Canadian Mineralogist
Vol. 22, pp. 173-183 (1984)

MINERALOGICAL AND CHEMICAL VARIATIONS IN CHRYSOTILE VEINS AND PERIDOTITE HOST-ROCKS FROM THE ASBESTOS BELT OF SOUTHERN QUEBEC*

ERSEN COGULU

Department of Geology, University of Ottawa, Ottawa, Ontario K1N 6N5

ROGER LAURENT

Département de Géologie, Université Laval, Québec, Québec G1K 7P4

ABSTRACT

Two types of serpentinites from the Thetford Mines – Black Lake area were studied; the first was selected from the Lake Asbestos mine and the second, from the Vimy Ridge deposit. The former, which has not undergone the oceanic episode of pervasive serpentinization, displays a complete transition from fresh peridotite to serpentinite associated with veins of chrysotile asbestos. The latter is typical ribbon-veined asbestos ore; the host peridotite has undergone serpentinization during both oceanic and continental episodes. Samples were studied under the microscope and analyzed by X-ray diffraction and electron microprobe. In the Lake Asbestos sample the following variations can be seen as the chrysotile asbestos vein is approached from the fresh peridotite: (1) Olivine is transformed into either lizardite or chrysotile in microveins in the fresh peridotite. (2) The peridotite host shows intense serpentinization in a narrow zone surrounding the asbestos vein. (3) The Mg/(Fe+Mg) and Mg/Si ratios vary as follows: a) they increase in the lizardite microveins of the fresh peridotite; b) Mg/(Fe+Mg) tends to remain constant in the serpentinized zone, whereas Mg/Si decreases significantly. Samples from Vimy Ridge display the following variations: (1) Mg/(Fe+Mg) and Mg/Si ratios increase from the margin to the centre in the vein-filling chrysotile. (2) The lizardite wall-rock of the chrysotile veins shows major variations in Mg/(Fe+Mg) and Mg/Si, apparently not related to distance from the vein.

Keywords: peridotite, lizardite, chrysotile, magnetite, brucite, stress, tension fracture, vein, pervasive serpentinization, continental serpentinization, Quebec Appalachians.

SOMMAIRE

Deux types de serpentinites de la région de Thetford Mines – Black Lake ont été étudiés sous le microscope et analysés par diffraction X et par microsonde électronique. Le premier a été échantillonné à la mine du lac d'Amiante et le second dans la région de Vimy Ridge. L'échantillon représentatif de la mine du lac d'Amiante a échappé à la serpentinization océanique, et a été serpentinisé seulement pendant l'épisode continental. Il présente toutes les transitions entre la péridotite saine et la veine de chrysotile. Dans cette transition, on observe les variations minéralogiques et chimiques suivantes: (1) l'olivine est transformée soit en lizardite, soit en chrysotile dans les microveines de la péridotite. (2) La péridotite se trouve serpentinisée dans une étroite zone entourant les veines de chrysotile. (3) Les rapports Mg/(Fe+Mg) and Mg/Si varient comme suit: a) ils croissent dans les microveines de lizardite, et b) Mg/(Fe+Mg) tend à rester contant dans la zone serpentinisée, tandis que Mg/Si diminue sensiblement. Les échantillons de Vimy Ridge présentent des veines rubanées typiques. Ces roches ont été serpentinisées pendant les épisodes océanique et continental. Elles montrent les variations suivantes: (1) les rapports Mg/(Fe+Mg) et Mg/Si croissent de la bordure vers le centre des veines de chrysotile. (2) La roche encaissante à lizardite montre de grandes variations dans les rapports de Mg/(Fe+Mg) et Mg/Si, sans relation évidente avec la distance jusqu'aux parois de la veine.

Mots-clés: péridote, lizardite, chrysotile, magnétite, brucite, contrainte, fracture tensionnelle, veine, serpentinisation pénétrante, serpentinisation continentale, Appalaches québécoises.

INTRODUCTION

The chrysotile asbestos deposits of Quebec are associated with serpentinized ultramafic rocks forming the lower unit of ophiolites in the Eastern Townships of Quebec. The principal asbestos deposits are located at Thetford Mines, Black Lake and Asbestos (Fig. 1).

The following characteristics are common to all these deposits (Cooke 1937, Riordon 1975, Lamarche & Wicks 1975). (1) They are situated near the lower tectonic contact of peridotite with Cambrian country rocks. (2) Faults, shear-zones and fractures control the location of asbestos veins within the peridotites. (3) Sheets of granitic rocks are present within or in the vicinity of the deposits. (4) The peridotite host-rocks underwent two distinct episodes of serpentinization.

The ophiolites of the Appalachians occur in a narrow structural belt extending from Baie Verte (Newfoundland) to Brompton Lake (southern Quebec).

*Publication 26-83, Ottawa-Carleton Centre for Geoscience Studies.

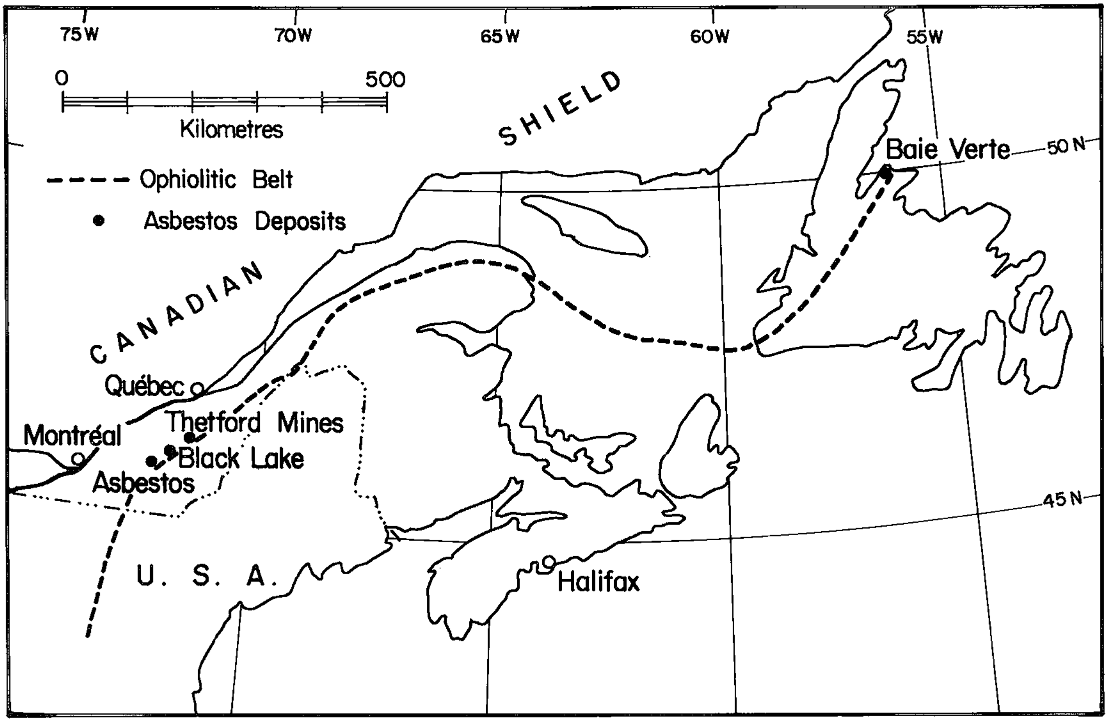

FIG. 1. Location of the principal asbestos deposits in southern Quebec.

