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RODINGITES IN SERPENTINIZED ULTRAMAFIC ROCKS OF THE ABITIBI GREENSTONE BELT, ONTARIO

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ABSTRACT

This is the first mineralogical and geochemical study of rodingites that occur within serpentinized ultramafic rocks of the Abitibi greenstone belt in Ontario. Remnants of the original texture and mineralogy are locally preserved; the mineralogical and textural changes associated with the rodingitization process can thus be traced. Rodingite protoliths include diabase and lamprophyre dykes, mafic lithic inclusions, serpentinites and intermediate volcanic rocks. Clinozoisite and epidote represent the early stage of alteration, and are followed by the appearance of hydrogrossular and prehnite, which form at the expense of epidote. The most advanced stage of alteration is represented by a completely recrystallized, fine-grained, diopside-bearing rock. Mass-balance calculations, using data from a lamprophyre for the first two stages, suggest an isovolume replacement during which Ca, Al and Fe were added, whereas Na, K and Mg were removed. Crystallization temperatures of 270–330°C at pressures of 1–2 kbars were obtained from primary fluid inclusions in late-stage diopside. The fluid had a low salinity (1–2.5 equiv. wt.% NaCl). The rodingitization process was not different in Archean times than in the Phanerozoic, so that the difference in tectonic settings is not an important factor. Thus, deformation is not an integral part of the process, although it certainly affects the final texture and distribution of the rocks.

Keywords: rodingite, rodingitization process, Abitibi greenstone belt, fluid inclusions, epidote, grossular, diopside, prehnite, vesuvianite, serpentinite.

SOMMAIRE

Nous présentons ici les résultats d'une première étude minéralogique et géochimique des rodingites associées aux roches ultramafiques serpentinisées de la ceinture de roches vertes de l'Abitibi, en Ontario. Les rodingites contiennent quelques exemples de la texture et de la minéralogie originelles, ce qui permet de reconstruire les changements survenus au cours de la métasomatose. Ont été affectés: diabase, filons lamprophyriques, enclaves lithiques mafiques, serpentinites et roches volcaniques intermédiaires. Clinozoïsite et épidote représenteraient le stade précoce de l'altération; hydrogrossulaire et prehnite ont cristallisé par la suite, aux dépens de l'épidote. Pendant le stade le plus avancé de la transformation, la roche est devenue complètement recristallisée, et riche en diopside à granulométrie fine. Les bilans géochimiques fondés sur les données pour un lamprophyre font penser que pendant les deux premiers stades du remplacement, qui serait isovolumique, Ca, Al et Fe ont été ajoutés, tandis que Na, K et Mg ont été lessivés. Les inclusions fluides primaires dans la diopside tardive indiquent une formation à 270–330°C et 1–2 kbars à partir d'une phase fluide de faible salinité (équivalent à 1–2.5% NaCl par poids). La rodingitisation dans l'archéen ne semble pas différer des exemples phanérozoïques; les différences entre les contextes tectoniques ne seraient donc pas importants. La déformation ne semble pas essentielle au processus, mais influence certainement la texture des rodingites, ainsi que leur distribution.

(Traduit par la Rédaction)

Mots-clés: rodingite, ceinture de roches vertes de l'Abitibi, métasomatose, inclusions fluides, épidote, grossulaire, diopside, prehnite, vesuvianite, serpentinite.

INTRODUCTION

Rodingites are calcium-rich, silica-undersaturated rocks that form by metasomatism of rocks during serpentinization (Thayer 1966; Coleman 1977). It is not surprising that rodingites are found associated with almost all types of serpentinite, as calcium-rich waters appear to be a product of the low-temperature alteration of ultramafic rocks (Barnes *et al.* 1967, Wenner 1979). Rodingites are dredged from present-day ocean floors (Honnorez & Kirst 1975) and are found in Archean serpentinites (Anhaeusser 1979). The serpentinized ultramafic rocks of the Abitibi greenstone belt are no exception to this rule; rodingites have been found in the Dundonald sill, the Bowman, Munro, Reeves and United chrysotile asbestos mines, and the Garrison chrysotile asbestos deposit, although no detailed studies have been carried out on any of these occurrences.

The purpose of this paper is threefold: firstly, we wish to determine, where possible, the characteristics of the rodingite protoliths; secondly, we describe the mineralogy and the textures of the rodingites, and finally, we attempt to establish some of the intensive parameters relevant to their formation.

ANALYTICAL METHODS

The characterization of mineral phases was carried out using a Guinier – de Wolff X-ray camera

(Cu$K\alpha$ radiation) and electron microprobe. Indexed diffraction patterns were refined using the program of Appleman & Evans (1973). Mineral compositions were determined with a Materials Analysis Company Model 400 electron microprobe equipped with a Kevex Model 5000A energy-dispersion spectrometer, automated to produce simultaneous multi-element analysis and data reduction (Plant & Lachance 1973). Operating conditions were the same as described by Wicks & Plant (1983). Whole-rock analyses were carried out by X-ray-fluorescence spectroscopy. Fused beads and powder pellets were prepared for major and trace elements, respectively. The observed and accepted values agree to approximately 1%. Fluid-inclusion measurements were obtained using a Linkam TH600 Fluid Inclusion Stage and the operating conditions and calibration methods of MacDonald & Spooner (1981).

GEOLOGICAL SETTING

The Archean metavolcanic rocks that constitute the Abitibi greenstone belt have been divided into Lower and Upper Supergroups (Jensen & Pyke 1982). Both units display the sequence, from older to younger, of komatiitic through tholeiitic to calc-alkaline volcanic rocks. Large sill-like bodies composed of komatiitic ultramafic and gabbroic rocks occur within the Lower Supergroup and may represent magmatic reservoirs for the komatiitic volcanic rocks of the Upper Supergroup (Pyke 1982).

The basal sequence of the Upper Supergroup consists of both ultramafic and basaltic komatiites and Mg- and Fe-rich tholeiitic basalts (Pyke 1982). Large sill-like bodies of ultramafic komatiite, pyroxenite and gabbro differentiates also are found in the Upper Supergroup, but the relationships are more complex than in the Lower Supergroup because these bodies, which are possible magma reservoirs for the overlying tholeiitic volcanic rocks, occur in the same stratigraphic level as komatiitic flows (Naldrett & Mason 1968, MacRae 1969, Arndt 1975).

TABLE 1. RODINGITE LOCALITIES IN THE ABITIBI GREENSTONE BELT

LOCALITY	TOWNSHIP	STRATIGRAPHIC POSITION	STATUS
Bowman Mine	Deloro	L. Supergroup	minor chrysotile producer
Garrison mine	Garrison	U. Supergroup	major chrysotile deposit
Hedman mine	Warden	U. Supergroup	light aggregate producer
Dundonald sill	Dundonald	U. Supergroup	not applicable
United mine	Midlothian	L. Supergroup	minor chrysotile deposit
Munro mine	Munro	U. Supergroup	major chrysotile producer
Reeves Mine	Reeves	?	major chrysotile producer

Metamorphism in the Abitibi greenstone belt, based on mineral assemblages in the greenstones (Jolly 1982), occurred at pressures below 3 kbars and temperatures less than 350°C. These temperatures were exceeded in thermal aureoles developed around plutons, in which amphibolite- and greenschist-grade hornfels were produced (Jolly 1982).

