16.99	51.01	3.01	19.41	1.02	9.92	101.74	.67	.46	.04	1.16
	W81-163	079	.43	15.20	50.90	47.31	28.38	1.72	1.65	99.54	.99	.09	.68	.20
	2.	080	.12	10.95	52.18	6.54	21.11	.98	7.54	99.42	.76	.37	.08	1.03
	W81-183	081	.13	8.24	63.49	1.90	12.35	.45	13.52	100.08	.84	.64	.02	2.27
	2.	082	.13	8.22	62.75	2.40	11.83	.51	13.70	99.54	.84	.66	.03	2.30
	2.	083	.12	8.11	61.88	2.87	12.22	.68	13.22	99.11	.84	.64	.04	2.16
	2.	084	.09	8.11	61.69	3.10	11.81	.61	13.47	98.87	.84	.65	.04	2.21
	2.	085	.14	8.07	61.35	3.11	11.47	.51	13.66	98.31	.84	.66	.04	2.25

12:12 APR 07 '83 APP6.PJ092914

		T102	AL203	CR203	FE203	FEO	MNO	MGO	TOTAL	CRT	MRT	FRT	CRFE
W81-181A	146	.18	13.66	54.51	5.54	12.52	.29	14.25	100.95	.73	.65	.07	1.72
	2.	.16	13.16	53.27	5.00	17.26	.23	10.94	100.02	.73	.51	.06	1.29
	2.	.18	13.17	53.39	4.64	19.99	.27	9.35	100.98	.73	.44	.06	1.14
	2.	.17	13.10	52.77	5.22	20.78	.18	8.90	101.12	.73	.42	.06	1.08
	2.	.20	12.69	52.15	5.55	22.39	.19	7.78	100.96	.73	.37	.07	.99
W81-181B	151	.21	13.43	53.69	5.89	12.13	.13	14.37	99.85	.73	.66	.07	1.72
	2.	.20	13.42	54.10	5.27	14.69	.27	12.79	100.75	.73	.59	.06	1.50
	2.	.16	12.99	53.74	5.28	17.65	.30	10.81	100.93	.74	.50	.06	1.27
	2.	.17	13.03	52.98	5.58	19.65	.23	9.63	101.27	.73	.45	.07	1.13
	2.	.18	12.09	52.55	4.80	23.40	.19	6.87	100.08	.74	.33	.06	.97
W81-192A	156	.14	13.83	55.09	3.94	12.91	.21	13.85	99.98	.73	.64	.05	1.77
	2.	.17	14.48	54.88	3.73	13.45	.21	13.73	100.64	.72	.63	.04	1.71
	2.	.09	14.41	54.21	5.50	12.43	.26	14.43	101.33	.72	.66	.06	1.72
	2.	.13	13.54	54.07	5.05	12.02	.22	14.23	99.26	.73	.66	.06	1.79
	2.	.16	14.80	54.10	5.04	12.37	.18	14.59	101.25	.71	.66	.06	1.75
W81-192A	161	.13	14.05	54.33	5.07	12.36	.25	14.30	100.49	.72	.66	.06	1.75
	2.	.15	13.90	54.96	4.86	12.83	.22	14.13	101.05	.73	.65	.06	1.73
	2.	.15	13.88	55.61	4.60	12.77	.19	14.28	101.48	.73	.65	.05	1.77
	2.	.15	13.26	54.63	4.20	13.03	.18	13.53	98.98	.73	.63	.05	1.73
	2.	.13	12.84	54.24	4.05	22.12	.43	7.96	101.78	.74	.37	.05	1.07
W81-192B	166	.14	13.71	52.44	6.33	16.94	.36	11.36	101.29	.72	.53	.08	1.25
	2.	.13	15.02	51.68	4.46	18.63	.32	10.27	100.51	.70	.48	.05	1.18
	2.	.14	14.48	52.15	4.40	18.01	.36	10.50	100.03	.71	.49	.05	1.23
	2.	.15	14.70	51.73	5.19	17.17	.30	11.19	100.43	.70	.52	.06	1.25
	2.	.16	14.96	51.36	4.84	18.71	.32	10.24	100.60	.70	.48	.06	1.16
W81-174	171	.14	11.38	55.10	5.41	15.06	.86	11.68	99.63	.76	.56	.07	1.49
	2.	.12	11.46	55.15	5.63	15.24	.95	11.61	100.16	.76	.56	.07	1.47
	2.	.11	11.36	55.54	5.53	15.32	.96	11.59	100.40	.77	.56	.07	1.47
	2.	.13	11.64	55.79	4.72	16.00	.96	11.20	100.44	.76	.54	.06	1.45
	2.	.06	11.39	54.68	5.83	14.79	1.04	11.65	99.43	.76	.57	.07	1.48

12:12 APR 07 '83 APP7.PJ092914

	T102	AL203	CR203	FE203	FED	MNO	MGO	TOTAL	CRT	MRT	FRT	CRFE	
W81-174	176	.11	11.75	55.35	5.05	15.21	.95	11.64	100.06	.76	.56	.06	1.50
2.	177	.14	11.62	54.89	5.94	15.56	1.03	11.48	100.66	.76	.55	.07	1.42
2.	178	.13	11.63	54.80	5.63	15.10	1.01	11.64	99.94	.76	.56	.07	1.47
2.	179	.13	11.73	54.93	5.20	15.56	.98	11.36	99.89	.76	.55	.06	1.45
2.	180	.13	11.64	55.05	4.99	15.88	.89	11.18	99.76	.76	.54	.06	1.44
W81-174	181	.13	11.63	54.84	5.33	15.31	.91	11.51	99.66	.76	.55	.07	1.46
2.	182	.11	11.61	54.97	5.96	15.29	.89	11.79	100.53	.76	.56	.07	1.45
2.	183	.09	10.51	55.59	6.32	16.38	1.06	10.78	100.74	.78	.52	.08	1.37
2.	184	.13	11.43	55.37	5.68	15.45	.99	11.54	100.59	.76	.55	.07	1.45
2.	185	.11	11.45	55.20	5.84	15.28	1.01	11.64	100.62	.76	.56	.07	1.46
W81-100	186	.16	11.22	51.90	5.96	25.56	.54	5.22	100.56	.76	.25	.08	.87
2.	187	.13	11.38	51.42	5.80	26.32	.50	4.68	100.23	.75	.23	.07	.84
2.	188	.16	12.90	49.68	5.23	26.24	.48	4.76	99.45	.72	.23	.07	.82
2.	189	.15	12.70	50.54	5.62	26.83	.55	4.63	101.02	.73	.22	.07	.81
2.	190	.47	6.55	40.78	21.88	28.19	.54	3.28	101.69	.81	.16	.29	.51
W81-1928	191	.16	14.64	52.66	5.79	14.36	.23	13.19	101.03	.71	.60	.07	1.47
2.	192	.13	14.98	52.72	5.46	14.92	.21	12.92	101.35	.70	.59	.06	1.43
2.	193	.16	15.00	52.50	5.44	15.44	.31	12.55	101.41	.70	.57	.06	1.39
2.	194	.09	14.99	50.71	4.50	21.55	.27	8.36	100.47	.69	.39	.06	1.02
2.	195	.14	15.44	48.84	6.22	22.58	.32	7.92	101.46	.68	.37	.08	.91
W81-1928	196	.16	14.92	52.16	5.07	15.26	.30	12.44	100.31	.70	.57	.06	1.41
2.	197	.17	14.95	52.81	5.02	15.22	.27	12.66	101.10	.70	.58	.06	1.43
2.	198	.15	15.19	52.47	5.17	15.43	.29	12.63	101.60	.70	.58	.06	1.40
2.	199	.12	14.67	52.92	5.30	15.43	.26	12.49	101.19	.71	.57	.06	1.40
2.	200	.13	13.99	51.61	4.87	20.60	.31	8.86	100.37	.71	.42	.06	1.07
W81-868	201	.15	10.86	51.80	4.96	25.01	.81	4.94	98.54	.76	.25	.06	.90
2.	202	.14	10.69	51.53	5.86	25.32	.96	4.76	99.26	.76	.24	.08	.87
W81-86	203	.18	11.28	52.37	3.66	24.66	1.05	5.02	98.22	.76	.25	.05	.94