They represent parts of slices of upper mantle and Proto-Atlantic oceanic crust obducted onto the North American plate during the Lower of Middle Ordovician (Church & Stevens 1971, Laurent 1975, 1979). During their evolution the ultramafic rocks were subjected to serpentinization in two main episodes: an early episode when they were still part of the ocean floor and a later episode when they were incorporated into the North American plate (Laurent 1975, Laurent & Hébert 1979).

The oceanic episode took place under conditions of relatively low fugacity of oxygen and at temperatures lower than 340° C, giving rise to a pervasive serpentinization essentially characterized by the pseudomorphic replacement of olivine and orthopyroxene by lizardite ± chrysotile and magnetite (Laurent & Hébert 1979). The later, continental episode occurred when the ophiolites were tectonically emplaced in their present position. During this late episode the commercial veins of chrysotile asbestos were formed. Oxygen-rich meteoric waters, perhaps mixed with connate water, played an important role during the second episode of serpentinization, which has overprinted the first. Serpentine minerals of the oceanic episode were reworked while chrysotile fibres grew in dilation fractures and tension gashes filled by serpentine-saturated solutions.

Some peridotite bodies contain zones that have been preserved from the pervasive serpentinization of the oceanic episode. The Lake Asbestos and British Canadian deposits of Black Lake locally contain fresh peridotite cut by narrow serpentinized zones that encase veins of chrysotile asbestos (Fig. 2). This particular occurrence provides the opportunity for a detailed study of the genesis of the chrysotile asbestos vein-association in the absence of effects of the first, pervasive serpentinization. The serpentine textures and mineral associations produced by pervasive serpentinization of the peridotite have been described in detail by Cressey (1979), Wicks & Plant (1979), Wicks & Whittaker (1977) and Wicks *et al.* (1977), but the textures and mineral associations of the chrysotile asbestos veins have not been as extensively studied. The purpose of this paper is to describe and interpret the mineralogical and chemical variations of asbestos veins and adjacent host-rocks produced during the single episode of formation of chrysotile ore. In order to do this, we have chosen to study samples of fresh peridotite bearing chrysotile veins and the associated serpentinized zone. This report is a summary of our preliminary work.

Location of Samples

A representative sample from the Lake Asbestos

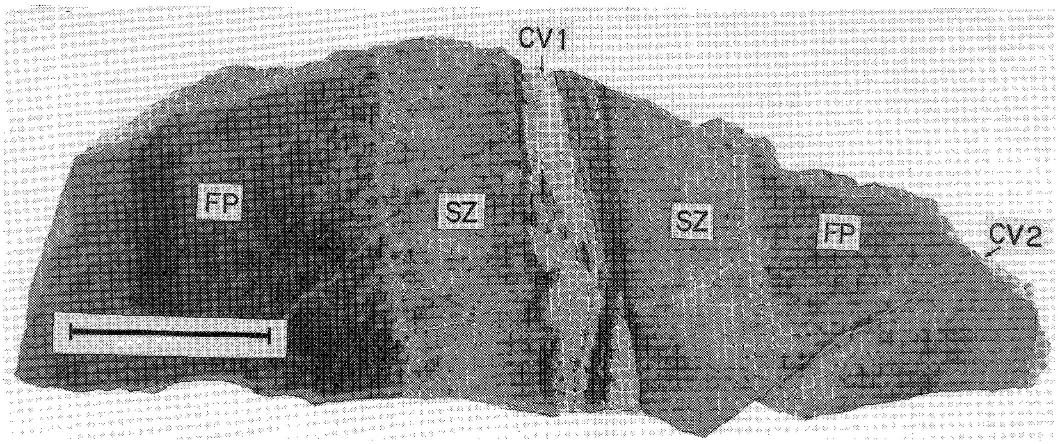

FIG. 2. Fresh peridotite containing chrysotile asbestos veins with enclosing serpentinized zone. Lake Asbestos mine, Black Lake. FP fresh peridotite, SZ serpentinized zone, CV1 longitudinal vein, CV2 diagonal vein. Scale bar represents 5 cm.

deposit (SE pit, elevation 46 m; mine co-ordinates: N46.015, E71.220) contains fresh peridotite and chrysotile veins surrounded by a serpentinized zone (SZ, Fig. 2). The chrysotile veins occupy the central part of the serpentinized zone. They fill a stockwork of longitudinal, cross and diagonal joints, of which longitudinal veins are the thickest and may reach 3 cm across (CV1, Fig. 2). Diagonal veins (CV2) are of medium thickness (0.5 cm), whereas cross veins (CV3; see Fig. 4) are the thinnest (less than 1 mm). The latter are perpendicular to the longitudinal veins and only occur within the serpentinized zone associated with the large veins. The contact of the veins of chrysotile asbestos with the wall rock is sharp, although not always linear. Veins of picrolite are sometimes present within the longitudinal veins of chrysotile. Two samples from the Vimy Ridge deposit (mine co-ordinates: N46.004, E 71.250) are typical ribbon-veined asbestos ore (Cooke 1937, Riordon 1975). They contain sets of simple, parallel veins of chrysotile, the width of the veins varying between 1 and 5 mm. The host peridotite has undergone serpentinization during both the oceanic and continental episodes.

Methods of Study

Samples were studied petrographically and analyzed by X-ray powder diffraction and electron microprobe. The powder-diffraction method of identification used for serpentine minerals was that of Whittaker & Zussman (1956). Microprobe analyses were done with an ARL electron microprobe (EMX-SM121000) at 20 kV and 10 μA using natural olivine and diopside standards provided by the Geophysical Laboratory, Carnegie Institution of Washington. Integration time was ten seconds, and four points were examined per analysis. The data were corrected using a ZAF program. Replicate analyses of standards indicate that the determinations have a relative accuracy of $\pm$ 1 to 2% for major elements. The serpentine-group minerals were identified independently using a Gandolfi 114.6-mm-diameter camera with nickel-filtered Cu*K*α radiation. Six compositions given on Table 1 were determined with a Cambridge Mark V electron microprobe (Carleton University, Ottawa). Specimens were analyzed with 15 kV acceleration potential and a beam current of 50 nA as measured on pure iron. Raw X-ray data were reduced using the computer program of Rucklidge and Gasparrini (1969). Measured major elements are accurate to 1 to 2%.

