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Cr-RICH CALC-SILICATES FROM THE HEMLO AREA, ONTARIO

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ABSTRACT

Cr-rich calc-silicate rocks occur in the Cadi Zone of the White River gold prospect of LAC Minerals Ltd., Hemlo area, Ontario. The calc-silicates are associated with a major fracture zone at lithological boundaries between metabasites and metasediments. The characteristic mineral assemblage includes clinopyroxene, grandite (Cr-poor brown garnet and Cr-bearing green garnet), calcic amphibole, epidote, plagioclase, microcline, chromite, uvarovite, prehnite, pumpellyite, chlorite, titanite, apatite, with variable but generally minor amounts of calcite and accessory pentlandite, pyrrhotite, magnetite, and, less commonly, chalcopyrite, pyrite, sphalerite, Fe-rich siegenite, millerite, and molybdenite. Cr-bearing minerals include: chromite, uvarovite, grandite (up to 5.15 wt.% Cr_2O_3), epidote (up to 11.77 wt.% Cr_2O_3), chlorite (up to 3.50 wt.% Cr_2O_3), prehnite (up to 1.21 wt.% Cr_2O_3), and pumpellyite (up to 2.56 wt.% Cr_2O_3). There is a compositional gap between Cr-bearing grandite garnet ($Gr_{54}An_{25}Uv_{16}$) and uvarovite ($Gr_{37}An_{11}Uv_{40}$), but uvarovite appears to have crystallized later. The calc-silicates were formed by metasomatic replacement of komatiite and komatiitic basalt, with secondary enrichment of Cr. Element partitioning and textural evidence suggest the attainment of equilibrium among the major mineral phases (clinopyroxene, calcic amphibole, grandite garnet, and epidote), zincian chromite and fluids. Ambient metamorphic conditions involved a temperature of 400±50°C, a pressure of about 2–4 kbars, and a H_2O-rich fluid with $X(CO_2) < 0.03$. The crystallization of the anomalously Cr-rich silicate minerals in amygdule-like cavities (along with albite and calcite in veins) took place later, in a low- to very-low-grade alteration event.

Keywords: White River gold prospect, Hemlo mining camp, Ontario, calc-silicates, uvarovite, zincian chromite, chromian epidote, Cr-rich minerals.

SOMMAIRE

On trouve des roches à calc-silicates enrichis en Cr dans la zone de Cadi de l'indice aurifère de White River (société LAC Minerals), dans le camp minier de Hemlo, Ontario. Les calc-silicates sont associés à une zone de fissures importante à l'interface entre métabasites et métasédiments. L'assemblage caractéristique comprend clinopyroxène, grandite (grenat brun à faible teneur de Cr et grenat vert riche en Cr), amphibole calcique, épidote, plagioclase, microcline, chromite zincifère, uvarovite, prehnite, pumpellyite, chlorite, titanite et apatite, avec des quantités variables de calcite et des accessoires pentlandite, pyrrhotite, magnétite, et, plus rarement, chalcopyrite, pyrite, sphalérite, siegenite ferreuse, millerite et molybdenite. Les minéraux chromifères sont: chromite, uvarovite, grandite (maximum de 5.15% de Cr_2O_3 par poids), épidote (11.77%), chlorite (3.50%), prehnite (1.21%) et pumpellyite (2.56%). Une lacune de composition existe entre grandite chromifère ($Grs_{54}Adr_{25}Uv_{16}$) et uvarovite ($Grs_{37}Adr_{11}Uv_{40}$), mais l'uvarovite semble avoir cristallisé tardivement. Les calc-silicates témoignent de la métasomatose de komatiite et de basalte komatiitique, avec enrichissement secondaire en Cr. La répartition des éléments et l'évidence texturale font penser que les phases minérales importantes (clinopyroxène, amphibole calcique, grenat granditique et épidote), la chromite zincifère et une phase fluide aqueuse [$X(CO_2) < 0.03$] ont atteint l'équilibre à 400±50°C entre 2 et 4 kbars. La formation de minéraux à teneur anomale en Cr dans des cavités qui ressemblent à des amygdules, et la cristallisation de calcite et d'albite dans les fissures, seraient dues à une altération postérieure, à faible température.

(Traduit par la Rédaction)

Mots-clés: indice aurifère de White River, camp minier de Hemlo, Ontario, calc-silicates, uvarovite, chromite zincifère, épidote chromifère, minéraux chromifères.

INTRODUCTION

Calc-silicate rocks with chromite and uvarovite (and Cr-bearing grandite garnet) are rare and occur chiefly in metamorphosed limestones and skarns. The best known occurrence is the skarn at Outokumpu in northern Karelia, Finland (Eskola 1933, von Knorring 1951, Hiltunen 1982, von Knorring *et al.* 1986).

This paper describes an unusual occurrence of Cr-rich calc-silicate rocks containing chromite, uvarovite, and Cr-bearing grandite garnet. The association is found along a major fracture zone at lithological boundaries between metasediments and metabasites of the Playter Harbour Group of the Hemlo – Heron Bay Archean greenstone belt, on the White River gold prospect of LAC Minerals Ltd., Hemlo area, Ontario. Carbonate rocks have not been recognized in or near the study area. Textures and mineral chemistry indicate that these calc-silicate rocks formed metasomatically. However, the anomalously Cr-rich silicate minerals (uvarovite, chromian epidote, chromian chlorite, and Cr-bearing prehnite and pumpellyite) formed after the main metasomatic assemblage during a low- to very-low-grade alteration event, wherever sufficient chromium was present in the calc-silicate rocks. The calc-silicate rocks of the White River gold prospect were previously studied by Holding (1987).

GENERAL GEOLOGY

The White River gold prospect of LAC Minerals Ltd. is located 5 to 10 km southeast of the Hemlo gold deposit (*e.g.*, Harris 1986, Cameron & Hattori 1985), Hemlo, Ontario, in the Hemlo - Heron Bay Archean greenstone belt, which is part of the Shebandowan–Wawa Subprovince of the Superior Province of the Canadian Shield. The detailed geology of the White River property and vicinity is given in Pan & Fleet (1988), Muir (1982a, b), and Muir & Elliott (1987). Only a brief geological outline is presented here.

The supracrustal rocks, which strike approximately 120° and dip 60° north in the northwest part of the property, gradually changing to a strike of 85° and a dip of 50° north in the central and eastern parts, are divided into two groups. The Playter Harbour Group consists of high-iron tholeiitic basalts intercalated with clastic metasedimentary rocks that structurally overlie the Pukaskwa Gneissic complex. The overlying Heron Bay Group mainly consists of calc-alkaline intermediate to felsic metavolcanic rocks and clastic-dominated metasedimentary rocks. Numerous early (Archean) altered mafic dykes and bodies of quartz–feldspar porphyry occur parallel or subparallel to the foliation, and all lithologies are cut by north- and northwest-trending, later (Proterozoic) subalkaline diabase dykes.

The structural geology of the study area is very complex. The entire greenstone belt has been subjected to extensive ductile and brittle deformation (faulting and shearing), especially at lithological boundaries between metasedimentary and metavolcanic units. At least four generations of events have been recognized (Muir & Elliott 1987): the last structural event was associated with the two major fracture zones (the Hemlo Fault Zone in the Heron Bay Group and the Cadi Fracture Zone in the Playter Harbour Group).