RODINGITE LOCALITIES

Each sample locality is listed in Table 1, along with its relative setting within the stratigraphic sequence described above. All samples were collected from chrysotile asbestos mines or deposits (Vos 1971), with the sole exception of the Dundonald sill. We contend that this situation is more a reflection of available outcrop than of genetic significance. Firstly, several of the localities are within open-pit mines (Reeves, Munro, United) or exploration drifts (Garrison) and do not reflect the normal situation of sparse outcrop in this part of the Abitibi belt. Secondly, a serpentinized ultramafic rock must be a certain thickness to host a chrysotile asbestos deposit, and the same thick bodies, compared to thinner bodies, are more likely to host inclusions. This statement does not apply to dykes that may cross-cut any serpentinized ultramafic rocks. Finally, chrysotile asbestos develops within a specific set of conditions, whereas any ultramafic rock exhibits some degree of serpentinization. In Phanerozoic terranes, rodingites are associated with serpentinization, not neccessarily with chrysotile asbestos (Coleman 1977).

Rodingites were found in large serpentinized ultramafic bodies in both Supergroups. The Bowman and United mines occur in what are interpreted to be large komatiitic sills dominated by thick serpentinized ultramafic layers, with minor pyroxenite and gabbro (Pyke *et al.* 1978, Kretschmar & Kretschmar 1986). Both bodies were emplaced into the Lower Supergroup volcanic rocks (Pyke 1982). The Munro mine (Satterly 1951, Hendry & Conn 1957) and the Garrison deposit (Vos 1971) occur in the serpentinized ultramafic layer of large komatiitic sills or flows that also contain pyroxenite and gabbro layers. The Hedman mine occurs in a serpentinized ultramafic layer of a differentiated body having tholeiitic affinity (Arndt 1975). The Dundonald sill is also a differentiated layered intrusive body of tholeiitic affinity that has a serpentinized ultramafic layer (Naldrett & Mason 1968). These bodies were intruded into or extruded as part of the basal sequence of the Upper Supergroup. The Reeves mine occurs in a large serpentinized ultramafic intrusive body, but its nature and position in the stratigraphy are not well established (Milne 1972).

The occurrences of rodingites within these bodies vary both in geological setting and rock type. Small gabbro xenoliths (<45 cm in diameter) were rodingitized in the Bowman mine (Pyke *et al.* 1978), in the Hedman mine, in the Garrison deposit, and in the Dundonald sill. These xenoliths occur in the upper part of the ultramafic layers, near pyroxenite and gabbroic layers. In the United mine, rodingitized gabbro dykes occur at the contact between peridotite and gabbro. Narrow diabase dykes (<30 cm wide) were rodingitized in the Munro mine, the United mine (Kretschmar & Kretschmar 1986), and the Garrison deposit. Lamprophyre dykes (<2 m wide) were rodingitized in the Munro mine. Rodingitized xenoliths of uncertain parentage occur in the Munro mine. All Munro mine samples were collected in and around the B pit (Wicks *et al.* 1984). Rodingites also developed at the contact between serpentinite and volcanic rocks in the Reeves (Milne 1972) and United mines (Kretschmar & Kretschmar 1986).

Mineralogy and Textures of Rodingite Protoliths

Five protoliths were recognized in partly rodingitized samples: coarse-grained gabbro, medium- to fine-grained diabase, lamprophyre, pyroxenite and fine-grained, foliated andesite. In addition, fine-grained rodingite assemblages were found dispersed throughout the Munro serpentinite, occurring interstitially to and as replacements of serpentine pseudomorphs after olivine. Unidentified rodingitized xenoliths occur in the upper part of the ultramafic layer at Munro.

The gabbros are coarse grained. In samples in which clinopyroxene dominates over plagioclase, the pyroxene is subhedral, equant to elongate, up to 0.3 × 1.4 cm. In gabbros in which plagioclase is dominant, the clinopyroxene tends to be more equant, anhedral and interstitial to the plagioclase laths, which are up to 0.7 cm long. A coarse-grained gabbro–norite was found in the Dundonald sill. It contains both clinopyroxene and polysutured orthopyroxene. The primary textural features that can still be recognized resemble those of gabbro in thick differentiated bodies such as the Munro–Beatty komatiite (Wicks *et al.* 1984) and Fred's Flow (Arndt 1977).

Primary textures are better preserved in gabbro than in diabase. The diabase contains phenocrysts of plagioclase and glomerophyric aggregates of pyroxene, with some amphibole in a fine-grained groundmass. The plagioclase exhibits polysynthetic twinning; in one sample, the plagioclase is labradorite (An_{50}), based on the Michel-Lévy method.

Pigeonite, inverted pigeonite and harrisitic textures are recognized in the pyroxenite inclusions. The lamprophyre dyke in the Munro mine is rodingitized only at its margin. In the center, the lamprophyre dyke contains large phenocrysts of hornblende, pyroxene, minor orthoclase (Carlsbad twins, negative optic sign) and biotite in a groundmass of orthoclase, acicular amphibole and pyroxene.

Mineralogy of the Rodingites

The minerals identified during this study are listed in Table 2. Results of representative microprobe ana-

TABLE 2. CHARACTERISTIC MINERALS IN RODINGITE FROM THE ABITIBI BELT

Locality	Rodingite protolith	Di[+]	Hgr	Ep	Prh	Tr	Ves	Tte	Chl	Phl
Munro	diabase	xxx	xx	x	x	xx	x	x	xxx	xxx
	lamprophyre	x		xxx				x		
	serpentinite	xx	x	x		x				
Garrison	diabase	xxx	xxx		xxx		x	x	x	
	gabbro	xx	xxx		x		x	x		
United	diabase	xx	xxx	x	xx			x		
	pyroxenite	xxx	xxx	x			?	x		
	gabbro				x			x		
Dundonald	diabase	xx	xxx			xx	x			
	gabbro	xx	xxx		x	x		x		
Bowman	gabbro	xx	xxx	x	x		?	x		
Hedman	gabbro	xx	xxx		xxx		?		x	
Reeves	andesite	xxx	x	xxx		xx	x	xx		

xxx important mineral phases, xx common, x present, ? may be present (see text for details)

+ mineral abbreviations after Kretz (1983) except for hgr (hydrogrossular) and Tte (titanite)

TABLE 3. REPRESENTATIVE COMPOSITIONS OF MINERALS IN RODINGITE FROM ABITIBI BELT

	Diopside			Hydrogrossular				Vesuvianite	Phlogopite	Chlorite
	Munro W82 116	Munro W82 123A phenocryst	Reeves W82 307 vein	Garrison *	Bowman W82 237	Munro W82 116A	Reeves W82 307	Garrison W82 137	Munro W82 116A	Munro W82 116A
SiO_2	54.20	55.14	52.71	39.37	39.35	38.63	39.48	38.56	37.48	30.66
TiO_2	0.00	0.00	0.00	0.00	0.00	1.35	0.74	0.24	1.56	0.12
Al_2O_3	0.28	0.25	0.52	21.23	21.35	16.55	18.96	19.59	14.89	14.89
Cr_2O_3	0.08	0.07	0.10	0.05	0.06	0.16	N.D.	0.06	0.02	0.02
FeO	1.46	1.77	10.26	1.25	0.66	6.08	2.83	2.79	8.82	8.82
MnO	0.24	0.18	0.52	0.19	0.34	0.19	0.25	0.09	0.25	0.13
MgO	17.58	17.76	12.44	0.27	0.29	0.40	1.62	0.27	30.30	28.98
CaO	25.43	25.79	24.10	36.55	36.86	35.67	37.23	36.92	0.01	0.01
Na_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.00	0.00	0.00
K_2O	0.07	0.06	0.06	0.09	0.07	0.09	N.D.	0.08	4.35	0.08
Total	99.34	101.02	100.71	99.00	98.98	99.12	101.38	98.60	97.68	83.71

*Specimen donated by Dr. L. Jensen. Values reported in wt.%. Samples analyzed using an MAC electron microprobe (see text for details). Total iron is expressed as FeO.

lyses (10 out of 100) are shown in Table 3. The major minerals are diopside and hydrogrossular, with lesser amounts of epidote-group minerals, prehnite, vesuvianite and chlorite. In addition, relict phlogopite, amphibole and plagioclase were found in the chlorite-rich reaction zone between the serpentine and rodingite. Note that the amount and thus importance of the various minerals vary among localities and that not all minerals are present at each locality.

