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PARAGENESIS OF SERPENTINE ASSEMBLAGES IN HARZBURGITE TECTONITE AND DUNITE CUMULATE FROM THE QUÉBEC APPALACHIANS

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Abstract

Two types of peridotite occur within the ophiolite suites of the Quebec Appalachians: (1) a harzburgite tectonite of mantle origin, which forms the basal unit of the ophiolite complexes, and (2) an overlying dunite of cumulate origin. Both types are serpentinized, but only the first clearly shows ubiquitous tectonic fabrics and bears rich asbestos ore. The rocks are polymetamorphic, and serpentinization developed in two main episodes, early oceanic and late continental. The oceanic episode took place under low activity of oxygen after the peridotites had cooled to below 350°C. This was a pervasive serpentinization characterized by the pseudomorphic replacement of olivine and orthopyroxene by *lizardite* ± *chrysotile* ± *brucite* ± *magnetite* ± *awaruite,* which ran to completion in the cumulate peridotites but only partly affected the harzburgite tectonite. The extent of pervasive serpentinization controlled the later development of the asbestos veins. When the ophiolites were emplaced by obduction, a relatively low degree of serpentinization allowed the formation of fractures in the harzburgite tectonite, whereas the high degree of serpentinization of the dunite cumulate inhibited its fracturing. The action of oxygen-rich waters started the growth of asbestos veins in dilation fractures throughout the harzburgite during the tectonic transport and emplacement of the ophiolites. The typical paragenesis in asbestos veins is *chrysotile* ± *magnetite* ± *brucite,* which was formed under low-greenschist-facies P–T conditions as shown by the mineral composition of the Cambrian metabasaltic country rock. In shear zones, platy and fibrous *antigorite* ± *brucite* developed at the expense of mesh lizardite and vein chrysotile.

Sommaire

Deux types de péridotite se rencontrent dans le cortège ophiolitique des Appalaches du Québec: (1) une harzburgite tectonite provenant du manteau et formant l'unité de base des complexes ophiolitiques; (2) surmontant celle-ci, une dunite cumulat. Ces deux péridotites sont serpentinisées, mais seule la première possède une fabrique évidente de tectonite et contient les plus riches minéralisations d'amiante. Ces roches sont polymétamorphiques. La serpentinisation s'y est développée au cours de deux épisodes principaux, le premier océanique et le second continental. L'épisode océanique s'est déroulé dans des conditions de faible activité d'oxygène et après le refroidissement des péridotites à une température inférieure à 350°C. Cette serpentinisation, de caractère pénétrant, est caractérisée par le remplacement pseudomorphique de l'olivine et de l'orthopyroxène par *lizardite* ± *chrysotile* ± *brucite* ± *magnétite* ± *awaruite;* complète dans la dunite cumulat, elle n'est que partielle dans la harzburgite tectonite. Le degré de serpentinisation pénétrante gouverne le développement ultérieur des veines d'amiante. Au moment de la mise en place des ophiolites par obduction, le faible degré de serpentinisation de la harzburgite tectonite y a favorisé la formation d'un grand nombre de cassures, ce qui n'a pas pu se produire dans la dunite cumulat entièrement serpentinisée. L'action de solutions aqueuses riches en oxygène a provoqué la formation des veines d'amiante dans les cassures qui s'ouvraient dans la harzburgite pendant le transport et la mise en place tectoniques des ophiolites. Dans les veines d'asbestos, la paragenèse typique, *chrysotile* ± *magnétite* ± *brucite,* résulte des conditions de basses pression et température du début du facies schiste vert, comme l'indique la composition minéralogique des roches encaissantes métabasaltiques d'âge Cambrien. Dans les zones de cisaillement, l'*antigorite* écailleuse ou fibreuse et la *brucite* remplacent la lizardite réticulée ou le chrysotile filonien.