The terminology used in this paper relating to serpentinization follows that of Wicks *et al.* (1977) and Wicks & Whittaker (1977).

MINERALOGY

The Lake Asbestos deposit

The host peridotite has a harzburgitic composition, with olivine (65–95%), orthopyroxene (5–35%) and chromian spinel (less than 1%). The representative sample of this deposit contains all transitions from fresh peridotite to completely serpentinized peridotite with associated veins of chrysotile asbestos (Fig. 2). The dark olive-green fresh peridotite is easily distinguished from the strongly serpentinized yellowish green zone surrounding the veins. The thickness of the serpentinized zone varies in proportion to the thickness of the chrysotile vein, the ratio of the thickness of the serpentinized zone to that of the vein varying between 8 and 3. In the representative sample of the Lake Asbestos deposit, the

TABLE 1. LIZARDITE MICROVEINS IN FRESH PERIDOTITES, LAKE ASBESTOS DEPOSIT*

	1	2	3	4	5	6	7	8
SiO_2	42.36	40.54	40.20	41.17	41.29	42.1	40.17	42.0
Al_2O_3	0.40	0.37	0.40	0.35	0.42	-	0.32	-
MgO	40.78	41.01	40.97	40.81	40.47	43.4	41.26	43.9
FeO	1.94	1.57	1.62	1.67	1.53	1.40	1.38	1.30
Cr_2O_3	0.00	0.00	0.01	0.02	0.10	-	0.02	-
MnO	0.06	0.06	0.06	0.04	0.07	0.1	0.05	-
NiO	0.34	0.41	0.25	0.20	0.42	-	0.26	-
Total	85.88	83.96	83.51	84.26	84.31	87.0	83.47	87.2
Mg/(Fe+Mg)	0.976	0.980	0.980	0.979	0.981	0.982	0.982	0.984
Mg/Si	1.44	1.51	1.52	1.48	1.47	1.54	1.54	1.56

* Samples are arranged in order of decreasing distance from the vein (see Figs. 4 and 5). The symbol "-" signifies "below detection limit". Analyses 1, 2, 3, 4, 5, 7 were done on Cambridge Mark V microprobe (Carleton University, Ottawa), and analyses 6 and 8 on the ARL microprobe (Université Laval, Québec).

thickness of the serpentinized zone is 70 mm (twice 35 mm); the thickness of the longitudinal chrysotile vein is 18 mm; the ratio serpentinized zone/chrysotile vein is 3.89. The total volume of the serpentinized zone has been increased by 25% owing to the development of the chrysotile asbestos vein.

According to Cooke (1937), this ratio is relatively constant in a given orebody, but varies from one orebody to the next (see Tables VII to X, Cooke 1937). Our petrographic work suggests that the ratio is mainly controlled by the degree of serpentinization of the serpentinized zone adjacent to the vein. Where this zone is wholly serpentinized, the ratio is at a minimum (between 3 and 4). Where the degree of serpentinization of this zone decreases, the ratio of the thickness of the serpentinized zone to that of the chrysotile vein increases up to 8 or more. However, the thickness of the vein can also vary independently from that of the serpentinized zone, which indicates that the development of a vein is controlled by more than one factor. The stress field and the chemical parameters of the environment of formation are considered to be important in this respect. Those points cannot be handled statistically at this stage of our work because we cannot determine accurately in the field the degree of serpentinization of the serpentinized zones adjacent to the veins. This is the main reason why we selected a suite of samples; we describe in detail a representative example of that suite.

Two types of chrysotile veins are distinguished on the basis of their internal structure: simple or composite. The simple type consists of a single vein composed of chrysotile fibres that are continuous from wall to wall. Composite veins consist of groups of several veins varying in composition and structure. There are composite veins composed of chrysotile asbestos with picrolite, the latter forming bands or lenses parallel to walls. Another type of composite vein contains veins of magnetite and brucite that cut obliquely across veins of chrysotile fibres.

Petrographic examination of the fresh peridotite reveals two types of microveins: fracture filling and replacement. The former type shows sharp and linear contacts and cuts across the olivine grain-boundaries; these microveins are also parallel to the main vein CV1 and are filled by ribbon-type lizardite along the margin and magnetite at the vein centre (RL, Fig. 3a). Replacement veins have serrated margins and display a gradual replacement of olivine by serpentine. There are two systems of serrated veins, both diagonal with respect to the main vein (CV1). System 1 (Liz V1) consists of simple lizardite replacing olivine; it cuts the second system 2 (Liz V2) at an angle of 40–45°. The veins of the latter are thicker and zoned, with a central zone of chrysotile developed by replacement of the lizardite forming the border zone (Figs. 3a, 4). The contact between these two serpentine minerals is serrated. The veins of the system Liz V2 are parallel to the diagonal veins of chrysotile (CV2).

In some cases the serrated veins of chrysotile are observed in fresh peridotite. These veins are also zoned, with a marginal zone composed of chrysotile replacing the olivine wall (Fig. 3b). The central zone is filled with cross fibres of chrysotile and magnetite. The contact between the marginal and central zones is sharp.

Peridotite grades into serpentinite through a narrow transition zone averaging 1 mm in thickness. The mesh texture is characteristic of this transition; olivine relics are surrounded by lizardite or chrysotile rims (Fig. 3c). The serpentinized zone consists mainly of lizardite, replacement chrysotile, brucite and magnetite.

The hourglass texture dominates in the serpentinized zone; however, it is commonly overprinted by the replacement of lizardite by either chrysotile or brucite and magnetite. The replacement chrysotile has developed along and oriented roughly normal to microfractures, and produces a microscopic vein with sharply serrated margins (Fig. 3d). The microfractures are irregular and tightly closed, with no serpentine developed in the plane of the fracture. Where the microfractures are closely spaced, almost complete replacement of the lizardite occurs, which gives rise to a variety of massive ore of chrysotile asbestos called mass fibre. Close to the main veins of chrysotile, the microfractures are commonly oriented parallel to veins, and the wall rock is completely transformed into replacement chrysotile.