Plagioclase

In gabbros from the United mine, the anorthite content ranges between An_{50} and An_{20}. Chlorite pseudomorphs of plagioclase were found in the chlorite-rich rims adjacent to rodingite. The plagioclase grains were either chloritized or saussuritized prior to rodingitization.

Diopside

Diopside compositions (Table 3, Fig. 1) range from $En_{49}Fs_1Wo_{50}$ to $En_{26}Fs_{25}Wo_{49}$. In some instances, we could not establish whether individual grains of diopside belong to the rodingite or to its protolith. Each locality appears to have a unique composition. In the Munro mine, diopside in phenocrysts and that in late-stage veins from the diabase dyke have similar composition (Fs_2–Fs_4 and Fs_1–Fs_3, respectively), with a constant 0.5 wt.% Al_2O_3. In the Reeves mine, the compositions of diopside in the matrix and in the coarse-grained veins from rodingitized andesite are Fs_{13}–Fs_{17} and Fs_{15}–Fs_{18}, with 2.4–3.7 and 0.5–2.1 wt.% Al_2O_3, respectively. In the Garrison deposit, glomerophyric diopside from rodingitized gabbro is Fs_{17}–Fs_{21}, with a variable 1–3 wt.% Al_2O_3. In one example from the Garrison deposit, a diopside characterized by $En_{32}Fs_{20}Wo_{49}$ is enclosed by hydrogrossular. Two observations concerning diopside are noteworthy. Both the grain size and the Fe content of diopside decrease with increasing extent of rodingitization.

Hydrogrossular

Microprobe totals for hydrogrossular tend to be less than 100% (Table 3, Fig. 1). The microprobe analyses indicate that hydrogrossular contains less than 3 wt.% FeO and 1 wt.% MgO, although some hydrogrossular contain up to 41% andradite. The microprobe data and the cell parameters (Table 4) suggest that hydrogrossular contains water, but we do not know the $SiO_4/(OH)_4$ value so that we use the term *hydrogrossular* rather than *hibschite* (Passaglia & Rinaldi 1984).

If it is anisotropic, hydrogrossular is difficult to distinguish from vesuvianite optically unless an optic sign can be determined. In our samples, hydrogrossular is consistently corroded, so that this was not possible. The presence of sector zoning in hydrogrossular is diagnostic if present. In some cases, X-ray-diffraction studies were necessary to distinguish hydrogrossular from vesuvianite, so that vesuvianite may be more abundant than generally reported.

Epidote, prehnite and vesuvianite

The epidote-group minerals epidote and clinozoisite are important constituents of the rodingites. Clinozoisite occurs primarily after plagioclase but

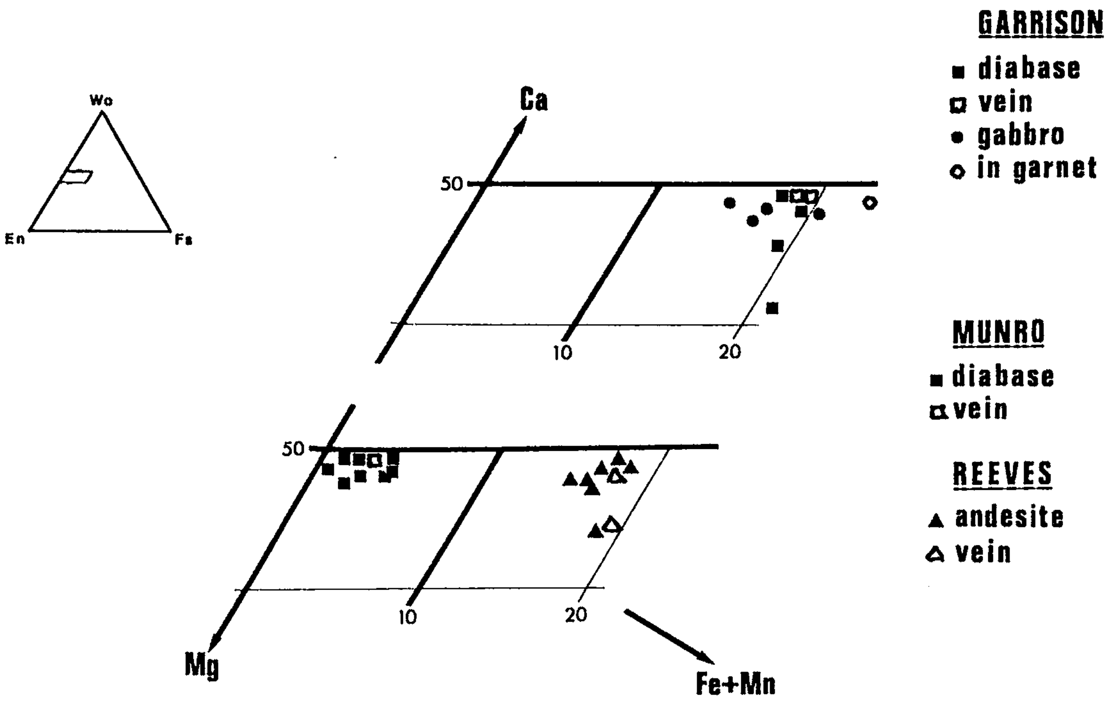

FIG. 1. Chemical composition of clinopyroxene and hydrogrossular in rodingites from the Abitibi greenstone belt.

may form after pyroxene as well. Clinozoisite also occurs in veins cross-cutting fresh diabase and lamprophyre. Prehnite occurs both as a matrix mineral and in veins. In the matrix, it is associated with clinozoisite, hydrogrossular and diopside. Vesuvianite was identified by X-ray diffraction. Microprobe data for hydrogrossular and vesuvianite in the Garrison samples are similar but in the Reeves mine sample, vesuvianite is poorer in Ca and richer in Al and Fe than hydrogrossular.

Tremolite, chlorite and phlogopite

Tremolite occurs in the reaction zones between serpentine and xenoliths of unidentified rocks in the Munro mine, and between serpentine and andesite in the Reeves mine. Chlorite occupies a position similar to tremolite, but chlorite occurs in all reaction zones. No fresh phlogopite has been found, but partly chloritized grains were observed within chlorite reaction zones at the Munro mine. Microprobe analysis indicates that phlogopite replacement by chlorite was accompanied by the loss of Ti, K and Si, and an increase in Al and Fe.

TEXTURES OF THE RODINGITES

Rodingitization of gabbro took place by the pseudomorphic replacement of plagioclase by hydrogrossular + prehnite and chlorite. Coarse clinopyroxene is replaced by fine-grained diopside or chlorite, and in one sample from the Dundonald sill, by amphibole.

