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CHROMIAN MUSCOVITE, UVAROVITE, AND ZINCIAN CHROMITE: PRODUCTS OF REGIONAL METASOMATISM IN NORTHWEST NELSON, NEW ZEALAND

ALVA CHALLIS

Institute of Geological and Nuclear Sciences Ltd., P.O. Box 30 368, Lower Hutt, New Zealand

RODNEY GRAPES

Research School of Earth Sciences, Victoria University of Wellington, P.O. Box 600, Wellington, New Zealand

KEN PALMER

Analytical Facility, Victoria University of Wellington, P.O. Box 600, Wellington, New Zealand

Abstract

Chromian muscovite ("fuchsite") with up to 8.5% Cr_2O_3, uvarovite garnet (up to 83% Uv), zincian chromite (up to 13.7% ZnO), and chromian rutile (up to 3.3% Cr_2O_3), are variously associated with chlorite, biotite, epidote, kyanite, and tourmaline, all Cr-bearing, in Lower Paleozoic quartzite, biotite schist, marble, and carbonated ultramafic rocks in Northwest Nelson, New Zealand. Sulfides and carbonates associated with the Cr-silicates and oxides include pyrite, galena, gersdorffite, pentlandite, and calcite, siderite, cerussite, magnesite, dolomite, and ankerite. Chromium mineralization of the host rocks takes the form of thin seams, and broad zones tens of meters wide that parallel host-rock schistosity and exhibit varying intensities of green coloration. All the Cr-rich localities occur within 3–4 km of Early Cretaceous granitic plutons and are close to, or lie within, major fault zones. Field relationships, mineral textures, rock associations, and compositions indicate that the mineral paragenesis is metasomatic in origin, and the result of hydrothermal fluids from the granitic plutons interacting with ultramafic rocks or detrital chromite derived from them.

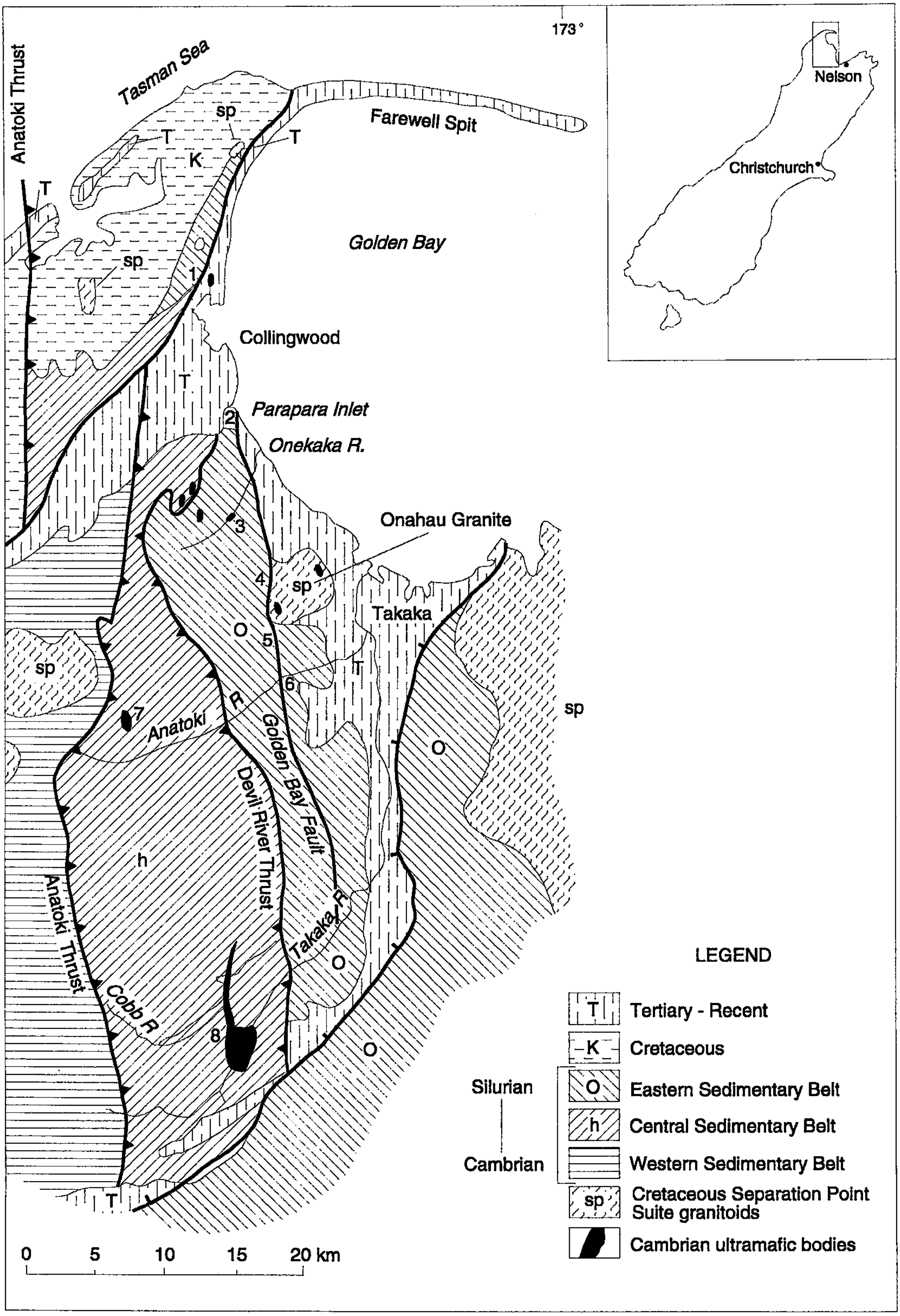
Keywords: chromian muscovite, uvarovite, zincian chromite, chromian rutile, Cr-silicates, analyses, metasomatism, Nelson, New Zealand.

Sommaire

Nous documentons une association de muscovite chromifère ("fuchsite") contenant jusqu'à 8.5% de Cr_2O_3, d'uvarovite (jusqu'à 83% du pôle Uv), de chromite zincifère (jusqu'à 13.7% de ZnO), et de rutile chromifère (jusqu'à 3.3% de Cr_2O_3) avec chlorite, biotite, épidote, kyanite et tourmaline chromifères dans les grès, schistes à biotite, cipolins, et roches ultramafiques carbonatées du secteur nord-ouest de Nelson, en Nouvelle-Zélande. Parmi les sulfures et carbonates associés aux silicates et oxydes chromifères se trouvent pyrite, galène, gersdorffite, pentlandite, calcite, sidérite, cerussite, magnésite, dolomite et ankérite. La minéralisation en chrome des roches hôtes se présente sous forme de minces couches, et de zones floues étalées sur des dizaines de mètres, parallèles à la schistosité de l'encaissant, et montrant une intensité variable d'une coloration verte. Tous les exemples d'enrichissement en Cr sont situés au plus à 3–4 km d'un contact avec un pluton granitique d'âge crétacé précoce, et, dans chaque cas, près d'une zone de failles ou bien dans une telle zone. Selon les relations de terrain, les critères texturaux, l'association des roches et les données chimiques, la paragenèse des minéraux chromifères aurait une origine par métasomatose, et résulterait de l'interaction d'une phase fluide issue des plutons granitiques avec le cortège de roches ultramafiques, ou bien la chromite détritique dérivée de celles-ci.

(Traduit par la Rédaction)

Mots-clés: muscovite chromifère, uvarovite, chromite zincifère, rutile chromifère, silicates de chrome, composition chimique, métasomatose, Nelson, Nouvelle-Zélande.


173°
Nelson
Christchurch
Tasman Sea
Anatoki Thrust
Farewell Spit
Golden Bay
Collingwood
Parapara Inlet
Onekaka R.
Onahau Granite
Takaka
Anatoki R.
Golden Bay Fault
Devil River Thrust
Takaka R.
Anatoki Thrust
Cobb R.
0 5 10 15 20 km
LEGEND
T Tertiary - Recent
K Cretaceous
Silurian
Cambrian
O Eastern Sedimentary Belt
h Central Sedimentary Belt
Western Sedimentary Belt
sp Cretaceous Separation Point Suite granitoids
Cambrian ultramafic bodies

INTRODUCTION

Chromian muscovite (previously termed "fuchsite" where the Cr content exceeds 1 wt% Cr_2O_3) is relatively rare, although there are eight previously reported occurrences in New Zealand (Hutton 1942, Cooper 1976, Railton & Watters 1990). It was first reported from Lower Paleozoic rocks in Northwest Nelson by Bell *et al.* (1907), in quartzite boulders at Parapara Inlet (Fig. 1), and in mica-rich layers in quartzite (probably the source of the boulders) about 1.5 km south of the inlet. Chromian muscovite also was recorded in the Arthur Marble at Copperstain Creek, 8 km south of the inlet (Wodzicki 1972), and in quartz–biotite schist in the Onekaka Schist at Campbell Creek, 13 km south of the inlet (Grindley 1971). Chromian garnet (uvarovite) has been reported previously from only three localities in New Zealand, all associated with ultramafic rocks of the Dun Mountain Ophiolite belt (Railton & Watters 1990). There are no published data on the chromian muscovite and associated Cr–Zn-rich minerals in Northwest Nelson. In this paper, we describe six new occurrences of chromian muscovite, variously associated with chromian garnet, zincian chromite, and Cr-bearing varieties of chlorite, margarite, biotite, kyanite, epidote, tourmaline and rutile, and discuss their origin in terms of regional Cr–Zn metasomatism associated with widespread intrusion of Early Cretaceous granitic rocks.

GENERAL GEOLOGY

Early Cambrian to Early Devonian rocks in Northwest Nelson form three main north–south-striking belts, termed the Western, Central, and Eastern Sedimentary Belts, which are separated by thrust faults (Fig. 1). The Western Sedimentary Belt consists of quartz-rich sandstone, mudstone, and graptolitic black shale. The Central Sedimentary Belt is characterized by volcanic rocks, volcanogenic sediments, and carbonate rocks. The Eastern Sedimentary Belt is composed of carbonate and quartz-rich sediments. Volcanic rocks of the Central Sedimentary Belt contain a small layered mafic–ultramafic body, the Cobb Igneous Complex (Grindley 1980), probably emplaced in the Lower or Middle Cambrian and rapidly uplifted and unroofed by the Upper Cambrian, as indicated by the presence in Upper Cambrian – Ordovician sediments of detrital grains of a distinctive chromite with >63% Cr_2O_3 that occurs in this complex (Hunter 1975, Pound 1993). Small lenses of serpentinized and metasomatized ultramafic rocks, some possibly representing fault slivers from the main Cobb mass, occur throughout the Central Sedimentary Belt (Fig. 1), and talcose ultramafic inclusions occur in the Onahau Granite (Grindley 1971).

Deformation, metamorphism, and mineralization

Rocks in all three belts have been subjected to several episodes of deformation and recrystallization, with intense faulting, folding, and nappe formation, particularly in the Central Belt (Grindley 1980, Cooper 1989). The Late Silurian – Early Devonian Tuhua Orogeny was the main pre-Cretaceous tectonic event, resulting in the development of a low-grade regional metamorphic fabric with lineations generally parallel to the axes of recumbent folds. In the Early Cretaceous, the Rangitata Orogeny in Northwest Nelson was marked by intrusion of the Separation Point Batholith and its satellite plutons, which produced widespread amphibolite-grade metamorphism in the northern part of the region. The Cretaceous metamorphism overprints earlier fabrics, resulting in a regional NNE-trending schistosity (Grindley 1980). The presence of kyanite, almandine, staurolite and margarite in pelitic horizons within the Onekaka Schist indicates that T–P conditions of 500–550°C and 6–8 kbar were reached. These minerals are associated with chromian muscovite, which defines the regional Early Cretaceous S_1 fabric of the schist and has been crenulated by a less intense S_2 fabric. In the southern half of the area, remote from plutons of Cretaceous granitic rocks, the rocks show only low-grade metamorphism (Grindley 1980).

Molybdenum and Cu–Pb–Zn mineralization characterizes the Separation Point Suite (Tulloch & Brathwaite 1986). Grindley & Wodzicki (1960) proposed that base metal and Au–Ag mineralization at the junction of the Central and Eastern Sedimentary Belts was concentrated along low-angle thrusts and was produced by metasomatic fluids active at the front of a deep-seated nappe. However, Brathwaite & Pirajno (1993) considered that some of this mineralization is associated with stratiform sulfide deposits. Copper – lead – zinc mineralization in the area of Copperstain Creek in the Eastern Belt (Fig. 1, locality 4)

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FIG. 1. Sketch map showing main structural features, distribution of rock types, and localities mentioned in the text: 1 Plumbago Creek, 2 Parapara Inlet, 3 Onekaka River, 4 Copperstain Creek, 5 Campbell and Contact creeks, 6 Anatoki River – Go-Ahead Creek, 7 Calphurnia Creek, 8 Cobb Ultramafic Complex.

is attributed to emplacement of granitic plutons of the Separation Point Suite (Wodzicki 1972), and in other parts of the Eastern Belt, Ordovician quartzite carries Pb–Zn–Ag–Au–As mineralization which Bates (1989) considered to be hydrothermal in origin. Grindley (1980) stated that the post-Rangitata orogenic phase of declining temperatures and pressures was accompanied by sporadic mineralization of the Separation Point contact rocks and along shear zones. All occurrences of chromian muscovite and associated Cr-rich minerals described in this paper occur in rocks that lie within thermal aureoles of the widespread early Cretaceous granitic plutons, in or near major fault zones, and close to lenses of ultramafic rocks.

Age relations

Dates obtained from K–Ar (Wodzicki 1972), Rb–Sr (Aronson 1968) and Ar–Ar (Takagami & Watanabe, pers. comm., 1993) give whole-rock ages of S_1 fabric-forming biotite, muscovite, and hornblende in the Onekaka Schist ranging from 87 to 106 Ma. A K–Ar age for chromian muscovite from a mica-rich seam at Parapara Inlet yielded an age of 98.7 ± 2.2 Ma (R. Grapes, unpubl. data). The oldest ages of the Onekaka Schist overlap the youngest zircon ages from the Separation Point Suite of rocks, between 105 to 116 Ma (Kimborough *et al.* 1993), and imply that amphibolite-grade metamorphism, mineralization, and deformation are related to emplacement and cooling of the Early Cretaceous granitic plutons.