15:49 APR 07 '83 APP10.PJ092914

	TIQ2	AI203	CR203	FE203	FEQ	MMQ	MGQ	TOTAL	CRL	MRT	FRL	CREE
W80-65	215	16.20	48.82	5.78	16.43	.34	11.36	99.27	.67	.54	.07	1.21
4.	216	16.85	50.62	5.46	16.58	.42	12.07	102.11	.67	.55	.06	1.26
4.	217	16.75	49.10	3.41	18.05	.41	12.06	101.68	.66	.53	.04	1.18
4.	218	16.80	50.39	4.96	16.50	.34	11.96	101.10	.67	.55	.06	1.27
4.	219	16.52	51.58	6.35	16.45	.38	11.74	101.18	.70	.54	.08	1.26
4.	220	16.84	49.88	5.51	16.23	.30	12.15	101.06	.67	.55	.07	1.26
NICOLA DEPOSIT												
W80-94	226	39.23	37.40	5.98	21.17	.23	9.75	100.93	.53	.43	.07	.79
5.	227	33.23	39.89	5.27	21.53	.19	9.43	100.39	.53	.42	.06	.79
5.	228	22.21	35.38	9.42	23.23	.22	8.13	101.19	.55	.37	.11	.66
5.	229	31.22	78.41	5.39	22.15	.33	9.02	101.28	.55	.40	.06	.79
W80-97	230	18.52	52.52	10.34	26.39	.58	3.66	98.92	.87	.19	.14	.80
5.	231	36.23	49.40	5.24	21.31	.28	9.50	100.30	.53	.43	.06	.80
5.	232	54.14	55.62	10.24	27.93	.61	2.42	98.78	.96	.13	.14	.81
W80-99	233	31.14	13.48	5.83	23.75	.28	6.75	99.55	.70	.32	.07	.88
5.	234	32.12	99.50	5.73	24.52	.29	6.30	100.35	.72	.30	.07	.88
5.	235	39.16	12.45	6.33	24.15	.13	6.93	99.99	.66	.32	.08	.80
5.	236	43.16	58.46	6.37	23.98	.25	7.34	101.49	.65	.34	.08	.82
5.	237	45.15	99.46	6.05	24.08	.30	6.96	100.36	.66	.32	.08	.82
5.	238	41.14	36.45	8.24	23.94	.30	6.66	99.52	.68	.32	.10	.78
5.	239	38.15	91.46	5.57	24.19	.25	6.69	99.47	.66	.31	.07	.82
5.	240	41.16	50.46	6.12	23.24	.24	7.56	100.26	.65	.35	.08	.84
5.	241	23.12	41.50	6.25	24.47	.29	6.11	99.88	.73	.29	.08	.87
5.	242	45.16	53.46	5.45	23.95	.13	7.27	100.61	.66	.33	.07	.84
SCOTTIE CREEK DEPOSIT												
W80-120	243	29.21	64.45	5.58	11.20	.19	15.95	100.40	.59	.70	.06	1.57
6.	244	27.21	96.46	5.00	11.95	.11	15.67	101.03	.58	.69	.06	1.53
6.	245	25.21	97.46	5.20	11.95	.16	15.66	101.21	.58	.68	.06	1.52
6.	246	31.22	20.46	4.65	12.53	.20	15.41	101.65	.58	.67	.05	1.50
6.	247	23.21	24.45	5.78	11.52	.25	15.60	100.29	.59	.69	.07	1.53

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		TI02	AL203	CR203	FE203	FEO	MNO	MGO	TOTAL	CRT	MRT	FRT	CRFE
W80-122	248	.27	22.65	44.54	5.15	12.20	.10	13.44	100.35	.57	.68	.06	1.43
6.	249	.25	23.00	45.63	4.41	13.29	.18	15.00	101.76	.57	.65	.05	1.41
6.	250	.22	19.04	48.88	4.46	13.86	.20	13.95	100.62	.63	.63	.05	1.46
6.	251	.27	23.18	44.66	5.11	12.57	.25	15.38	101.42	.56	.67	.06	1.42
6.	252	.25	23.16	44.92	4.80	13.11	.16	15.09	101.49	.57	.66	.05	1.39
MT. SYDNEY-WILLIAMS													
W82-2A	262	.10	36.06	30.94	4.48	11.05	.29	17.33	100.25	.37	.72	.05	1.12
7.	263	.13	37.43	30.77	3.80	11.27	.33	17.54	101.27	.36	.72	.04	1.12
7.	264	.13	38.17	30.21	3.54	12.27	.31	17.07	101.69	.35	.70	.04	1.03
7.	265	.12	38.15	30.52	3.07	12.00	.29	17.18	101.33	.35	.70	.03	1.08
7.	266	.11	38.44	30.33	2.99	12.01	.25	17.23	101.36	.35	.70	.03	1.07
7.	267	.13	36.90	30.14	3.76	12.21	.27	16.66	100.08	.35	.69	.04	1.02
7.	268	.11	37.17	30.06	4.18	13.12	.29	16.31	101.24	.35	.67	.04	.95
7.	269	.13	37.89	30.23	3.40	12.69	.32	16.69	101.35	.35	.69	.04	1.00
7.	270	.14	12.96	37.97	15.79	26.07	.90	4.18	98.01	.66	.21	.21	.54
W82-17A	271	.19	10.35	36.83	21.40	28.21	.98	3.07	101.02	.70	.15	.28	.46
7.	272	.21	9.50	35.82	22.60	28.72	1.00	2.49	100.33	.72	.13	.30	.44
7.	273	.18	1.64	31.39	35.12	29.02	.86	1.25	99.46	.93	.07	.50	.33
W82-17B	274	.20	1.00	24.37	44.02	30.02	.76	.90	101.27	.94	.05	.62	.23
7.	275	.18	.25	17.38	52.59	23.51	.71	4.57	99.19	.98	.24	.74	.17
W82-19	276	.23	.35	20.36	48.56	24.19	.91	3.94	98.54	.98	.21	.69	.21
7.	277	.22	.20	23.38	46.11	28.03	.87	1.92	100.73	.99	.10	.65	.23
W82-45	278	.07	39.82	27.96	3.44	12.83	.27	16.75	101.13	.32	.68	.04	.92
7.	279	.06	39.96	28.51	2.93	12.55	.25	16.98	101.24	.32	.69	.03	.97
7.	280	.06	40.14	28.57	2.53	12.80	.26	16.82	101.17	.32	.69	.03	.97
7.	281	.06	39.74	28.00	3.12	13.31	.23	16.39	100.85	.32	.67	.03	.90
W82-49	282	.05	30.10	38.64	2.09	15.46	.34	13.86	100.54	.46	.60	.02	1.11
7.	283	.01	30.93	36.92	2.60	16.03	.38	13.48	100.35	.44	.58	.03	1.01
7.	284	.04	29.38	39.60	2.50	15.24	.35	14.04	101.15	.47	.60	.03	1.14
7.	285	.03	31.13	38.62	1.95	14.39	.30	14.83	101.25	.45	.63	.02	1.20
7.	286	.02	30.58	39.12	1.79	14.53	.33	14.60	100.97	.46	.62	.02	1.21
7.	287	.03	30.27	39.39	2.10	13.94	.38	14.94	101.05	.47	.64	.02	1.25

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A4: BMDP CODING FOR CHROMITE ANALYSES IN A3

Appendix A3a lists, by analytical order, chromite analyses from B.C. alpine-type complexes and from the Anarchist deposit. The analysis, or record, number is in columns 2, 3 and 4 and corresponds to record numbers in appendix A3 which gives sample numbers and data.

Coding columns:

To facilitate use of BMDP (Bio-medical data processing) programmes (see A10) for data manipulation the first 12 columns were used as coding columns. Twelve code columns preceding the actual analysis allows results to be dealt with in terms of various geological parametres. A key to the coding columns and these parametres is given below:

Column 1: Location of chromite occurrences.