In the chrysotile asbestos veins, the growth of cross fibres is uninterrupted from one wall to the other. Fibrous magnetite was formed parallel to the chrysotile fibres. In some cases the magnetite crystals form cone-shaped groups whose tops lie at the centre of the veins; in other cases, magnetite cones extend from one wall to the other (Fig. 3e). Under the microscope the picrolite displays one of two different textures, cryptocrystalline or banded. X-ray powder-diffrac-

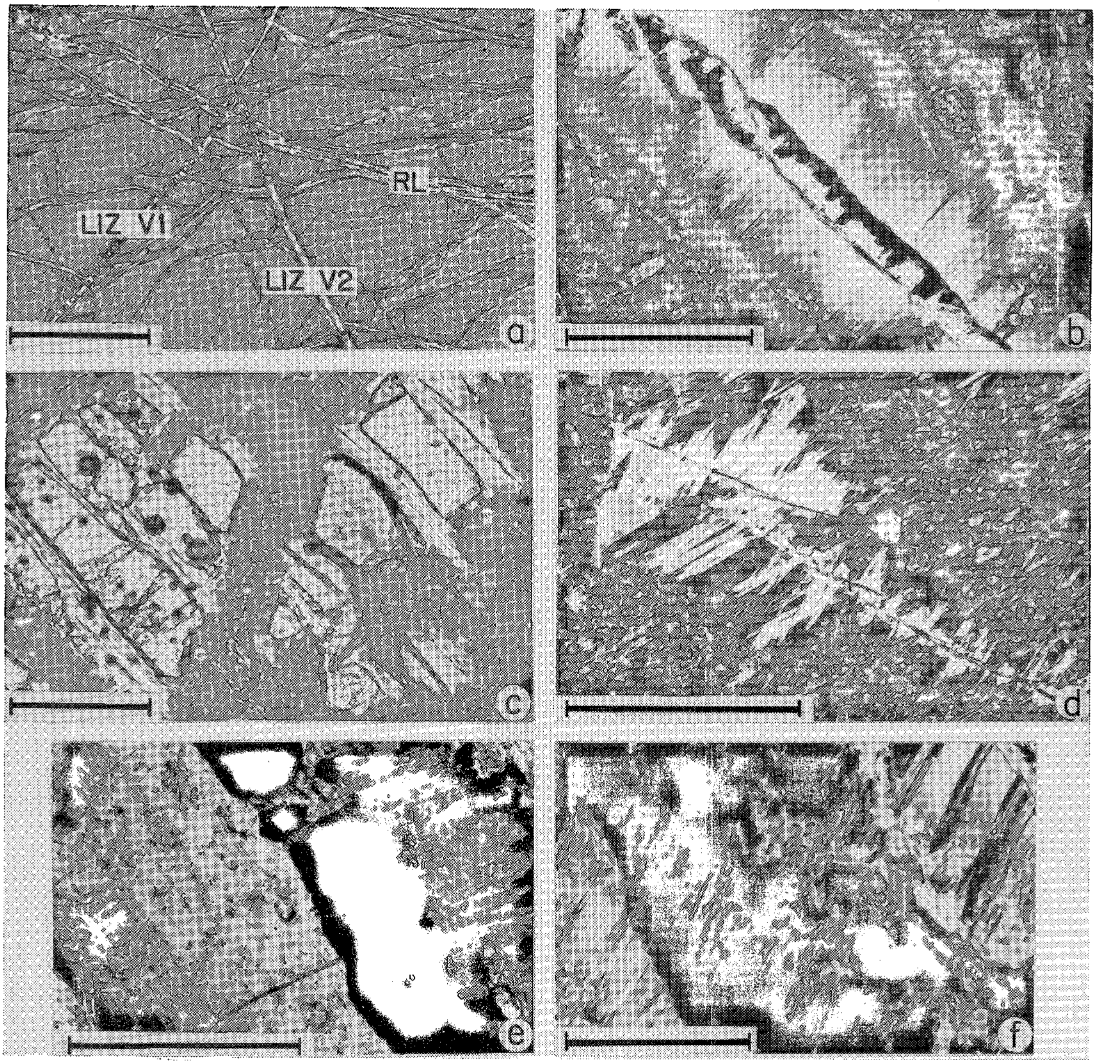

FIG. 3. a) Lizardite microveins in fresh peridotite. RL: ribbon lizardite. Liz V1 diagonal vein of system 1; Liz V2 diagonal vein of system 2. Lake Asbestos mine. Polarized light. Scale bar represents 0.4 mm. b) Serrated chrysotile vein replacing olivine. The central part of the vein consists of chrysotile and magnetite fibres. British Canadian mine, Black Lake. Polarized light. Bar scale represents 0.2 mm. c) Mesh texture in the transition zone. Mesh centre of olivine surrounded by mesh rim of lizardite. Lake Asbestos mine. Polarized light. Bar scale represents 0.4 mm. d) Serrated veins of replacement chrysotile in the serpentinized zone. Replacement chrysotile was partly replaced by later brucite and magnetite. Lake Asbestos mine. Polarized light. Bar scale represents 1 mm. e) Composite vein. Right-hand side: magnetite and chrysotile fibres. Left-hand side: banded picrolite. Lake Asbestos mine. Polarized light. Bar scale represent 1 mm. f) Composite vein. Chrysotile–magnetite fibres (upper right and lower left). Brucite and nonfibrous magnetite-bearing vein (centre). Lake Asbestos mine. Polarized light. Bar scale represents 4 mm.

tion analysis reveals that the cryptocrystalline picrolite is composed of lizardite, and the banded picrolite, which is made up of "apparent fibres" of γ-serpentine lying perpendicular to the banding (Fig. 3e), is composed of clinochrysotile. In deformed composite veins the picrolite veins are bent or broken and, in some cases, form *en échelon* lenses. In composite veins the contact between veins of magnetite–brucite and of chrysotile asbestos is very sharp (Fig. 3f).

The Vimy Ridge deposit

Samples from the Vimy Ridge deposit contain

TABLE 2. LIZARDITE IN THE SERPENTINIZED ZONE, LAKE ASBESTOS DEPOSIT*

	1	2	3	4	5	6	7	8
SiO_2	43.2	42.8	42.8	42.0	42.3	43.2	42.4	43.8
Al_2O_3	-	-	0.4	0.3	0.1	0.1	1.0	-
MgO	41.0	41.7	39.3	39.6	39.1	38.9	38.6	42.8
FeO	1.2	1.0	1.0	1.1	1.0	1.0	1.0	1.1
MnO	0.1	0.1	0.1	-	-	-	0.1	-
Total	85.5	85.6	83.5	83.0	82.5	83.2	83.1	87.7
Mg/(Fe+Mg)	0.985	0.986	0.986	0.986	0.986	0.986	0.986	0.986
Mg/Si	1.41	1.45	1.37	1.41	1.38	1.35	1.36	1.45

* Samples are arranged in order of decreasing distance from the vein (see Figs. 4 and 5). Analyses were done on the ARL electron microprobe (Université Laval, Québec).