The White River property is predominantly characterized by low- to medium-grade metamor-

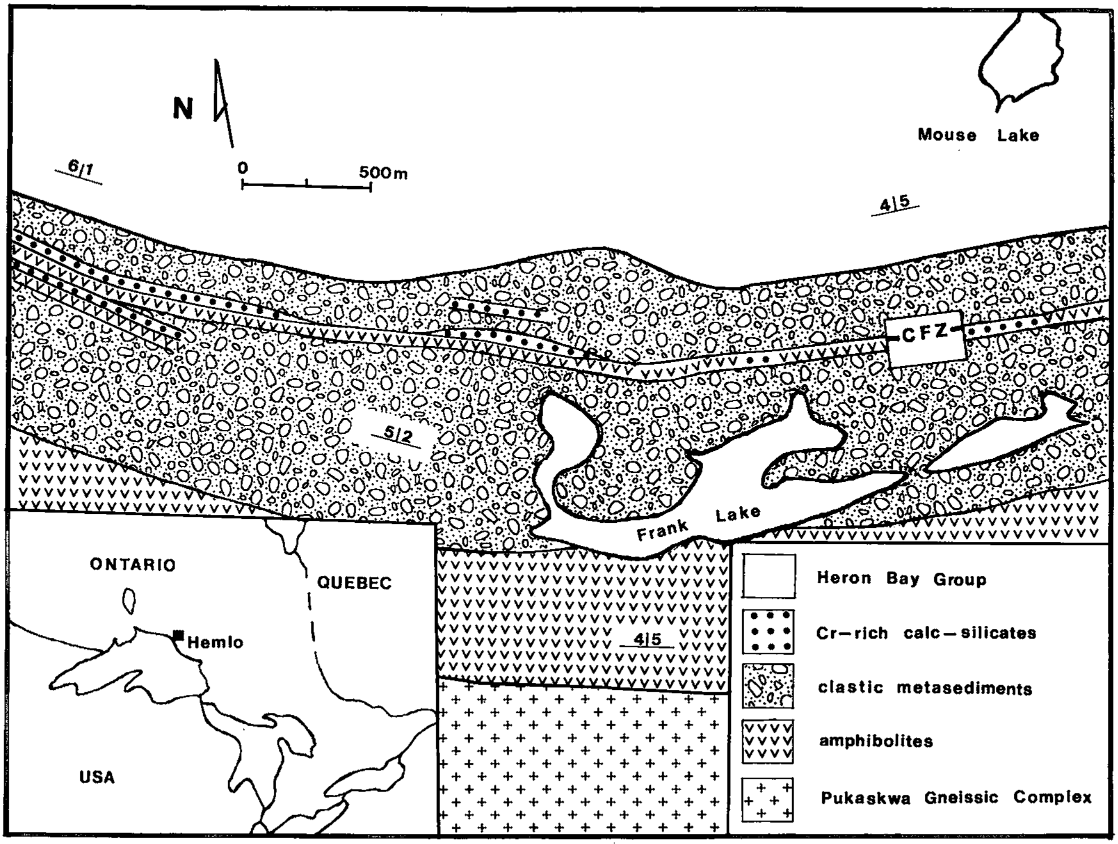

FIG. 1. Geological map of the Playter Harbour Group and Cadi Fracture Zone at the White River gold prospect of LAC Minerals Ltd. Hemlo, Ontario (prepared with assistance of LAC Minerals Ltd.); CFZ is Cadi Fracture Zone.

phism; a greenschist-to-amphibolite transition facies (epidote–amphibolite facies) is indicated by the presence of the assemblages: micas + chlorite + quartz + oligoclase + K-feldspar ± garnet ± andalusite ± titanite in metapelites and oligoclase + actinolitic hornblende - hornblende + quartz + K-feldspar + chlorite + biotite + epidote and, locally, calcite in metabasites (*cf.* Laird & Albee 1981). A narrow zone of medium-grade metamorphism (middle amphibolite facies: kyanite–sillimanite zone), characterized by the assemblage sillimanite + quartz + garnet + biotite + andesine + K-feldspar + muscovite ± kyanite ± staurolite ± cordierite ± anthophyllite ± cummingtonite, is present in the Heron Bay Group rocks in the central portion of the greenstone belt, and encloses the dominant regional structure: the Lake Superior Shear Zone (locally referred to as the Hemlo Shear Zone: Hugon 1984, Pan & Fleet 1988).

The Playter Harbour Group mainly consists of mafic metavolcanic rocks and overlying clastic metasedimentary rocks (Fig. 1). The White River Cr-rich calc-silicate rocks occur as conformable thin bands or lenses (1 to 10 m thick) within the Cadi Fracture Zone and are situated at or near the lithological boundaries between the clastic metasediments and a layer of metabasite at the top of the Playter Harbour Group.

The clastic metasediment of the Playter Harbour Group is of variable thickness (400–700 m) and consists of strongly foliated grey-white, calcic-amphibole-bearing quartz–feldspar mica schists (quartz + oligoclase + microcline ± biotite ± chlorite ± actinolitic hornblende - hornblende ± epidote). Locally, minor almandine-rich garnet poikiloblasts also are present. The clastic metasediment is mineralogically similar to metasedimentary rocks of the Heron Bay Group but contains more lithic fragments. A blastopsammitic texture, with clastic quartz and feldspar relics in a weakly foliated or unfoliated fine-grained mafic matrix, also is locally observed in the eastern part of the study area.

The underlying or, in some cases, enveloping metabasite (amphibolite) associated with the calc-silicate rocks is a laterally extensive band about 30 m thick (Fig. 1). Pillow structures are locally well-preserved. The mineral assemblage is actinolitic hornblende - hornblende + epidote + oligoclase + quartz + microcline + biotite + chlorite + titanite.

Actinolite (or tremolite)–chlorite–talc schists of ultrabasic bulk chemical composition are sporadically present in the Cadi Zone, and a lens (about 20 m thick) of ultramafic rocks of pseudo-microspinifex texture of tremolite, talc, and chlorite after olivine also is present within the overlying metasedimentary rocks, parallel to the foliation plane of the metasediments.

The Cadi Fracture Zone is set off from the surrounding rocks by a magnetic anomaly. Results of very low frequency (VLF) and ionization potential (IP) electromagnetic surveys also delineate it distinctly (Holding 1987). Within the Cadi Zone, Z-shaped drag folds related to ductile shearing are locally present, as are mafic and ultramafic breccias that have been completely metamorphosed to actinolite–chlorite–talc schists.

PETROGRAPHY AND MINERAL CHEMISTRY

The White River calc-silicate rocks are distinctly yellowish green, medium to coarse grained, and locally develop a crude foliation parallel to the compositional banding. They also are characterized by the association of clinopyroxene, epidote, grandite garnet, calcic amphibole, epidote, plagioclase, microcline, chromian epidote, chromite, uvarovite, chromian chlorite, prehnite, pumpellyite, titanite, apatite, calcite, with molybdenite locally present, and variable amounts of pentlandite, pyrrhotite, magnetite, and, less commonly, chalcopyrite, pyrite, sphalerite, Fe-rich siegenite, and millerite (work in progress). Thin clinopyroxene–epidote–actinolite-rich yellowish green bands (0.2 to 3 cm thick) are intercalated with thin, light-colored grandite–feldspar-rich bands.

Quartz occurs rarely as interstitial grains within the major calc-silicate mineral phases. Carbonate is sporadically abundant (Holding 1987). However, in the samples of the present study, the only carbonate observed (calcite) is minor or rare. Calcite is virtually absent or present only in cross-cutting veins in those calc-silicate rocks enveloped by metabasites. The composition varies from 96.4 mol.% $CaCO_3$ in the rock matrix to 99.6 mol.% $CaCO_3$ in the veins.

Major mineral phases were analyzed in detail with the JEOL JXA-8600 electron microprobe at the University of Western Ontario (15 kV, 10 nA, 1–5 μm beam diameter, and 20-second counts, with natural minerals as standards). In most cases, at least three grains of each phase were analyzed, and three to five spots on each grain were analyzed to check the homogeneity of each phase. Representative compositions are reported in Tables 1–7.

Clinopyroxene

Clinopyroxene, the most abundant mineral phase in the White River calc-silicate rocks, is yellowish green, and generally forms xenoblastic to idioblastic, medium- to coarse-grained crystals of short prismatic habit. Texturally, it appears compatible with all other major mineral phases.