1. Murray Ridge
2. Mitchell Range
3. Anarchist Deposit
4. Bridon Deposit
5. Nicola (Cameo L.) Deposit
6. Scottie Creek
7. Mt. Sydney-Williams
8. Pinchi Mt.

Columns 2 - 4: Analysis (record) number.

Column 5: Host rock.

1. Dunite
2. Harzburgite
3. Orthopyroxenite
4. Gabbro

5. Rodingite

6. Limestone

Column 6: Chromite texture.

1. Accessory disseminated chromite

2. Disseminated layer

3. Disseminated pod

4. Massive layer

5. Massive pod

6. Aggregate layer

7. Aggregate pod "Aggregate" is equivalent to
heavily disseminated

8. Massive dyke or vein (Anarchist deposit)

Column 7: Position of beam on grain.

1. Rim analysis

2. Core analysis

Column 8: Types of solid inclusions in chromite.

1. Inclusion free

2. Olivine

3. Orthopyroxene

4. Clinopyroxene

5. Amphibole

6. Mica (chlorite)

7. Plagioclase

8. Sulphide (Fe, Ni)

9. Platinum Group Minerals (PGM)

Column 9: Fluid inclusions in chromite.

1. Fluid inclusion free

2. Fluid inclusions present

Column 10: Serpentinization.

1. Minerals surrounding chromite unserpentinized
2. Minerals surrounding chromite serpentinized

Column 11: Fabric of host rock.

1. Massive texture
2. Foliated
3. Lineated

Column 12: Chromite alteration.

1. Chromite has ferritchromit and/or magnetite rims
2. Chromite is unaltered.

Columns 13 - 15: Blanks

16 - 20: TiO_2

21 : Blank

22 - 26: Al_2O_3

27 : Blank

28 - 32: Cr_2O_3

33 : Blank

34 - 38: Fe_2O_3

39 : Blank

40 - 44: FeO

45 : Blank

46 - 50: MnO

51 : Blank

52 - 56: MgO

57 : Blank

58 - 63: Total

100121111212	206026222222	212026222222
100221211212	206126222222	212126222222
100321111211	206226222222	212226222222
100421211211	206326222222	212326222222
100521112212	206417281221	212426222222
100621212212	206517281221	212526222222
100711112211	206617281221	212627222221
100811212211	206717281221	212727222221
100911112211	206817281221	212827222221
101011212211	206927222221	212927222221
101121111212	207027222221	213027282222
101221211212	207127222221	213127282222
101326100220	207227222221	213227282222
201426200220	207327222221	213327282222
201624281222	207427282222	213425222222
201724281222	207527282222	213525222222
201824281222	207627282222	213625222222
201924281222	207727282222	213725222222
202026222222	207827282222	213826222222
202226222222	207921221220	213926222222
202326222222	208021221220	214024221222
202426222222	208117222222	214124221222
202526222222	208217222222	214224221222
202626222222	208317222222	214324221222
202726222222	208417222222	214424221222
202826222222	208517222222	214524221222
202926222222	208626222221	214624221222
203026222222	208726222221	214724221222
203126222222	208826222221	214824221222
203226222222	208926222221	214924221222
203326222222	209026222221	215024221222
203426222222	209117282222	215124221222
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204527221222	210211222212	216226221222
204627221222	210311222212	216326221222
204727221222	210411222212	216426221222
204827221222	210511222212	216526221222
204927221222	210627212221	216621221222
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205222221222	210927212221	216921221222
205322221222	211027212221	217021221222
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205517222221	211225222222	217226222222
205617222221	211325222222	217326222222
205717222221	211425222222	217426222222
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205917222221	211626222222	217626222222
	211726222222	217726222222
	211826222222	217826222222
	211926222222	217926222222

218026222222
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A5: OLIVINE ANALYSES

IC RESULTS
SUPER RECAL FOR P.C. DUTIES

	1	2	3	4	5	6	7	8
SI02	39.06	47.17	41.23	42.44	41.95	39.87	47.75	47.11
TI02	.00	.02	.00	.00	.00	.01	.00	.00
A203	.01	.00	.00	.02	.00	.01	.00	.00
FE0	6.45	6.61	7.02	6.75	6.67	9.38	8.50	8.48
MI0	.09	.13	.14	.13	.02	.19	.21	.31
NI0	.34	.40	.42	.51	.46	.36	.38	.44
MD0	51.05	51.71	51.42	51.62	51.49	49.74	50.50	49.67
CA0	.01	.00	.00	.00	.01	.00	.00	.00
MA20	.00	.00	.01	.03	.03	.00	.00	.00
K20	.00	.00	.00	.01	.00	.00	.00	.01
SUM	97.01	101.06	101.03	101.51	100.63	99.56	102.34	101.22
SI	.977	.977	1.000	1.010	1.007	.983	1.016	1.014
AI	.000	.000	.000	.001	.000	.000	.000	.000
TI	.000	.000	.000	.000	.000	.000	.000	.000
ME	1.902	1.841	1.848	1.831	1.842	1.838	1.788	1.782
FE	.135	.132	.141	.134	.114	.193	.169	.172
MI	.002	.003	.007	.003	.000	.004	.004	.006
NI	.007	.008	.008	.010	.009	.007	.007	.009
CA	.000	.000	.000	.000	.000	.000	.000	.000
MA	.000	.001	.000	.001	.001	.000	.000	.000
K	.000	.000	.000	.000	.000	.000	.000	.000
D	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000
FO	93.38	93.31	92.92	93.16	93.22	90.43	91.37	91.07
FA	6.62	6.69	7.08	6.84	6.88	9.57	8.63	8.93
F/H	.072	.073	.078	.075	.073	.108	.097	.100
F/H	.067	.068	.072	.070	.068	.097	.088	.092

1 WBI-77: GROUNDMASS OL. IN HARTBURGITE
2 WBI-77: GROUNDMASS OL. IN HARTBURGITE
3 WBI-77: GROUNDMASS OL. IN HARTBURGITE
4 WBI-77: GROUNDMASS OL. IN HARTBURGITE
5 WBI-77: GROUNDMASS OL. IN HARTBURGITE
6 WBI-1928: GROUNDMASS OL. IN HARTBURGITE
7 WBI-1928: GROUNDMASS OL. IN HARTBURGITE
8 WBI-1928: GROUNDMASS OL. IN HARTBURGITE

13	W81-193:	GRUNDMASS III.	IN	HARZBURGITE
14	W81-193:	GRUNDMASS OL.	IN	HARZBURGITE
15	W81-193:	GRUNDMASS OL.	IN	HARZBURGITE
16	W81-193:	GRUNDMASS OL.	IN	HARZBURGITE

21	WB1-16.13	GROUNDMASS OL.	IN HARTBURGITE
22	WB1-16.13	GROUNDMASS OL.	IN HARTBURGITE
23	WB2-MCH	GROUNDMASS OL.	IN DUNIT
24	WB2-MCH	GROUNDMASS OL.	IN DUNIT

1 SUPER RECAL

SUPER RECAL FOR P.C. OLIVINES

	25	26	27	28	29	30
SI02	41.97	41.65	41.75	41.69	41.36	41.51
TI02	.00	.02	.00	.00	.00	.00
A203	.00	.00	.00	.00	.00	.00
FEO	8.09	7.72	6.08	6.08	6.20	6.44
MMO	.00	.13	.14	.12	.12	.10
NIO	.00	.00	.25	.30	.27	.30
MO	51.42	50.77	51.64	52.48	51.48	52.15
CAO	.13	.11	.00	.00	.00	.00
MA20	.00	.00	.00	.00	.00	.00
K20	.00	.00	.00	.00	.00	.00
SUM	101.61	100.40	99.86	100.67	99.43	100.50