Rodingitized fine-grained diabase in the Munro mine is an equigranular rock consisting of diopside, hydrogrossular, prehnite, clinozoisite and vesuvianite. Veins of coarser-grained diopside, prehnite, chlorite and carbonate cross-cut the matrix. In the United mine diabase, plagioclase alters to hydrogrossular and chlorite, with clinozoisite needles penetrating relict plagioclase. The matrix has altered to pyroxene and amphibole. Prehnite, epidote and titanite are minor phases in the matrix. The plagioclase phenocrysts in the Garrison diabase have altered to diopside and amphibole, whereas the matrix was altered to hydrogrossular, vesuvianite, diopside, prehnite and chlorite. Veins consisting of equigranular diopside and hydrogrossular cross-cut the matrix. Diopside dominates in the Munro rodingites after diabase, whereas hydrogrossular dominates in all the others.

Rodingitized pyroxenite from the United mine contains hydrogrossular ± titanite after pigeonite lamellae, and diopside after the remaining portion of the pyroxene.

The least-altered portion of the lamprophyre of

TABLE 4. DIRECT-CELL PARAMETERS OF MINERALS IN RODINGITE FROM ABITIBI BELT

Sample	a+	b	c	β (°)	Standard Error 2θ++	Number of Peaks indexed
Hydrogrossular						
W82-136	1.1871(2)			90.0(0)	0.0023	7
W82-137	1.1871(1)			90.0(0)	0.0022	13
W82-138	1.1865(1)			90.0(0)	0.0016	9
W82-158	1.1870(3)			90.0(0)	0.0027	9
W82-236	1.1898(2)			90.0(0)	0.0020	5
W82-307	1.1857(4)			90.0(0)	0.0030	4
Vesuvianite						
W82-139	1.5615(53)	1.5615(53)	1.1833(65)	90.0(0)	0.0020	7

+Cell paramaters are in nanometers.
++Referenced to quartz standard.

Munro mine consists of pyroxene and amphibole phenocrysts within a matrix of needle-shaped amphibole, orthoclase, quartz, epidote and chlorite. It can be classified as vogesite, based on its mineralogy. Toward the margin, which is the most extensively altered part, pyroxene and zoisite-altered phenocrysts are set in a matrix of epidote-group minerals, pyroxene, titanite and minor carbonate. Approximately 75% of the rock consists of clinozoisite and epidote. Diopside is a minor phase, and the carbonate appears to postdate rodingitization. Commonly, diopside and epidote veins cross-cut the alteration assemblage. Hydrogrossular was not observed in the altered lamprophyre. Sample W83-112, which represents the original compositions of the lamprophyre, contains 6.22 wt.% CaO (Table 5). Samples W83-65-C (17.3 wt.% CaO), W83-65-11 (20% CaO) and W83-58-1 (24.7% CaO), in a sequence of increasing amounts of Ca, represent an increasing extent of alteration as defined by the mineral assemblages.

The least-rodingitized andesite at the Reeves mine consists of clinozoisite and chlorite, which are replaced by diopside and tremolite with increasing degree of alteration. The most altered rocks have a fine-grained granular texture consisting predominantly of diopside with minor clinozoisite, hydrogrossular and tremolite after epidote. The hydrogrossular is cloudy and anhedral, and epidote is cut by anastomosing microfissures delineated by tremolite and chlorite. A set of late diopside veins cross-cuts the alteration.

An unusual occurrence of rodingitized serpentine was found in the Munro sill. Fine-grained pyroxene, garnet and epidote occur after interstitial pyroxene between pseudomorphically serpentinized olivine grains. In addition, some serpentinized olivine grains have been altered to pyroxene. This type of alteration has been observed in the Jeffrey mine in southeastern Quebec (Wares & Martin 1980) and in the Alexo area of Ontario (N.T. Arndt, pers. comm.). The process appears to begin with the alteration of the pyroxene to diopside and epidote, and then continues with the alteration of serpentine to diopside.

CHANGES IN WHOLE-ROCK CHEMISTRY

Coleman (1967) has used the ACF diagram to define the rodingite field. Molar proportions of appropriate oxides from our samples were calculated from whole-rock compositions (Table 5, Fig. 2). Our samples plot in or near the rodingite field regardless of the extent of rodingitization. Given the wide range in protolith composition, this fact suggests that any rock type can be rodingitized in the presence of a Ca-rich fluid.

Mineralogical and chemical changes can be quantified for the Munro lamprophyre, as the middle of the dyke still is unaltered. Losses and gains of various elements were calculated by the method of Gresens (1967). This method utilizes the system of equations:

$$100[fv \frac{g^B}{g^A} Cn^B - Cn^A] = Xn$$

where fv is the volume factor, A, the protolith, B, the product, g, the density, Cn, the weight fraction of component n, and Xn, the amount of component n lost or gained during alteration. This system of equations is underconstrained, so that either fv or Xn must be known. Gresens (1967) described a method using bulk-rock compositions, which approximates fv. A composition–volume diagram (Gresens 1967, Fig. 3) is constructed by calculating

TABLE 5. WHOLE-ROCK COMPOSITIONS OF RODINGITES, SERPENTINITES, AND THEIR CONTACT ZONE FROM THE ABITIBI BELT

Mine	Munro			Garrison			Munro		
Sample	116-R*	116-C	116-S	123-R	123-C	123-S	581**	65C	113
SiO_2	39.86	33.81	37.87	39.97	35.43	35.40	40.90	48.20	46.40
TiO_2	0.57	0.58	0.10	0.55	0.74	0.31	0.63	0.66	0.83
Al_2O_3	11.68	10.41	2.86	10.49	7.82	6.90	14.90	12.80	14.80
Cr_2O_3	0.06	0.08	0.17	0.05	0.08	0.25	0.01	0.02	0.02
Fe_2O_3	5.24	2.91	4.81	4.95	2.16	4.26	8.00	8.01	9.10
FeO	1.08	3.86	1.83	1.57	1.56	2.72	0.90	<0.10	<0.01
MnO	0.21	0.54	0.13	0.19	0.69	0.31	0.18	0.18	0.17
MgO	8.15	33.07	37.92	9.19	36.88	36.27	5.84	5.93	8.20
CaO	28.86	1.23	0.04	27.87	0.81	0.24	24.70	17.30	6.51
Na_2O	0.28	0.16	0.13	0.22	0.06	0.32	0.07	0.24	3.57
K_2O	0.02	0.03	0.03	0.02	0.01	0.09	0.04	3.18	2.14
P_2O_5	0.42	0.41	0.03	0.42	0.54	0.18	0.36	0.37	0.45
L.O.I.	1.76	12.38	12.88	1.83	13.13	12.41	4.23	2.16	6.70
Total	98.19	99.47	98.80	97.32	99.91	99.66	100.76	99.15	98.90

*Letter is an abbreviation of: Rodingite (R); Contact (C); Serpentinite (S).
**The last three entries represent least (113), intermediate (65C), and most (581) altered lamprophyre. Values reported in wt. %. L.O.I.: loss on ignition. Composition determined by x-ray fluorescence spectroscopy.

Xn for a set of *fv*. The intersection of the curves for the assumed immobile components Zr and Ti with the line $Xn = 0$ was used to obtain a value of *fv* of 1.05. This value indicates that a very small volume increase accompanied rodingitization. The results (Fig. 3) suggest that Ca, Si, Al, Fe, and P increased, whereas Mg, Na, K and volatiles were lost during rodingitization. These results support petrographic observations that primary hornblende and feldspar(s) alter to epidote and diopside.