Although there is considerable compositional variation among the samples analyzed (Table 1), no significant zoning was detected within individual grains. Within the pyroxene quadrilateral, the clinopyroxene compositions vary within the diopside to hedenbergite series, with very minor "other than quadrilateral" components (*cf.* Robinson 1980). The molar ratio Mg/(Mg + Fe + Mn) ranges from 0.51 to 0.77, and the Cr content attains 0.72 wt.% Cr_2O_3.

TABLE 1. REPRESENTATIVE COMPOSITIONS OF CLINOPYROXENE

SAMPLE	1	4	5	6	7	8
SiO_2 (wt. %)	51.59	52.25	53.47	52.25	52.91	52.53
TiO_2	0.09	0.16	0.07	0.00	0.00	0.07
Al_2O_3	0.63	1.15	0.54	1.36	0.23	0.91
Cr_2O_3	0.29	0.40	0.00	0.72	0.14	0.57
FeO*	12.22	8.22	5.60	7.93	9.22	9.76
MgO	10.38	12.18	14.05	12.36	12.52	11.13
MnO	0.61	0.54	0.35	0.45	0.59	0.62
CaO	23.68	24.48	24.92	24.26	24.93	24.03
Na_2O	0.17	0.34	0.26	0.16	0.29	0.73
K_2O	0.00	0.02	0.02	0.00	0.04	0.02
Total	99.66	99.74	99.28	99.49	100.9	100.4
	Structural formulae on the basis of 6 oxygens					
Si	1.986	1.968	1.984	1.967	1.980	1.980
^{IV}Al	0.014	0.032	0.016	0.033	0.010	0.020
^{VI}Al	0.015	0.019	0.018	0.028	0.000	0.020
Ti	0.003	0.005	0.002	0.000	0.000	0.002
Cr	0.009	0.012	0.000	0.021	0.004	0.017
Mg	0.595	0.684	0.781	0.694	0.699	0.625
Fe	0.394	0.259	0.175	0.250	0.289	0.308
Mn	0.020	0.017	0.011	0.014	0.019	0.017
Ca	0.977	0.988	0.996	0.979	1.000	0.970
Na	0.013	0.025	0.019	0.012	0.021	0.053
K	0.000	0.001	0.001	0.000	0.002	0.001
F/FM	0.374	0.275	0.183	0.276	0.293	0.330
X	0.57	0.65	0.77	0.66	0.69	0.59

* is total iron as FeO; F/FM is molar Fe/(Fe + Mg) value; X is diopside mole fraction.

TABLE 2. REPRESENTATIVE COMPOSITIONS OF CHROMITE

SAMPLE	2c	2m	4c	4m	5	6c	6m
TiO_2 (wt. %)	0.10	0.13	0.20	0.12	0.10	0.27	0.09
Al_2O_3	10.08	7.40	11.25	8.99	11.95	11.78	6.36
Cr_2O_3	47.80	47.66	50.25	50.04	49.99	49.89	52.51
Fe_2O_3*	8.32	10.87	3.80	6.23	1.20	3.75	8.40
FeO	25.04	25.06	26.45	26.61	31.73	27.53	26.01
MgO	0.21	0.13	0.41	0.34	0.37	0.48	0.17
MnO	1.94	2.29	1.80	2.04	2.20	2.44	3.09
ZnO	6.59	5.62	5.72	5.28	2.41	4.14	3.36
NiO	0.00	0.00	0.09	0.00	0.00	0.00	0.00
V_2O_3	0.05	0.07	0.11	0.16	0.00	0.00	0.11
CoO	0.09	0.06	0.17	0.21	0.11	0.00	0.11
Total	100.2	99.6	100.3	100.0	100.1	100.3	99.3
	Structural formulae on the basis of 4 oxygens						
Ti	0.003	0.004	0.005	0.003	0.002	0.007	0.002
Al	0.349	0.318	0.470	0.379	0.516	0.488	0.232
Cr	1.350	1.371	1.408	1.433	1.447	1.391	1.530
V	0.001	0.002	0.003	0.005	0.000	0.000	0.002
Fe^{3+}	0.224	0.301	0.099	0.167	0.047	0.099	0.235
Fe^{2+}	0.749	0.776	0.787	0.795	0.876	0.812	0.802
Mg	0.011	0.008	0.022	0.018	0.020	0.025	0.009
Mn	0.059	0.073	0.054	0.062	0.069	0.073	0.097
Zn	0.174	0.157	0.150	0.139	0.065	0.108	0.091
Ni	0.000	0.000	0.003	0.000	0.000	0.000	0.000
Co	0.003	0.002	0.006	0.006	0.003	0.000	0.002
C/CA	0.76	0.81	0.75	0.79	0.74	0.74	0.87
M/FM	0.01	0.01	0.03	0.02	0.02	0.03	0.01
X	.0005	-	.0012	-	.0013	.0015	-

c is core; m is margin; * is calculated from ideal stoichiometry; nd is not determined; C/CA is molar Cr/(Cr + Al) value; M/FM is molar Mg/(Fe^{2+} + Mg) value; X is spinel mole fraction.

TABLE 3. REPRESENTATIVE COMPOSITIONS OF GARNET

SAMPLE	1Uvc	1Uvm	1Gr	2Grc	2Grm	3Gr	8Uvc	8Uvr
SiO_2 (wt. %)	36.50	37.37	39.23	37.40	37.41	37.80	35.87	35.83
TiO_2	0.60	0.44	0.38	1.41	1.42	0.54	0.22	0.16
Al_2O_3	4.00	10.05	19.75	11.93	12.19	14.98	5.40	6.39
Cr_2O_3	20.05	12.67	0.27	5.15	3.88	0.96	20.12	18.48
Fe_2O_3*	4.84	3.62	3.84	8.53	9.83	8.90	3.28	4.57
FeO	0.58	2.96	1.88	0.00	0.00	0.63	1.44	1.66
MnO	1.00	1.56	0.59	0.50	0.50	1.00	0.80	0.72
MgO	0.16	0.12	0.13	0.07	0.07	0.05	0.03	0.02
CaO	33.00	31.01	34.68	35.28	35.66	35.01	32.39	32.43
Total	99.7	99.8	100.7	100.3	100.9	99.9	99.6	100.2
	structural formulae on the basis of 12 oxygens							
Si	2.978	3.002	2.980	2.951	2.931	2.984	2.957	2.920
Al	0.384	0.952	1.767	1.110	1.125	1.394	0.524	0.613
Ti	0.036	0.027	0.022	0.083	0.083	0.041	0.011	0.010
Cr	1.293	0.806	0.016	0.322	0.240	0.062	1.312	1.191
Fe^{3+}	0.296	0.218	0.219	0.506	0.579	0.528	0.198	0.280
Fe^{2+}	0.040	0.199	0.120	0.000	0.000	0.042	0.099	0.113
Mn	0.069	0.106	0.038	0.033	0.033	0.067	0.056	0.050
Mg	0.019	0.014	0.015	0.008	0.008	0.006	0.003	0.002
Ca	2.883	2.671	2.822	2.983	3.010	2.968	2.860	2.830
Gr	14.9	37.0	82.6	54.1	54.9	65.4	18.9	21.2
And	14.8	10.9	11.0	25.3	28.9	26.4	9.9	14.0
Uv	64.7	40.3	0.8	16.1	12.0	3.1	65.6	59.6
Alm	1.3	6.6	4.0	0.0	0.0	1.4	3.3	3.8
Sps	2.3	3.5	1.3	1.1	1.1	2.2	1.9	1.7
Py	0.6	0.5	0.5	0.3	0.3	0.2	0.1	0.1
F/FA	0.435	0.186	0.110	0.313	0.339	0.275	0.274	0.313
X	-	-	0.62	-	0.29	0.46	-	-

Uv is uvarovite; c is core; m is margin; * is calculated from ideal stoichiometry; Gr is grossular; And is andradite; Alm is almandine; Sps is spessartine; Py is pyrope; F/FA is molar Fe^{3+}/(Fe^{3+} + Al) value; X is grossular mole fraction.