	25	26	27	28	29	30
SI	1.002	1.002	1.006	1.007	1.003	1.003
AL	.000	.000	.000	.000	.000	.000
TI	.000	.000	.000	.000	.000	.000
MG	1.830	1.827	1.856	1.873	1.841	1.848
FF	.162	.156	.123	.122	.124	.129
MM	.000	.001	.003	.006	.005	.006
NI	.000	.000	.005	.006	.005	.006
CA	.003	.003	.000	.000	.000	.000
MA	.000	.000	.000	.000	.000	.000
K	.000	.000	.000	.000	.000	.000
O	4.000	4.000	4.000	4.000	4.000	4.000
FO	91.89	92.14	93.80	93.90	93.67	93.52
FA	8.11	7.86	6.20	6.10	6.33	6.48
F/M	.088	.087	.068	.066	.049	.070
F/FM	.081	.080	.063	.062	.064	.066

25 MB2-441 GROUNDMASS OL. IN MINITE
26 MB2-441 GROUNDMASS OL. IN HARTWURGITE
27 MB2-47A1 INCLUSION OL. IN CHROMITE IN DI

28 MB2-47A1 INCLUSION OL. IN CHROMITE IN DI
29 MB2-47A1 INCLUSION OL. IN CHROMITE IN DI
30 MB2-47A1 INCLUSION OL. IN CHROMITE IN DI

A6: PYROXENE ANALYSES

SUPER RECAL FOR QFX

2	3
6.70	6.59
33.06	33.35
.56	.57
57.55	57.68
.01	.01
1.66	1.72
.41	.42
.03	.03
.14	.12
100.12	100.29

1.981	1.981	1.981	1.981
.019	.019	.019	.019
.031	.031	.031	.031
.010	.010	.010	.010
.000	.000	.000	.000
.001	.001	.001	.001
.011	.011	.011	.011
.014	.014	.014	.014
.002	.002	.002	.002
.000	.000	.000	.000
10.7	10.7	10.7	10.7
87.48	87.48	87.48	87.48

.115	.115
.101	.101

3 QFX 1 SPOT 3
4 QFX 2 CIRCLE 2

A7: AMPHIBOLE ANALYSES

IC RESULTS
SUPER RECAL

SUPER RECAL FOR R.F. AMPHIBOLITES IN CHROMITE

	1	2	3	4	5
SI02	46.34	46.04	44.83	48.44	41.46
TI02	.37	.36	.34	.31	.43
AL2O3	10.01	10.89	10.26	8.67	10.14
CR2O3	2.23	1.85	2.14	2.15	2.27
FeO	2.31	1.84	2.30	2.18	2.23
MnO	.07	.00	.03	.02	.04
NiO	.07	.15	.05	.14	.01
MgO	20.85	19.93	21.54	20.30	21.40
CaO	14.69	15.44	14.52	17.54	14.57
Na2O	3.12	3.19	3.00	3.31	3.15
K2O	.04	.03	.03	.02	.03
H2O	2.16	2.15	2.13	2.21	2.04
SUM	102.26	101.91	101.19	105.51	97.77

SI	6.440	6.415	6.308	6.588	4.086
AL	1.560	1.585	1.692	1.381	1.754
TI	.080	.202	.009	.000	.000
YI	.039	.038	.038	.032	.047
MG	4.319	4.137	4.517	4.096	4.682
FE	.268	.217	.271	.247	.274
MN	.008	.000	.004	.002	.005
NI	.008	.017	.004	.015	.001
CR	.245	.204	.238	.230	.263
CA	2.187	2.304	2.189	2.544	2.292
NA	.841	.861	.818	.869	.897
K	.007	.005	.003	.003	.006
H	2.000	2.000	2.000	2.000	2.000
D	24.000	24.000	24.000	24.000	24.000
0	100.00	100.00	100.00	100.00	100.00
F/H	.064	.052	.061	.061	.060
F/TN	.060	.050	.057	.057	.056

1 W81-192B1 INCL. AMPH. IN CHROMITE IN HAR
2 W81-192B1 INCL. AMPH. IN CHROMITE IN HAR
3 W81-192B1 INCL. AMPH. IN CHROMITE IN HAR
4 W81-192B1 INCL. AMPH. IN CHROMITE IN HAR
5 W81-192B1 INCL. AMPH. IN CHROMITE IN HAR

A8: CHLORITE ANALYSES

16. RESULTS
1 SUPER RECAL

2 SUPER RECAL FOR P.C. CHROMITE IN CHROMITE

	1	2	3	4	5	6	7	8
SI02	31.69	35.16	33.50	32.14	31.32	32.58	33.78	35.40
TI02	.01	.01	.00	.02	.02	.02	.00	.00
A203	15.32	14.09	14.95	16.32	12.77	16.36	14.04	13.13
C203	1.87	2.45	1.86	2.70	3.65	2.49	2.56	1.03
FE0	1.60	2.59	2.49	1.32	1.73	.88	1.39	1.43
MNO	.01	.04	.01	.02	.01	.00	.03	.00
NIO	.29	.15	.20	.42	.43	.36	.40	.36
MGO	35.23	34.98	35.48	35.17	32.77	34.70	35.18	35.27
CAO	.01	.00	.01	.04	.03	.05	.01	.01
MA20	.00	.00	.00	.05	.00	.00	.00	.00
K20	.00	.00	.00	.03	.01	.01	.02	.01
H20	12.56	13.06	12.91	12.86	11.93	12.83	12.79	12.78
SUM	98.59	102.53	101.41	101.06	93.67	100.28	100.20	99.42

SI	6.044	6.451	6.221	5.982	6.290	6.087	6.331	6.639
AL	1.956	1.549	1.779	2.018	1.710	1.913	1.669	1.361
AE	1.488	1.497	1.492	1.565	1.312	1.688	1.432	1.540
TL	.001	.001	.000	.003	.003	.003	.000	.000
FE	.255	.397	.387	.206	.123	.137	.218	.224
HN	.002	.006	.002	.003	.002	.000	.005	.000
CR	.282	.355	.273	.398	.380	.368	.378	.153
MG	10.015	9.566	9.820	9.766	9.809	9.662	9.858	9.858
MI	.044	.022	.030	.063	.069	.054	.060	.054
CA	.002	.000	.002	.008	.006	.010	.002	.002
NA	.000	.000	.000	.018	.000	.000	.000	.000
K	.000	.000	.000	.007	.003	.002	.005	.002
H	16.000	16.000	16.000	16.000	16.000	16.000	16.000	16.000
0	36.000	36.000	36.000	36.000	36.000	36.000	36.000	36.000
F/M	.026	.042	.021	.021	.013	.014	.023	.023
F/M	.025	.040	.021	.021	.013	.014	.022	.022

1 W81-1931CHL. INCL. IN CHROMITE IN HARZ.
2 W81-1931 CHL.D. INCL. IN CHROMITE IN HARZ
3 W81-1931 CHL.D. INCL. IN CHROMITE IN HARZ
4 W81-1071 CHL.D. INCL. IN CHROMITE IN HARZ

5 W81-1071 CHL.D. INCL. IN CHROMITE IN HARZ
6 W81-1071 CHL.D. INCL. IN CHROMITE IN HARZ
7 W81-1531 CHL.D. INCL. IN CHROMITE IN HARZ
8 W81-1531 CHL.D. INCL. IN CHROMITE IN HARZ

A9: PLATINUM - GROUP MINERAL ANALYSES

315

MURU INDEX	REPTD RDDS	SPECIMENS	AVERAGE CAL	YES	NO	STND ST. IN	OB. IN	CALIN	VAR	HOM	NO	WT. PC	RECAL	MOL	EL	ZED	ABS	FLU	ZAF
0.0	1	4	0.0	1	4	0.0	1	4	0.0	1	4	0.0	1	4	0.0	1	4	0.0	1