Mineral Assemblages and Bulk Compositions

Results of whole-rock analyses of Cr-rich schistose quartzites from Plumbago Creek, Parapara Inlet, Contact Creek, and Anatoki River – Go-Ahead Creek, and schist from the Onekaka River, are given in Table 1. Mineral assemblages in rocks from all localities are given in Table 2.

Plumbago Creek

At Plumbago Creek, near Collingwood (Fig. 1, locality 1), chromian muscovite, uvarovite, and zincian chromite occur in Ordovician biotite schist and quartzite, mapped as Bay Schist, faulted against Arthur Marble to the east (Bishop 1971). The outcrop of the marble immediately upstream consists of a fault breccia containing highly deformed and elongate fragments of quartz – muscovite – chlorite – epidote – magnetite – chromite schist, quartz – biotite – chromian muscovite – chlorite – magnetite – chromite schist, and angular fragments of quartzite containing varying amounts of K-feldspar, chromian muscovite, muscovite, chromian chlorite, uvarovite, magnetite, rutile, and chromite. The fault breccia is followed to

TABLE 1. RESULTS OF XRF ANALYSES OF Cr–BEARING SCHIST AND QUARTZITE, NORTHWEST NELSON, NEW ZEALAND

	Plumbago Creek			Parapara Inlet		Onekaka Stream		Contact Creek	Anatoki River
wt.%	1	2	3	4	5	6	7	8	9
SiO_2	86.24	84.34	86.64	79.78	63.93	44.06	39.66	77.93	78.55
TiO_2	0.11	0.21	0.38	0.67	0.76	0.80	0.74	0.20	1.23
Al_2O_3	1.81	1.73	5.88	13.38	23.56	35.46	32.82	13.57	12.86
Fe_2O_3*	3.30	3.25	3.36	0.24	0.37	1.42	5.23	0.51	0.31
MnO	0.54	0.33	0.06	nd	0.01	0.02	0.04	0.02	0.01
MgO	0.12	0.16	0.43	0.31	0.61	1.25	5.56	0.38	0.50
CaO	5.17	6.39	0.03	0.02	0.02	0.59	0.65	0.67	0.03
Na_2O	0.06	0.08	0.02	0.55	0.89	0.72	0.54	0.81	0.17
K_2O	0.01	0.16	1.60	3.39	6.22	9.56	7.54	3.54	3.76
P_2O_5	0.06	0.09	0.02	0.02	0.01	0.02	0.02	0.02	0.11
LOI	2.27	0.63	0.65	1.81	3.38	4.71	5.90	1.71	1.99
Total	100.25	97.37	99.03	100.71	99.77	98.62	98.69	99.35	99.52
ppm									
As	34	45	14	<2	<2	66	57	460	8
Ba	34	110	178	373	599	1165	1135	191	957
Ce	6	10	14	5	5	4	2	<2	172
Cr	3029	20082	3012	116	3848	8096	8030	3172	872
Cu	12	9	23	<2	<2	5	<2	10	<2
Ga	6	4	10	18	32	29	31	10	17
La	6	8	8	3	3	3	<2	<2	250
Nb	<2	4	6	14	14	<2	<2	<2	19
Ni	5	9	100	<2	2	36	274	659	4
Pb	265	212	12	23	36	31	16	15	229
Rb	<2	5	64	124	239	254	206	142	128
Sc	<2	3	8	17	20	27	55	11	8
Sr	13	5	5	141	238	188	227	871	104
Th	4	4	6	<2	2	<2	<2	2	13
U	8	3	2	3	2	<2	<2	<2	3
V	29	84	72	157	248	262	215	142	111
Y	29	28	6	24	23	7	8	2	34
Zn	125	217	113	9	53	40	104	18	8
Zr	40	188	100	184	133	24	39	7	217

* All Fe as Fe_2O_3
LOI is loss on ignition at 1000°C
nd = not detected

1 Uvarovite-poor quartzite, Plumbago Creek
2 Uvarovite-rich layer in 1, Plumbago Creek
3 Chromian muscovite quartzite, Plumbago Creek
4 Schistose chromian muscovite-poor quartzite, Parapara Inlet
5 Chromian muscovite-rich band interlayered with 4, Parapara Inlet
6 Chromian muscovite-rich schist, Onekaka Stream
7 Chromian muscovite-rich schist, Onekaka Stream
8 Chromian muscovite quartzite, Contact Creek
9 Schistose chromian muscovite quartzite, Anatoki River - Go Ahead Creek

TABLE 2. MINERALS PRESENT IN Cr–RICH ROCKS FROM NORTHWEST NELSON, NEW ZEALAND

	1	2	3	4	5	6	7	8	9	10	11
Quartz	x	x	x	x	x	x	x	x	x	x	x
Plagioclase							x		x		
K-feldspar	x	x	x								
Muscovite	x		x	x	x	x	x			x	x
Chromian-muscovite			x	x	x	x	x	x	x	x	x
Margarite						x	x				
Kyanite								x			
Chlorite	x	x	x			x	x			x	x
Biotite						x	x			x	
Epidote							x				
Uvarovite	x	x									
Grossular		x									
Tourmaline								x		x	
Apatite	x	x	x	x		x	x			x	
Zircon	x	x	x	x		x	x			x	
Rutile	x	x	x	x		x	x	x	x	x	x
Zincian-chromite	x	x	x	x		x		x			
Sulfides	Py						Py	Py	Gs Py		Gs Pn
Carbonates	Cal	Cal Cer					Sid			Cal	Mgs Dol

Abbreviations: Cal = calcite; Cer = cerussite; Dol = dolomite; Gs = gersdorffite; Mgs = magnesite; Pn = pentlandite; Py = pyrite; Ga = galena; Sid = siderite

1 Uvarovite-rich quartzite, Plumbago Creek
2 Uvarovite-poor quartzite, Plumbago Creek
3 Chromian muscovite quartzite, Plumbago Creek
4 Schistose chromian-muscovite quartzite, Parapara Inlet
5 Chromian muscovite-quartz veins in schistose quartzite, Parapara Inlet
6 Chromian muscovite schist, Onekaka River
7 Chromian muscovite-bearing biotite schist, Campbell Creek
8 Chromian muscovite-kyanite-chromite-tourmaline vein, Campbell Creek
9 Chromian muscovite-quartzite, Contact Creek
10 Chromian muscovite-rich patch in Arthur Marble, Copperstain Creek
11 Chromian muscovite-bearing metasomatized ultramafic, Calphurnia Creek

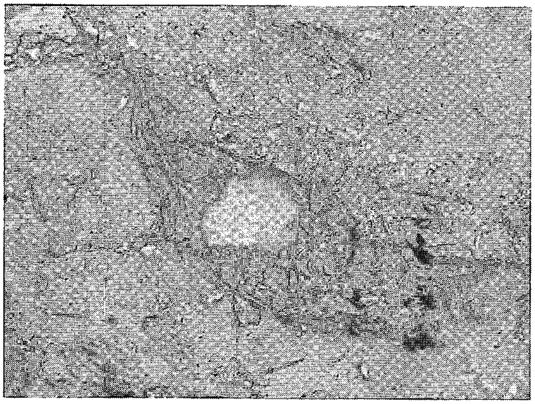

FIG. 2. Aggregates of chromian muscovite enclosing corroded zincian chromite in quartzite, Plumbago Creek. Plane light. Width of photo 0.6 mm.

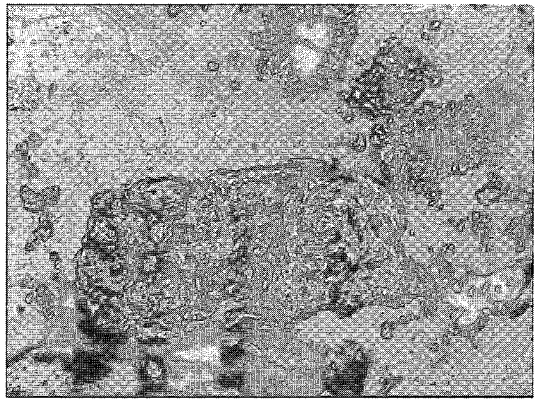

FIG. 3. Aggregate of uvarovite crystals fringed by chromian chlorite, lower half of field. Small rosettes of uvarovite surrounding core of zincian chromite, top centre. Quartzite, Plumbago Creek. Plane light. Width of photo 1.5 mm.

the west by bands of chromian-muscovite-rich and chromian-muscovite-poor quartzite, and biotite – chromian muscovite schist. The quartzite is schistose and foliated, with thin 5-mm bands of micaceous quartzite containing up to 10% vivid green chromian muscovite parallel to the foliation. The muscovite is slightly pleochroic, with α bright aquamarine and γ yellowish aquamarine. Many of the chromian muscovite aggregates, in both the fault breccia and the quartzite, contain small (<50 μm), highly corroded grains of zincian chromite (Fig. 2). Calcite is locally abundant interstitially, and as veinlets cutting the quartzite.

Fine-grained quartzite float with thin (20 mm), bright green, subparallel layers rich in uvarovite and zincian chromite occur in the lower reaches of Plumbago Creek, where it cuts through Late Pleistocene gravels. Except for quartzite fragments in the fault breccia described previously, uvarovite-bearing quartzite was not found in outcrop, and the stream pebbles have probably been derived from the gravels, with the original source no longer exposed. In the garnet-rich bands, finely crystalline aggregates of bright emerald green uvarovite form up to 50% of the rock. Many of the aggregates form a corona around deep reddish brown, almost opaque grains of zincian chromite, and are rimmed by pale brown, rather turgid and distinctly birefringent garnet, and rarely, chromian chlorite (Fig. 3). Fine-grained, interstitial microcline forms up to 5% of the rock, and tiny needles of chromian rutile are widespread. In some uvarovite-poor bands, unsutured quartz grains are surrounded by a thin film of brown clay, calcite is plentiful, and cerussite is a minor constituent as small, scattered crystals associated with colorless grossular. In these bands, grossular is the main garnet, and the coexisting uvarovite is confined to aggregates surrounding scarce grains of chromite.

Compositions of chromian muscovite and uvarovite quartzites are compared with that of uvarovite-poor quartzite in Table 1 (anal. 1–3). There is a much higher Ca content in the garnet-bearing rocks, and higher Al in the chromian muscovite quartzite. In terms of trace elements, there is notable enrichment in Cr (at 2.6% Cr_2O_3, Cr is a major element in the uvarovite quartzite). The concentration of Zn is high in all three rocks, and there is a positive correlation with the level of Cr. Lead is enriched in both the uvarovite-rich and uvarovite-poor quartzite owing to the presence of cerussite. The high loss on ignition (2.27% LOI) in the uvarovite-poor quartzite reflects the presence of carbonates.

Parapara Inlet

In a quarry on the southeastern side of Parapara Inlet (Fig. 1, locality 2), a pale green, chromian-muscovite-bearing quartzite member of the Onekaka Schist (Bishop 1971), approximately 60 m wide, contains a conspicuous, bright green layer of mica-rich schist 0.5 m in width. The layer is exposed for about 6 m along strike within cream to pale-brown-colored, amphibolite-grade quartzite. In detail, the mica-rich layer is made up of alternating darker and lighter green laminae 0.2–0.5 mm thick. The darker laminae contain more chromian muscovite, and in the darkest laminae, quartz is virtually absent. The mineral assemblage in the chromian muscovite schist is essentially quartz, chromian muscovite and rutile, with accessory chromite, magnetite, zircon and apatite. Chromian muscovite occurs as single grains in mica-rich laminae, with a strong dimensional orientation parallel to the S_1

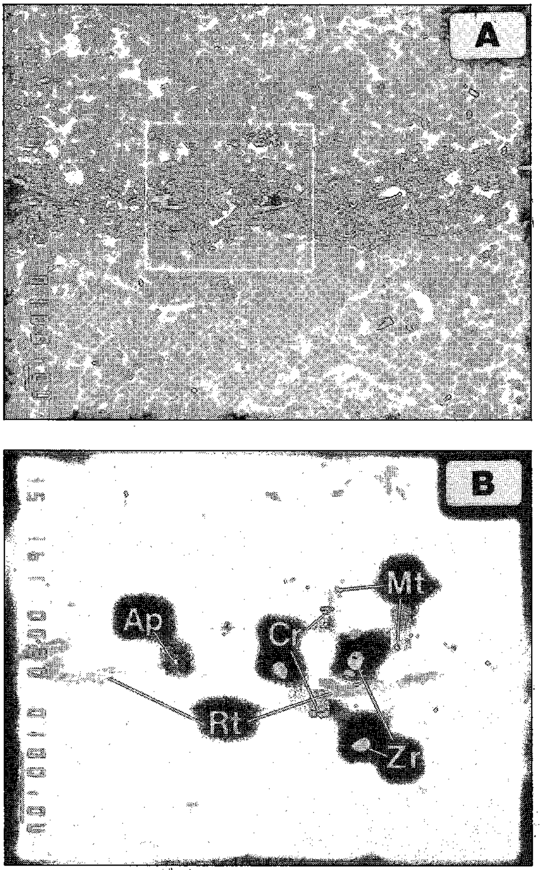

FIG. 4. A. Back-scattered electron image showing Cr-muscovite-rich laminae (defining S_1) in quartzose schist, Parapara Inlet. Bright grains are rutile, chromite, magnetite, zircon, and apatite. Bar scale: 100 µm. B. Back-scattered electron image of area marked in A showing distribution and relative grain size and habit of rutile (Rt), with lighter grey tones richer in Cr, Zn–Mn chromite (Cr), chromian magnetite (Mt), zircon (Zr), and apatite (Ap). Bar scale: 100 µm.

schistosity (Fig. 4A) and as "knots" (100–200 µm in diameter) or single grains within a mosaic of quartz. Tiny (typically <10 µm) grains of zincian chromite and chromian rutile are scattered throughout the muscovite-rich lamellae (Fig. 4B). The mica is typically deformed by a S_2 crenulation cleavage. Lenses and knots of quartz that occur within the schistose quartzite locally contain segregations of bright emerald-green chromian muscovite and tourmaline. Also present is a *ca.* 3-cm-thick seam of chromian muscovite within more psammitic schist. Bulk silica contents of the mica-rich and quartz-rich layers (Table 1, anal. 4, 5) indicate proportions of muscovite to quartz of 68:32 and 38:62, respectively. This is paralleled by differences in Al, K, Ba, Cr, Ga, and Rb between the mica-poor and mica-rich parts of the rock. Pale brownish pink streaks throughout the schistose quartzite are rich in rutile, as indicated by high TiO_2. Analysis of the chromian-muscovite-rich seam shows that it is essentially monomineralic (Table 1, anal. 6). High bulk Ce and V result from the presence of these elements in pseudobrookite, as qualitatively determined by electron-microprobe analysis.