Chromite

Chromite occurs as an accessory mineral in almost all of the samples examined, either as clean euhedral, subhedral, or anhedral grains of millimeter size or as inclusions in uvarovite grains. These are optically rather homogeneous and normally have a very thin porous and slightly brighter margin. Chemical analyses of chromite (Table 2) confirm this observation and reveal that the grain margins are richer in the Fe_3O_4 component and lower in Cr/Fe^{3+}, which properties are similar to chromite from rocks equilibrated in the lower amphibolite facies (*cf.* Lipin 1984). The White River chromite contains up to 6.59 wt.% ZnO, up to 3.4 wt.% MnO, and minor V and Ni; in these respects, it is similar to zincian chromite from Outokumpu (von Knorring *et al.* 1986). It also has minor amounts of Co. However, it has less Cr and more Fe^{3+} than the zincian chromite at Outokumpu. In respect to its extremely low Mg content [less than 0.48 wt.% MgO and Mg/(Mg + Fe) <0.03)], high total iron and significant Al contents, it resembles chromite from stratiform deposits that have been attributed to alteration or metasomatic processes (*cf.* von Knorring *et al.* 1986, Lipin 1984). The White River chromite plots near the (Fe,Cr)-rich corner of the base of the spinel prism, with Cr/(Cr + Al) ranging from 0.72 to 0.87.

Garnets

In field exposures, one of the most distinctive features of the White River calc-silicate rocks is the presence of large euhedral grains of green Cr-bearing grossular and brown Cr-poor grossular. Uvarovite is observed in thin sections and is, in most cases, a minor phase. Euhedral, medium- to coarse-grained (up to 0.8 mm) crystals of brown Cr-poor grossular and green Cr-bearing grossular are mainly present in thin garnet-rich quartz–feldspar bands or as fine grains closely associated with clinopyroxene, epidote, calcic amphibole, and plagioclase. Anomalous birefringence and prominent dodecahedral twinning occur in both Cr-poor and Cr-bearing garnets. Single crystals and composite twinned grain fragments were removed from polished thin sections for an X-ray precession study. Some composite, compositionally zoned crystals do exhibit a small rotation of reciprocal lattice rows, but careful study of the single and twinned crystals failed to detect evidence of either a lower symmetry or lattice strain (*cf.* Allen & Buseck 1988).

Compositions of the garnets are given in Table 3. The proportions of ferrous to ferric iron have been estimated by assuming ideal stoichiometry, and end-member compositions are calculated by using the nomenclature and procedure of Rickwood (1968). Garnet compositions also are plotted on a uvarovite–grossular–andradite composition triangle (Fig. 2).

The brown Cr-poor garnet, which is largely grandite (grossular–andradite) without significant uvarovite component, is the most common species. Results of electron-microprobe analyses reveal that the brown garnet is characterized by low Cr (< 0.80 wt.% Cr_2O_3) and variable amounts of Mg (up to 1.89 wt.% MgO) and Ti (up to 1.66 wt.% TiO_2); it ranges from $Gr_{54}An_{35}$ to $Gr_{84}An_{11}$. Although slight compositional differences are found in different rocks, no significant compositional zoning has been detected.

Green euhedral Cr-bearing garnet is also a major phase and occurs where brown Cr-poor garnet is absent. It is generally color and compositionally zoned from a green core to a yellowish green margin, and contains higher Cr in the core than the margin; for example, Cr_2O_3 ranges from 5.15 to 3.84 wt.% in Sample 2. The morphology of the zoning is similar to that of the common growth-zoning of grossular from hydrothermal and skarn deposits (*cf.* Allen & Buseck 1988). However, these Cr-bearing garnet grains never contain enough Cr to be uvarovite. Although these large crystals of grandite garnet vary in both color and Cr content in different samples, these is no compositional gap (*e.g.*, Fig. 2).

Uvarovite, present as a minor phase, occurs in deep green fibrous aggregates surrounding a rounded relic core of chromite. An electron-microprobe analysis reveals that the uvarovite content decreases systematically with distance away from the chromite core. The decrease in uvarovite content of sample No. 1 is from 65 to 40 mol.% [Table 3, Fig. 2 (solid circles)], but the andradite content remains fairly constant at about 12±2 mol.%, both within grains and from grain to grain. X-ray-precession studies of grains removed from polished thin sections indicate that the uvarovite granules are randomly oriented: they do not exhibit a preferred crystallographic orientation with respect to the single-crystal chromite core. Although both grandite and uvarovite occur together in almost all samples examined, they are texturally and compositionally distinct and are separated by a well-defined compositional gap ($Gr_{54}An_{25}Uv_{16}$ to $Gr_{37}An_{11}Uv_{40}$). Grandite and uvarovite do not occur in mutual contact, and they appear to represent different generations of garnet crystallization, with the uvarovite having crystallized later.

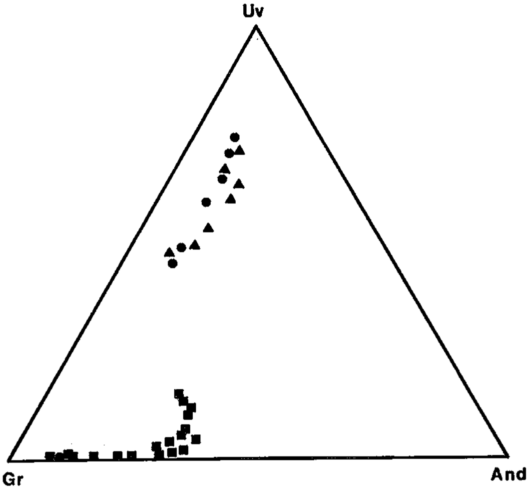

FIG. 2. Garnet compositions from the White River Cr-rich calc-silicate rocks on the uvarovite(Uv) – grossular(Gr) – andradite(And) compositional plane. Solid triangles represent uvarovite; solid squares represent grandite; solid circles represent those compositions from sample No.1.

In contrast, uvarovite and Cr-poor grandite have been reported from a Cr-rich granoblastic xenolith of calc-silicate gneiss in a small granodiorite body near the Kiglapait layered complex, Labrador (Kalamarides & Berg 1988; Fig. 3). Grandite contacts uvarovite, and both apparently coexisted at 2 kbars and 500°C. However, these garnets from Labrador are conspicuously more andradite-rich than those at White River (Fig. 3). The uvarovite from the White River calc-silicate rocks is relatively rich in Fe^{3+} and poor in Cr compared to that from Outokumpu, which is consistent with the difference in chromite composition from the two localities.