TO 100X

WB1-108A CIRCLE 1	RU	OS	PD	IR	RH	AS	PT	6 CYC	1EL	BKD	OBS	CORR	P/B	STND ST. IN	OB. IN	CALIN	VAR	HOM	NO	WT. PC	RECAL	MOL	EL	ZED	ABS	FLU	ZAF
378	372	61.57	12461.000	.299	.2878	.63	1	2	42.32	40.75	.246	RU 1.10	1.28	1.00	1.42												
182	160	7.047	1781.000	.091	.0881	.01	0	2	12.03	11.58	.037	OS 1.32	.996	1.00	1.32												
26	20	2.827	877.658	.015	.0142	.00	0	1	1.94	1.86	.011	PD 1.03	1.10	1.00	1.12												
127	106	4.823	15411.000	.069	.0663	.00	0	1	9.05	8.71	.028	IR 1.32	.995	1.00	1.32												
18	13	2.277	13431.000	.009	.0091	.00	0	1	1.28	1.23	.007	RH 1.10	1.22	1.00	1.35												
36	15	.6671	1097.697	.009	.0089	.00	0	1	.98	.95	.008	AS 1.03	1.00	1.00	1.03												
5447	52.48	3906.248	.345	.345	.3328	.00	0	1	36.27	34.92	.664	B 1.03	1.08	1.01	1.12												
0	0	.0000	14111.000	.000	.0000	.00	0	1	103.9	100.0	.000	PT 1.33	.994	1.00	1.32												
0	0	.0000	14111.000	.000	.0000	.00	0	1	103.9	100.0	.000	PT 1.33	.994	1.00	1.32												

TO 100X

WB1-86B HIGH RU	RU	OS	PD	IR	RH	AS	PT	6 CYC	1EL	BKD	OBS	CORR	P/B	STND ST. IN	OB. IN	CALIN	VAR	HOM	NO	WT. PC	RECAL	MOL	EL	ZED	ABS	FLU	ZAF
312	51.54	12461.000	.250	.2502	1.29	2	2	35.42	36.51	.235	RU 1.10	1.29	1.00	1.42													
199	8.778	17391.000	.114	.1142	.45	1	2	14.90	15.36	.053	OS 1.31	.996	1.00	1.30													
21	14	2.050	879.658	.011	.0107	.00	0	1	1.38	1.42	.009	PD 1.02	1.09	1.00	1.11												
137	116	5.277	15221.000	.076	.0760	.00	0	1	9.91	10.22	.035	IR 1.31	.994	1.00	1.30												
19	14	2.536	13431.000	.011	.0106	.00	0	1	4.43	4.47	.009	RH 1.09	1.24	1.00	1.35												
83	61	2.817	1097.697	.039	.0389	.00	0	1	4.11	4.24	.037	AS 1.02	.999	1.00	1.02												
4306	41.49	3906.248	.273	.2731	.00	0	1	29.71	30.63	.622	S 1.02	1.13	1.01	1.16													
2	2	.7033E-01	14111.000	.001	.0011	.73	0	1	97.00	100.0	.15	.001	PT 1.32	.994	1.00	1.31											

WB1-86B AVERAGE	RU	OS	PD	IR	RH	AS	PT	6 CYC	1EL	BKD	OBS	CORR	P/B	STND ST. IN	OB. IN	CALIN	VAR	HOM	NO	WT. PC	RECAL	MOL	EL	ZED	ABS	FLU	ZAF
287	47.47	12461.000	.230	.2304	4.11	7	3	32.93	33.65	.219	RU 1.09	1.31	1.00	1.43													
241	10.63	17301.000	.139	.1392	4.45	12	3	18.02	18.41	.064	OS 1.30	.996	1.00	1.29													
21	15	2.130	882.658	.011	.0111	.16	1	1.42	1.45	.009	PD 1.01	1.09	1.00	1.10													
136	115	5.226	15041.000	.076	.0763	.39	1	9.87	10.09	.034	IR 1.30	.994	1.00	1.29													
18	13	2.348	13431.000	.010	.0098	.00	0	1	1.33	1.36	.009	RH 1.09	1.25	1.00	1.36												
83	62	2.833	1097.697	.039	.0392	.00	0	1	4.10	4.19	.037	AS 1.02	1.00	1.00	1.02												
4306	41.49	3906.248	.273	.2731	.00	0	1	30.05	30.70	.629	S 1.01	1.15	1.01	1.18													
2	2	.7033E-01	14111.000	.001	.0011	.30	0	1	97.88	100.0	.15	.001	PT 1.31	.994	1.00	1.30											

TO 100X

WB1-86B CENTRE HIGH OS	RU	OS	PD	IR	RH	AS	PT	6 CYC	1EL	BKD	OBS	CORR	P/B	STND ST. IN	OB. IN	CALIN	VAR	HOM	NO	WT. PC	RECAL	MOL	EL	ZED	ABS	FLU	ZAF
244	238	39.33	12461.000	.191	.1910	.00	0	1	27.79	28.09	.185	RU 1.08	1.35	1.00	1.46												
347	325	14.33	17211.000	.189	.1888	.00	0	1	24.20	24.45	.085	OS 1.29	.996	1.00	1.28												
20	13	1.892	884.658	.010	.0098	.00	0	1	1.25	1.26	.008	PD 1.00	1.09	1.00	1.09												
130	109	4.953	14851.000	.073	.0733	.00	0	1	9.39	9.49	.033	IR 1.29	.995	1.00	1.28												
19	14	2.442	13431.000	.010	.0102	.05	0	1	1.41	1.43	.009	RH 1.08	1.28	1.00	1.39												
83	62	2.825	1097.697	.039	.0391	.01	0	1	4.06	4.10	.036	AS 1.01	1.00	1.00	1.01												
4306	41.49	3906.248	.273	.2731	.00	0	1	30.71	31.04	.643	S 1.00	1.18	1.02	1.20													
2	2	.7033E-01	14111.000	.001	.0011	.00	0	1	98.95	100.0	.15	.001	PT 1.30	.994	1.00	1.29											

A10: MICROPROBE STANDARDS USED

A10

List of standards used

Khromite (Cr, Al, Fe, Mg)

Boettcher pyroxene (Ca, Ni, Si, Mg)

Kaers (Ti)

R1596 (Mn)

Czech. olivine (Internal standard)

Cam Olivine (Ni)

Carlos (Fe, Mg, Si, Ni, Mn)

Mill (Ni, for peak; runs done on Cam 01.)

SAFF (As)

PGE's (pure metal standards used)

PYRI (Fe, S)

OPX2 (Ca, Si, Mg)

HYPE (Fe, Mg, Si, Cr)

KAK (Ti, Na, Al)

FN16 (Fe, Ni)

— All: MICROPROBE RUNNING CONDITIONS

Microprobe running conditions for chromite analyses.

Channel	Bragg	Window	Lower Level	Channel	Bragg	Window	Lower Level
1 Cr	40 3	2.246	2.245	2 Al	36 33	0.617	0.616
3 Fe	33 40	2.657	2.654	4 Mg	43 40	0.520	0.520
5 Ti	48 33	1.871	1.869	6 Mn	62 56	2.447	2.445

Channels 1, 3 and 5 were run on spectrometer #1 using Quartz.

Channels 2, 4 and 6 were run on spectrometer #2; KAP was used for

2 and 4 (Al & Mg) and LiF was used for 6 (Mn).

Standards used were Khro, Kaers and R1596; Cr, Al, Fe, Mg from Khro;

Ti from Kaers and Mn from R1596.

Counting times were 40 seconds and 20 seconds for background counts.

The microprobe was run at 15 KV and a beam current of 0.5×10^{-7} amps.

Microprobe running conditions:

Chromite, silicate, sulphide and alloy microprobe analyses were done at Carleton University, Department of Geology, on a Cambridge MK V electron microprobe. Data collected, as counts per second, was reduced to weight percent oxides using the correction programme of Rucklidge & Gasparri (1969). In addition chromite was analysed at Memorial University, St. Johns, Newfoundland, on a JEOL JX50A electron microprobe and at BRGM - CNRS, Orléans, France, on a CAMEBAX microprobe. Table A9-1 gives comparisons of analyses with Carleton data and shows variances to be within acceptable limits.

For all elements analysed in chromite, silicates, sulphides and alloys, $K_{\alpha 1}$ X-rays were used. Corrections for peak overlaps, as for the Ru $L_{\beta 1}$ overlap on Pd $K_{\alpha 1}$, have been made.