Onekaka River

Where the Onekaka River passes through Arthur Marble (Fig. 1, locality 3), and for some distance upstream from the marble, chromian muscovite schist is common as float. The source of the pebbles is most probably the Bay Schist exposed upstream of the marble. The schist float is essentially quartz-free and consists of the assemblage chromian muscovite – chlorite – margarite – chromite – rutile – zircon, with considerable variation in the proportions of mica and chlorite. Brownish chromian chlorite has largely replaced porphyroblasts of biotite, is intergrown with,

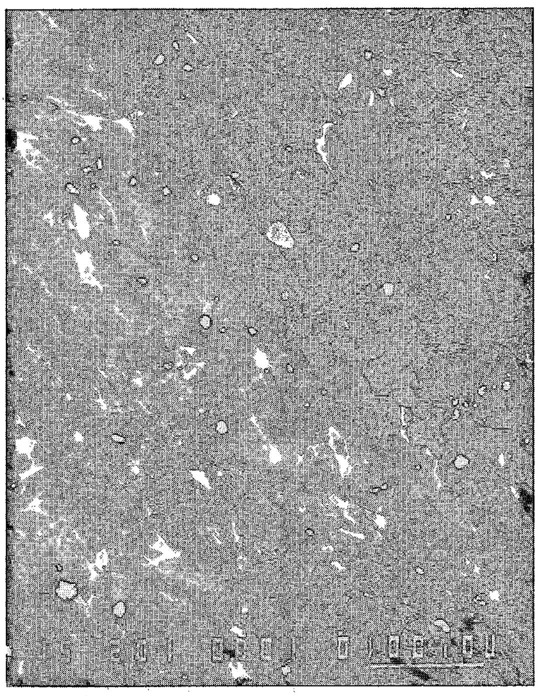

FIG. 5. Large porphyroblast of chromian chlorite surrounded and partly intergrown with chromian muscovite (darker grey tone) that has a heterogeneous distribution of Cr. The surrounding area consists of an interlocking mass of chromian muscovite. Bright crystals are rutile and zincian chromite. Chlorite–chromian muscovite schist, Onekaka River. Bar scale: 100 µm.

and surrounded by, finer-grained chromian muscovite, and is set in a matrix of interlocking chlorite, chromian muscovite, and minor margarite (Fig. 5). Tiny grains of zincian chromite and chromian rutile are scattered throughout. Although the mineral assemblage is the same in the two rocks, sample 6 contains considerably more chromian muscovite, and the bulk composition closely resembles that of muscovite. Higher Fe and Mg in sample 7 reflects the higher content of chlorite in this rock. High bulk Cr (Table 1, anal. 6, 7) is due to the abundance of chromian muscovite, chlorite, rutile, and chromite. The chromite contains 2–3% ZnO, resulting in a bulk-rock content of 40 and 104 ppm Zn. High barium contents of around 1100 ppm are due to the abundance of chromian muscovite containing 0.06–1.4% BaO. Both the Parapara Inlet and Onekaka River rocks contain considerably more Ba, Sr and Rb than rocks from Plumbago Creek; rocks from Plumbago Creek are higher in Pb and Zn (Table 1, anal. 1–3).

Copperstain Creek

In the upper reaches of Copperstain Creek, close to the Golden Bay Fault (Fig. 1, locality 4), the Arthur Marble contains pale green films of chromian muscovite along some of the schistosity planes. The muscovite is associated with biotite, chlorite, rutile, tourmaline, fluorapatite, and pyrite.

Campbell Creek

Chromian-muscovite-rich segregations up to several cm wide occur within biotite schist in Campbell Creek (Fig. 1, locality 5). The schist is also replaced by fine-grained chromian muscovite associated with coarse-grained zoned epidote, biotite, chlorite, rutile, and pyrite. A boundary of the replacement "front" may be partly delineated by siderite, rutile, and biotite (Fig. 6). In areas where replacement is intense, newly formed plagioclase (labradorite) has grown within a chromian muscovite matrix. Other Cr-rich minerals are associated with quartz segregations that are aligned parallel to S_1 and consist of chromian muscovite – kyanite – chromite – tourmaline – quartz. Quartz and deep blue kyanite with up to 1.4% Cr_2O_3 (crystals up to 20 mm in length) are intergrown with chromian muscovite and abundant, euhedral, deep red (in thin section) chromite ranging from 10 to 200 μm in diameter, rutile, and pyrite. Strongly zoned tourmaline ranging from 10 to 300 μm in diameter forms clusters of crystals.

Contact Creek

Close to Campbell Creek, in Contact Creek, a few meters from the Onahau (Separation Point Suite) Granite contact, a layer of chromian muscovite quartzite approximately 0.5 m in width associated along the margins with massive, rusty-colored quartz,

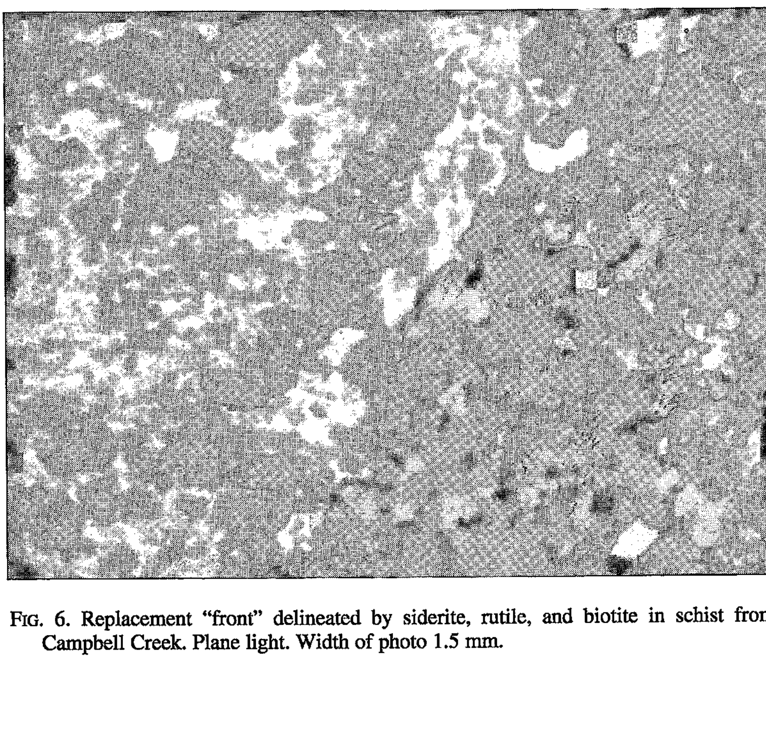

FIG. 6. Replacement "front" delineated by siderite, rutile, and biotite in schist from Campbell Creek. Plane light. Width of photo 1.5 mm.

is parallel to the S_1 schistosity developed in the biotite schist host-rock. The quartzite consists of slightly sinuous, millimeter-thick, closely spaced mica-rich and mica-poor laminae, with the muscovite flakes parallel to the schistosity. On surfaces normal to the S_1 schistosity, the rock is characterized by white spots (up to 1 mm in diameter) and segregations consisting of aggregates of oligoclase. The plagioclase poikilitically encloses tiny, randomly oriented crystals of chromian muscovite. Also present are disseminated grains of rutile and gersdorffite, and pyrite forms thin stringers along the S_1 schistosity. High levels of As (460 ppm) and Ni (659 ppm) (Table 1, anal. 8) are due to the presence of gersdorffite.

TABLE 3. COMPOSITION OF CHROMIAN MUSCOVITE, NORTHWEST NELSON, NEW ZEALAND

wt.%	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	47.90	45.52	46.20	46.46	46.75	47.04	47.25	45.36	45.99	46.67	46.8	47.49	49.19	44.97	45.88
TiO_2	0.66	0.56	0.75	0.47	0.36	0.69	0.51	0.16	0.80	0.62	0.69	0.58	0.31	0.42	0.69
Al_2O_3	30.43	28.61	34.03	35.71	33.53	33.64	34.07	36.98	33.38	34.65	31.4	30.68	30.41	35.15	33.06
Cr_2O_3	2.78	8.47	3.61	1.13	4.74	1.38	1.99	0.06	1.67	1.17	0.12	1.03	5.19	3.44	1.99
FeO*	0.58	0.63	0.23	0.41	0.32	0.02	0.46	0.75	0.93	1.04	0.92	1.16	0.86	0.16	0.86
MnO	nd	nd	nd	nd	nd	0.09	nd	nd	0.08	0.04	nd	0.10	nd	nd	0.04
MgO	1.94	1.76	0.55	0.48	0.48	0.87	0.87	0.87	1.20	0.94	2.62	2.56	2.15	0.40	1.38
NiO	nd	nd	nd	nd	nd	nd	nd	nd	nd	0.24	nd	nd	0.16	nd	0.16
ZnO	nd	nd	nd	nd	nd	nd	nd	nd	nd	0.14	nd	nd	0.25	0.13	0.17
CaO	0.06	0.05	nd	nd	nd	nd	nd	nd	nd	0.06	0.16	0.10	0.10	nd	0.14
Na_2O	0.41	0.18	0.95	0.99	0.99	0.35	0.41	0.57	0.40	0.56	0.31	0.23	0.05	2.13	0.35
K_2O	11.33	11.40	9.76	9.42	9.62	10.55	10.32	10.26	9.59	10.63	11.51	11.22	9.39	8.14	10.21
BaO	0.31	0.26	0.28	0.30	0.32	0.44	nd	0.22	1.50	0.87	nd	nd	nd	nd	0.27
F	0.69	0.51	0.31	0.29	0.26	0.98	0.35	nd	nd	0.11	0.32	0.26	nd	0.62	0.24
Cl	nd	nd	nd	nd	nd	nd	nd				0.04	0.04	nd	0.08	0.04
Total	97.09	97.97	96.67	95.66	97.37	96.26	96.23	95.23	95.46	97.70	94.9	95.35	98.24	95.64	95.48
-O=F, Cl	0.29	0.21	0.13	0.12	0.11	0.41	0.15	-	-	0.05	0.14	0.12	-	0.28	0.11
Total	96.80	97.76	96.54	95.54	97.26	95.84	96.08	95.23	95.46	97.65	94.8	95.2398.24		95.36	95.37
							Ions on basis of 22(O)								
Si	6.341	6.102	6.095	6.254	6.138	6.205	6.221	6.028	6.175	6.133	6.298	6.369	6.392	5.962	6.147
^{IV}Al	1.659	1.898	1.905	1.746	1.862	1.795	1.779	1.972	1.825	1.867	1.702	1.631	1.608	2.038	1.853
Σ(tet)	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
^{VI}Al	3.090	2.623	3.388	3.646	3.327	3.467	3.509	3.822	3.458	3.501	3.289	3.219	3.050	3.485	3.368
Cr^{3+}	0.291	0.898	0.376	0.118	0.492	0.144	0.207	0.006	0.177	0.122	0.013	0.109	0.533	0.361	0.211
Fe^{2+}	0.064	0.071	0.025	0.045	0.035	0.002	0.051	0.083	0.104	0.114	0.104	0.130	0.093	0.018	0.096
Mn	-	-	-	-	-	0.010	-	-	-	-	0.005	-	0.020	-	0.005
Mg	0.383	0.352	0.108	0.094	0.094	0.171	0.171	0.172	0.240	0.184	0.525	0.512	0.416	0.079	0.276
Ni	-	-	-	-	-	-	-	-	-	0.025	-	-	0.017	-	0.017
Zn	-	-	-	-	-	-	-	-	-	0.014	-	-	0.014	0.013	0.017
Ti^{4+}	0.066	0.058	0.074	0.047	0.036	0.068	0.051	0.040	0.081	0.061	0.070	0.058	0.030	0.042	0.070
Σ(oct)	3.894	4.002	3.971	3.950	3.984	3.862	3.989	4.083	4.060	4.021	4.006	4.028	4.183	3.968	4.060
Ca	0.009	0.007	-	-	-	-	-	-	-	0.008	0.023	0.014	0.014	-	0.020
Na	0.105	0.047	0.243	0.253	0.252	0.090	0.015	0.147	0.104	0.143	0.081	0.060	0.013	0.548	0.091
K	1.914	1.950	1.643	1.584	1.611	1.775	1.734	1.740	1.643	1.782	1.976	1.920	1.557	1.377	1.745
Ba	0.016	0.014	0.014	0.015	0.016	0.023	-	0.028	-	-	-	-	-	-	0.014
Σ(XII)	2.044	2.018	1.900	1.852	1.879	1.888	1.839	1.898	1.826	1.978	2.080	1.994	1.584	1.925	1.870
F	0.289	0.216	0.129	0.121	0.108	0.409	0.146	-	-	0.046	0.136	0.110	-	0.260	0.102
Cl	-	-	-	-	-	-	-	-	-	-	0.009	0.009	-	0.018	0.009
Σ(interlayer)	0.289	0.216	0.129	0.121	0.108	0.409	0.146	-	-	0.046	0.145	0.119	-	0.278	0.111

1 Homogeneous grain, chromian muscovite quartzite, Plumbago Creek
2 Cr-rich part of a grain, chromian muscovite quartzite, Plumbago Creek
3,4,5 Main part of grain, Cr-poor lamellae and Cr-rich lamellae, chromian muscovite-rich layer in quartz schist, Parapara Inlet
6 Homogeneous grain, quartz-chromian muscovite vein in quartz schist, Parapara Inlet
7 Homogeneous grain, chromian muscovite quartzite, Contact Creek
8,9 Cr-poor and Cr-rich parts of grain, chromian muscovite-rich schist pebble, Onekaka River
10 Homogeneous grain, chromian muscovite-rich replacement part of biotite schist, Campbell Creek
11,12 Cr-poor and Cr-rich parts of grain, Arthur Marble, Copperstain Creek
13 Homogeneous grain interstitial to carbonate, metasomatized ultramafic rock, Calphurnia Creek
14 Cr-rich part of grain, chromian muscovite-kyanite-chromite-quartz vein, Campbell Creek
15 Chromian muscovite,schistose chromian muscovite quartzite, Anatoki River - Go-Ahead Creek

Anatoki River – Go-Ahead Creek

Approximately 3 km south of Contact Creek, three pale green, weakly banded chromian-muscovite-bearing layers of quartzose schist occur close to the Golden Bay Fault (Fig. 1, locality 6). The layers range in width from about 80 m to 100 m and strike parallel to S_1, dipping 70°SW. As at Parapara Inlet, veins, pods, and knots of quartz are common throughout the schist, and in hand specimen, the chromian-muscovite-bearing rocks contain nests of bright green mica, together with deep red rutile, along fractures and in drusy cavities. Notable are the high bulk contents of TiO_2, P_2O_5, Ce, La, and Pb (Table 1, anal. 9), reflecting the relative abundance of rutile and apatite together with minor monazite and galena.