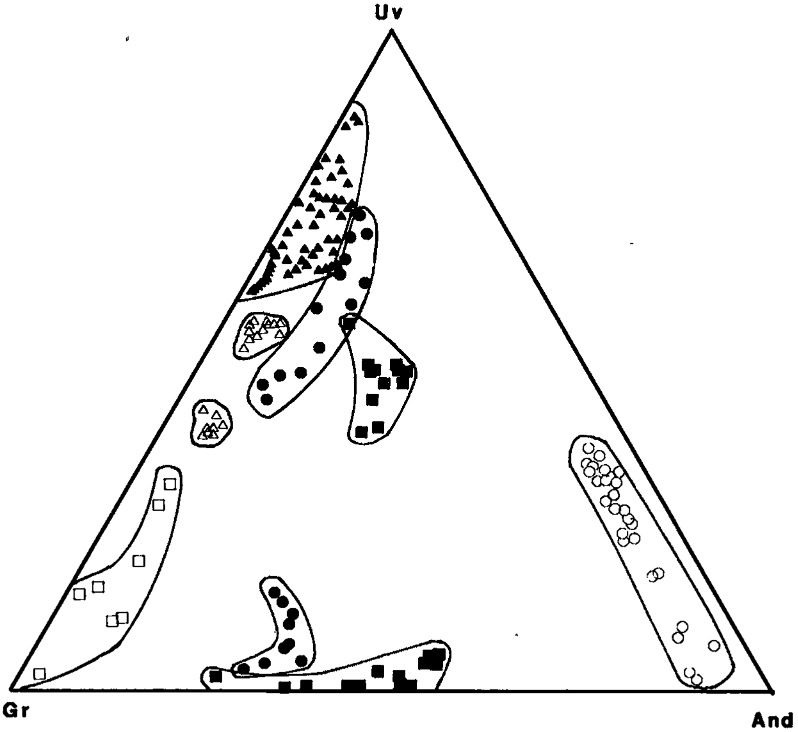

FIG. 3. Comparison of Cr-garnet compositions on the uvarovite(Uv) - grossular(Gr) - andradite(And) compositional plane. Solid circles represent Cr-garnet from the White River calc-silicates; solid squares represent garnet from Labrador (Kalamarides & Berg 1988): solid triangles represent garnet from Outokumpu (von Knorring *et al.* 1986); open triangles represent garnet from Luikonlahti (von Knorring *et al.* 1986); open circles represent garnet from Reaume Township (Duke & Bonardi 1982); and open squares represent garnet from some Canadian localities (Dunn 1978).

TABLE 4. REPRESENTATIVE COMPOSITIONS OF EPIDOTE-GROUP MINERALS

SAMPLE	1	2	2Max	2Min	4	6	7	9
SiO_2 (wt. %)	40.98	38.41	36.82	37.30	38.15	39.03	38.11	39.80
TiO_2	0.02	0.09	0.03	0.04	0.10	0.05	0.10	0.10
Al_2O_3	29.74	23.01	16.04	19.70	23.84	22.20	23.61	24.65
Cr_2O_3	0.07	1.57	11.77	6.56	0.53	2.63	0.30	0.05
Fe_2O_3*	3.97	10.77	9.29	8.62	10.68	10.18	11.70	3.59
MnO	0.19	0.01	0.23	0.36	0.16	0.07	0.18	0.28
MgO	0.00	0.05	0.06	0.07	0.04	0.18	0.02	0.00
CaO	24.70	23.10	22.52	22.50	23.84	23.15	23.38	24.51
Na_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
K_2O	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.00
Total	99.67	97.10	95.76	95.15	97.34	97.51	97.42	97.85
	Structural formulae on the basis of 12.5 oxygens							
Si	2.988	3.003	2.940	3.004	2.975	3.038	2.979	2.939
Al	2.554	2.128	1.552	1.870	2.191	2.036	2.175	2.567
Ti	0.001	0.005	0.002	0.002	0.006	0.003	0.006	0.006
Cr	0.004	0.097	0.764	0.418	0.032	0.162	0.019	0.003
Fe	0.242	0.704	0.638	0.581	0.696	0.663	0.765	0.200
Mn	0.012	0.001	0.016	0.025	0.011	0.005	0.012	0.004
Mg	0.000	0.006	0.007	0.008	0.004	0.021	0.002	0.006
Ca	1.929	1.935	1.981	1.942	1.991	1.931	1.958	1.972
Na	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004
K	0.000	0.000	0.000	0.000	0.000	0.002	0.002	0.000
Ps	0.087	0.249	-	-	0.196	0.245	0.262	0.072
X	0.682	0.185	-	-	0.252	0.158	0.201	0.686

Max is the maximum Cr_2O_3 content in epidote; Min is the minimum Cr_2O_3 content in epidote; * is total iron as Fe_2O_3; Ps is pistacite; X is clinozoisite mole fraction.

Epidote

Epidote-group minerals are ubiquitous in overlying clastic metasediments and underlying metabasites and are one of the most abundant mineral phases in these calc-silicate rocks. They generally form xenoblastic or idioblastic crystals with a short prismatic habit and variable color, but pleochroism is generally absent.

Epidote compositions are given in Table 4. A considerable variation in epidote composition is present in each analyzed rock, as indicated by the total variation in pistacite (Ps), from 7 to 27 mol.%. There is a gap in Ps content from 11 to 19 mol.%, but whether or not this represents a miscibility gap between Ps 12 to Ps 22, as proposed by Strens (1965) for epidote-group minerals in greenschist- and amphibolite-facies rocks, is not clear because of the small number of samples analyzed.

Consistent with the presence of chromite and

TABLE 5. REPRESENTATIVE COMPOSITIONS OF CALCIC AMPHIBOLE

SAMPLE	7	8	9	10
SiO_2 (wt. %)	52.13	54.14	52.14	55.36
TiO_2	0.06	0.00	0.00	0.10
Al_2O_3	2.52	0.63	3.38	1.27
Cr_2O_3	0.45	0.70	0.09	0.07
Fe_2O_3*	1.14	0.78	0.58	0.08
FeO	12.37	12.21	11.74	10.14
MgO	14.39	15.52	15.47	17.38
MnO	0.42	0.57	0.28	0.20
CaO	13.04	13.30	12.70	12.93
Na_2O	0.21	0.04	0.66	0.47
K_2O	0.27	0.06	0.22	0.18
Total	97.01	97.95	97.53	96.83
Structural formulae on the basis of 23 oxygens				
Si	7.657	7.860	7.581	7.866
^{IV}Al	0.343	0.110	0.419	0.134
^{VI}Al	0.093	0.000	0.160	0.079
Fe^{2+}	1.519	1.482	1.421	1.210
Fe^{3+}	0.127	0.086	0.063	0.008
Mg	3.150	3.358	3.336	3.680
Mn	0.052	0.070	0.034	0.024
Cr	0.053	0.082	0.012	0.010
Ti	0.007	0.000	0.000	0.006
Ca	2.052	2.069	1.969	1.970
Na^{M4}	0.000	0.000	0.004	0.023
Na^A	0.060	0.011	0.180	0.054
K	0.051	0.011	0.041	0.016
F/FM	0.325	0.306	0.299	0.247
X	0.06	0.12	0.06	0.17

* is calculated by using the "mid point" method of Papike et al. (1974); F/FM is molar Fe/(Fe + Mg) value; X is tremolite mole fraction.

uvarovite, Cr-bearing epidote (with up to 2.63 wt.% Cr_2O_3) is common in these calc-silicate rocks. Cr-bearing epidote grains are generally yellowish. A few deep brown Cr-rich epidote grains, which are very fine-grained (micrometer scale) and occur in contact with either chromite or uvarovite in amygdule-like cavities, are rather inhomogeneous in chemical composition, with Cr_2O_3 contents from 6.56 to 11.7 wt.%. As far as we are aware, the 11.77 wt.% Cr_2O_3 in epidote of sample No. 2 is the highest reported in the literature (*cf.* Deer *et al.* 1986, Grapes 1981), and reveals a new end-member in the epidote group, $Ca_2CrAl_2Si_3O_{12}(OH)$.

Calcic amphibole

Calcic amphibole occurs as pale green, fibrous or elongate (up to 3 mm long) prisms in close association with clinopyroxene, epidote, and chlorite; their preferred orientation defines the weakly to moderately developed foliation in these calc-silicate rocks. Compositions are reported in Table 5. Calcic amphibole is mainly tremolite–actinolite, with low Al (< 3.41 wt.% Al_2O_3) and alkali contents. The molar value Mg/(Mg + Fe + Mn) ranges from 0.54 to 0.80. Minor Cr (up to 0.70 wt.% Cr_2O_3) also is detectable.