TABLE 3. REPLACEMENT CHRYSOTILE IN THE SERPENTINIZED ZONE, LAKE ASBESTOS DEPOSIT*

	1	2	3	4	5	6	7	8
SiO_2	43.0	44.4	44.1	43.1	41.6	41.9	42.0	43.7
Al_2O_3	-	-	-	-	-	0.4	-	-
MgO	43.1	42.0	42.2	40.7	39.2	39.2	39.2	41.8
FeO	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
MnO	0.1	0.1	0.1	-	-	0.1	0.1	-
Total	87.1	87.4	87.3	84.7	81.7	82.5	82.2	86.4
Mg/(Fe+Mg)	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990
Mg/Si	1.50	1.44	1.42	1.46	1.40	1.39	1.39	1.42

* Samples are arranged in order of decreasing distance from the vein (see Figs. 4 and 5). Analyses were done on the ARL electron microprobe (Université Laval, Québec).

numerous parallel simple veins. Microscope examination reveals that the wall rock between chrysotile asbestos veins was completely serpentinized. Rock textures are similar to those observed in the serpentinized zone of Figure 2, but the main constituents are lizardite, bastite and magnetite. The hourglass texture is dominant, and serrated veins are commonly observed. The relict texture of serrated replacement-chrysotile was transformed almost completely into lizardite during the second episode of serpentinization. Pyroxene may be pseudomorphically replaced by either lizardite or chlorite. Magnetite forms either subhedral disseminated grains or a vein-filling. Sharp-walled asbestos veins commonly cut bastite and lizardite grains into two halves that can be observed on both sides of the veins. The growth of chrysotile is uninterrupted between the two walls. Fibrous magnetite was in some instances formed parallel to chrysotile.

Chemical Data

Lakes Asbestos

Systematic microprobe analyses were done on the sample shown in Figures 2 and 4 between points A and B, where a complete transition between the fresh peridotite to completely serpentinized peridotite with associated chrysotile asbestos veins is displayed. Data are given in Tables 1 to 3.

The cation Mg/(Fe+Mg) and Mg/Si ratios (Figs. 4, 5, 6) were calculated on the basis of the major oxide data (Tables 1 to 5). These values indicate that (1) the Mg/(Fe+Mg) and Mg/Si ratios of the lizardite microveins in the fresh peridotite, the lizardite and the replacement chrysotile in the serpentinized zone all are distinctly different (Figs. 4, 5). Thus, the chemical data confirm that these phases constitute distinct paragenetic groups. (2) The following changes occur as the chrysotile asbestos vein is approached from point A within the wall rock: a) Mg/(Fe+Mg) and Mg/Si increase in the lizardite microveins of the fresh peridotite (Figs. 4, 5). b) The ratio Mg/(Fe+Mg) tends to remain constant in the lizardite of the intensely serpentinized zone (SZ) (Fig. 4). c) The same ratio remains constant in the replacement chrysotile of the SZ (Fig. 4). d) The ratio Mg/Si tends to decrease in the lizardite and the replacement chrysotile of the SZ (Fig. 5). e) Each petrogenetic group of serpentine is chemically distinct from the others in term of their respective Mg:Fe:Si proportions, as shown on a variation diagram of Mg/Si *versus* Mg/(Fe+Mg) (Fig. 6).

Vimy Ridge

Microprobe analyses were performed at the margin and centre of the asbestos chrysotile veins as well as in the lizardite wall-rock. Data are given in Tables 4 and 5 and in Figure 6. These data indicate that: a) In vein-filling chrysotile, the Mg/(Fe+Mg) and Mg/Si ratios increase from the margin to the centre (Fig. 6). This trend is clearly shown by the veins 3 and 4, which have a thickness of about 5 mm. A similar trend in Mg/Si is apparent for veins 1 and 2, which are thinner. In this case the points analyzed with the microprobe were separated by no more than 0.5 mm. The observed trend is analogous to the development stages since the chrysotile fibres started forming at the margin (M) and grew toward the centre (C). The change in chemical composition appears to be regular and identical in veins 3 and 4 of sample 114779 and in veins 1 and 2 of sample 3828772. b) The lizardite forming the wall rock of the chrysotile veins shows major variations in Mg/(Fe+Mg) and Mg/Si (Fig. 6), but these variations are apparently not related to the distance separating the lizardite from the chrysotile vein. c) The values of Mg/(Fe+Mg) in the vein-filling chrysotile at Vimy Ridge are much lower than those of the replacement chrysotile in the SZ at Lake Asbestos. Values of the Mg/Si ratio are similar.

Discussion and Interpretation

Field observations and structural studies of the chrysotile veins in the asbestos belt of southern Quebec indicate that they fill a stockwork of expansion fractures (Cooke 1937, Riordon 1955, Riordon & Laliberté 1972, Laurent 1975, Laurent & Hébert 1979). The material cementing the fractures and