Calphurnia Creek

A small lens of sheared and metasomatized ultramafic rock in the headwaters of the Anatoki River (Fig. 1, locality 7) is a quartz – magnesite – ankerite – muscovite rock. The original igneous texture is preserved in parts of the rock, with magnesite replacing olivine, and ankerite and quartz possibly replacing pyroxene. Fine-scale layering of alternating quartz-rich and carbonate-rich bands may represent original mineralogical layering, common in the Cobb Igneous Complex (Hunter 1977). Thin chromian-muscovite-rich stringers, less than 1 mm wide, are roughly parallel to the quartz–carbonate layering and are associated with widely disseminated small (<50 μm) euhedral crystals of bismuthian gersdorffite and cobaltian violarite mantled by an unusually Ni-rich pentlandite which, apart from diffuse patches of iron hydroxides, are the only opaque minerals in the rock.

Mineral Chemistry

Chromian muscovite

Representative compositions of Cr-bearing muscovite are given in Table 3. In the present study, the highest level of Cr_2O_3 recorded is 8.5%, in muscovite from quartzite in Plumbago Creek. Variable Cr content is found in all muscovite samples examined, and is the result of both intragrain and intergrain inhomogeneity in any one sample. Most muscovite grains exhibit some zoning, with Cr-rich areas forming irregularly distributed patches, rim, core, or more regular lamella-like intergrowths of Cr-rich and Cr-poor muscovite. Maximum compositional variability generally lies within a 3–4% range in Cr_2O_3, but in most grains it is less than 1% Cr_2O_3. TiO_2 contents are between 0.15 and 1.7%, and in the presence of rutile probably represent saturation levels at this grade of metamorphism. FeO + MgO contents (with MgO > FeO) do not exceed 2.6%, indicating only limited phengite substitution (up to 16% of the octahedral site occupied by Fe and Mg). Muscovite with greater amounts of FeO + MgO coexists with chlorite ± biotite. There is limited substitution of Na for K (0.4–1.0% Na_2O) in most cases, but muscovite in the chromian muscovite – kyanite – chromite – tourmaline – quartz segregations in Campbell Creek contains 2.1–2.7% Na_2O, indicating a paragonite content of between 28–34%. Ba is usually present, in amounts up to 1.5% BaO. Muscovite in the Arthur Marble, in the calcite-bearing quartzites from Plumbago Creek, and in the Calphurnia Creek sample contains small amounts of Ca (0.05–0.16% CaO) consistent with the bulk composition of these rocks. Small amounts of Zn (up to 0.33% ZnO) and Ni (up to 0.30% NiO) occur in the chromian muscovite from Campbell Creek, Calphurnia Creek, and in more Cr-rich mica from Anatoki River – Go-Ahead Creek. Fluorine, up to 1.3%, is present in all grains of muscovite except those from Onekaka River and Calphurnia Creek.

In muscovite, chromium substitutes for octahedrally coordinated Al (up to 22% of the octahedral sites), as indicated by the negative correlation between Cr and ^{VI}Al in Figure 7. Except for muscovite in the quartzose schist from Parapara Inlet, this relationship implies that increasing Cr $\rightleftharpoons$ ^{VI}Al substitution is accompanied by increasing incorporation of Fe, Mg, Ti (and Mn, Ni, Zn), in the octahedral sites as a phengite substitution; $^{VI}(R^{2+})$ + ^{VI}Si $\rightleftharpoons$ ^{VI}Al + ^{IV}Al, and possible exchanges involving Ti, such as $(Mg,Fe)^{2+} + Ti^{4+} \rightleftharpoons 2^{VI}Al$, $Ti^{4+} + {}^{IV}Al \rightleftharpoons {}^{IV}Al + {}^{IV}Si$ or $Ti^{4+} + 2^{IV}Al \rightleftharpoons (Mg,Fe)^{2+} + 2^{IV}Si$. A plot of ^{IV}Al + (^{VI}Al + Cr + Ti) *versus* $^{VI}R^{2+}$ + ^{IV}Si in the inset diagram in Figure 7 shows a good fit to the overall scheme of coupled substitution, taking into account the uncertainty of the Ti substitution(s) and the unknown amount of Fe^{3+} present, and shows the extent of muscovite–celadonite solid solution.

Uvarovite and grossular

Uvarovite is the rarest of the six common types of anhydrous garnet. Deer *et al.* (1982) recommended that the name only be used for garnet compositions in which uvarovite is the dominant component, and nearly all analyzed garnet grains associated with zincian chromite from quartzite in Plumbago Creek meet this requirement, with compositions of $Uv_{36-83}Grs_{8-31}Adr_{10-26}$. An unusual feature of the more Cr-rich uvarovite at Plumbago Creek (Table 4, anal. 2–4) is that the andradite component is more important than the grossular component. Only in some rims of zoned grains (Table 4, anal. 5), and in birefringent, more Fe-rich garnet mantling some garnet aggregates (Table 4, anal. 1) does the proportion of grossular exceed that of andradite. The garnet in about 80% of rosettes is usually very homogeneous in composition ($Uv_{74}Adr_{16}Grs_8$). A patchy, diffuse

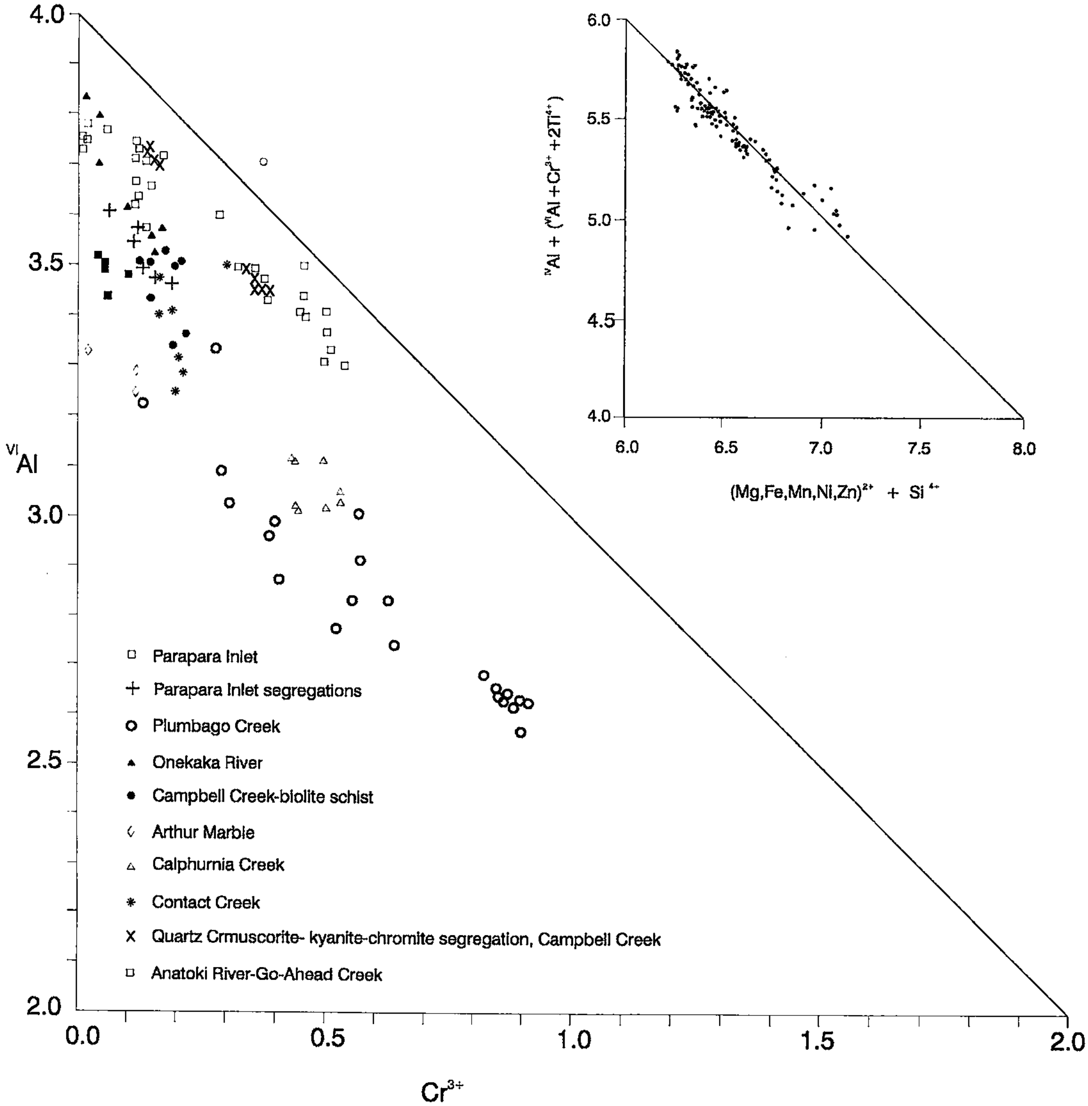

FIG. 7. Composition of chromian muscovite in terms of Cr^{3+} – $^{VI}Al^{3+}$ substitution. The inset diagram shows the combined coupled substitutions involving tetrahedral and octahedral sites in terms of $^{VI}(Mg,Fe,Mn,Ni,Zn)^{2+}$ + $^{IV}Si^{4+}$ *versus* $^{VI}(Al^{3+},Cr^{3+},Ti^{4+})$ + $^{IV}Al^{3+}$. Al and Cr concentrations expressed in atoms per formula unit.

zoning was detected in a few of the rosettes that have a core of zincian chromite (Fig. 8) and in these, the garnet nearest the core has the highest uvarovite content recorded (Uv_{83}), whereas the rim is depleted in Cr, significantly enriched in Al, and slightly enriched in Fe, Ti, Mn, and Ca (Table 4, anal. 4, 5). A few homogeneous rosettes are mantled by pale, brownish green, distinctly birefingent garnet and chromian chlorite; this garnet is enriched in Fe and Al, and depleted in Cr, with a composition $Uv_{36}Adr_{26}Grs_{31}$, which represents the lowest uvarovite content recorded in garnet of the Plumbago Creek suite. The pronounced birefringence (visual estimate) of the rim garnet supports the findings of Mariko & Nagai (1980), who reported maximum birefringence in the grossular–andradite series at $Adr_{40}Grs_{60}$. Disregarding the uvarovite component, the Plumbago Creek garnet has a composition of $Adr_{46}Grs_{54}$. The presence of a significant uvarovite component does not appear to affect the birefringence.

TABLE 4. REPRESENTATIVE COMPOSITIONS OF UVAROVITE GARNET, PLUMBAGO CREEK, NORTHWEST NELSON, NEW ZEALAND

wt.%	1	2	3	4	5
SiO_2	36.56	36.18	35.88	35.01	35.08
TiO_2	0.23	0.16	0.20	0.14	0.37
Al_2O_3	7.74	2.33	2.45	1.50	6.76
Cr_2O_3	11.22	22.56	23.90	24.67	16.81
Fe_2O_3	8.71	4.84	3.21	4.37	6.06
FeO*	2.27	0.43	1.08	0.93	0.00
MnO	0.48	0.32	0.36	0.73	0.82
MgO	0.03	0.00	0.00	0.09	0.11
CaO	32.25	33.06	32.47	31.91	33.36
Total	99.49	99.88	99.55	99.35	99.37

* FeO calculated assuming stoichiometry

Ions on basis of 24(O)

Si	5.957	5.990	5.959	5.884	5.771
^{IV}Al	0.043	0.010	0.041	0.116	0.229
^{VI}Al	1.447	0.452	0.439	0.330	1.081
Cr	1.452	2.952	3.142	3.278	2.180
Fe^{3+}	1.070	0.601	0.400	0.553	0.753
Ti	0.031	0.020	0.018	0.018	0.037
Mg	0.008	-	-	0.021	0.030
Fe^{2+}	0.310	0.070	0.153	0.131	-
Mn	0.062	0.050	0.048	0.104	0.112
Ca	5.628	5.864	5.781	5.747	5.870
Alm	5.2	1.1	2.5	0.5	-
Adr	26.3	16.1	9.6	13.8	17.0
Grs	31.1	7.9	7.9	-	25.0
Prp	0.4	-	-	0.4	1.3
Scm	0.5	-	0.4	0.3	0.8
Sps	1.1	0.8	1.2	1.8	-
Uvr	36.2	74.1	78.7	83.3	56.4

1 Fe-rich uvarovite overgrowth in quartzite
2 Average (n = 20) unzoned uvarovite without chromite cores
3 Unzoned uvarovite surrounding chromite core
4 Uvarovite-rich garnet in contact with chromite core
5 Rim of uvarovite-rich garnet

In uvarovite-poor layers of the quartzite, where there are only scarce, isolated grains of uvarovite, usually with a core of zincian chromite, the predominant garnet is a colorless grossular, containing over 90% grossular and no uvarovite. This garnet is locally abundant and is intergrown with fine-grained cerussite or calcite (or both). Very similar coexistence of uvarovite and grossular (grandite) was reported from the White River area, Hemlo, Ontario (Pan & Fleet 1989). The authors proposed a metasomatic origin for the garnet and considered that the uvarovite was formed later than the grossular, in a second, lower-temperature event. However, in the Plumbago Creek quartzite, both garnets appear to have formed at the same time, with the compositional difference being due to the presence of scattered grains of chromite, around which uvarovite formed in preference to grossular.

In Figure 9, the compositions of uvarovitic garnet at Plumbago Creek are plotted on a Uv–Grs–Adr triangular diagram, together with fields of garnet from similar environments. The most closely comparable samples of uvarovite are from skarn developed at the contact of the Cu–Ni–Co sulfide deposit of Outokumpu, Finland (von Knorring *et al.* 1986). Here, the host rocks are mica schist with bands of quartzite, and the mineral assemblage is very similar to that found in the Plumbago Creek quartzites and schists. Zincian chromite (up to 14% ZnO) forms the core of aggregates of uvarovite, and chromian muscovite is developed in parts of the Outokumpu skarn.