A well-developed reaction rim in the Munro mine was chosen for detailed study of the metasomatic exchanges. The reaction zone ranges from 2 to 20 cm in width, and there is a zonation from partly altered biotite near the serpentinite, to chlorite with fine-grained clinozoisite needles near the rodingite. Petrographic observation of chlorite pseudomorphs after plagioclase laths and zoned plagioclase indicate that the chlorite-rich reaction zone is formed at the expense of the dyke rather than the serpentinite. The boundary between chlorite and rodingite is quite sharp, whereas between chlorite and serpentinite it is more diffuse. The reaction rim is shown schematically in Figure 4.

The edge of the dyke was defined by using Cr/Ti values (Sanford 1982). Values of 0.01–0.11 in the dyke, 0.11–0.14 in the reaction zone and 0.83–1.73 in the serpentinite suggest that the reaction zone formed at the expense of the dyke. Variations in major oxides are less clear but appear to be consistent with this choice. Concentrations of MgO and H_2O are much lower, and that of CaO is much greater in the rodingite than in the serpentinite or in the reaction zone (Fig. 4). Al_2O_3 and SiO_2 are lower in the reaction rim than in the rodingite, and appear to have increased in the serpentinite. There is a loss of Na and K from both the rodingite and the reaction zone.

FLUID INCLUSIONS

Primary fluid inclusions were found in diopside from the gabbro in the Bowman mine. The freezing temperature of 24 inclusions ranges between -40°C to -50°C, and the final melting temperature of ice, from -0.93 to +0.4°C. These values indicate that the fluid is a low-salinity H_2O containing less than 1.6 wt.% NaCl equiv. (Potter *et al.* 1978). Using pressure corrections of 1 and 2 kbars (Jolly 1982) and the homogenization temperature ($\bar{x} = 208 \pm 6$°C), the formation temperature corresponds to 270°C at one kbar and 330°C at two kbars.

DISCUSSION

The dominant minerals in the rodingitized gabbros and diabase are diopside, hydrogrossular and prehnite, whereas the dominant minerals in the rodingitized lamprophyre and andesite are epidote and clinozoisite. Prehnite, hydrogrossular and diopside occupy late-stage cross-cutting veins. The mineral assemblages observed in the rodingites from the Abitibi greenstone belt are similar to those observed in rodingites from Phanerozoic terranes. All of these minerals are associated with subgreenschist-facies metamorphism (Rice 1983). Our fluid-inclusion

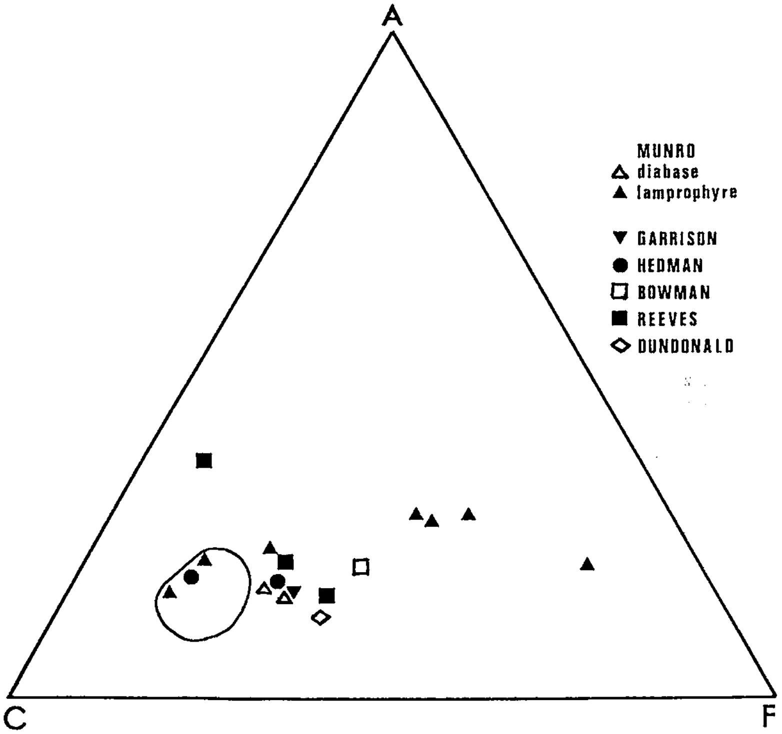

FIG. 2. ACF plot of Abitibi belt rodingites, showing the rodingite field as delineated by Coleman (1977).

results from diopside agree with this assessment of a low temperature. In addition, the presence of CO_2-free inclusions is consistent with the absence of carbonate phases in these assemblages.

As part of the lamprophyre at Munro mine was not rodingitized, this outcrop will be used to demonstrate mineralogical and chemical changes that accompany rodingitization. The initial reaction identified in the lamprophyre destabilizes plagioclase and produces clinozoisite. The second reaction involves the breakdown of hornblende and clinozoisite to form epidote with minor diopside and tremolite. This change in mineralogy is accompanied by a change in bulk chemistry. These stages can be recognized within the rodingitized andesite in the Reeves mine as well, in which diopside dominates at the contact between rodingite and serpentinite, and epidote and clinozoisite are found at a distance from the contact.

Coleman (1967, 1977) proposed several reactions to describe the onset of rodingitization:

$$\underset{\text{(anorthite)}}{3CaAl_2Si_2O_8} + Ca^{2+} + 2H_2O = \underset{\text{(zoisite)}}{2Ca_2Al_3Si_3O_{12}(OH)} + 2H^+$$

$$\underset{\text{(zoisite)}}{2Ca_2Al_3Si_3O_{12}(OH)} + 5Ca^{2+} + 2H_2O = \underset{\text{(hydrogrossular)}}{Ca_3Al_2Si_{2.5}O_{10}(OH)_2} + 4H^+$$

and

$$\underset{\text{(anorthite)}}{1.5CaAl_2Si_2O_8} + 0.5Ca^{2+} + 1.5H_2O = \underset{\text{(prehnite)}}{Ca_2Al_2Si_3O_{10}(OH)_2} + 0.5Al_2O_3 + H^+$$

$$\underset{\text{(prehnite)}}{2Ca_2Al_2Si_3O_{10}(OH)_2} + 2Ca^{2+} = \underset{\text{(hydrogrossular)}}{2Ca_3Al_2Si_{2.5}O_{10}(OH)_2} + 0.5Si^{4+}$$

in which plagioclase alters first to zoisite or prehnite, which then alter to grossular. This intermediate step may not be necessary, however, as

$$\underset{\text{(anorthite)}}{CaAl_2Si_2O_8} + 2Ca^{2+} + 3H_2O + 0.5SiO_2 = \underset{\text{(hydrogrossular)}}{Ca_3Al_2Si_{2.5}O_{10}(OH)_2} + 4H^+$$

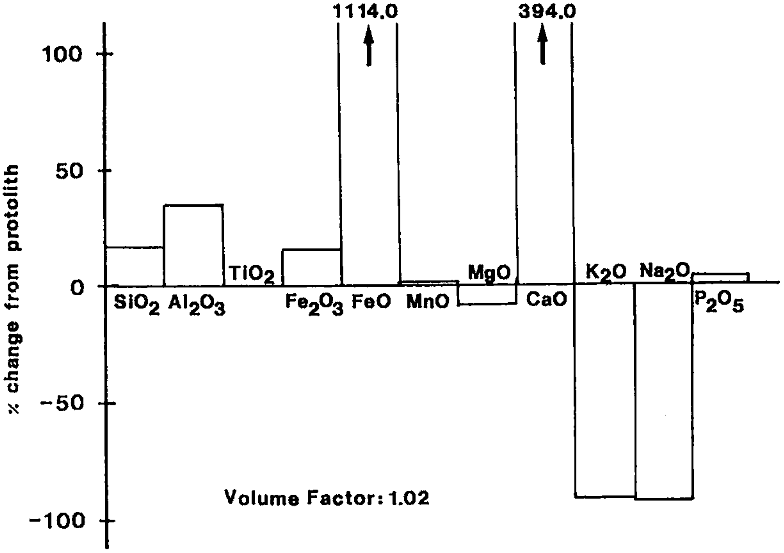

FIG. 3. Chemical changes that resulted from rodingitization of the Munro mine lamprophyre. Magnitude of volume factor indicates that no volume change occurred as a result of rodingitization.