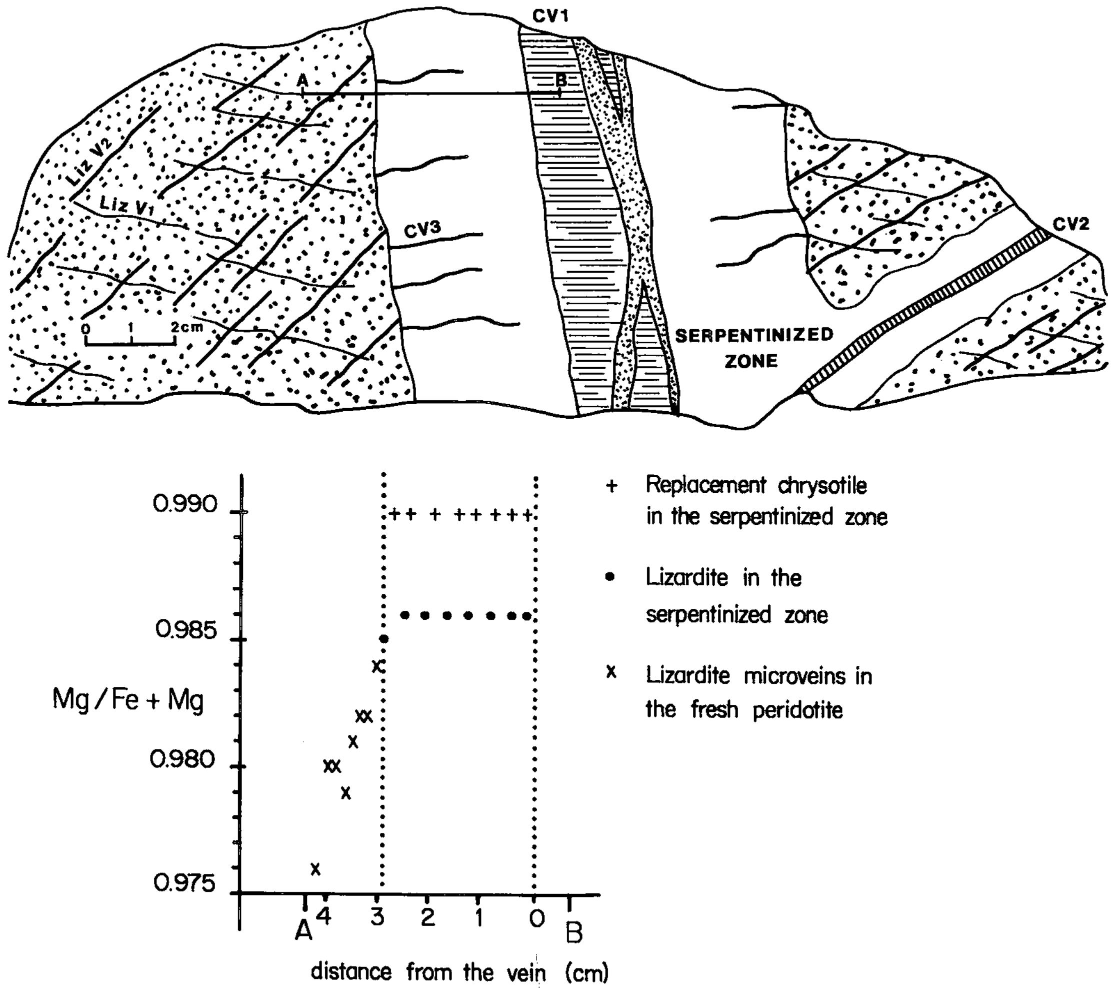

FIG. 4. Variation diagram showing Mg/(Fe + Mg) *versus* distance from the longitudinal vein of chrysotile. Representative sample of the Lake Asbestos mine (see Figure 2).

forming the chrysotile veins has a similar chemical composition to the host rock and presumably was derived by solution or diffusion from the wall rock. As the process of serpentinization is promoted by a highly mobile fluid phase, there is a clear potential here for mass transfer; the development of chrysotile veins illustrates the mobility of the major elements Mg, Si and Fe during serpentinization. In this study, we have attempted to document the main steps of this mobilization.

The paragenetic mineral assemblages of the wall rock and asbestos vein are similar and mainly consist of serpentine, magnetite and brucite. This similarity in mineral composition is consistent with synchronous formation and close cogenetic relationship of the two assemblages, as has been pointed out previously by Lamarche & Wicks (1975), Wicks (1979) and Wicks & Plant (1979). Lizardite, replacement chrysotile, magnetite and brucite make up the bulk of the strongly serpentinized zone adjacent to the chrysotile asbestos veins. The asbestos veins are usually composed of chrysotile and fibrous magnetite. Brucite is very rare except in composite veins, where it is associated with nonfibrous magnetite. This observation has an obvious bearing on the problem of mass transfer. It documents depletion of Si and the existence of an excess of Mg and Fe in the system at a relatively late stage of the serpentinization process. Excess Mg is taken up by brucite, and excess Fe, by magnetite.

Has all excess mobilized Mg and Fe finally been precipitated and kept in the system, or have substan-

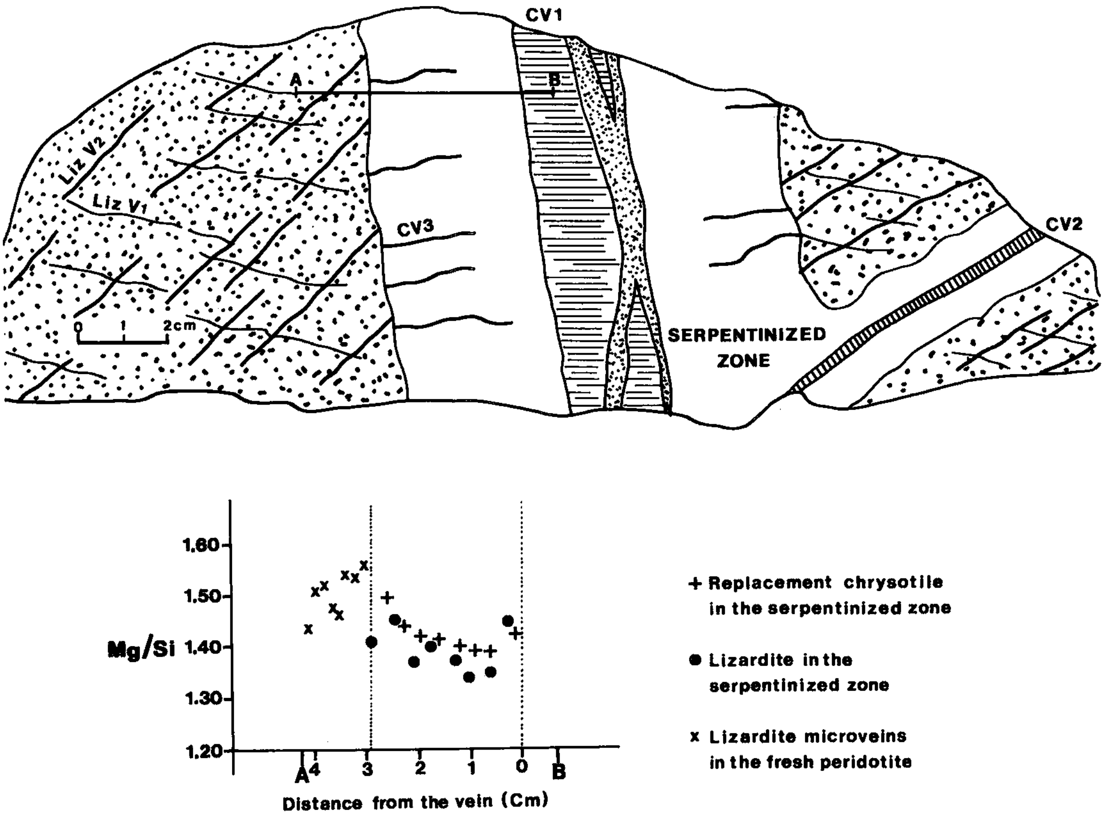

FIG. 5. Variation diagram showing Mg/Si *versus* distance from the longitudinal vein of chrysotile. Lake Asbestos mine (see Figure 2).