Zincian chromite

Representative compositions of zincian chromite from Plumbago Creek, Parapara Inlet, Parapara River, Onekaka River, and Campbell Creek are given in Table 5, together with the composition of chromite from the Cobb Igneous Complex. Chromite with Zn contents of 2.7–13.7% ZnO occurs as tiny corroded crystals in chromian muscovite grains at Plumbago Creek and Parapara Inlet, and is found as larger and less corroded grains at the center of uvarovite aggregates at Plumbago Creek. At Campbell Creek, chromian muscovite – kyanite – chromite – tourmaline – quartz segregations contain abundant zincian chromite, with between 2.2 to 4.8% ZnO. Here, all the chromite grains are euhedral and have an overgrowth

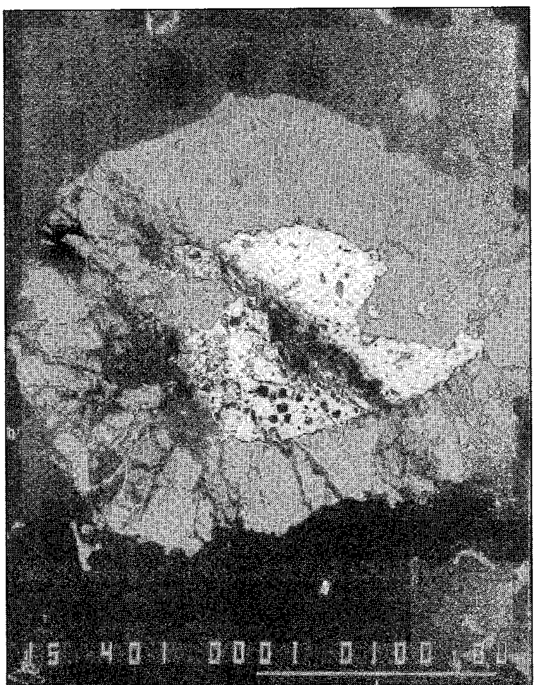

FIG. 8. Back-scattered electron image of grain of zincian chromite (bright) surrounded by uvarovite, showing patchy zonation with lower Cr and higher Fe (darker area at top of grain). Bar scale: 100 μm.

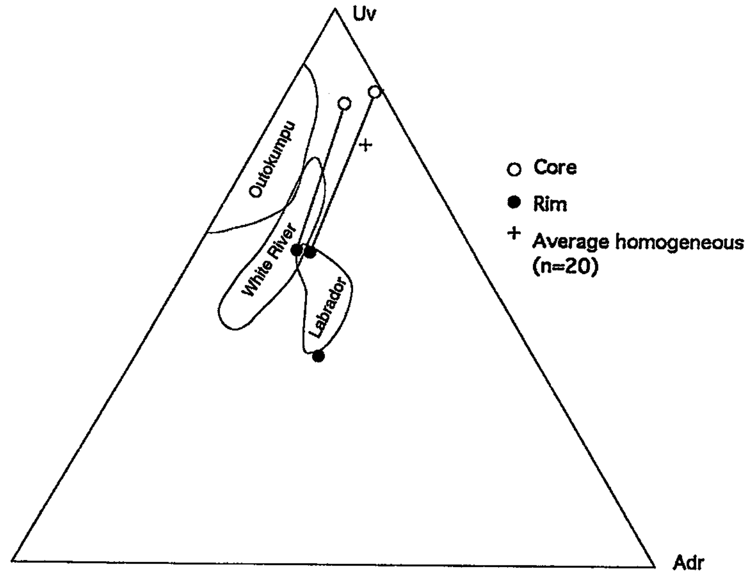

FIG. 9. Composition of uvarovite from Plumbago Creek quartzite in terms of Uv–Grs–Adr content. Fields of garnet compositions from similar environments at Outokumpu (von Knorring *et al.* 1986), White River, Ontario (Pan & Fleet 1989) also are shown.

TABLE 5. REPRESENTATIVE COMPOSITIONS OF ZINCIAN CHROMITE, NORTHWEST NELSON, NEW ZEALAND

wt.%	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	nd	nd	nd	nd	nd	nd	nd	nd	0.16	0.10	0.06	0.27	nd	nd	nd
TiO_2	nd	nd	0.09	nd	0.30	nd	nd	nd		0.27	0.08	0.07	nd	nd	nd
Al_2O_3	1.61	9.63	8.13	14.63	15.10	0.41	23.14	20.22	2.82	20.43	20.83	10.84	6.67	1.69	0.08
Cr_2O_3	63.46	54.28	58.35	50.67	49.51	20.86	40.50	44.17	63.07	43.54	43.82	55.14	64.82	58.36	33.38
Fe_2O_3	1.20	1.90	nd	nd	nd	47.39	nd	0.34	1.18	0.16	0.64	nd	1.00	9.56	35.51
FeO	21.76	19.44	22.69	31.02	17.05	29.93	31.32	31.51	26.45	25.79	26.45	26.95	17.05	21.56	24.15
MnO	1.66	1.18	0.34	0.16	3.51	1.52	0.36	nd	2.94	2.20	2.29	2.69	0.03	2.40	2.38
MgO	0.17	0.40	1.24	0.48	0.70	nd	0.73	0.80	0.75	1.91	1.67	0.89	10.46	4.05	2.07
ZnO	8.88	13.51	9.06	2.35	13.74	nd	2.83	2.70	2.21	4.78	4.64	3.31	nd	1.90	0.92
NiO	nd	nd	nd	nd	nd	nd	nd	nd	nd	0.14	0.13	0.09	nd	0.20	0.78
Total	98.74	100.34	99.90	99.31	99.91	100.11	98.88	99.74	99.46	99.30	100.55	100.25	100.03	99.72	99.27

* Fe_2O_3 assigned assuming stoichiometry
nd = not detected

Cations per 3 sites

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Si	-	-	-	-	-	-	-	-	0.006	0.003	0.002	0.009	-	-	-
Ti	-	-	0.002	-	0.007	-	-	-	-	0.007	0.002	0.002	-	-	-
Al	0.071	0.407	0.344	0.603	0.625	0.018	0.920	0.808	0.122	0.813	0.820	0.449	0.263	0.072	0.004
Cr	1.895	1.541	1.655	1.399	1.368	0.627	1.080	1.184	1.833	1.162	1.156	1.531	1.710	1.668	0.982
Fe^{3+}	0.034	0.051	-	-	-	1.355	-	0.009	0.033	0.004	0.016	-	0.031	0.260	1.005
Fe^{2+}	0.688	0.584	0.681	0.906	0.499	0.951	0.884	0.893	0.813	0.728	0.738	0.792	0.482	0.652	0.759
Mn	0.053	0.036	0.010	0.005	0.104	0.049	0.010	-	0.092	0.063	0.065	0.080	0.004	0.073	0.076
Mg	0.010	0.021	0.066	0.025	0.036	-	0.036	0.040	0.041	0.096	0.083	0.047	0.517	0.218	0.116
Zn	0.248	0.359	0.240	0.060	0.355	-	0.070	0.068	0.06	0.12	0.114	0.085	-	0.051	0.026
Ni	-	-	-	-	-	-	-	-	-	0.004	0.003	0.002	-	0.006	0.024

1 Chromite core of uvarovite, uvarovite-rich quartzite, Plumbago Creek
2 Chromite core of uvarovite, quartzite, Plumbago Creek
3,4 Small chromite grains in chromian muscovite, quartz schist, Plumbago Creek
5 Chromite from chromian muscovite-rich schist, Parapara Inlet
6 "Ferritchromit" from chromian muscovite-rich schist, Parapara Inlet
7,8 Chromite from chromian muscovite-chlorite schist, Onekaka River
9 Homogeneous chromite grain in chromian muscovite-kyanite-chromite-tourmaline-quartz segregation, Campbell Creek
10 Homogeneous chromite grain in segregation, Campbell Creek
11,12 Core and rim of chromite grain in segregation, Campbell Creek
13 Chromite from chromitite layer in serpentinite, Cobb Igneous Complex
14,15 Core and "ferritchromit" replacement rim of chromite grain in metasomatized serpentinite, Parapara River

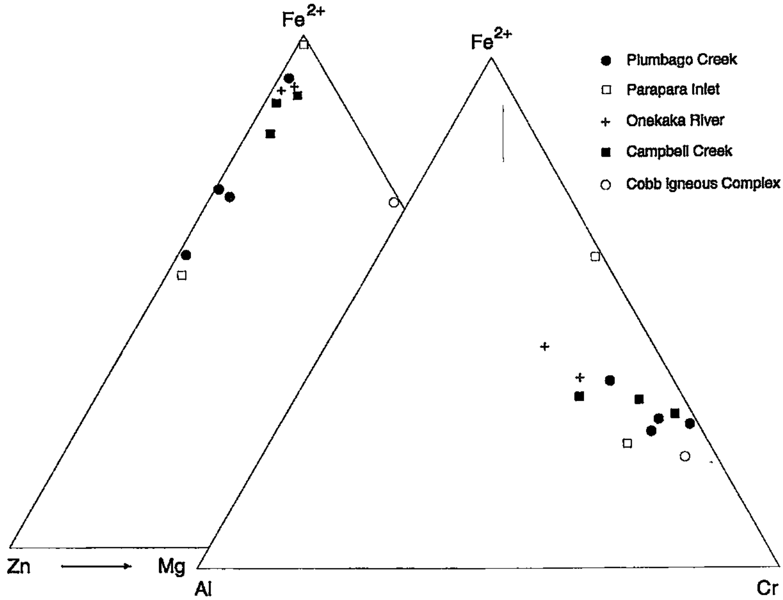

FIG. 10. Composition of zincian chromite from Plumbago Creek, Parapara Inlet, Onekaka River, and Campbell Creek, together with that of high-Cr chromite from the Cobb Ultramafic Complex.

that encloses abundant quartz, although in most cases, core and overgrowth have essentially the same composition (43.6% Cr_2O_3, 26% FeO, 20.6% Al_2O_3). However, the margin of some grains is richer in Cr (55% Cr_2O_3) and poor in Al (10.8% Al_2O_3). Rarer homogeneous grains of chromite with higher Cr (~62% Cr_2O_3), apparently without overgrowth, also occur (Table 5). Notable is the high Mn content of zincian chromite from Plumbago Creek, Parapara Inlet, and Campbell Creek (1.1%–3.5% MnO). Chromite compositions are plotted on Fe^{2+} – Zn – Mg and Fe^{2+} – Al – Cr diagrams in Figure 10. Much of the chromite occurs as tiny (<20 μm) grains, highly corroded, with a "spongy" texture that makes analysis by electron microprobe difficult. The highest Zn contents (>13.5% ZnO) are associated with small grains of highly corroded chromite with variable Cr_2O_3 contents. Larger, less altered grains in uvarovite are fairly homogeneous, with a composition of around 9% ZnO, and Cr_2O_3 contents of 63–64% (Table 5, anal. 1). Small grains of chromite in chromian muscovite schist from the Onekaka River, and the mica schist from Plumbago Creek, have lower Zn contents (2.3–2.8% ZnO) and considerably higher Fe contents, ~31% FeO. This may be due to further alteration of a previously more Zn-rich chromite toward "ferritchromit", as documented by Wylie *et al.* (1987). In the micaceous quartzite at Parapara Inlet, there are rare grains of chromite containing appreciable Fe^{3+} (47.39% Fe_2O_3) relative to Fe^{2+} (29.93% FeO), significant Mn (1.52% MnO), low Cr (20.86% Cr_2O_3), very low Al (0.41% Al_2O_3), and no Zn or Mg. This composition corresponds to that of zone C of "ferritchromit" alteration described by Wylie *et al.* (1987). These authors observed distinct anisotropy in the "zone-C" material, suggesting that the phase does not have the isometric structure typical of spinel. All chromite grains analyzed here are highly depleted in Mg (0–1.91% MgO) relative to chromite from the Cobb Igneous Complex (10.5–13.3% MgO; Hunter 1974). There is an inverse relationship between (Zn+Mn) and (Fe+Mg) and between (Zn+Mn+Fe) and Mg (Table 5), indicating that Zn can substitute for both Fe and Mg in the spinel structure (*cf.* Bevan & Mallinson 1980, Marshall & Dollase 1984, Wylie *et al.* 1987). Zinc in all cases of chromite analyzed from the Cobb Complex (Hunter 1974), and detrital chromite in metasediments distal from outcrops of the Separation Point granitic suite (Hunter 1975), was found to be below the limit of detection, ~0.08% ZnO.