Prehnite

Prehnite is invariably present in amygdule-like cavities with very fine-grained Cr-rich epidote, pumpellyite, chromian chlorite and, locally, calcite. Prehnite has a characteristic bow-tie habit and shows parallel extinction, with positive elongation and high birefringence. Prehnite has traditionally been considered to be very restricted in chemical composition, with minor substitution of Fe^{3+} for Al in octahedral sites. A microprobe analysis of prehnite (Table 6) from the White River calc-silicate rocks shows no significant variation in composition; it has very small amount of total iron (< 2.50 wt.% expressed as Fe_2O_3) and a Cr_2O_3 content less than 1.21 wt.%.

TABLE 6. COMPOSITIONS OF PREHNITE AND PUMPELLYITE

SAMPLE	6prh	9prh	6pum	9pum
SiO_2 (wt. %)	42.11	42.95	37.37	38.17
TiO_2	0.00	0.00	0.13	0.00
Al_2O_3	22.24	23.13	24.00	23.39
Cr_2O_3	1.13	1.21	1.51	1.56
Fe_2O_3*	2.65	1.15	1.61	2.70
MnO	0.00	0.00	0.00	0.14
MgO	0.00	0.00	4.10	3.73
CaO	26.30	26.80	23.68	23.65
Total	94.43	95.24	92.56	94.18
Structural formulae on the basis of 11 oxygens for prehnite and 24.5 oxygens for pumpellyite				
Si	2.972	2.979	5.996	6.114
Ti	0.000	0.000	0.016	0.000
Al	1.849	1.888	4.534	4.414
Cr	0.063	0.067	0.190	0.198
Fe	0.138	0.060	0.194	0.326
Mn	0.000	0.000	0.000	0.022
Mg	0.000	0.000	0.980	0.892
Ca	1.989	1.992	4.070	4.058

prh is prehnite; pum is pumpellyite; * is total iron as Fe_2O_3.

Pumpellyite

Pumpellyite in minor amounts also is present in the amygdule-like cavities with other calc-silicate minerals, such as prehnite and Cr-rich epidote, as well as chromian chlorite and, locally, calcite. Its presence was confirmed by Gandolfi X-ray powder-diffraction patterns on grains removed from a polished thin section. Pumpellyite shows the diagnostic "oak leaf" habit and is generally colorless, with high birefringence. Results of two chemical analyses of pumpellyite from the White River calc-silicate rocks are reported in Table 6. These pumpellyite grains are generally magnesium-bearing and contain up to 4.1 wt.% MgO, 2.56 wt.% Cr_2O_3 and 2.70 wt.% FeO* (total iron as FeO), whereas contents of other components are generally low or virtually absent.

Chlorite

Minor colorless or sometimes brown to deep brown chlorite occurs sporadically in amygdule-like

TABLE 7. REPRESENTATIVE COMPOSITIONS OF CHLORITE

SAMPLE	1	4	5	9
SiO_2 (wt. %)	28.50	27.03	29.80	28.06
TiO_2	0.00	0.00	0.00	0.00
Al_2O_3	18.00	18.89	17.50	17.32
Cr_2O_3	1.01	3.50	0.78	1.24
FeO*	19.04	17.13	15.96	16.99
MgO	20.02	19.74	21.79	20.31
MnO	0.30	0.36	0.17	0.34
CaO	0.02	0.02	0.02	0.02
K_2O	0.00	0.05	0.00	0.00
Total	86.89	86.72	85.99	84.54
Structural formulae on the basis of 28 oxygens				
Si	5.873	5.648	6.101	5.907
^{IV}Al	2.127	2.352	1.899	2.093
^{VI}Al	2.146	2.298	2.322	2.204
Cr	0.163	0.578	0.128	0.206
Mn	0.005	0.064	0.029	0.061
Fe	3.218	3.449	2.732	2.991
Mg	6.148	5.335	6.649	6.373
Ca	0.005	0.004	0.004	0.005
K	0.000	0.013	0.000	0.000
F/FM	0.348	0.397	0.293	0.319
A/AFMM	0.313	0.338	0.336	0.313

* is total iron as FeO; F/FM is molar Fe/(Fe + Mg) value; A/AFMM is molar Al/(Al + Fe + Mg + Mn) value.

cavities or as large, randomly oriented plates cutting the foliation plane in the White River calc-silicate rocks and, like Cr-rich epidote, prehnite, pumpellyite, and uvarovite, appears to have formed later than the rest of the White River calc-silicate rocks. The electron-microprobe data (Table 7) show that the chlorite is clinochlore, with a very limited compositional variation, and a molar ratio Mg/(Mg + Fe) ranging from 0.56 to 0.71, and Al/(Al + Mg + Fe + Mn), from 0.296 to 0.338. The Cr_2O_3 content is up to 3.50 wt.%; therefore, it can be considered as chromian chlorite.

Feldspars

Feldspars (plagioclase with subordinate microcline) are common in the White River calc-silicate rocks. They generally form coarse-grained (up to 1 cm in diameter) xenoblastic crystals in thin grandite–feldspar-rich bands and, locally, as fine- to medium-grained crystals closely associated with clinopyroxene, grandite and epidote. Plagioclase is partly altered to sericite, whereas microcline, with well-developed cross-hatched twinning, is not visibly altered.

No significant compositional zoning was detected. Surprisingly, the plagioclase is sodium-rich (mainly oligoclase) rather than the calcium-rich variety typical of many calc-silicate rocks, and shows a slight compositional variation from An_{14} to An_{23}. The microcline composition is about $Or_{95}Ab_2An_0Ce_3$; it consistently contains a small amount of Ba (about 2 wt.% BaO), but Ca is virtually absent. Albite (Ab > 99 mol.% also is present in veins, and appears to be late.

Other minerals

Accessary titanite is widespread. All grains analyzed contain a small amount of Al (up to 3.81 wt.% Al_2O_3), but are otherwise near the ideal formula. Accessary apatite in some specimens is characterized by high F contents (up to 3.86 wt.%). It is the only F-bearing phase present.

ELEMENT PARTITIONING

The partitioning of elements between different mineral pairs, especially of cations in octahedral coordination, has been examined to determine the state of equilibrium of the mineral assemblages. The distribution of Al/Fe^{3+} between epidote and garnet, and of Fe^{2+}/Mg between calcic amphibole and clinopyroxene and between calcic amphibole and chlorite, are given on Figure 4.

The distribution of Fe^{2+} and Mg between clinopyroxene and calcic amphibole shows a good correlation and gives a distribution coefficient (K_D) about 1.09, which is consistent with data for amphibolite-facies rocks (Mueller 1961, Rice 1977, Kretz & Jen 1978). The fractionation of octahedrally coordinated Fe^{3+} and Al between grandite and epidote also shows good correlations and yields distribution coefficients ranging from 1.1 to 1.5, which are consistent with data from a Cu-bearing skarn deposit in Japan (Kitamura 1975). However, the distribution of Fe^{2+} and Mg between calcic amphibole and chlorite is not systematic, which further confirms the textural observation that chlorite developed later than calcic amphibole and clinopyroxene. As noted above, the andradite component in uvarovite garnet is rather constant and insensitive to the change of $Fe^{3+}/(Fe^{3+} + Al)$ in epidote. This insensitivity also suggests that the crystallization of uvarovite occurred later than epidote and grandite garnet. Note also on Figure 4B that the Al content in the uvarovite markedly increases from the Cr-rich core to the Cr-depleted margin without significant change in the Fe^{3+} content.