tial amounts of Mg and Fe been removed from the system? The precise amount of brucite and magnetite formed during serpentinization cannot be ascertained because of their irregular distribution, so that it is not possible to make direct mass-balance calculations. Another approach is possible on the basis of volume changes. The volume occupied by a vein is equal to the increase in volume of the serpentinized zone adjacent to the vein. This measurement indicates volume increases varying between 10 and 35%. In the case of the sample from Lake Asbestos mines, the increase in volume is 25%. Calculations predict volume increases of about 40% when the serpentinization reaction produces chrysotile (88 volume %) and magnetite (12%); the increase is about 50% when chrysotile (82%) and brucite (18%) are produced. When both magnetite and brucite are produced by serpentinization, the increase in volume must vary between 40 and 50%. There is a large discrepancy between the observed and calculated changes in volume. The observed changes in volume are not sufficiently large, even when one takes into consideration the orthopyroxene content of the peridotite and the sum of the R^{2+} cations in the rock-forming olivine and orthopyroxene. This theoretical consideration and the late occurrence and irregular distribution of brucite and magnetite in wall rocks and veins strongly suggest that an average loss is around 10 (oxide volume) % of MgO and FeO, which have been removed from the system. The country rock in contact with peridotite is strongly chloritized, and this chlorite-bearing reaction zone could be a by-product of the transfer in solution of Mg and Fe from the peridotite into the nearby silica-rich rocks.

At the sample scale, the microprobe work documents the main stages of mobilization and defines the chemical trends. Embryonic serpentinization starts with the development of lizardite and magnetite microveins in the fresh peridotite. Within the strongly serpentinized zone adjacent to a chrysotile asbestos vein, lizardite develops extensively from the lattice of microveins previously formed. Replacement chrysotile and magnetite constitute the following phase; finally, brucite and magnetite replace the former minerals in the last phase of

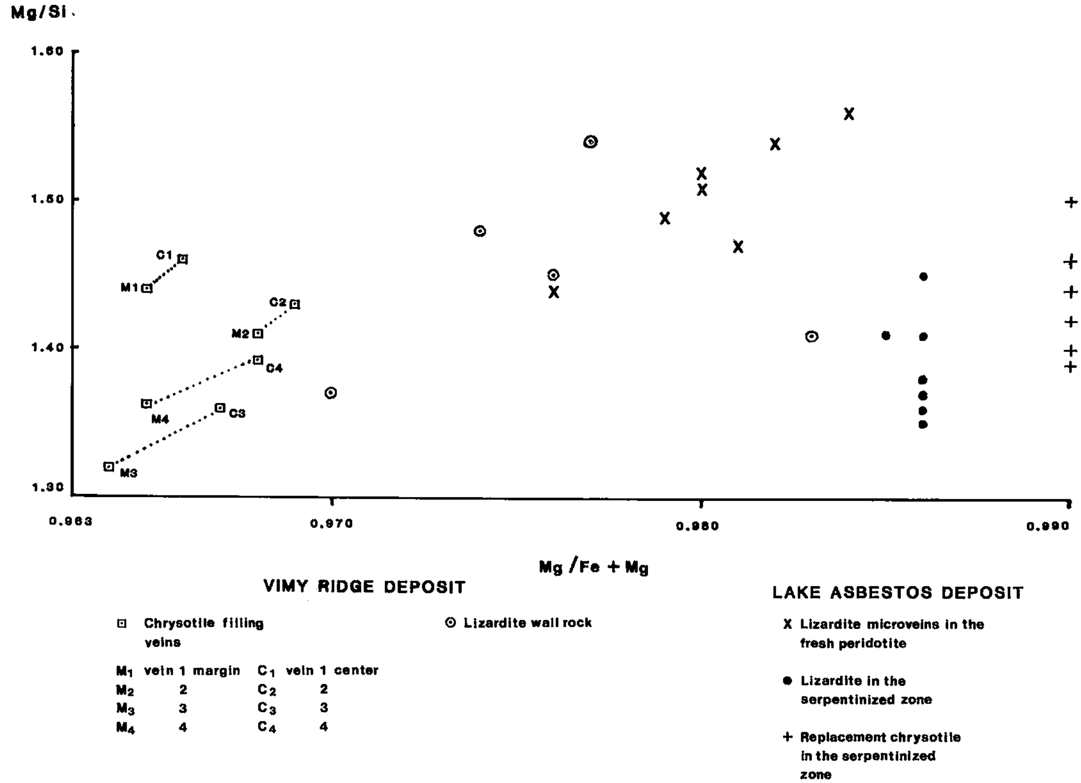

FIG. 6. Variation diagram showing Mg/Si *versus* Mg/(Fe + Mg).

serpentinization within the wall rock. During this evolution, the composition of serpentine varies systematically (Figs. 4, 5). The ratio Mg/(Fe + Mg) increases from the lizardite microveins to the replacement chrysotile, whereas Mg/Si decreases. This trend shows that the Fe content of the successive serpentine minerals decreases.

This evolution is reproduced even at the much smaller scale of single crystals, as illustrated by the data on the chrysotile veins from Vimy Ridge. The chrysotile fibres of Vimy Ridge have relatively low values of the low Mg/(Fe + Mg) ratio at the beginning of their growth (margin), and higher values of the Mg/(Fe + Mg) ratio in their final stage of growth (centre). From our microprobe data it is clear that the tendency for Fe to enter into the serpentine structure decreases during serpentinization. This necessarily leads to Fe enrichment in the residual fluid during the late stages of the process.

The lizardite forming the wall rock of the Vimy Ridge chrysotile veins shows large chemical variations (Fig. 6), with no clear trend with respect to either mode of genesis of the lizardite or distance from the vein contact. This large chemical variation may result from multistage serpentinization. The rock was first pervasively altered during an episode of oceanic serpentinization and was later reserpentinized during the late episode that led to the development of the chrysotile veins. Multistage lizardite, as defined by our data, has a Mg/(Fe + Mg) ratio intermediate between that of the Lake Asbestos lizardite and the vein-filling chrysotile. Therefore, the wall-rock lizardite of Vimy Ridge represents multistage serpentinization, in contrast to the single-stage lizardite of Lake Asbestos (an observation in agreement with the model of evolution).