Table A9-1 shows slightly higher Cr_2O_3 , FeO and lower TiO_2 , MnO and Fe_2O_3 from Memorial compared to Carleton data. MgO is essentially identical. The largest discrepancy is for Cr_2O_3 , at 2.15 wt. percent, but is not large enough to effect overall trends or create anomalous points.

Comparison of data from France and Carleton (Table All-1) shows good agreement and consistently low totals. Low totals are attributed to a poor polish.

Table All-1: Comparison of microprobe data from Memorial University and BRGM - CNRS (France) with Carleton University data, averaged analyses. Number of points in brackets.

Oxide	Memorial U. sample W80-58	Carleton U. sample W81-86	BRGM - CNRS (France)
TiO ₂	0.08	0.11 0.16	0.11
Al ₂ O ₃	14.34	15.51 10.61	11.24
Cr ₂ O ₃	54.44	52.29 51.77	52.91
Fe ₂ O ₃	1.47	4.25 4.91	3.67
FeO	15.39	14.96 24.11	24.67
MnO	0.47	1.08 1.02	0.92
MgO	12.47	12.18 5.22	5.16
Total	100.36 (4 pts)	100.38 97.80 (5 pts) (5 pts)	98.68 (6 pts)

A12: BMDP COMMAND FILE PROGRAM EXAMPLES AND
OXIDE & RATIO PLOTS WITH ALL DATA POINTS

TO SEE REMARKS AND A SUMMARY OF NEW FEATURES FOR
THIS PROGRAM, STATE NEWS, IN THE PRINT PARAGRAPH.

This version of BMDP has been converted for use on
Honeywell CP6 (Level 66/DPS 8) computers by
Statistical Software Section
Carleton University Computing Centre
1208 Arts Tower
Ottawa, Canada K1S 5B6
(613) 231-7547

PROGRAM CONTROL INFORMATION .

/PROBLEM

TITLE IS 'RATIO PLOTS, COMPOSITE AND BY AREA, B.C.'.

/INPUT

CASE=358.

VAR=10.

FORMAT IS '(F1.0,F3.0,10X,7F6.2)'.

UNIT IS 3.

/VARIABLE

NAMES ARE ID, RDY, TI02, AL203, CR203, FE0, MNO, MGO, CRT, MRT, FRT.

ADD=3.

GROUPING IS RDY.

BLANKS ARE MISSING.

LABEL IS ID.

/GROUP

CODES(1) ARE 1,2,3,4,5,6,7,8.

NAMES(1) ARE MURR, MITR, ANAR, BRID, NICO, SCOT, MSW, PHT.

/TRANSFORM

CRT=((CR203/152.02)/((CR203/152.02)+(AL203/101.94))).

MRT=(MGO/43.32)/((MGO/43.32)+(FE0/71.85)).

FRT=(FE203/159.70)/((FE203/159.70)+(CR203/152.02)+(AL203/101.94)).

/PLOT

MINIMUM=(10)0,0,0.

MAXIMUM=(10)1,1,1.

SIZE=70,42.

YVAR=10,12.

XVAR=11,11.

GROUPS ARE 1,2,3,4,5,6,7,8.

GROUPS ARE 1.

GROUPS ARE 2.

GROUPS ARE 3.

GROUPS ARE 4.

GROUPS ARE 5.

GROUPS ARE 6.

GROUPS ARE 7.

MRT=(MGO/43.32)/((MGO/43.32)+(FE0/71.85)).
 FRT=(FE203/159.70)/((FE203/159.70)+(CR203/152.02)+(AL203/101.94)).
 /PLOT
 MINIMUM=(10)0,0,0.
 MAXIMUM=(10)1,1,1.
 SIZE=70,42.
 YVAR=10,12.
 XVAR=11,11.
 GROUPS ARE 1,2,3,4,5,6,7,8.
 GROUPS ARE 1.
 GROUPS ARE 2.
 GROUPS ARE 3.
 GROUPS ARE 4.
 GROUPS ARE 5.
 GROUPS ARE 6.
 GROUPS ARE 7.
 GROUPS ARE 8.
 STATISTICS.
 CHAR=GROUP.
 1PAGE 2
 /END

OPROBLEM TITLE IS
 RATIO PLOTS, COMPOSITE AND BY AREA, B.C.

NUMBER OF VARIABLES TO READ IN.	10
NUMBER OF VARIABLES ADDED BY TRANSFORMATIONS.	3
TOTAL NUMBER OF VARIABLES	13
NUMBER OF CASES TO READ IN.	358
CASE LABELING VARIABLES	ID
MISSING VALUES CHECKED BEFORE OR AFTER TRANS.	NEITHER
BLANKS ARE.	MISSING
INPUT UNIT NUMBER	3
REWIND INPUT UNIT PRIOR TO READING.	YES
NUMBER OF WORDS OF DYNAMIC STORAGE.	15358
NUMBER OF CASES DESCRIBED BY INPUT FORMAT	1

***** TRAN PARAGRAPH IS USED *****

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COPIE DE QUALITEE INFERIEURE

Statistical Software Section
Carleton University Computing Centre
1208 Arts Tower
Ottawa, Canada K1S 5B6
(613) 231-7547

325

PROGRAM CONTROL INFORMATION

/PROBLEM

TITLE IS 'CHROMITE CHEMISTRY, S. TO C. B.C., COMPOSITE PLOTS'.

/INPUT

CASE=358.

VAR=9.

FORMAT IS '(F1.0,A3,10X,7F6.2)'.

UNIT IS 3.

/VARIABLE

NAMES ARE DDY,ID,TIO2,AL2O3,CR2O3,FE2O3,FeO,MNO,MGO.

GROUPING IS DDY.

BLANKS ARE MISSING.

/GROUP

CODES(1) ARE 1,2,3,4,5,6,7,8.

NAMES(1) ARE MURR,MITR,ANAR,BRID,NICO,SCOT,MSW,PMT.

/PLOT

MINIMUM=(4)0,0,(7)0,(9)0.

MAXIMUM=(4)100,100,(7)100,(9)100.

SIZE=70,42.

YVAR=5,7.

XVAR=4,9.

GROUPS ARE 1.

GROUPS ARE 2.

GROUPS ARE 3.

GROUPS ARE 4.

GROUPS ARE 5.

GROUPS ARE 6.

GROUPS ARE 7.

GROUPS ARE 8.

STATISTICS.

CHAR=GROUP.

/END

1PAGE 2 CHROMITE CHEMISTRY, S. TO C. B.C., COMPOSITE PLOTS

OPROBLEM TITLE IS
CHROMITE CHEMISTRY, S. TO C. B.C., COMPOSITE PLOTS

NUMBER OF VARIABLES TO READ IN. 9
NUMBER OF VARIABLES ADDED BY TRANSFORMATIONS. 0
TOTAL NUMBER OF VARIABLES 9

1PAGE 6 RATIO PLOTS - CHROMITE FROM DIFFERENT HOST ROCKS

	MEAN	ST. DEV.	REGRESSION LINE	RES. MS.
X	.52035	.16329	$X = -.55092*Y + .89010$	.01933
Y	.67115	.15602	$Y = -.50298*X + .93288$	.01765

PAGE 7 RATIO PLOTS FOR FLUID INCL, CHROMITE DATA

N= 356
COR=-.5457

MRT

	MEAN	ST.DEV.	REGRESSION LINE	RES.MS.
X	.52901	.16351	X=-.79833*Y+ .57443	.01853
Y	.06903	.11319	Y=-.37778*X+ .26548	.00902

PAGE 6 OXIDE PLOTS - CHROMITE FROM DIFFERENT HOST ROCKS

	MEAN	ST. DEV.	REGRESSION LINE	RES. MS.
X	17.133	9.9514	$X = -.61822*Y + 47.145$	55.566
Y	48.547	10.683	$Y = -.71248*X + 60.753$	64.039

PAGE 7 OXIDE PLOTS - CHROMITE FROM DIFFERENT HOST ROCKS

A13: OLIVINE - SPINEL AND 2-PX GEOTHERMOMETRY

Olivine - spinel geothermometry:

Olivine - spinel geothermometry is dependant upon partitioning of Fe^{+2} - Mg between olivine and spinel. Olivine and spinel must co-exist and be in equilibrium. For these reasons olivine inclusions in Cr-spinel and chromite are used since they are least likely to have had their primary compositions, at least post sub-solidus compositions, altered by serpentinization.