Chlorite

Representative compositions of chlorite are given in Table 6. Values of X_{Mg} (Mg/[Mg + Fe]) range from 0.13 to 0.67, and the chlorite can be classed as

TABLE 6. REPRESENTATIVE COMPOSITIONS OF CHROMIAN CHLORITE, BIOTITE AND MARGARITE, NORTHWEST NELSON, NEW ZEALAND

wt.%	1	2	3	4	5	6	7	8	9	10
SiO_2	28.78	25.75	29.30	26.42	30.05	25.83	28.47	37.10	38.99	30.72
TiO_2	nd	0.12	0.09	0.19	0.29	0.16	0.08	1.82	1.27	0.20
Al_2O_3	20.36	21.67	20.44	20.04	15.09	21.88	23.00	18.44	16.81	48.88
Cr_2O_3	2.76	1.22	0.93	0.05	2.16	1.34	1.41	1.76	0.45	0.69
FeO*	27.70	13.94	17.08	27.51	33.16	15.21	12.46	12.86	15.33	0.29
MnO	0.70	nd	0.24	0.18	1.27	0.18	nd	0.57	nd	nd
MgO	6.57	20.84	19.16	14.07	1.63	21.42	18.38	13.65	12.82	0.19
NiO	0.08	nd	nd	0.07	2.49	0.21	nd	nd	0.11	nd
ZnO	nd	nd	nd.	0.11	nd	0.13	nd	nd	0.11	nd
CaO	0.25	nd	0.11	nd	0.90	nd	nd	0.08	0.10	9.98
Na_2O	nd	nd	nd	nd	0.37	0.18	nd	0.38	0.08	0.84
K_2O	nd	nd	0.10	0.04	nd	nd	1.41	9.93	9.47	0.08
BaO	nd	nd	nd	nd	nd	nd	nd	0.63	0.21	0.46
F	nd	nd	nd	nd	nd	nd	nd	0.59	0.65	nd
Cl	0.25	nd	nd	nd	nd	nd	nd	nd	nd	nd
Total	87.45	83.54	87.45	88.68	87.38	84.84	84.92	97.84	96.40	92.33
-O=F	-	-	-	-	-	-	-	0.25	0.27	-
-O=Cl	0.06	-	-	-	-	-	-	-	-	-
Total	87.39	83.54	87.45	88.68	87.38	84.84	84.92	97.59	96.13	92.33

* All Fe as FeO
nd = not detected

	Ions on basis of 28(O)								Ions on basis of 22(O)		
Si	6.149	5.373	6.140	5.893	5.566	6.768	5.318	Si	5.398	5.734	4.191
^{IV}Al	1.851	2.627	2.107	2.563	2.232	2.682	2.221	^{IV}Al	2.602	2.166	3.809
Σ(tet)	8.000	8.000	8.000	8.000	8.000	8.000	8.000	Σ(tet)	8.000	8.000	8.000
^{VI}Al	3.273	2.703	2.739	2.414	2.774	2.629	3.283	^{VI}Al	0.561	0.648	4.052
Cr^{3+}	0.467	0.200	0.148	0.008	0.385	0.218	0.226	Cr^{3+}	0.202	0.052	0.074
Fe^{2+}	4.948	2.428	2.873	4.847	6.240	2.447	2.115	Fe^{2+}	1.568	1.886	0.033
Ti^{4+}	-	0.018	0.015	0.033	0.054	0.028	0.014	Ti^{4+}	0.199	0.140	0.012
Mn	0.133	-	0.041	0.032	0.242	-	-	Mn	0.070	-	-
Mg	2.092	6.481	5.743	4.417	0.547	6.573	5.561	Mg	2.960	2.810	0.039
Ni	0.010	-	-	0.012	0.451	-	-	Ni	-	0.013	-
Zn	-	-	-	0.017	-	-	-	Zn	-	0.012	-
								Σ(oct)	5.560	5.561	4.219
Ca	0.057	-	0.024	-	0.217	-	-	Ca	0.012	0.016	1.459
Na	-	-	-	-	-	-	-	Na	0.107	0.023	0.222
K	-	-	0.026	-	-	-	-	K	1.843	1.777	0.014
Cl	0.090	-	-	-	-	-	-	Ba	0.036	0.012	0.025
Σ	11.070	11.650	11.609	11.780	10.910	11.895	11.199	Σ(interlayer)	1.998	1.828	1.720
XMg	0.30	0.73	0.67	0.52	0.08	0.73	0.72	XMg	0.271	0.302	-
								F	0.34	0.40	-

1 Chromian chlorite, uvarovite quartzite, Plumbago Creek
2 Chromian chlorite, chromian muscovite schist, Onekaka River
3 Chromian chlorite, biotite schist, Onekaka River
4 Chlorite, biotite schist, Campbell Creek
5 Chromian chlorite (penninite), metasomatized ultramafic, Calphurnia Creek
6 Chloritized biotite, chromian muscovite schist, Onekaka River
7 Chloritized biotite, chromian muscovite schist, Onekaka River
8 Chromian biotite, Arthur Marble, Copperstain Creek
9 Chromian biotite, biotite schist, Campbell Creek
10 Margarite, chromian muscovite schist, Onekaka River

ripidolite or brunsvigite (Hey 1954). Except for chlorite in the biotite schist from Campbell Creek, the chlorite is chromian, containing between 0.9 and 2.8% Cr_2O_3. A penninite chlorite from the Calphurnia Creek ultramafic rock contains significant Mn (1.27% MnO) and Ni (2.49% NiO), consistent with the presence of Ni- and Mn-bearing carbonate.

Margarite

Margarite with around 0.7% Cr_2O_3 (Table 6) occurs as a rare phase intergrown with muscovite and chlorite in the chromian-muscovite-rich pebbles from Onekaka River. The margarite contains 0.46% BaO, with Ba substituting for Ca. Rare Cr-bearing margarite also occurs with kyanite in more strongly pelitic schist layers at the Parapara Inlet locality, although it is not directly associated with chromian muscovite.

Biotite

Red-brown biotite (X_{Mg} in the range 0.34–0.40), with between 0.4 and 1.8% Cr_2O_3 (Table 6) occurs with chromian muscovite in the Arthur Marble at Copperstain Creek, and biotite schist at Campbell Creek. As with coexisting muscovite, the biotite contains fluorine (0.6–0.8%). Textural relationships, such as intergrowths, suggest contemporaneous growth of the two minerals. In chromian-muscovite-rich pebbles from Onekaka River, porphyroblasts of biotite have been chloritized (Table 6), giving a distinctive brown color to the replacement chlorite.

K-feldspar

Minor interstitial K-feldspar occurs in the uvarovite – zincian-chromite-bearing quartzite and chromian muscovite quartzite in the fault breccia at Plumbago Creek. The feldspar is very fresh, homogeneous microcline of composition $An_{0.4}Ab_{5.3}Or_{94.3}$. Ba content ranges from 0.30 to 0.43% BaO.

Plagioclase

Oligoclase with the composition $An_{25.2-26}Ab_{73.9-73}Or_{0.9-1}$ occurs as disseminated clusters of grains in the chromian muscovite quartzite at Contact Creek, these clusters give a white spotted appearance to the rock. Labradorite ($An_{63.9-50.1}Ab_{35.6-49.3}Or_{0.5-0.6}$) occurs within the chromian muscovite matrix that replaces biotite schist in Campbell Creek.

Epidote

Idiomorphic epidote with Cr_2O_3 varying between 1.4 and 2.2% (Table 7) is associated with the fine-grained chromian muscovite replacement in Campbell

TABLE 7. REPRESENTATIVE COMPOSITIONS OF CHROMIAN EPIDOTE AND TOURMALINE, NORTHWEST NELSON, NEW ZEALAND

wt.%	1	2	3	4	5	6	7	8	9
SiO_2	39.31	38.74	38.24	38.41	36.96	36.59	36.40	85.45	37.12
TiO_2	0.22	0.08	0.31	0.37	0.13	0.16	0.49	0.57	0.41
Al_2O_3	29.13	28.02	31.36	30.33	36.40	35.35	35.03	29.51	31.55
Cr_2O_3	1.46	2.02	2.64	2.28	1.73	0.80	1.07	0.06	1.29
Fe_2O_3*	3.87	4.08	-	-	-	-	-	-	-
FeO*	-	-	2.04	2.16	2.85	7.32	8.16	8.63	1.99
B_2O_3#	-	-	11.33	11.06	11.05	10.83	10.90	10.35	10.86
MnO	0.22	0.49	0.08	0.04	nd	nd	0.11	nd	nd
MgO	0.16	0.27	10.97	10.30	6.89	4.96	4.57	7.14	10.03
NiO	0.11	0.22	0.12	0.10	nd	nd	nd	nd	nd
ZnO	-	-	0.32	0.15	nd	0.34	0.11	nd	nd
CaO	23.74	22.30	2.76	2.16	0.38	0.18	0.70	1.68	1.66
Na_2O	nd	nd	1.44	1.88	1.76	1.70	2.19	1.56	1.41
K_2O	nd	nd	0.09	0.10	nd	nd	nd	0.05	0.07
F	-	-	0.82	0.42	0.32	0.17	0.14	0.53	0.73
Total	98.22	96.22	102.52	99.88	98.52	98.41	99.83	95.53	97.12
-O=F			0.32	0.18	0.14	0.07	0.06	0.22	0.31
Total			102.20	99.70	98.38	98.34	99.77	95.31	96.81

* All Fe as Fe_2O_3 or FeO
\# B_2O_3 calculated assuming 3 B atoms in formulae
nd = not detected

Ions on basis of 12.5(O)			Ions on basis of 29(O)							
Si	3.024	3.045	B	3.000	3.000	3.000	3.000	3.000	3.000	3.000
Σ(tet)	3.024	3.045	Si	5.867	6.034	5.821	5.869	5.804	5.947	5.939
^{IV}Al	2.641	2.596	Al(tet)	0.133	-	0.179	0.131	0.196	0.053	0.061
Cr^{3+}	0.089	0.125	Al_Z	5.538	5.617	6.000	6.000	6.000	5.782	5.889
Fe^{3+}	0.224	0.241	Al_Y	-	-	0.579	0.553	0.388	-	-
Ti^{4+}	0.013	0.005	Cr^{3+}	0.320	0.283	0.215	0.101	0.135	0.008	0.163
ΣY	2.967	2.967	Ti^{4+}	0.036	0.044		0.019	0.059	0.072	0.049
Mn	0.014	0.033	Fe^{2+}	0.262	0.284	0.375	0.982	1.088	1.211	0.266
Ca	1.957	1.878	Mn	0.010	0.005	-	-	0.015	-	-
Mg	0.018	0.032	Mg	2.508	2.412	1.617	1.186	1.086	1.785	2.392
Ni	0.007	0.014	Ni	0.015	0.013	-	-	-	-	-
ΣX,W	1.996	1.957	Zn	0.036	0.017	-	0.040	0.013	-	-
ΣY										
Ps	7.8	8.4	ΣY	3.187	3.058	2.801	2.881	2.784	3.065	2.870
			Ca	0.454	0.364	0.064	0.031	0.120	0.302	0.285
			Na	0.428	0.573	0.537	0.529	0.677	0.507	0.437
			K	0.018	0.020	-	-	-	0.011	0.014
			ΣX	0.900	0.957	0.601	0.560	0.797	0.820	0.736
			F	0.398	0.209	0.070	0.086	0.071	0.281	0.369

1,2 Core and rim of epidote from biotite schist, Campbell Creek
3,4 Core and rim of tourmaline in fuchsite-rich replacement of Arthur Marble
5,6,7 Core, inner rim and rim of Tourmaline from chromian muscovite-kyanite-chromite-tourmaline-quartz segregation, Campbell Creek
8,9 Core and rim of tourmaline in chromian muscovite schistose quartzite, Anatoki River - Go Ahead Creek

Creek biotite schist (Fig. 6). The epidote is pale yellow, with a dark blue interference color characteristic of clinozoisite, and is weakly zoned between the rather limited compositional extremes of $Ps_{7.5}$ and $Ps_{8.5}$. The epidote also contains 0.11–0.22% NiO.

Tourmaline

Tourmaline is present in the chromian-muscovite-rich parts of the Arthur Marble in Copperstain Creek, and has been reported previously in quartzofeldspathic and pelitic schists from this locality (Wodzicki 1972). The tourmaline in the marble is weakly zoned, with a brown-green Mg–Ca–Cr-rich core, and a pale green Fe–Na-rich rim (Table 7). Cr contents vary between 2.3 and 2.7% Cr_2O_3. Significant is the presence of ~0.11% NiO, 0.15–0.32% ZnO, and 0.40–0.85% F. Abundant tan-colored tourmaline occurs in the chromian muscovite – kyanite – chromite – tourmaline – quartz segregations in Campbell Creek. The grains are zoned with respect to Fe (2.8–8.2% FeO), Mg (6.9–4.6% MgO), and Cr (1.8–0.9% Cr_2O_3) (Table 7). The core tends to have higher levels of Cr and Mg. In the chromian-muscovite quartzite between Anatoki River and Go-Ahead Creek, tourmaline occurs as tiny grains with a greenish brown Fe-rich core and a pale brown Fe-poor rim. The core contains virtually no Cr, whereas the rim has ~1.3% Cr_2O_3. Fluorine contents vary between 0.5 and 0.8% (Table 7). Chromian-muscovite-bearing quartz segregations at Parapara Inlet also contain tiny needles of pale yellow-green to olive-green tourmaline with 0.4–1.4% Cr_2O_3. The crystals are zoned with Fe, Ca, Cr increasing, and Mg, Na decreasing from core to rim. Small amounts of Zn (0.10–0.18% ZnO) are present, and the F-content varies between 0.30 and 0.62% (Table 7).

Rutile

Honey-brown-colored rutile is ubiquitous as an accessory in all samples studied, and is characterized by Cr contents ranging between 0.9 and 3.3% Cr_2O_3. In the chromian muscovite – kyanite – chromite – tourmaline – quartz veins from Campbell Creek, rutile contains up to 0.16% CoO, 0.23% ZnO, 0.08% MgO, and between 0.16 and 0.23% F. The presence of F is surprising, and it presumably substitutes for OH that is known to occur within rutile (Vlassopoulos *et al.* 1993, Rossman & Smyth 1990). Although most grains are homogeneous, qualitative electron-microprobe analyses show that others contain areas that are enriched in Nb and Ta (up to about 4 wt%).

Kyanite

Blue kyanite is conspicuous in chromian muscovite – kyanite – chromite – tourmaline – quartz segregations at Campbell Creek. The grains are chemically homogeneous and contain 1.41–1.44% Cr_2O_3, 0.21–0.39% Fe_2O_3, and up to 0.2% ZnO. Kyanite has been reported elsewhere within the Onekaka Schist in association with quartz lenses and knots (Grindley 1971) that are aligned parallel with S_1, and we have collected float samples containing kyanite crystals up to 4 cm long. A bulk X-ray-fluorescence analysis of this kyanite indicates that it contains only 8 ppm Cr, and it is not usually associated with chromian muscovite. Rare kyanite – chromian-muscovite-rich layers also occur at Parapara Inlet (H. Stevenson, pers. comm., 1994), where the kyanite forms porphyroblasts that contain between 0.5 and 1.3% Cr_2O_3. Associated minerals are chromian rutile, rare zincian chromite (2–3% ZnO) and pseudobrookite.

Carbonates

Calcite accompanies muscovite and uvarovite in the quartzites from Plumbago Creek. In biotite schist at Campbell Creek, yellowish brown *siderite* with between 2.8 and 3.4% MnO occurs with chromian muscovite along the boundaries of dense areas of fine-grained chromian muscovite (Fig. 6). The ultramafic rock from Calphurnia Creek contains ferroan *magnesite*, ferroan *dolomite* (ankerite), and a nickel carbonate with 34.9% NiO and 2.9% CoO [possibly *zaratite*, $Ni_3CO_3(OH)_4{\cdot}4H_2O$]. A small amount of *cerrusite* occurs in the quartzites in Plumbago Creek and Anatoki River – Go-Ahead Creek.