We have observed plagioclase as well as zoisite and prehnite altering to hydrogrossular. In addition, the replacement of zoisite with prehnite is described by the reaction

$$\underset{\text{(zoisite)}}{2Ca_2Al_3Si_3O_{12}(OH)} + 3SiO_2 + 2Ca^{2+} + 4H_2O = \underset{\text{(prehnite)}}{3Ca_2Al_2Si_3O_{10}(OH_2)} + 4H^+$$

All of these reactions are consistent with the apparent increase in Ca and water, and the loss of Na and K from the system with increasing rodingitization.

Laurent (1980) defined two mineral assemblages in rodingites in the serpentinized harzburgites from the Thetford Mines ophiolite in Quebec. The earlier assemblage, which comprises the bulk of the rodingite, consists of diopside, hydrogrossular and clinozoisite. The later assemblage occupies cross-cutting veins and consists of zoisite, grossular, prehnite, diopside, vesuvianite and wollastonite. Laurent associated the formation of the early assemblage with the production of lizardite mesh-rim textures during serpentinization under the ocean floor. He associated the later assemblage with the production of lizardite hourglass and chrysotile interlocking textures and chrysotile asbestos veins that presumably formed during emplacement of the ophiolite.

According to Laurent (1980), the different mineral assemblages reflect different regimes of serpentinization and rodingitization. These regimes are defined by thermodynamic parameters as well as by the tectonic environment. Using his model, we can define two episodes of rodingitization as well. Late-stage veins cross-cut most samples found in the chrysotile deposits, but no veins were found in samples from the Dundonald sill. This finding is consistent with the two episodes of serpentinization found in the asbestos deposits, and the single one recognized in the Dundonald sill (Wicks *et al.* 1983).

Although we can define two episodes of rodingitization based on cross-cutting relationships, we can also subdivide the first episode into stages based on the observations made on the lamprophyre: a first stage in which feldspar alters to clinozoisite, a second stage in which hornblende and zoisite alter to form epidote and diopside, and a third stage in which all minerals alter to diopside.

The consistently corroded margins of hydrogrossular in the other rodingites indicate that it is an early phase. However, different stages are not as apparent in the other rodingites, primarily because of the persistence of diopside in both the matrix and the veins. Vein diopside has a chemistry similar to that of the matrix that it cross-cuts. In addition, the grain size of the matrix diopside decreases with increases in the extent of alteration, a trend that is accompanied by a loss of Fe.

Modal variations in mineralogy within rodingites of the same protolith could be due to variation in the rodingitization regime. For example, diopside dominates in rodingitized Munro diabase, whereas

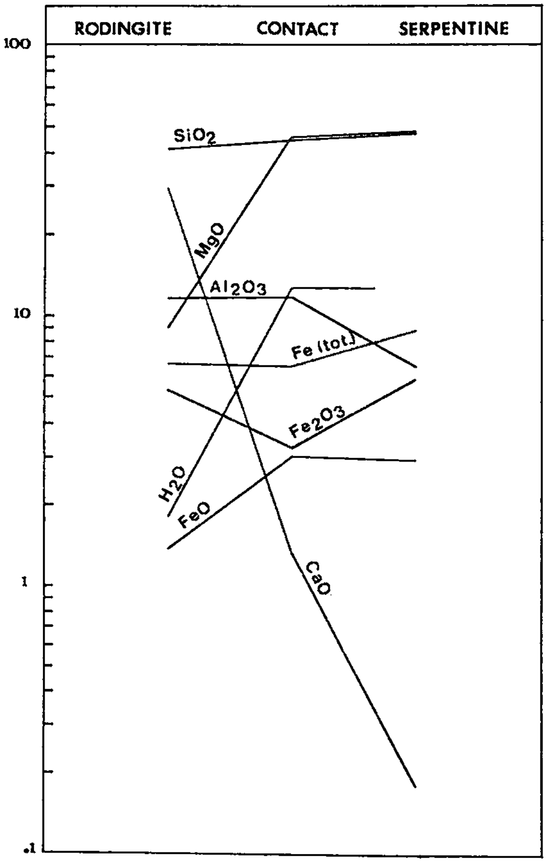

FIG. 4. Schematic representation of chemical changes across the reaction zone between the rodingite protolith and the serpentinite in the Munro mine.

hydrogrossular dominates in all the others, although hydrogrossular is corroded in these diabase rocks. The Munro serpentinite contains antigorite in addition to lizardite and chrysotile. We suggest that a change in the regime of serpentinization at Munro, reflected in a change from lizardite–chrysotile to antigorite, resulted in a change in rodingite mineralogy (production of diopside), due to the liberation of Mg during recrystallization of the serpentine.

Using the observations and reactions given above, we can define three types of rodingites in the Abitibi belt, representing a different extent of, or regime of, rodingitization. *Epidote-rich rodingites* represent the initial stage of rodingitization, in which either clinozoisite or zoisite may be the dominant modal phase. Minor phases include diopside and titanite. The Munro lamprophyre dyke and the less-rodingitized andesite of Reeves represent this stage. *Grossular-rich rodingites*, which formed by the alteration of epidote-group minerals to hydrogrossular and prehnite, represent a second stage of rodingitization. Hydrogrossular forms most commonly after clinozoisite, prehnite or plagioclase, and uncommonly after pyroxene. Prehnite predates hydrogrossular in some rocks but occurs interstitially to hydrogrossular in others. Minor diopside may be present as well. The Garrison and United diabases and the Hedman gabbro are examples of this type. *Diopside-rich rodingites* represent a third stage of rodingitization, in which the epidote-group minerals, hydrogrossular, prehnite and relict pyroxene recrystallize to fine-grained diopside. The Munro diabase and the more rodingitized andesite at the Reeves mine are examples of this type. Although stage 1 represents the initial phase of rodingitization, it can be followed either by stage 2 or stage 3. Observations made on Phanerozoic (Adib & Pamic 1980) and ocean-floor rodingites (Honnorez & Kirst 1975) are consistent with these stages, as well as with the reactions proposed by Coleman (1967).

The stages of rodingitization are not always related to different events of serpentinization that could be defined by serpentine mineral assemblages. The best example of this is found in the Dundonald sill gabbro. The rodingitized gabbro consists of diopside and hydrogrossular. Based on the stages outlined above, it is a highly rodingitized rock. The olivine in the sill has been pseudomorphically replaced by lizardite without the formation of antigorite or chrysotile. The serpentinized olivine indicates that only one serpentinization event occurred, whereas the gabbro has experienced two stages of rodingitization during the same event. Furthermore, we have not been able to characterize rodingite textures in a manner similar to that used to describe serpentine textures. For example, Wicks & Whittaker (1977) classified serpentine textures into pseudomorphic and nonpseudomorphic textures, which correspond to retrograde and prograde serpentinization. Our observations indicate that there are no specific rodingite textures associated with either retrograde or prograde serpentine. Thus one cannot predict in detail serpentinite mineralogy and texture from rodingite mineralogy and texture or *vice versa*. The correlation between serpentinization and rodingitization based on mineralogy and texture is not straightforward.