Irvine (1965) described Fe^{+2} - Mg partitioning for Fe_2SiO_4 - Mg_2SiO_4 (olivine) and $\text{Fe}(\text{Cr}_x, \text{Al}_y, \text{Fe}_z^{+3})_2\text{O}_4$ - $\text{Mg}(\text{Cr}_x, \text{Al}_y, \text{Fe}_z^{+3})_2\text{O}_4$ (spinel) with three exchange reactions using a model formula, $\text{R}^{++}\text{R}_2^{+++}\text{O}_4$, which Cr-spinel closely approximates:

In terms of the above three reactions solid solution between spinel and olivine end members can be expressed with the following general reaction:

where,

$$x = \frac{\text{Cr}}{\text{Al} + \text{Cr} + \text{Fe}^{+3}}$$

$$y = \frac{\text{Al}}{\text{Al} + \text{Cr} + \text{Fe}^{+3}}$$

$$z = \frac{\text{Fe}^{+3}}{\text{Al} + \text{Cr} + \text{Fe}^{+3}}$$

x, y, z are the trivalent cations in spinel and total one.

For exchange reaction .4 the empirical equilibrium distribution coefficient is:

$$K_D = \frac{X_{\text{Mg}}^{\text{Ol}} \cdot X_{\text{Fe}}^{\text{Sp}+2}}{X_{\text{Fe}^{+2}}^{\text{Ol}} \cdot X_{\text{Mg}}^{\text{Sp}}} \quad .5$$

where,

$$X_{\text{Mg}}^{\text{Ol}} = \frac{\text{Mg}}{(\text{Mg} + \text{Fe}^{+2})_{\text{olivine}}}, \quad \text{and}$$

$$X_{\text{Fe}^{+2}}^{\text{Sp}} = \frac{\text{Fe}^{+2}}{(\text{Mg} + \text{Fe}^{+2})_{\text{spinel}}}$$

Mole fractions, $X_{\text{Mg}}^{\text{Ol}}$, are used in place of activity values since olivine and spinel are assumed to have ideal behaviour for the temperature ranges involved (Bradley, 1962; Irvine, 1965). Activity coefficients (correction factors for non-ideal behaviour) are thus equal to 1, and mole fraction are directly used.

Using the exchange reactions set out by Irvine (1965) for spinel-olivine equilibrium, Jackson (1969) has calculated an olivine-spinel geothermometer assuming ideal Fe^{+2} - Mg mixing between olivine and spinel at high temperatures. Relating the Fe^{+2} - Mg distribution co-efficient from the general equation, .4, to standard Gibbs free energy of formation of products and reactants gives:

$$K_D = ((-\Delta G^\circ_{1/2Mg_2SiO_4} - X\Delta G^\circ_{FeCr_2O_4} - Y\Delta G^\circ_{FeAl_2O_4} - Z\Delta G^\circ_{Fe^{+2}Fe^{+3}_2O_4} + \Delta G^\circ_{1/2Fe_2SiO_4} + X\Delta G^\circ_{MgCr_2O_4} + Y\Delta G^\circ_{MgAl_2O_4} + Z\Delta G^\circ_{MgFe^{+3}_2O_4})/RT) \quad .6$$

$\Delta G^\circ_{1/2Mg_2SiO_4}$ and $\Delta G^\circ_{1/2Fe_2SiO_4}$ are standard

Gibbs free energies for the olivine end members and the remaining X, Y, Z G terms are for the spinel end members. R is the gas constant (R = 1.987 calories/degree/mole) and T is temperature in degrees Kelvin (K). To determine T (K) Jackson (1969) combined expressions .5 and .6 in the form:

$$T(K) = ((-\Delta G^\circ_{1/2Mg_2SiO_4} - X\Delta G^\circ_{FeCr_2O_4} - Y\Delta G^\circ_{FeAl_2O_4} - Z\Delta G^\circ_{Fe^{+2}Fe^{+3}_2O_4} + \Delta G^\circ_{1/2Fe_2SiO_4} + X\Delta G^\circ_{MgCr_2O_4} + Y\Delta G^\circ_{MgAl_2O_4} + Z\Delta G^\circ_{MgFe^{+3}_2O_4})/R \ln \quad .7$$

$$\frac{x_{Mg}^{O1}}{x_{Fe}^{O1+2}} \cdot \frac{x_{Fe}^{Sp+2}}{x_{Mg}^{Sp}}$$

Substituting Gibbs free energy values into expression .7 and using R = 1.987 cal./deg./m., T can be expressed as:

$$T(K) = \frac{5590X + 1018Y - 1702Z + 2400}{.90X + 2.56Y - 3.08Z - 1.47 + 1.987 \ln K_D Mg - Fe^{+2}} \quad .8$$

Use of the olivine - spinel geothermometer must take into account several uncertainties. Jackson (1969) estimates up to ± 300 degrees C differences from uncertainty inherent from free energy data. Obata et al (1974) suggest that non-ideal mixing occurs in olivine at lower temperatures. Roeder et al (1979) show that below 1200 degrees C redistribution of Fe^{+2} - Mg between spinel and olivine ceases whereas it is significant above 1200 degrees C. Between 1200 and 1350 degrees C, at 1 atm to 15 kb, Fujii (1977) has shown that Fe^{+2} - Mg partitioning between olivine and spinel behaves either in ideal fashion, or nonidealities cancel each other. The work of Roeder et al (1979) thus shows that Fe^{+2} - Mg redistribution occurs below liquidus temperatures and he revises the Jackson (1969) geothermometer by using a different Gibbs free energy value for chromite (FeCr_2O_4) such that T is now expressed as:

$$T \text{ (K)} = \frac{3480X + 1018Y - 1720Z + 2400}{2.23X + 2.56Y - 3.08Z - 1.47 + 1.987 \ln K_{\text{D Fe}^{+2} - \text{Mg}}} .9$$

Temperatures derived by Roeder et al (1979) using their equation, .9, for experimentally heated samples are equivalent to the actual temperatures used in experimental runs. In addition Roeder et al. (1979) has also found subsolidus temperatures for unheated samples to be consistent with those for heated samples. Jackson's (1969) conclusion that magmatic temperatures result from the olivine-spinel geothermometer are not substantiated, instead the olivine-spinel geothermometer gives temperatures of subsolidus equilibration.

Temperatures higher than expected are derived from the Jackson (1969) geothermometer which erroneously leads to conclusions of

magmatic equilibration. High temperatures result for high Al Cr-spinels, about 200 degrees C higher than in experimental runs (Roeder et al., 1979). Poorly known G values for high Al spinels may be one reason together with nonideal mixing of high Al spinels and olivines (Roeder et al., 1979). Engl and Evans (1980) maintain that Fe loss to Pt-wire or furnace atmosphere during the experimental runs of Roeder et al. (1979) cause some error leading to temperatures of equilibration too low for the Roeder et al. (1979) geothermometer. However, Roeder et al. (1980) state that Fe loss is negligible and does not effect temperatures. It is concluded that anomalously high temperatures from the Jackson (1969) geothermometer result from uncertainties related to Al in high Al spinels.