Other minerals

Zircon and *apatite* are widespread accessories. The apatite contains fluorine, generally in amounts <1%. *Gersdorffite* occurs in the Calphurnia Creek ultrabasic rock, and in quartzite from Contact Creek, near Campbell Creek. At the former locality, it contains up to 2.8% Bi and is associated with cobaltian *violarite* and *pentlandite*. *Pyrite* forms small stringers in the chromian muscovite quartzite at Contact Creek and contains between 0.5 and 0.6% NiO. Pyrite also is present as large anhedral grains in the chromian muscovite – kyanite – chromite – tourmaline – quartz segregations at Campbell Creek, where it contains between 0.23 and 0.72% NiO and up to 2.9% CoO. Pyrite is also found with chromian muscovite in the Arthur Marble at Copperstain Creek, and in chromian muscovite quartzite from the Anatoki River – Go-Ahead Creek area. Small amounts of *pseudobrookite* occur in the seam of chromian muscovite at Parapara Inlet. Qualitative electron-microprobe analysis indicates the presence of up to about 8% V_2O_3 + Ce_2O_3. The chromium content varies between 0.3 and 0.5% Cr_2O_3, Zn between 0.17 and 0.20% ZnO, and the level of MnO is ~1.9%.

Discussion

There is considerable variation in the scale and intensity of development of Cr–Zn-bearing minerals in the Lower Paleozoic Onekaka Schist of Northwest Nelson, from thin seams 2–3 cm thick to zones up to 100 m wide. Field and textural relationships of the chromium-bearing silicates and oxides indicate that they can be largely explained by (i) *in situ* metamorphism of Cr-rich sedimentary horizons, and (ii) metasomatism by the action of Cr- (and Zn–Mn)-bearing fluids.

The two mechanisms of chromium enrichment are demonstrated in Figure 11, where bulk-rock Cr content is plotted against K_2O (a measure of mica content, or original clay content, in the absence of K-feldspar). Low-grade metamorphic correlatives of the Onekaka Schist, the Hailes Quartzite and metasediments of the Wangapeka Formation (Grindley 1971, 1980) show trends of increasing Cr with increasing K, as might be

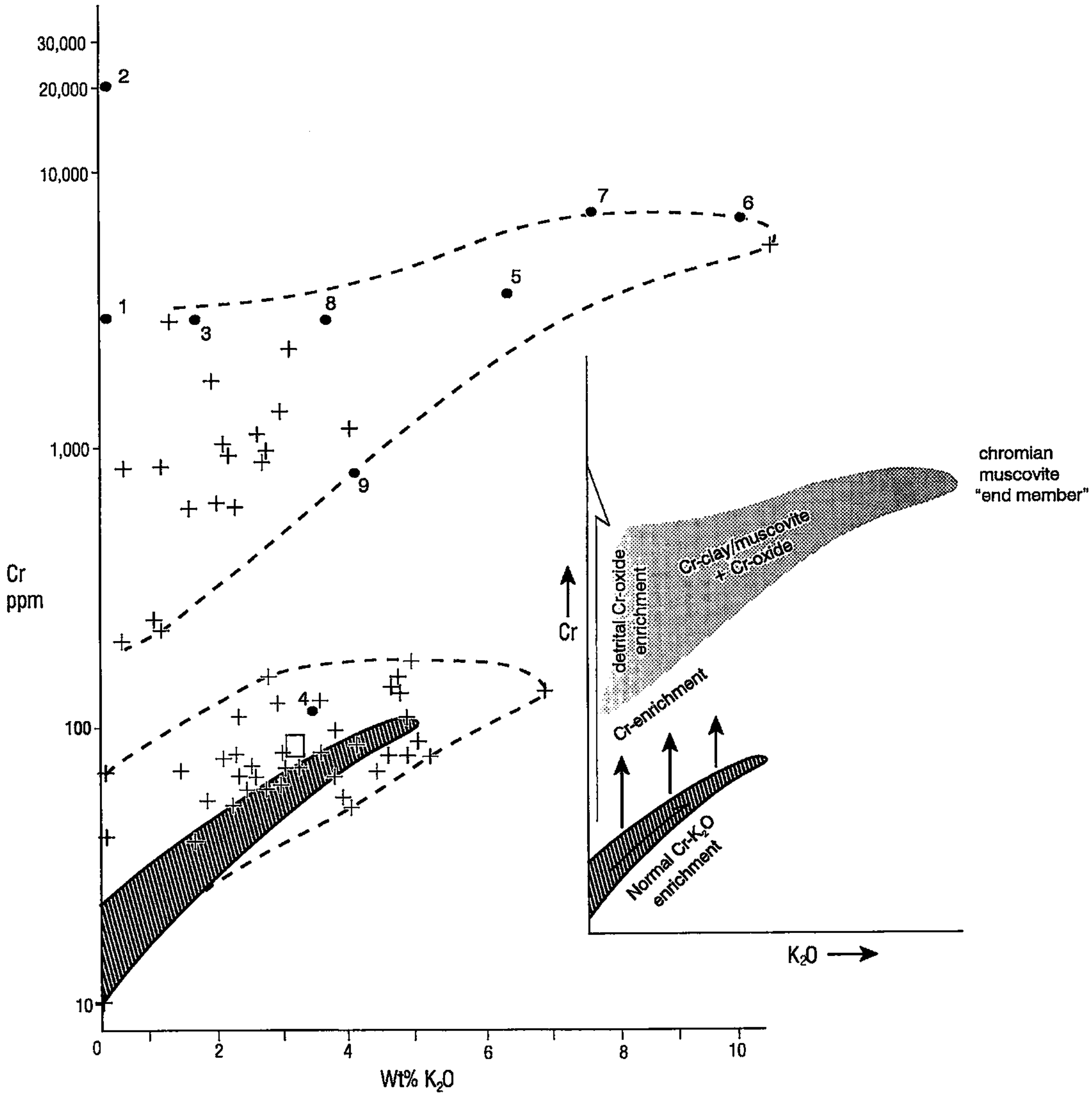

FIG. 11. Log-normal plot of bulk-rock Cr (ppm) *versus* K_2O (wt%) for Onekaka schists (crosses). Samples numbered 1–9 (solid circles) refer to compositions given in Table 1. Open square represents the composition of average shale (Turekian & Wedepohl 1961). An explanation of composition fields and trends is given in the inset diagram, and in the text. The trend of normal Cr–K_2O enrichment is given by compositions of low-grade metamorphic equivalents of the Onekaka Schist (unpublished data of Grapes & Palmer).

expected from sedimentation trends encountered in marine sediments (van de Kamp & Leake 1985), in which clay minerals absorb Cr from seawater (Elderfield 1970). In contrast, samples of Onekaka Schist plot as two separate fields: low-Cr (<200 ppm) samples with K_2O ranging between 1 and 6.5%, and high-Cr (>850 ppm) samples, with K_2O ranging from 0.01 to 10%. In the low-Cr field, the increase of Cr to values higher than those of the inferred background, defined on the basis of the low-grade equivalents of Onekaka Schist, reflects Cr-enrichment. Those rocks that define the high-Cr field contain detrital chromite, together with chromian muscovite. The uvarovite quartzites from Plumbago Creek lie on a trend of increasing modal chromite without any concomitant increase in muscovite (clay) content. From considerations of bulk-rock Cr_2O_3 and K_2O, the chromite – uvarovite and deep emerald-green chromian muscovite layers in particular are inferred to represent original Cr-rich sedimentary layers ("black sand leads") of chromite, or horizons containing Cr-substituted clays derived from weathering of an ultramafic source-rock (Shaw & Bush 1978, Treloar 1987, Güven 1988). The almost monomineralic seams of chromian muscovite at Parapara Inlet have the highest Cr and K_2O and represent an "end-member" composition. The absence of chromite in these seams could imply that it has been completely consumed to form chromian muscovite.

Source, composition, and reaction of detrital chromite

The most obvious source of detrital chromite in the Onekaka Schist is the Cobb Ultramafic Complex (Fig. 1). Compositions of chromite from the main Cobb ultramafic body (Hunter 1974), and of detrital chromite that occurs in low-grade Cambrian rocks of Northwest Nelson (Hunter 1975, Pound 1993) are identical and characterized by high Mg (10.5–13.3% MgO), very low levels of Zn (<0.08% ZnO) and Mn (<0.2% MnO). Such high-Mg and low-Zn–Mn chromite is not found in the Onekaka Schist, which suggests that the chromite could either have been derived from a source other than the Cobb Ultramafic Complex, for which there is no evidence, or that Cobb chromite compositions have been modified since they were deposited. Regarding the second alternative, the Zn–Mn-rich compositions of chromite partly replaced by "ferritchromit" and chromian magnetite in serpentinite at Parapara River (Table 5, anal. 13) are identical to those typically associated with metasomatic alteration of ultramafic rocks through interaction with fluids derived from a granitic source, or during serpentinization associated with Cu–Zn–Pb mineralization (Thayer *et al.* 1964, Moore 1977, Bevan & Mallinson 1980, von Knorring *et al.* 1986, Wyllie *et al.* 1987, Treloar 1987, Pan & Fleet 1989, Béziat & Monchoux 1991, Bjerg *et al.* 1993). It is significant that the Parapara serpentinite occurs close to an area of Pb–Zn–Cu mineralization associated with the Richmond Hill granitic pluton (E. Wilson pers. comm., 1994). As stated previously, Cu–Pb–Zn–Mo and Au–Ag mineralization is typically associated with Early Cretaceous granitic rocks in Northwest Nelson. The relationship also suggests that the detrital chromite associated with chromian muscovite in the Onekaka Schist may also have been modified by Zn and Mn substitution for Mg and Fe^{2+}, respectively, at the same time as the mineralization event.

Although compositions of the detrital chromite are quite variable (Table 5), variation in Zn and Mn can, in part, be attributed to *in situ* reactions. Chromite with some of the highest Zn occurs in a reaction relationship involving the formation of uvarovite at Plumbago Creek: magnesian chromite + $CaCO_3$ + SiO_2 + (Zn, Mn) = Zn–Mn-enriched chromite + uvarovite + CO_2, and chromian muscovite at Parapara Inlet and Onekaka River: magnesian chromite + Cr-poor muscovite + Zn–Mn = Zn–Mn-enriched chromite + chromian muscovite.

An alternative hypothesis, that the high Zn is the result of an isochemical reaction involving removal of $FeCr_2O_4$ and concentration of Zn in detrital chromite that already contained a small component of $ZnCr_2O_4$, was rejected in view of the fact that all analyzed grains of chromite from outside the contact aureoles of Early Cretaceous granitic plutons contain less than 0.08% ZnO, and the Zn-enriched chromite is not depleted in Cr or Fe. Some late concentration of Zn, in already metasomatically Zn-enriched chromite, may have occurred in the case of the very small, highly corroded grains in chromian muscovite, but for relatively large, less corroded grains at the center of uvarovite aggregates, which typically contain about 9% ZnO, some introduction of Zn seems required, or a possible precursor sphalerite may have been involved.

The irregular distribution of Cr within much of the chromian muscovite suggests that Cr was too immobile to achieve even small-scale homogenization during metamorphism. It also underscores the effect of original sedimentary variations in Cr content, and the persistence of Cr-rich horizons because of limited diffusion under amphibolite-facies conditions of metamorphism. The relatively immobile behavior of Cr during metamorphism contrasts with the relative mobility of Cr in metal-rich hydrothermal fluids as discussed below. Similar contrasting behavior of Cr has also been noted at Outokumpu by Treloar (1987).

Synmetamorphic Cr and Zn metasomatism

Evidence for a Cr–Zn-(and Mn)-bearing synmetamorphic fluid responsible for the alteration of detrital chromite, precipitating new chromian mica and other

Cr silicates and oxides, or resulting in Cr-enrichment of Cr-poor muscovite, is provided by: (i) the presence of chromian muscovite, tourmaline, and rutile in metamorphic segregations of quartz that originally lacked them (Parapara Inlet, Anatoki River – Go-Ahead Creek), (ii) the occurrence of wide, moderately Cr-rich bands containing disseminated chromian muscovite and chromian rutile within otherwise Cr-poor quartzite (Parapara Inlet, Anatoki River – Go-Ahead Creek), and (iii) almost monomineralic samples of chromian muscovite from Onekaka River, chromian muscovite-rich segregations in biotite schist from Campbell Creek, and in the Arthur Marble at Copperstain Creek, clear textural evidence of host-rock replacement by chromian muscovite-rich assemblages.

Mineral assemblages from Onekaka River, Campbell Creek and Copperstain Creek allow an approximation of some chemical parameters for the metasomatic fluid as a function of $f(O_2)$ in the system $Na_2O - K_2O - CaO - Fe_2O_3 - Al_2O_3 - SiO_2 - H_2O - O_2$, where muscovite coexists with chlorite ± biotite ± epidote ± margarite ± plagioclase ± quartz in the stability field of kyanite. According to Rosing *et al.* (1987), for $a(H_2O) = 1$ and 5 kbar at 550°C, the limiting parameters are: $\log aSiO_{2(aq)} \approx -1.0$, $\log aCa^{2+}/a^2H^+ = 6$, $\log aK/a^2H^+$ in the range 3.8–4.9; $\log aMg^{2+}/a^2H^+$ in the range 4–4.5, and $f(O_2) \approx 10^{-18}$ (*i.e.*, between that of the HM and QFM buffer curves). Additional information is provided by the presence of tourmaline, which requires acid fluids (pH <6.0), increased activity of Al (Morgan & London 1989), and the presence of boron, whereas the widespread presence of accessory fluorapatite points to a comparatively high aHF/aH_2O in such acid fluids. This is consistent with the presence of fluorine in chromian muscovite, biotite, tourmaline, and rutile. Barsukova *et al.* (1979) showed that titanium is mobile under conditions of high concentration of fluoride and low pH of the fluid. It is expected that rutile will precipitate from a metasomatic aqueous fluid if the activity of H_2O decreases, *e.g.*, through the coprecipitation of muscovite and other hydrous phases, or dilution of the fluid phase by CO_2 at Copperstain Creek, where it invaded the Arthur Marble, and possibly at Campbell Creek, where rutile is associated with siderite. Accessory zircon, apatite, and rare monazite (this occurring in quartz segregations at Anatoki River – Go-Ahead Creek), are commonly associated with chromian muscovite and rutile (Fig. 4b), and are possible precipitates from a supercritical aqueous fluid with elevated F that underwent an increase in pH by interaction with the country rock (Ayers & Watson 1991). At Parapara Inlet and Anatoki River – Go-Ahead Creek, the association of chromian muscovite – chromian rutile ± tourmaline, with drusy encrustations of quartz formed along fracture planes and within cavities in quartz segregations, indicates that the fluid also was saturated with silica, possibly derived by partial solution of quartz in the host rock.