Vesuvianite was observed in the rodingitized diabase and andesite but not in the rodingitized gabbros or lamprophyres. Presumably this pattern of distribution is due to the greater extent of rodingitization of diabase and andesite, because vesuvianite requires more calcium than zoisite, hydrogrossular or prehnite. Grain size is also a factor. The fine grainsize of diabase and andesite appears to enhance reaction rates and results in a more extensive rodingitization than in similarly situated but coarse-grained gabbro and lamprophyre.

The presence of relict phlogopite and tremolite in the chlorite reaction rim adjacent to the diabase dyke but not adjacent to the lamprophyre dyke may be due to the relative time of emplacement of the dykes. A dyke emplaced into contact with a hot peridotite in the presence of water may be a more favorable environment for the crystallization of phlogopite and tremolite, in contrast to the emplacement of a dyke into a cold, dry serpentinite. A late-stage emplacement of the lamprophyre is consistent with the more pristine mineralogy observed in its center.

Coleman (1967) used an ACF diagram to delineate a field in which the chemical compositions of thoroughly rodingitized rocks would plot. This field is characterized by the composition that represents various modal proportions of diopside and chlorite with hydrogrossular, prehnite or epidote. Coleman also indicated the trend toward this field of partly rodingitized greywackes and basalts and stated that the bulk chemistry of the protolith would have a minor effect on the outcome.

We believe that protolith chemistry should be emphasized because the type of chemical changes necessary to produce a rodingite will vary with the protolith. For example, basalts must lose alkalis and Mg, increase in ferric iron or gain Ca. Lamprophyres have high Fe^{3+}/Fe^{2+} values already, and the one in the Munro mine has low Mg values. This rock needs only to lose alkalis and a little Mg and to gain Ca to plot in the rodingite field. For Ca-rich protoliths, the bulk chemistry of the rodingite will evidently not indicate the extent of rodingitization.

The primary definition of the extent of rodingitization should be based on the minerals present and not on the location of the sample in an ACF diagram (Coleman 1977). The data presented by Coleman (1967), Wares & Martin (1980) and our paper bear this out. Our samples plot near the rodingite field regardless of their extent of rodingitization.

The ultramafic rocks in the Abitibi belt are either flows or sills; there is no evidence of a tectonite fabric. The absence of deformation is a marked difference between these rocks and those found in Phanerozoic mountain belts. In the latter environment, tectonite fabrics are common and indicate that the rocks originated in the mantle (Coleman 1977). Much attention has been drawn to the role of deformation and tectonism in Phanerozoic rocks as well as in samples dredged from the ocean floor. Coleman (1967) has invoked pressures greater than 4 kbars and temperatures of 200–500°C for the formation of rodingites containing aragonite. This regime contrasts sharply with that of present-day weathering of ultramafic rocks, which produces xonotlite in California (Barnes *et al.* 1972). Stable isotope data reconcile these two contrasting regimes. The data suggest that rodingitization occurs over a temperature range from 400 to 25°C (Wenner 1979).

Antigorite serpentinites host rodingites within the Tananao schist of Taiwan (Yui *et al.* 1988). Their enrichment in light stable isotopes of hydrogen and oxygen suggests that antigorite–tremolite and diopside are in isotopic equilibrium. Clinozoisite, which is found furthest from the serpentinite and apparently represents the least-altered schist in their study, is not in isotopic equilibrium with the other minerals. Yui *et al.* (1988) also noted that hydrogrossular commonly occurs with diopside; their observations and interpretations are consistent with our proposed division of rodingites.

As the Abitibi ultramafic rocks are sills and flows and occur interlayered with altered basalts that have not undergone metamorphism at a grade higher than low greenschist facies (Jolly 1982), temperatures and pressures could not have been higher than 400°C and 3 kbars, respectively. On the other hand, we did not find either xonotlite or pectolite, which would rule out rodingitization near 25°C.

The differences in tectonic style and degree of metamorphism of rodingite localities throughout the world suggest that rodingitization is simply a chemical process characterized by the addition of calcium, and the removal of silica and the alkalis from the protolith. If the rodingite protolith and the serpentinite are considered as one system, as suggested by Thayer (1966) and Černý (1968), rodingitization can be viewed as an autometasomatic process once water is present. In this view, the extent to which rodingitization progresses depends upon the chemical composition of the serpentine protolith.

The apparent sporadic absence of rodingites from some serpentinites has been noticed by several authors (Coleman 1967, Leaming 1978, Yui *et al.* 1988). We believe that the presence or absence of rodingite is governed by the composition and by the amount of fluid present. Firstly, if present, CO_2 will scavenge calcium to produce dispersed calcite or dolomite. Both minerals are common in some partly serpentinized peridotites. Less commonly, small clots of fine-grained diopside and garnet occur in the interstitial zones between serpentine pseudomorphs after olivine, as observed in the Munro mine serpentinite. In both instances, as calcium-bearing minerals are not concentrated but dispersed throughout the serpentinite, they would be difficult to recognize as rodingite in the field. Another factor that is important to the transport of cations and to the concentration of the calcium-bearing minerals is the amount of fluid flowing through the serpentinite. A high flow could flush calcium out of the serpentinite, a lower flow could concentrate calcium within the serpentinite, within inclusions or at lithological contacts.

The investigations of Anhaeusser (1979) and our own indicate that the rodingitization process has not changed since the Archean, despite the possibly different tectonic driving forces in Phanerozoic times than in Archean times. Therefore, the parameters that control the formation of rodingites in the Phanerozoic rocks apply also to the Archean and *vice versa*. Among these controls are protolith chemistry and grain size, and the extent of serpentinization. Factors that influence rodingitization but are not essential to its operation are multiple tectonic events and varying episodes of serpentinization.

CONCLUSIONS

The rodingites hosted by ultramafic sills in the Abitibi greenstone belt formed from several protoliths including dykes, lithic inclusions and volcanic rocks at the serpentinite contact. Variations in mineralogy and textural relationships allow us to define three groups of rodingites, each representing successive stages in alteration of the protolith: 1) epidote-rich rocks: earliest alteration of the protolith; 2) grossular–prehnite-rich rocks: intermediate alteration, and 3) diopside-rich rocks: final stage of alteration. The initial bulk-rock chemistry affects the modal proportion of minerals.

Observations and chemical trends reported here are similar to those found in Phanerozoic terranes, indicating that the rodingitization process has not changed since the Archean, a conclusion also reached by Anhaeusser (1979). Mass-balance calculations and fluid-inclusion data indicate that rodingitization was an isovolume process; in these examples, rodingitization was mediated by a low-salinity water at temperatures of approximately 300°C and at 1 kbar. Although deformation commonly affects the serpentinite host, it is not an essential factor in the rodingitization process. The parameters that appear to effect the process of rodingitization are: a) timing of emplacement of the dyke or intrusion into the ultramafic rock with respect to the onset of serpentinization, b) size of the protolith compared to that of the serpentinite, c) grain size of protolith, and d) extent of serpentinization.

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REFERENCES

ADIB, D. & PAMIC, J. (1980): Rodingites from the southeastern parts of the Neyriz ophiolite complex in the Zagros Range, Iran. *Arch. Sci. Genève* **33**, 281-289.

ANHAEUSSER, C.R. (1979): Rodingite occurrences in some Archean ultramafic complexes in the Barberton Mountain Land, South Africa. *Precambrian Res.* **6**, 49-76.