The correlations of the element distributions among these major mineral phases suggest that the main calc-silicate assemblage [including clinopyroxene, calcic amphibole, epidote, garnets (Cr-poor and Cr-bearing), plagioclase, microcline, chromite, titanite, and probably some calcite] were formed under equilibrium conditions. Equilibrium among the White River calc-silicate mineral phases and fluids also is inferred from other evidence. This includes the compatible textural relationships among major mineral phases, the absence of compositional

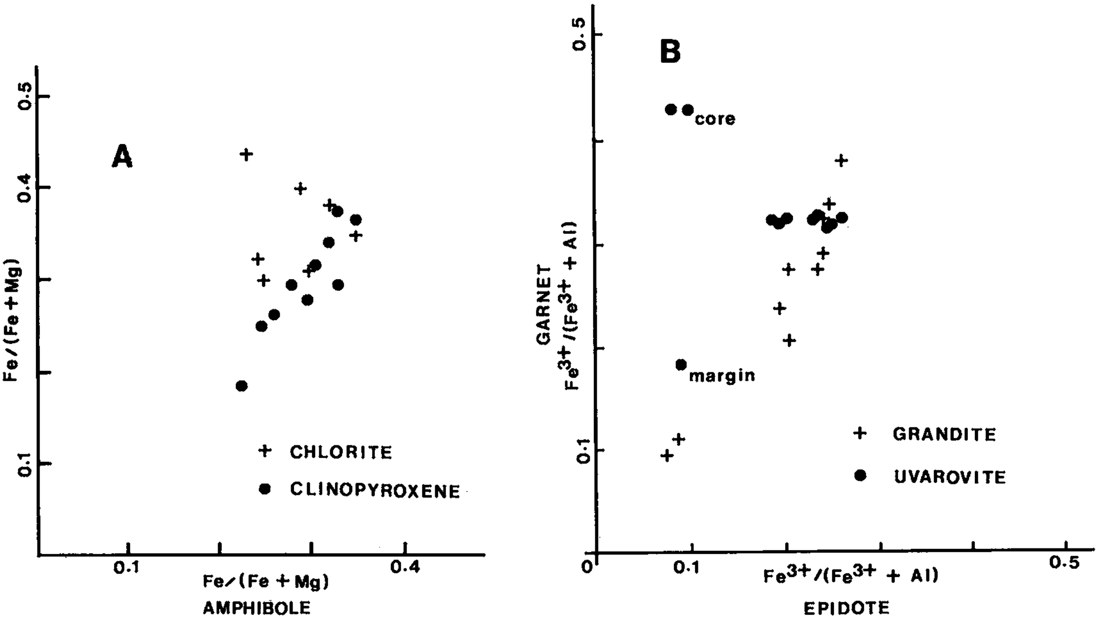

FIG. 4. Partitioning of octahedrally coordinated cations between major minerals pairs: (A) Fe^{2+}/Mg between clinopyroxene and calcic amphibole (circles) and between chlorite and calcic amphibole (crosses); (B) Fe^{3+}/Al between epidote and grandite garnet (crosses) and between epidote and uvarovite (circles).

zoning in the major mineral phases, and the occurrences of identical mineral assemblages at different locations within the Cadi Fracture Zone.

DISCUSSION

The Cr-enriched calc-silicate rocks from the Cadi Fracture Zone at the White River gold prospect, which contain chromite, uvarovite, and Cr-rich epidote, are similar to the well-known Outokumpu skarns of Finland (Eskola 1933, von Knorring 1951, Hiltunen 1982, von Knorring *et al.* 1986). However, carbonate rocks are not present in or near the study area, and calcite is only sporadically abundant. Furthermore, the Cr-rich calc-silicate rocks at the White River gold prospect are confined to lithological boundaries between metabasites and metasedimentary rocks and occupy a regional fracture-zone. Consideration of the morphology of the Cadi Fracture Zone and its structural relationship with underlying metabasites and overlying metasedimentary rocks indicates that the formation of the calc-silicate rocks was probably coeval with regional metamorphism. Also, the local abundance of well-preserved metabasic or metaultrabasic fragments (metamorphosed to actinolite ± chlorite schists) within the calc-silicate rocks points to a metasomatic replacement origin for the calc-silicate rocks. Therefore, the White River calc-silicate rocks are not of carbonate-replacement origin, but were produced by metasomatic processes that replaced volcanic or metavolcanic rocks within a major regional fracture-zone. Following many contemporary studies and reviews (*e.g.*, Sangster 1969, Einaudi *et al.* 1981, Einaudi & Burt 1982, Meinert 1984), the White River Cr-rich calc-silicates would be regarded as a variety of skarn deposit.

A Jensen cation plot (Jensen 1976; not presented here) of the bulk-rock compositions of the White River Cr-rich calc-silicate rocks yields a well-defined komatiitic trend; all bulk compositions fall into the field of komatiitic basalt, which implies a volcanogenic origin for the precursor to the calc-silicate rocks. Similar distributions also were obtained for some underlying metabasites (amphibolites), which have slightly lower Ca contents and higher Mg contents, equivalent to pyroxenitic compositions. It is reasonable to assume that there was a slight enrichment of calcium accompanied by depletion of magnesium without significant change in other components during the metasomatic processes. However, the chromium abundance (up to 5100 ppm) is elevated compared to other mafic and ultramafic metavolcanic rocks in the study area; therefore, secondary enrichment for chromium must have occurred as well.

The sporadic occurrences, incompatible textures, and element-partition patterns between calcic amphibole and chlorite, clinopyroxene and chlorite, and uvarovite and epidote suggest that the crystallization of uvarovite, Cr-rich epidote, prehnite, pumpellyite, chromian chlorite, albite and, possibly, some calcite (in veins) was later than the formation of the main metasomatic mineral assemblage of the White River calc-silicate rocks and represents either a late (retrograde) stage of metamorphism or metasomatism or even a later, separate event. The latter hypothesis is favored, as regional-scale, calc-silicate-like alteration veins with the mineral association of epidote, prehnite, actinolite, chlorite, albite, microcline, pumpellyite, clinopyroxene, sericite, and calcite transect the main foliation and are themselves not penetratively deformed (Pan & Fleet 1988). A study of the relationship of gold mineralization in the study area and the neighboring Hemlo gold deposit to this type of low- to very-low-grade, calc-silicate-like alteration is in preparation.

Metamorphic conditions

The P–T conditions, P–T–time paths, and the nature, composition, and sources of fluids that affected the White River area are the main subject of a separate study (in progress). Preliminary results relating to the calc-silicate rocks are discussed in this section. However, it should be pointed out that as the White River calc-silicate rocks occur in a fluid-dominant, fracture-controlled setting, P-T-X calculations based on equilibria from textural evidence and mineral chemistry should be treated with some caution.

As noted above, the crystallization of uvarovite, Cr-rich epidote, prehnite, pumpellyite, chromian chlorite, albite and some calcite was later than the formation of the White River calc-silicate rocks. Therefore, the metamorphic conditions were constrained based on the assemblage of clinopyroxene, garnet, epidote, calcic amphibole, chromite, oligoclase, microcline, and calcite. This association is similar to those in common metabasites equilibrated in the greenschist or lower amphibolite facies. Temperatures estimated from the two-feldspar geothermometer of Whitney & Stormer (1977) range from 350 to 400°C and also are consistent with greenschist or low-amphibolite facies metamorphic conditions. The two-feldspar geothermometer of Whitney & Stormer (1977) has been considered to be less successful for low-temperature assemblages (Nesbitt & Essene 1982). Temperatures estimated from the Fe/Mg partition between garnet and biotite [calibration of Ferry & Spear (1978) revised by Asworth & Evirgen (1985)] from overlying clastic metasediments are about 450±50°C. Therefore, an overall temperature of about 400±50°C is favored for the formation of the White River calc-silicate rocks, and is consistent with the formation temperatures of similar calc-silicate mineral assemblages in present active geothermal fields (Bird *et al.* 1984).

The pressure during metamorphism is not well constrained, because there is no well-calibrated geobarometer directly applicable to these calc-silicate rocks. However, the garnet + andalusite + plagioclase + quartz geobarometer assemblage (Ghent 1976, Ghent *et al.* 1979) present in the overlying metasedimentary rocks yields an independent pressure estimate of 2 to 4 kbar (work in progress).