The process of formation of asbestos is initiated by the reaction of water with the olivine and orthopyroxene of the peridotite. These minerals are pro-

TABLE 4. CHRYSOTILE ASBESTOS FILLING VIMY RIDGE TYPE VEINS*

	Vein 1 Margin	Vein 1 Centre	Vein 2 Margin	Vein 2 Centre	Vein 3 Margin	Vein 3 Centre	Vein 4 Margin	Vein 4 Centre
SiO_2	40.5	40.3	41.3	40.7	44.0	44.9	43.7	42.3
Al_2O_3	1.2	1.0	1.0	1.1	0.4	0.7	0.5	0.6
MgO	39.2	39.3	39.1	39.2	39.2	40.9	40.0	39.7
FeO	2.5	2.5	2.4	2.3	2.6	2.6	2.6	2.5
MnO	0.08	0.08	0.08	0.1	0.05	0.1	0.04	0.04
NiO	0.08	0.1	0.13	0.05	-	-	-	
Total	83.63	83.28	84.01	83.51	86.25	89.2	86.84	85.4
Mg/(Fe+Mg)	0.965	0.966	0.968	0.969	0.964	0.967	0.965	0.968
Mg/Si	1.44	1.46	1.41	1.43	1.32	1.36	1.37	1.39

* Veins 1 and 2, from sample 3828779 Vimy Ridge. Veins 3 and 4, from sample 114779 Vimy Ridge. Analyses were done on the ARL electron microprobe (Université Laval, Québec).

TABLE 5. LIZARDITE IN THE WALL ROCK OF VIMY RIDGE TYPE VEIN*

	1	2	3	4	5
SiO_2	41.1	41.3	40.0	43.5	43.1
Al_2O_3	0.8	0.9	1.0	0.6	0.7
MgO	40.8	40.3	41.3	40.1	40.8
FeO	2.0	1.8	1.8	2.3	2.7
MnO	0.08	0.08	0.05	0.03	0.03
NiO	0.1	-	0.2	-	-
Total:	84.88	84.38	84.38	86.53	87.33
Mg/(Fe+Mg)	0.974	0.976	0.977	0.970	0.983
Mg/Si	1.48	1.45	1.54	1.37	1.41

* Analyses 1, 2 and 3 from sample 3828772 Vimy Ridge. Analyses 4 and 5 from sample 114779 Vimy Ridge. Analyses were done on the ARL electron microprobe (Université Laval, Québec).

gressively replaced pseudomorphically by variable amounts of lizardite and chrysostile (± brucite and magnetite). A lattice of interconnected microveins of lizardite or chrysotile (or both), as shown by the Lake Asbestos sample, appears to represent the pathway of introduction of serpentinizing solutions, making possible chemical transfer. The microveins result from a combination of processes involving replacement, dissolution and precipitation. The development of the microvein lattice combined with the progressive replacement of the mineral grains causes the system to expand in volume.

The fibrous texture of the chrysotile and magnetite results from incremental dilations in tensile fractures (Durney & Ramsay 1973) for the cross fibres, or sometimes in shear fractures for the slip fibres. The growth of the chrysotile fibres is parallel to the direction of the minimum shear-stress. When the local stress-field is modified, the opening of the fracture and the growth of the fibres cease or change. A simple vein may remain preserved at this stage, or reopening of the fracture may occur, and a new generation of fibres may form as a distinct vein, or in continuation of the previously formed fibres. Which case occurs depends upon the stress field and the chemical environment. Significant changes in these factors will promote a new and distinct generation of veins.

CONCLUSIONS

1. The development of chrysotile veins in the asbestos belt of southern Quebec illustrates the mobility of the major elements Mg, Fe and Si during serpentinization.
2. The similarity in mineral composition between the wall rock and the veins implies that the assumption of synchronous formation and close cogenetic relationship between the two is valid.
3. Each petrogenetic group of serpentine is chemically distinct in terms of its Mg:Fe:Si proportions.
4. Removal of major elements occurred during serpentinization; Mg, Fe and Si were removed in solution from the peridotite and precipitated in the tension fractures to form fibrous chrysotile asbestos and magnetite.
5. Excess Mg and Fe crystallized later to form brucite and nonfibrous magnetite-bearing veins.

ACKNOWLEDGMENTS

We thank Dr. F.J. Wicks, Royal Ontario Ontario Museum, for constructive comments on this manuscript, and Dr. B.R. Rust, University of Ottawa, for reviewing the paper. This study was supported by the grant A8293 from the Natural Sciences and Engineering Research Council of Canada and by a joint grant from the Direction Générale de l'Enseignement Supérieur, Québec.

REFERENCES

CHURCH, W.R. & STEVENS, R.K. (1971): Early Proterozoic ophiolite complexes of the Newfoundland Appalachians as mantle–oceanic crust sequences. *J. Geophys. Res.* **76**, 1460-1466.

COOKE, H.C. (1937): Thetford, Disraeli and eastern half of Warwick map-areas, Quebec. *Geol. Surv. Can. Mem.* **211.**

CRESSEY, B.A. (1979): Electron microscopic studies of serpentine textures. *Can. Mineral.* **17**, 741-756.

DURNEY, D.W. & RAMSAY, J.G. (1973): Incremental strains measured by syntectonic crystal growth. *In* Gravity and Tectonics (K.A. Dejong & R. Scholten, eds.). J. Wiley & Sons, New York.

LAMARCHE, R.Y. & WICKS, F.J. (1975): Where to look for new asbestos deposits. *Third Int. Conf. Physics and Chemistry of Asbestos Minerals* (Univ. Laval) (abstr.).

LAURENT, R. (1975): Occurrences and origin of the ophiolites of southern Quebec, northern Appalachians. *Can. J. Earth Sci.* **12,** 443-455.

______ (1979): Environment of formation, evolution and emplacement of the Appalachian ophiolites from Quebec. *In* Ophiolites (A. Panayiotou, ed.), Proc. Ophiolite Symp. (Cyprus), 628-636.

______ & HÉBERT, Y. (1979): Paragenesis of serpentine assemblages in tectonite and dunite cumulate from the Québec Appalachians. *Can. Mineral.* **17**, 857-869.

RIORDON, P.H. (1975): Geology of the asbestos deposits of southern Quebec. *Ministère Rich. Nat. Québec, E.S.* **18.**

_____ & Laliberté R. (1972): Asbestos deposits of southern Quebec. *Int. Geol. Congr. 24th, Guidebook, Excursion B-08.*

Rucklidge, J.C. & Gasparrini, E.L. (1969): Specifications of a computer program for processing electron microprobe analytical data: EMPADR VII. *Dep. Geol., Univ. Toronto.*

Whittaker, E.J.W. & Zussman, J. (1956): The characterization of serpentine minerals by X-ray diffraction. *Mineral. Mag.* **31**, 107-126.

Wicks, F.J. (1979): Mineralogy, chemistry and crystallography of chrysotile. *Mineral. Assoc. Can. Short Course Handbook* **4**, 35-78.

_____ & Plant, A.G. (1979): Electron-microprobe and X-ray-microbeam studies of serpentine textures. *Can. Mineral.* **17**, 785-830.

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

_____, _____ & Zussman, J. (1977): An idealized model for serpentine textures after olivine. *Can. Mineral.* **15**, 446-458.

Received October 10, 1983, revised manuscript accepted January 11, 1984.