Introduction

Commercial mining of chrysotile from the serpentinized peridotites of the Québec Appalachians started a century ago, in 1878. Since then, the region has developed into one of the world's major producers of asbestos fibre. Studies by Cirkel (1910), Dresser (1913), Graham (1917), Cooke (1937), Faessler & Badollet (1947), Riordon (1955, 1975) and Aumento (1970) have led to many controversial hypotheses on the origin of the mineralization. These works, however, fail to answer several fundamental questions about (1) the mechanism of fibre growth, (2) the physical conditions that control the parageneses and (3) the temporal and spatial framework of serpentinization. A better understanding of the origin of asbestos deposits in the Québec Appalachians requires new knowledge about the petrogenesis and evolution of the host rocks. Structures, textures and mineral assemblages in peridotites from the Québec Appalachians are complex because they are the results of a long evolution. It is the purpose of our paper to outline the major stages of this evolution and to discuss textural features, mineral and rock compositions and physicochemical conditions that bear on the mineral parageneses observed. We stress what we consider to be the most significant features of the rocks studied; hence, countless details will be omitted in an attempt to give the reader a clear picture of the main facts. Our account, however, is based on observations collected during seven field seasons of mapping in the ophiolite belt of the Québec Appalachians (Laurent 1973, 1975a, 1977, Laurent *et al.* 1979a) and on detailed studies of the petrography of the serpentinized peridotites and associated rocks. Our field and petrographic work was carried out in collaboration with students whose theses give extensive descriptions of the field relationships, textures, mineralogy and chemistry of the ophiolite rocks (Y. Hébert 1974, Lamothe 1978, Beullac 1979, R. Hébert 1979, Rodrigue 1979, J. Beaudin *in prep.*, Y. Hébert *in prep.*).

The chrysotile-asbestos-rich peridotites of the Thetford Mines and Asbestos areas are part of a narrow ophiolite belt that extends discontinuously through the Canadian Appalachians from Baie Verte, Newfoundland, to southern Québec (Church 1972, Laurent 1975a, Williams & Talkington 1977, Williams & St-Julien 1978). The ophiolite belt, in part much dismembered and metamorphosed, consists of peridotites, gabbro cumulates, diabase sills, tholeiitic pillow lavas and red argillites (Lamarche 1972, St-Julien 1972, Laurent 1973, 1975a, 1977, Church 1977); these units have been emplaced tectonically within the Inner Zone of the Québec Appalachians in Early Ordovician time. The ophiolites are regarded as fragments of the oceanic crust and mantle underlying the Iapetus (Proto-Atlantic) Ocean, or smaller marginal inter-arc basins (Bird & Dewey 1970, Dewey 1974). If the peridotites represent parts of slices of upper mantle and oceanic crust, the following sequence of events must be considered: (1) the *formation* of the peridotites in an oceanic environment through processes of oceanic lithosphere accretion and sea-floor spreading; (2) the *fragmentation* and *tectonic emplacement* of the peridotites on the continent, and (3) *deformation* of the peridotites with the Cambro–Ordovician country rocks. Serpentinization took place in two main episodes during this evolution. An early serpentinization event that produced massive lizardite is assumed to have taken place in the oceanic environment, at low temperatures and at some remote distance from the spreading axis. Late serpentinization occurred in a dynamic regime, at higher temperatures than the first episode and contemporaneous with the tectonic transport and emplacement of the rocks into their present setting. The second serpentinization produced foliated textures and several generations of chrysotile + brucite and antigorite + brucite veins. The peridotites are cut by rootless granitic dykes that by field relationships can be shown to have been emplaced between the two episodes of serpentinization. The dykes have yielded early Ordovician K–Ar ages (Poole *et al.* 1963).

Peridotites Before Serpentinization

Two types of peridotite are distinguished: (1) a harzburgite tectonite of upper-mantle origin that forms the base of the obducted ophiolites and (2) an overlying dunite of cumulate origin. The presence of strong tectonite fabrics in the harzburgite and their general absence in the dunite cumulate show that the basal harzburgite had been complexly deformed prior to forming the floor on which the cumulates were deposited. Ave'Lallement & Carter (1970), Nicolas *et al.* (1972) and Green & Radcliffe (1972) have shown that a tectonite fabric in peridotite is likely to result from an episode of slow, extensive plastic deformation and recrystallization under deep crustal or upper-mantle pressure and temperature conditions. It is assumed that the ubiquitous tectonite fabric of the basal harzburgite in the Québec Appalachians was acquired under a spreading axis by plastic flow during solid-state emplacement into the developing oceanic lithosphere (Juteau *et al.* 1977).