Source of metasomatic fluids

In addition to the presence of detrital chromite, an ultramafic source for Cr (together with some Ni, Co, Mg, Mn, and Fe) in a metasomatic fluid is clearly indicated, and it may not be coincidental that all localities are in close proximity to known outcrops of Cambrian ultramafic rocks (Fig. 1). The effect of fluids in equilibrium with a granitic source on ultramafic rocks is demonstrated by the Onahau Granite, which contains at least two bodies of ultramafic rock (Fig. 1). These ultramafic bodies are altered to talc and antigorite with heazlewoodite. Chromite is absent, suggesting solution and mobilization of Cr by hydrothermal leaching (Kerrich & Fryer 1981, Treloar 1987). Late-stage hydrothermal muscovite in the Onahau Granite, near the margins, contains between 0.2 and 0.7% Cr_2O_3, which suggests the production of a late-stage fluid phase containing chromium. Mobility of chromium during the alteration of ultramafic rocks is evident in the carbonated rocks at Calphurnia Creek, and is commonly reported from shear zones within ultramafic rocks that have been hydrothermally altered (locally carbonated) by high-temperature, low-pH fluids (Kerrich *et al.* 1987).

Compared with the inferred leaching of Cr by high-temperature aqueous fluids, there was only limited removal of Ni from the ultramafic rocks, and only minor amounts of Ni occur in some muscovite, epidote, chlorite, biotite, tourmaline and pyrite. Heazlewoodite, gersdorffite, pentlandite, violarite, Ni-carbonate, and Ni-bearing chlorite remain in the ultramafic rocks within the Onahau Granite and at Calphurnia Creek, although minor gersdorffite is present in Onekaka Schist quartzite at Contact Creek.

If Cr and lesser amounts of Ni were leached from ultramafic rocks, it is also evident that Zn, together with Si, Al, K, Na, Sr, Ba, Rb, F ,B, Mn, Ti, As, and Pb were most probably also derived from a granitic source (*i.e.*, the Separation Point Suite). The Zn and Mn could be scavenged from biotite and magnetite, the main repositories of Zn and Mn, respectively (Johnson 1994). It is significant that *newly formed* chromite containing Zn (2.2–4.8% ZnO) and Mn (2.2–2.9% MnO) is found in quartz segregations together with chromian muscovite, kyanite, and tourmaline in Campbell Creek, adjacent to the Onahau Granite. This supports the possibility of Zn–Mn metasomatism of detrital chromite elsewhere in the Onekaka Schist. Significant also is the Zn and Mn contained in chlorite, biotite, tourmaline, and some rutile associated with chromian muscovite, and in chlorite associated with uvarovite.

Chromian rutile is found at nearly all localities of chromian muscovite and is inferred to be of metasomatic origin, with Ti, Nb, and Ta being scavenged from titaniferous magnetite and rutile from the granitic source. Rutile, in particular, is appreciably soluble in

H_2O at high temperature and low pressure, and dissolves by hydrolysis to form $Ti(OH)_4$ (Ayers & Watson 1993). The rare galena and pyrite in chromian muscovite quartzite and quartz segregations (Anatoki River – Go-Ahead Creek), gersdorffite and pyrite (Contact Creek), and cerussite (Plumbago Creek), are inferred to be the products of the same granite-derived, metal-rich fluids that were responsible for the minor Cu–Pb–Zn–Mo and Au–Ag mineralization associated with the Separation Point Suite, mentioned previously. It may also be important that all occurrences of the chromium minerals described in this paper are close to major faults, which may have acted as channelways for the fluids. The chromian muscovite localities at Plumbago Creek and Onekaka River lie within the shear zones of the Wakamarama and Onekaka faults, respectively, which must have been active in Early Cretaceous times if they did act as channelways.

Conclusions

Chromian muscovite, zincian chromite, uvarovite, and chromian rutile are variously associated with Cr-bearing silicates (chlorite, biotite, epidote, tourmaline, kyanite), carbonates, and sulfides (pyrite, galena, gersdorffite, pentlandite) in Lower Paleozoic quartzite, biotite schist, marble and ultramafic rocks in Northwest Nelson. Enhanced levels of Cr in the sediments involved deposition of detrital chromite and Cr-substituted clays derived by weathering of ultramafic rocks. Early Cretaceous amphibolite-facies metamorphism and synmetamorphic metasomatism associated with emplacement of granitic plutons resulted in leaching of Cr from ultramafic rocks by metal-scavenging fluids emanating from the granitic batholiths. Stabilization of chromian muscovite and uvarovite occurred by *in situ* high-temperature reaction of the fluid with detrital chromite, and widespread Cr–Zn–Mn metasomatism resulted in the formation of Cr-silicates and oxides both within original Cr-rich sedimentary horizons, and through replacement of Cr-poor lithologies.

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References

Aronson, J.L. (1968): Regional geochronology of New Zealand. *Geochim. Cosmochim. Acta* **32**, 669-697.

Ayers, J.C. & Watson, E.B. (1991): Solubility of apatite, monazite, zircon, and rutile in supercritical aqueous fluids with implications for subducted zone geochemistry. *Phil. Trans. Roy. Soc. London* **A 335**, 336-375.

________ & ________ (1993): Rutile solubility and mobility in supercritical aqueous fluids. *Contrib. Mineral. Petrol.* **114**, 321-330.

Barsukova, M.L., Kuznetsov, V.A., Dorofeyeva, V.A. & Khodakovskiy, L.I. (1979): Measurement of the solubility of rutile TiO_2 in fluoride solutions at elevated temperatures. *Geokhimiya* **7**, 1017-1027.

Bates, T.E. (1989): Parapara silver/gold/lead-zinc prospect. *In* Mineral Deposits of New Zealand. *Austral. Inst. Mining Metall., Monogr.* **13**, 117-118.

Bell, J.M., Webb, E.J.H. & Clarke, E. de C. (1907): The geology of the Parapara Subdivision, Karamea, Nelson. *N.Z. Geol. Surv., Bull.* **3**.

Bevan, J.C. & Mallinson, L.G. (1980): Zinc and manganese-bearing chromites and associated grossular from Zimbabwe. *Mineral. Mag.* **43**, 811-814.

Béziat, D. & Monchoux, P. (1991): Les spinelles chromozincifères du district aurifère de Salsigne (Montagne Noire, France). *Eur. J. Mineral.* **3**, 957-969.

Bishop, D.G. (1971): Sheet S1, S3 & Pt.S4 Farewell–Collingwood. Geological Map of New Zealand 1:63 360. *Dep. Sci. Indus. Res., Wellington, New Zealand.*

Bjerg, E.A., DeBrodtkorb, M.K. & Stumpfl, E.F. (1993): Compositional zoning in Zn-chromites from the Cordillera Frontal Range, Argentina. *Mineral. Mag.* **57**, 131-139.

Brathwaite, R.J. & Pirajno, F. (1993): Metallogenic map of New Zealand. *Inst. Geol. Nuclear Sci., Monogr.* **3**.

Cooper, A.F. (1976): Concentrically zoned ultramafic pods from the Haast Schist Zone, South Island, New Zealand. *N.Z. J. Geol. Geophys.* 19, 603-623.

COOPER, R.A. (1989): Early Paleozoic terranes of New Zealand. *J. Roy. Soc. N.Z.* **19**, 73-112.

DEER, W.A., HOWIE, R.A. & ZUSSMAN, J. (1982): *Rock-Forming Minerals.* **1A** *Orthosilicates.* Longman, London, U.K.

ELDERFIELD, H. (1970): Chromium speciation in sea water. *Earth Planet. Sci. Lett.* **9**, 10-16.

GRINDLEY, G.W. (1971): S8 Takaka. Geological Map of New Zealand 1:63000. *Dep. Sci. Indust. Res., Wellington, N.Z.*

________ (1980): S13 Cobb. Geological Map of New Zealand 1:63 000. *Dep. Sci. Indust. Res., Wellington, N.Z.*

________ & WODZICKI, A. (1960): Base metal and gold-silver mineralisation on the southest side of the Aorere Valley, northwest Nelson. *N.Z. J. Geol. Geophys.* **3**, 585-592.

GÜVEN, N. (1988): Smectites. *In* Hydrous Phyllosilicates (Exclusive of Micas) (S.W. Bailey, ed.). *Rev. Mineral.* **19**, 497-559.

HEY, M.H. (1954): A new review of chlorites. *Mineral. Mag.* **30**, 277-292.

HUNTER, H.W. (1974): *The Geology of the Takaka Igneous Complex, northwest Nelson, New Zealand.* Ph.D. thesis, Victoria Univ. of Wellington, Wellington, N.Z.

________ (1975): Source of detrital chromite in northwest Nelson. *N.Z. J. Geol. Geophys.* **18**, 511-514.

________ (1977): Geology of the Cobb Intrusives, Takaka Valley, northwest Nelson, New Zealand. *N.Z. J. Geol. Geophys.* **20**, 469-501.

HUTTON, C.O. (1942): Fuchsite-bearing schists from Dead Horse Creek, Lake Wakatipu Region, Western Otago. *Trans. Roy. Soc. N.Z.* **72**, 53-68.

JOHNSON, C.A. (1994): Partitioning of zinc among common ferromagnesian minerals and implications for hydrothermal mobilization. *Can. Mineral.* **32**, 121-132.

KERRICH, R. & FRYER, B.J. (1981): The separation of rare elements from abundant base metals in Archaean lode gold deposits: implications of low water/rock source regions. *Econ. Geol.* **76**, 160-167.

________, FYFE, W.S., BARNETT, R.L., BLAIR, B.B. & WILMORE, L.M. (1987): Corundum, Cr-muscovite rocks at O'Briens, Zimbabwe: the conjunction of hydrothermal desilicification and LIL-element enrichment, geochemical and isotopic evidence. *Contrib. Mineral. Petrol.* **95**, 481-498.

KIMBOROUGH, D.L., TULLOCH, A.J., GEARY, E., COOMBS, D.S. & LANDIS, C.A. (1993): Isotopic ages from the Nelson region of South Island, New Zealand: crustal structure and definition of the Median Tectonic Zone. *Tectonophys.* **225**, 433-448.

LÓPEZ SÁNCHEZ-VIZCAÍNO, V., FRANZ, G. & GÓMEZ-PUGNAIRE, M.T. (1995): The behavior of Cr during metamorphism of carbonate rocks from the Nevado–Filabride Complex, Betic Cordilleras, Spain. *Can. Mineral.* **33**, 85-104.

MARIKO, T. & NAGAI, Y. (1980): Birefringence and composition of grandite garnet from the Shinyama ore deposit of the Kamaishi mine, Iwane Prefecture, Japan. *Mineral. J. Japan* **10**, 181-191.

MARSHALL, C.P. & DOLLASE, W.A. (1984): Cation arrangement in iron-zinc-chromium spinel oxides. *Am. Mineral.* **69**, 928-936.

MOORE, A.C. (1977): Zinc-bearing chromite (donathite?) from Norway: a second look. *Mineral. Mag.* **41**, 351-355.

MORGAN, G.B. & LONDON, D. (1989): Experimental reactions of amphibolite with boron-bearing aqueous fluids at 200 MPa: implications for tourmaline stability and partial melting in mafic rocks. *Contrib. Mineral. Petrol.* **102**, 281-297.

PAN, YUANMING & FLEET, M.E. (1989): Cr-rich calc silicates from the Hemlo area, Ontario. *Can. Mineral.* **27**, 565-577.

POUND, K.S. (1993): *Geology of the Lower Paleozoic Haupiri Group rocks, Cobb Valley area, northwest Nelson, New Zealand.* Ph.D. thesis, Univ. of Otago, Otago, New Zealand.

RAILTON, G.L. & WATTERS, W.A. (1990): Minerals of New Zealand. *N.Z. Geol. Surv., Bull.* **104**.

ROSING, M.T., BIRD, D.K. & DYMEK, R.F. (1987): Hydration of corundum-bearing xenoliths in the Qôrqut Granite complex, Godthåbsfjord, West Greenland. *Am. Mineral.* **72**, 29-38.

ROSSMAN, G.R. & SMYTH, J.R. (1990): Hydroxyl contents of accessory minerals in mantle eclogites and related rocks. *Am. Mineral.* **75**, 775-780.

SHAW, H.F. & BUSH, P.R. (1978): The mineralogy and geochemistry of the Recent surface sediments of the Cilician Basin, NE-Mediterranean. *Marine Geol.* **27**, 115-136.

THAYER, T.P., MILTON, C., DINNIN, J. & ROSE, H. (1964): Zincian chromite from Outokumpu, Finland. *Am. Mineral.* **49**, 1178-1183.

TRELOAR, P.J. (1987): The Cr-minerals of Outokumpu. Their chemistry and significance. *J. Petrol.* **28**, 867-886.

TULLOCH, A.J. & BRATHWAITE, R.L. (1986): C7: Granitoid rocks and associated mineralisation of Westland-Nelson, New Zealand. Tour Guides A3, C2, and C7. *N.Z. Geol. Surv., Record* **13**, 65-92.

TUREKIAN, K.K. & WEDEPOHL, K.H. (1961): Distribution of the elements in some major units of the Earth's crust. *Geol. Soc. Am., Bull.* **72**, 175-192.

VLASSOPOULOS, D., ROSSMAN, G.R. & HAGGERTY, S.E. (1993): Coupled substitution of H and minor elements in rutile and the implications of high OH contents in Nb-and Cr-rich rutile from the upper mantle. *Am. Mineral.* **78**, 1181-1191.

VAN DE KAMP, P.C. & LEAKE, B.E. (1985): Petrography and geochemistry of feldspathic and mafic sediment of the north eastern Pacific margin. *Trans. Roy. Soc. Edinburgh, Earth Sci.* **76**, 411-449.

VON KNORRING, O., CONDLIFFE, E. & TONG, Y.L. (1986): Some mineralogical and geochemical aspects of chromium-bearing skarn minerals from northern Karelia, Finland. *Bull. Geol. Soc. Finland* **5**, 277-292.

WODZICKI, A. (1972): Mineralogy, geochemistry, and origin of hydrothermal alteration and sulphide mineralisation in the disseminated molybdenite and skarn-type copper sulphide deposit of Copperstain Creek, Takaka, New Zealand. *N.Z. J. Geol. Geophys.* **15**, 599-631.

WYLIE, A.G., CANDELA, P.A. & BURKE, T.M. (1987): Compositional zoning in unusual Zn-rich chromite from the Sykesville district of Maryland and its bearing on the origin of "ferritchromit". *Am. Mineral.* **72**, 413-422.

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