APPLEMAN, D.E. & EVANS, H.T., JR. (1973): Job 9214: indexing and least-squares refinement of powder diffraction data. *U.S. Geol. Surv., Comput. Contrib.* **20** (NTIS Doc. **PB2-16188**).

ARNDT, N.T. (1975): *Ultramafic Rocks of Munro Township and their Volcanic Setting*. Ph.D. thesis, Univ. Toronto, Toronto, Ontario.

______ (1977): Thick, layered peridotite–gabbro lava flows in Munro Township, Ontario. *Can. J. Earth Sci.* **14**, 2620-2637.

BARNES, I., LAMARCHE, V.C., JR. & HIMMELBERG, G. (1967): Geochemical evidence of present-day serpentinization. *Science* **156**, 830-832.

______, RAPP, J.B. & O'NEIL, J.R. (1972): Metamorphic assemblages and the direction of flow of metamorphic fluids in four instances of serpentinization. *Contrib. Mineral. Petrol.* **35**, 263-276.

ČERNÝ, P. (1968): Comments on serpentinization and related metasomatism. *Am. Mineral.* **53**, 1377-1385.

COLEMAN, R.G. (1967): Low-temperature reaction zones and alpine ultramafic rocks of California, Oregon and Washington. *U.S. Geol. Surv., Bull.* **1247**.

__________ (1977): *Ophiolites*. Springer-Verlag, Berlin.

GRESENS, R.L. (1967): Composition–volume relationships of metasomatism. *Chem. Geol.* **2**, 47-65.

HENDRY, N.W. & CONN, H.K. (1957): The Ontario asbestos deposit of Canadian Johns–Manville Company Limited. *In* Geology of Canadian Industrial Mineral Deposits. 6th Comm. Min. Metall. Congr., 36-45.

HONNOREZ, J. & KIRST, P. (1975): Petrology of rodingites from the Equatorial mid-Atlantic fracture zones and their geotectonic significance. *Contrib. Mineral. Petrol.* **49**, 233-257.

JENSEN, L.S. & PYKE, D.R. (1982): Komatiites in the Ontario portion of the Abitibi belt. *In* Komatiites (N.T. Arndt & E.G. Nisbet, eds.). George Allen & Unwin, London.

JOLLY, W.T. (1982): Progressive metamorphism of komatiites and related Archean lavas of the Abitibi area, Canada. *In* Komatiites (N.T. Arndt & E.G. Nisbet, eds.). George Allen & Unwin, London.

KRETSCHMAR, U. & KRETSCHMAR, D. (1986): Talc, magnesite and asbestos deposits in the Timmins - Kirkland Lake area, District of Timiskaming and Cochrane. *Ont. Geol. Surv., Study* **28.**

KRETZ, R. (1983): Symbols for rock-forming minerals. *Am. Mineral.* **68,** 277-279.

LAURENT, R. (1980): Regimes of serpentinization and rodingitization in Quebec Appalachian ophiolites. *Arch. Sci. Genève* **33,** 311-320.

LEAMING, S.F. (1978): Jade in Canada. *Geol. Surv. Can., Pap.* **78-19.**

MACRAE, N.D. (1969): Ultramafic intrusions of the Abitibi area, Ontario. *Can. J. Earth Sci.* **6,** 281-303.

MACDONALD, A.J. & SPOONER, E.T.C. (1981): Calibration of a LINKAM TH600 programmable heating-cooling stage for microthermometric examination of fluid inclusions. *Econ. Geol.* **76,** 1248-1258.

MILNE, V.G. (1972): Geology of the Kukatush-Sewell Lake area, District of Sudbury. *Ont. Div. Mines, Geol. Rep.* **97.**

NALDRETT, A.J. & MASON, G.D. (1968): Contrasting Archean ultramafic igneous bodies in Dundonald and Clergue townships, Ontario. *Can. J. Earth Sci.* **5,** 111-143.

PASSAGLIA, G. & RINALDI, R. (1984): Katoite, a new member of the $Ca_3Al_2(SiO_4)_3$ - $Ca_3Al_2(OH)_{12}$ series and a new nomenclature for the hydrogrossular group of minerals. *Bull. Minéral.* **107,** 605-618.

PLANT, A.G. & LACHANCE, A.R. (1973): Quantitative electron microprobe analysis using an energy-dispersive spectrometer. *Proc. Eighth Nat. Conf. Electron Probe Analysis (New Orleans), Pap.* **13.**

POTTER, R.W., CLYNNE, M.A. & BROWN, D.L. (1978): Freezing point depression of aqueous sodium chloride solutions. *Econ. Geol.* **73,** 284-285.

PYKE, P.R. (1982): Geology of the Timmins area. *Ont. Geol. Surv. Rep.* **219.**

______, MACVEIGH, J.G. & MIDDLETON, R.S. (1978): Volcanic stratigraphy and geochemistry in the Timmins mining area. *In* Toronto 78, *Geol. Soc. Am.-Geol. Assoc. Can.-Mineral. Assoc. Can., Ann. Meet., Field Trip Guidebook.*

RICE, J.M. (1983): Metamorphism of rodingites. I. Phase relations in a portion of the system CaO–MgO–Al_2O_3–SiO_2–CO_2–H_2O. *Am. J. Sci.* **283-A,** 121-150.

SANFORD, R. (1982): Growth of ultramafic reaction zones in greenschist to amphibolite facies metamorphism. *Am. J. Sci.* **282,** 543-616.

SATTERLY, J. (1951): Geology of Munro township. *Ont. Dept. Mines, Ann. Rep.* **60,** *pt.8.*

THAYER, T.P. (1966): Serpentinization considered as a constant-volume metasomatic process. *Am. Mineral.* **51,** 685-710.

VOS, M.A. (1971): Asbestos in Ontario. *Ont. Dep. Mines Northern Affairs, Ind. Minerals Rep.* **36.**

WARES, R.P. & MARTIN, R.F. (1980): Rodingitization of granite and serpentinite in the Jeffrey mine, Asbestos, Quebec. *Can. Mineral.* **18,** 231-240.

WENNER, D.B. (1979): Hydrogen, oxygen and carbon isotopic evidence for the origin of rodingites in serpentinized ultramafic rocks. *Geochim. Cosmochim. Acta* **43,** 603-614.

WICKS, F.J. & PLANT, A.G. (1983): The accuracy and precision of routine energy-dispersive electron microprobe analysis of serpentine. *X-ray Spect.* **12,** 59-66.

______, SCHANDL, E.S., OZORAY, J. & WAN, PU (1983): Mineralogy and geochemistry of the chrysotile asbestos deposits of Ontario. *In* Geoscience Research Grant Program, Summary of research 1982–1983 (V.G. Milne, ed.). *Ont. Geol. Surv., Misc. Pap.* **113,** 193-199.

______, WAN PU & HEDJRAN, K. (1984): Mineralogy and geochemistry of the chrysotile asbestos deposits of Ontario; Munro mine and Garrison deposit. *In* Geoscience Research Grant Program, Summary of research 1983-1984 (V.G. Milne, ed.). *Ont. Geol. Surv. Misc. Pap.* **121,** 99-110.

______ & WHITTAKER, E.J.W. (1977): Serpentine textures and serpentinization. *Can. Mineral.* **15,** 459-488.

YUI TZEN-FU, YEH HSUEH-WEN & LEE CHIHMING WANG (1988): Stable isotope studies of nephrite deposits from Fengtien, Taiwan. *Geochim. Cosmochim. Acta* **52,** 593-602.

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