The abundance of hydrous calc-silicate minerals and minor calcite in the White River calc-silicate rocks suggest that H_2O and CO_2 were the major species of the coexisting fluid phase. The common occurrence of titanite rather than of rutile + quartz + calcite, and the rarity of calcite, suggest that H_2O was the predominant gaseous species and that $X(CO_2)$ was very low.

Temperatures and fluid compositions for the formation of the White River calc-silicate rocks may also be calculated in the system of SiO_2–Al_2O_3–MgO–CaO–CO_2–H_2O at 3 kbar using the PTX-SYSTEM programs of Perkins *et al.* (1986) with the internally consistent thermodynamic data set of Berman *et al.* (1985), and assuming ideal mixing of H_2O and CO_2. Activities were calculated from the observed mineral compositions according to the following scheme (*cf.* Skippen & Carmichael 1977):

$$a_{\mathrm{Czo}} = [\mathrm{Ca}/2]^2 \cdot [1-(\mathrm{Fe} + \mathrm{Mn} + \mathrm{Cr})] \cdot [\mathrm{Si}/3]^3$$
$$a_{\mathrm{An}} = \tau \cdot X_{\mathrm{An}} \text{ where } \tau = 1.276 \text{ (Orville 1972)}$$
$$a_{\mathrm{Di}} = [\mathrm{Ca}] \cdot [\mathrm{Mg}] \cdot [\mathrm{Si}/2]^2$$
$$a_{\mathrm{Gr}} = [\mathrm{Ca}/3]^3 \cdot [\mathrm{Al}/2]^2 \cdot [\mathrm{Si}/3]^3$$
$$a_{\mathrm{Cc}} = \mathrm{Ca}/(\mathrm{Ca} + \mathrm{Fe} + \mathrm{Mg} + \mathrm{Mn})$$
$$a_{\mathrm{Tr}} = [1-(\mathrm{Na} + \mathrm{K})] \cdot [\mathrm{Ca}/2]^2 \cdot [\mathrm{Mg}/5]^5 \cdot [\mathrm{Si}/8]^8 \cdot [\mathrm{OH}/2]^2$$

Unfortunately, Cr_2O_3 is not included in the system of Berman *et al.* (1985), and the behavior of chromite in low-temperature metamorphism is not well studied. However, chromite is a characteristic mineral phase and appears to coexist with other major mineral phases in the calc-silicate rocks. Therefore, as a first approximation, spinel is included in the *PTX* calculations, with activities calculated from the analytical data of chromite following the scheme $a_{\mathrm{Sp}} = [\mathrm{Mg}] \cdot [\mathrm{Al}/2]^2$ (*cf.* Stroh 1976).

The temperatures calculated for the assemblages corresponding to the intersection of equilibria (1),(2),(5), and (6) (the invariant point I_1, Fig. 5) range from 390 to 440°C, whereas for those assemblages corresponding to the intersection (I_2) of equilibria (3), (4), (6), and (7) range from 360 to 410°C. These values are similar to or slightly higher than the temperatures estimated by using the two-feldspar geothermometer of Whitney & Stormer (1977) but agree well with temperatures estimated

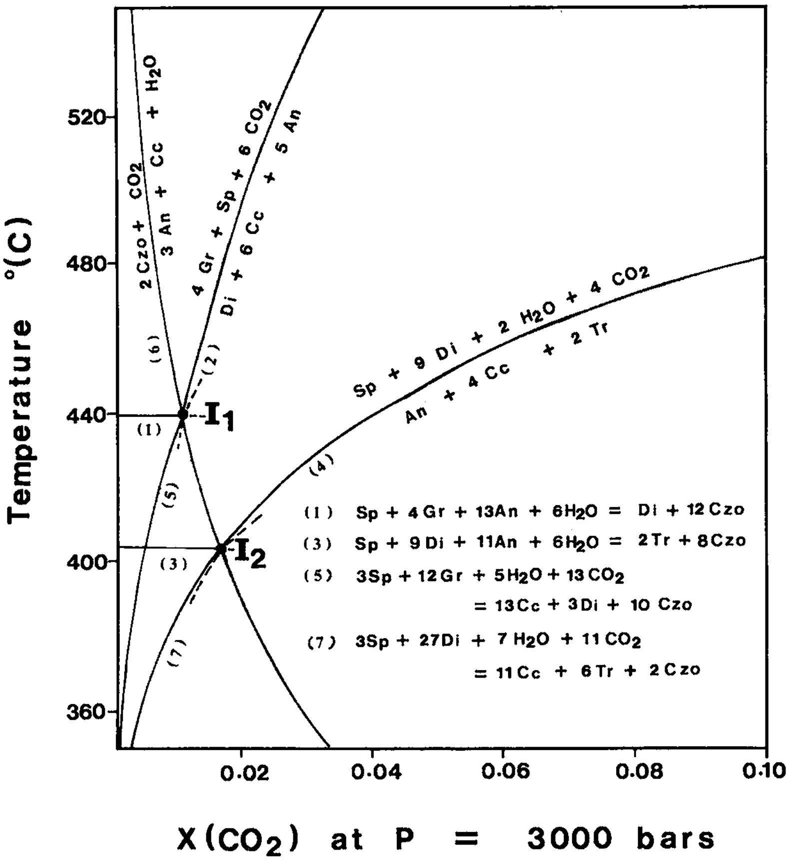

FIG.5. Calculated T-$X(CO_2)$ phase diagram section in the system of SiO_2-Al_2O_3-MgO-CaO-CO_2-H_2O at a pressure of 3 kbars, with mineral activities for present analytical data. Note that the precise positions of the invariant points I_1 and I_2 vary from sample to sample, but $X(CO_2)$ does not exceed 0.03. Solid lines are stable phase-boundaries; broken lines are metastable extensions. An is anorthite, Cc is calcite, Czo is clinozoisite, Di is diopside, Gr is grossular, Sp is spinel and Tr is tremolite.

from Fe/Mg partitioning between garnet and biotite from overlying clastic metasediments. The precise positions of the invariant points I_1 and I_2, which never exceed $X(CO_2) = 0.03$ (Fig. 5), indicate very low CO_2 fugacities during the formation of the White River calc-silicates.

The oxygen fugacities could vary significantly. Liou (1973) has concluded that the Ps content of epidote is a sensitive indicator of oxygen fugacity. The low Ps content (about Ps_{10}) of epidote in the Cr-rich calc-silicate rocks enveloped in metabasites suggests a relatively low fugacity of oxygen compared to the calc-silicate rocks in contact with the metasediments or within metasediments (up to Ps 27). This consideration is supported by the presence of pentlandite + pyrrhotite ± molybdenite in the former, and magnetite and sulfides in the latter.

The source of the hydrothermal (metasomatic) fluid is unknown. Oxidation of graphite-rich metasedimentary rocks, which is supported by the occurrence of graphite in the unfoliated matrix in the eastern part of the study area, might have provided CO_2. However, as noted above, calcite is virtually absent in most of the rocks enveloped by the metabasites. Dehydration of the hydrous minerals in the underlying metabasites may have contributed to the H_2O content in the fluid. However, the location of the White River calc-silicate rocks within a major regional fracture-zone suggests that the dilatant zone may have focused the movement of metamorphically derived fluids coeval with plutonic igneous activity (*cf.* Holding 1987). There are numerous small quartz-feldspar porphyry bodies in the study area. However, emplacement of the large granodioritic Cedar Lake Pluton on the northern boundary of the study area appears likely to have been associated with the late cross-cutting calc-silicate-like, low- to very-low-grade alteration that is widespread in Heron Bay Group rocks. We believe that the emplacement of this pluton may have been contemporaneous with the late alteration of the Cadi Zone calc-silicates, which resulted in remobilization of chromium and formation of the anomalously Cr-rich silicate minerals, such as uvarovite, Cr-rich epidote, prehnite, pumpellyite, and chromian chlorite in amygdule-like cavities, as well as the vein minerals albite and calcite.

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