The harzburgite tectonite grades locally into dunite. The harzburgite is homogeneous, but in places it contains alternating bands of olivine pyroxenite and dunite from 1 to 30 cm thick. The banding is complexly folded and overprinted by the main tectonic foliation of the rock. The tectonic foliation is defined by the preferential orientation of orthopyroxenes, lenses and stringers of spinels and mosaics of recrystallized olivine. The textures vary over short distances from granoblastic, with little cataclasis and only minor recrystallization of olivine, to mylonitic, with complete recrystallization of the olivine (Fig. 1). The most common texture is blastomylonitic, with orthopyroxene

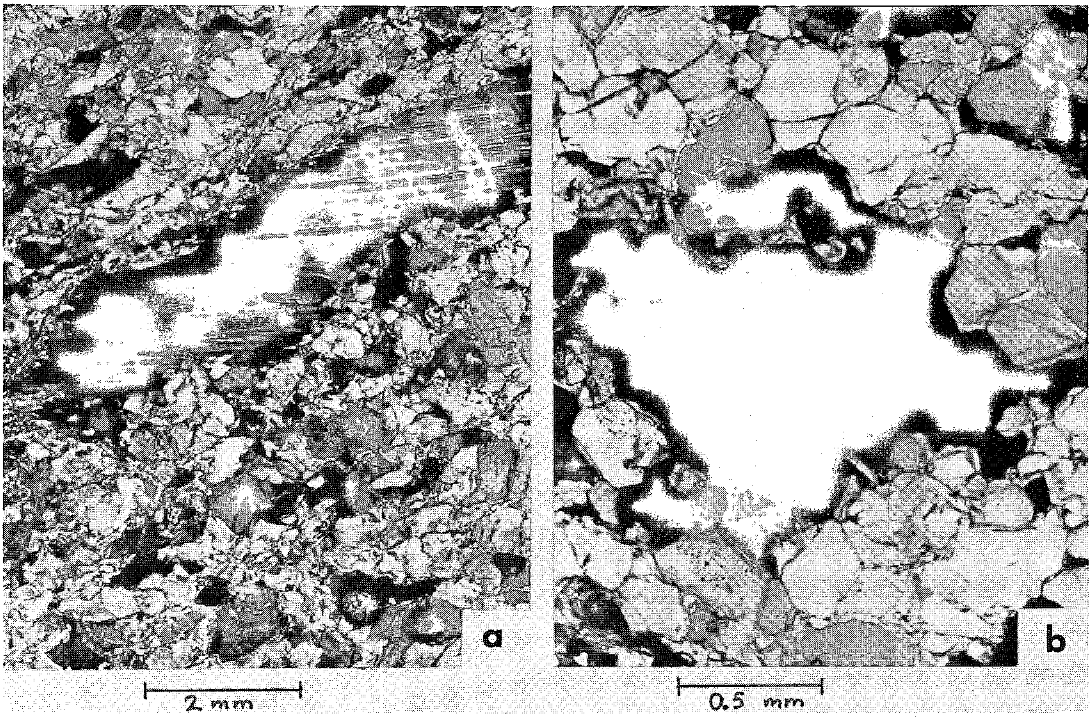

FIG. 1. (a) Blastomylonitic texture of fresh harzburgite tectonite with orthopyroxene phenoclast set in a foliated microblastic matrix of olivine grains. Crossed nicols. Sample 2–2776, Mont Albert. (b) Foliated microblastic matrix of olivine grains of two distinct sizes. Large olivine grain in the centre is at extinction. Crossed nicols. Same sample as (a).

phenoclasts 1 to 30 mm long set in a foliated microblastic matrix of olivine grains of two distinct sizes. The orthopyroxene phenoclasts have been bent, and contain deformation lamellae parallel to [100] as well as kink bands. The large olivine grains, up to 5 mm in size, are strained and granulated. Mosaics of much finer grained polygonal and unstrained neoblasts of olivine, many with triple-point grain boundaries, surround the large olivine grains, the orthopyroxene phenoclasts and the spinels (Laurent 1975b). In some occurrences the harzburgite is so strongly anisotropic that its fabric is nematoblastic, with olivine grains and orthopyroxene phenoclasts both containing sharp deformation lamellae that have length-to-width ratios as great as 8 and 12, respectively. An excellent example of this type of tectonite is the fresh harzburgitic dunite of the Lac du Diable area at Mont Albert (MacGregor 1962). In other occurrences in locally developed mylonite, all the olivine has been recrystallized. Similar textural variations have been described from peridotite xenoliths in alkali basalts (Mercier & Nicolas 1975) and in kimberlites (Boullier & Nicolas 1975). We also observed thin veins of orthopyroxenite that cut across the banding and foliation of the harzburgite, apparently cementing joint planes. This early jointing may have developed during decompression following the solid-state emplacement of this peridotite within the oceanic lithosphere. The joint systems were reactivated several times; this permitted the successive emplacement of magmas of gabbroic, dioritic and granitic composition. Bodies of gabbro and diorite, subsequently rodingitized, are consanguineous with the ophiolite assemblage. They were emplaced, we believe, at or near the spreading axis, whereas the granitic dykes were emplaced later, since they postdate the early episode of oceanic serpentinization. The harzburgite tectonite is composed of 65 to 95% olivine Fo_{89-92}, 5 to 35% orthopyroxene En_{90-94} with exsolution lamellae of clinopyroxene, and less than 1% chronian spinel of variable composition, particularly in Cr_2O_3 (35–55%) ene, and less than 1% chromian spinel of variable Gregor & Smith 1963, Irvine & Findlay 1972, Kacira 1971, Laurent 1975b, Y. Hébert, in prep.).