Spinel from alpine-type complexes show a range of compositions (Irvine & Findlay, 1972) which is similarly shown by B.C. alpine-type Cr-spinels and chromites. Use of the olivine-spinel geothermometer on spinels of extreme compositions is questionable, particularly where Al and possibly Fe^{+2} and Fe^{+} are high. Serpentinization can greatly effect Fe and Al contents of spinels and completely affected spinels are rare. To eliminate the effects of Fe^{+3} on equilibrium Fabries (1979) assumes spinel compositions to conform to the formula:

geothermometer which stems from Fe^{+2} - Mg reactions of Irvine (1965) Fabries (1979) defines T, free from the effects of Fe^{+3} as:

$$T(K) = \frac{4250Y_{Cr}^{Sp} + 1343}{\ln K_D + 1.825Y_{Cr}^{Sp} + 0.571} \quad .10$$

where,

$$Y_{Cr}^{Sp} = \frac{Cr}{Al + Cr + Fe^{+3}} \quad \text{and}$$

$$\ln K_D = \ln K_D' - 4.0Y_{Fe}^{Sp+3}$$

so that the apparent distribution co-efficient, K_D , is normalized to a ferric iron-free basis.

$$K_D = \frac{X_{Mg}^{01} \cdot X_{Fe^{+2}}^{Sp}}{X_{Fe^{+2}}^{01} \cdot X_{Mg}^{Sp}}$$

Fabries (1979, Table 2) finds that application of equation .10 to peridotitic spinels (lherzolite) gives results in close agreement with temperatures from heating experiments (Roeder et al., 1979).

Two pyroxene geothermometer

	Wood & Banno (1973)	Wells (1977)
1.	1003.6	899.6
2.	1039.5	941.7

W82-P2 from Pinchi Mt.

A14: SULPHIDE AND NI-FE ALLOY ANALYSES

Sulphide and Ni-Fe alloy analyses from Mt. Sydney-Williams

	S	Fe	Ni	As	Ru	Os	Ir	Total
W81-192A grain 1	33.26	30.30	33.14	.30	.00	.43	.84	98.27
W81-192A grain 2	31.89	27.82	37.40	.20	.00	.38	.81	98.50
W81-192A grain 3	32.96	29.44	33.47	.41	.00	.98	.64	97.90
W82-19	.11	47.87	42.81					90.79
W82-17B	.12	46.59	41.90					88.61

LEGEND

Nephrite.

Norite dike.

Metapelite (argillite & slate).

Metavolcanics (andesite).

Norite ; massive, layered.

Dunite.

Harzburgite.

Layered zone: d-dunite.
opx-orthopyroxenite.

Disseminated chromite (crt) layer.

(All samples are W82-....)

Asb.

Tildesley Creek

WEST PEAK

Outcrop area

2 of 1

Cross fibre asbestos

Geological contact: observed, assumed

Layering: inclined, vertical

Foliation: inclined, vertical

Breccia (tectonic)

Fault: displacement unknown, known

Talcose sheared hornblende
dunite

Prominent ridge-line

Peak

Torn, stream-flow
direction

Bog

Creek

Decar

Vdh

Inset C

125° 23'

78/80
-34
86
81

34

N
(t)

81
-50
54

n
n

Middle River

4 of 1

Inset A

Tildesley

Layered zone: d-dunite.
opx-orthopyroxenite.

Disseminated chromite (crt) layer.
(All samples are W82-....)

54
Mt. SYDNEY
& sample

Bog.

KEY-WILLIAMS; Geology

locations.

6 of

47 folded quartz veins &
harzburgite xenoliths.

SCALE

54° 54'

Inset - B

Where are Insets A & B located?
Scale on insets?

8 of 8

Legend

Dunite ; f1, foliated.

Harzburgite; f2, foliated, m, massive, c, coarse-grained,
2a, altered- chlorite + talc.

Anorthositic gabbro.

Norite ; m, massive with sub-ophitic texture.

Gabbro dykes; pre-obduction.

Rodinigte, dykes.

Nephrite; f, foliated - dark green, 'b, brown.

Carbonate - recrystallized, with chert nodules.

Talc alteration zone, grey-green.

Cherty siltstone.

Laminated argillite-siltstone.

Ferruginous siltstone-slate.

Coarse tectonic breccia, finely comminuted
serpentine matrix.

Breccia lenses, mylonitic.

Tarn.

X

Chromite occurrence.

Thrust fault with dip direction.

Limit of outcrop - ridges &
cirques; observed geological
contact.

Assumed geological contact.

X Chromite occurrence.

Thrust fault with dip direction.

Limit of outcrop - ridges & cirques; observed geological contact.

Assumed geological contact.

Foliation, strike & dip.

76

55° 15'

3 of

compound chromitite pod X

f2h

BROME PEAK

Simpson deposit

SOUTHWEST RIDGE SUMMIT

chromite layers

CACHE CREEK GROUP

Geology of the Mitchell Range, B.C.

54

SCALE

22h

T

57

142h.1

37

57

61-17

8

T

$$N_{(t)}$$

CACHE CREEK GROUP

Williston Lake

Mitchell Range

Takla L.

5 Trembleur L.

Stuart L.

Fort St. James

27

Vanderhoof

16

97

Prince George

87

6 of 6

W81-18
W81-17

W81-15, 15b
-16-

f2h

W81-21

W81-22
W81-23
W81-24

W81-25

Zone with 10-15%
disseminated crt
W81-26

f2h

W81-36

W81-37

W81-38

W81-39

W81-40

W81-27

f2h1

W81-74

W81-75

W81-76

f2h

W81-161

f2h

W81-162

Setm

Setm

Setm

W81-763

W81

1-110
81-109
-123

6 of 6

PINCHI FAULT ZONE

Murray Ridge : Geology

24

LE

Cretaceous conglomerate.

Cache Creek Group; limestone,
chert, phyllite, greywacke,
basalt.

R

Rodingite dyke.

Harzburgite

Layered
separated

Dunite layer

Orthopyroxene

Joint; strike

Fault zone

Assumed

45 Fold axis

SCALE

0 1/4

1/2

3/4

0 0.5 1.0

contour interval; 500ft. (

3 of 3

3 of 3

53

53

67

67

81

81

1000

1000

contour interval; 500ft. (152.4 m.)

24

343

Murray Ridge Sample location map.

(accompanies geological map)

W80-22

W80-23

SCALE

1/4 1/2 3/4 1 mi
0.5 1.0 1.5 km

119 14

LEGEND

Shuswap Complex; granodiorite.

Wispy chromite layers.

Chromitite layers.

Serpentinized harzburgite.

Anarchist Group; meta-greywacke, meta-siltstone.

Chromite zone contacts.

Chromitite layers, strike and dip.

Foliation, strike and dip.

Fault contact.

SCALE

24

granodiorite.

s.

gite.

a-greywacke, meta-siltstone.

fs.

strike and dip.

p.

SCALE

343

6 6

OF / DE

Fig No? Table?

LEGEND

1. Limestone, white.
2. Silty limestone, grey.
3. Interbedded silty limestone and siltstone.
4. Siltstone.

- Bedding, strike and dip.
- Shearing, strike and dip.
- Joint plane, strike and dip.
- Breccia.

SCALE

GEOLOGY & SAMPLE LOCATIONS:

NICOLA DEPOSIT

LEGEND

Coast Range Intrusion; quartz diorite.

Harzburgite and minor dunite with chromite.

Cache Creek Group; limestone and calcareous siltstone.

Chapperton Group; meta-siltstone and meta-argillite.

Fault.

Chromite showing.

Fault breccia.

Bedding; strike and dip.

Foliation; strike and dip.

(All samples are W80-.....)

Alacran showing
(fractures)

-106, 107, 108

-105

orthopyroxene lenses

-100, 101

-92, -89

Cameo Lake
showing

-104

-111

Cameo L.

LE LOCATIONS:

POSIT

Alacrin showing

(french)

-106, 107, 108

Eileen L

N (H)

1/2 mi

80 km.

Raymer L.

orthopyroxene lenses

-100, 101

-105

-92

-89

Cameo Lake showing

75

-103

-104

-111

Cameo L

LEGEND

ange Intrusion; quartz diorite.

gite and minor dunite with chromite.

Creek Group; limestone and
ous siltstone.

on Group; meta-siltstone and meta-

■ Chromite showing.

breccia.

; strike and dip.

; strike and dip.

(All samples are W80-.....)

END

1 0 0 9 8 4

FIN