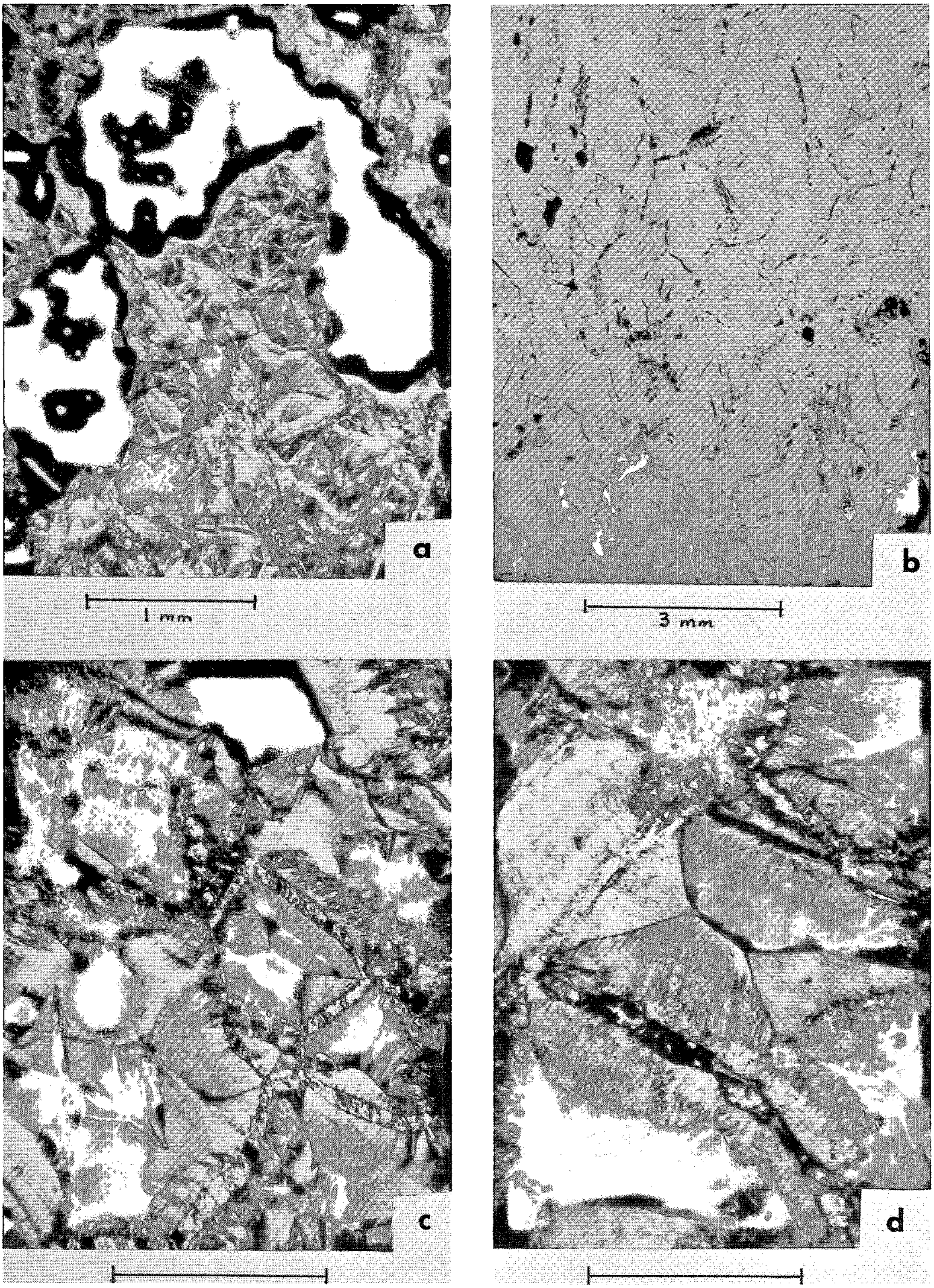

FIG. 2. (a) Lizardite pseudomorphic texture in chromite-rich dunite cumulate. Chromite contains inclusions of fresh olivine. Crossed nicols. Sample 75–26772. Provençal Hill, Black Lake. (b) Lizardite pseudomorphic texture in dunite cumulate. Natural light. Sample 70–26772. Provençal Hill, Black Lake. (c, d) Lizardite hourglass textures in dunite cumulate. Crossed nicols. Sample 2–28674, Caribou Lake, near Black Lake.

The lower part of the cumulates overlying the harzburgite consists of alternating layers of dunite and chromite-rich dunite. Beds of dunite several metres thick are fine grained and isomodal, whereas chromite-rich layers are thin and exhibit graded bedding. Textures of these rocks, where not obliterated by younger cataclastic deformation, are everywhere allotriomorphic (adcumulus). They are not foliated in spite of the fact that locally they are tightly folded around axes parallel to their bedding. Since cumulate textures were not obliterated, folding of these rocks must have occurred plastically before the end of their crystallization, *i.e.*, at relatively high temperatures and in the presence of residual liquid. This suggests that during the sedimentation of the cumulates the magma chamber was tectonically active. Plastic folding was followed by formation of fractures (now filled by veins of pyroxenite or gabbro), showing that tectonic activity continued after the cumulates had cooled enough to undergo brittle failure. Olivines in the cumulate dunite are completely replaced by lizardite with mesh (Figs. 2a & b) and hourglass (Figs. 2c & d) textures, although fresh olivine (Fo_{94-97}) is preserved as inclusions in poikilitic chromite (Kacira 1971, Y. Hébert, in prep.). Compared with the chromian spinels from the harzburgite tectonite, cumulate chromite shows a narrower compositional range but is, on the average, slightly richer in Cr_2O_3 (48–60%) and poorer in Al_2O_3 (7–16%). Olivine and chromite of the cumulate dunites are interpreted as the earliest fractionation products of the differentiation of a parental magma of picritic composition (Laurent *et al.* 1979b).

Oceanic Serpentinization

The first episode of serpentinization was pervasive; it was characterized by the replacement of olivine and orthopyroxene by lizardite. Pervasive serpentinization ran to completion in the dunite cumulate but affected the harzburgite tectonite only in part: serpentinized rocks are irregularly distributed and rocks that range from fresh to wholly serpentinized can be observed. A first episode of rodingitization is related to this episode of serpentinization. The early gabbroic intrusive rocks, and to a lesser extent, the diorites, have been converted to rodingitic assemblages of clinozoisite, diopside and hydrogrossular (Olsen 1961, De 1972). Minerals of this rodingitic assemblage are overprinted by cataclastic deformation that predates the widespread development of reddish-brown biotite in the intrusive rocks (Olsen 1961).

Pervasive serpentinization of olivine in the dunite cumulate produced lizardite pseudomorphs in mesh and hourglass textures with either isotropic or hourglass lizardite in the mesh centres (Fig. 2). Concentrates of magnetite formed during the process occur at serpentine grain-boundaries. These textures are illustrated by Wicks *et al.* (1977, Figs, 1c, 1d, 3b) and correspond to their cases 1 and 3. Here, serpentinization advances at right angles to grain boundaries, either wholly replacing olivine at a uniform rate and constant volume or leaving a central core of unaltered olivine which is replaced by randomly oriented serpentine in a later episode.

On the other hand, pervasive serpentinization of the harzburgite tectonite produced a suite of rocks with a great variety of textures owing to variations in the pre-existing foliated fabrics and to a system of early fractures. Preferential pseudomorphic growth of lizardite proceeded along the foliation and on fractures so that the resulting serpentinization is anisotropic (Fig. 3). We observed a lepidoblastic matrix of apparently fibrous lizardite enclosing subunits of olivine and

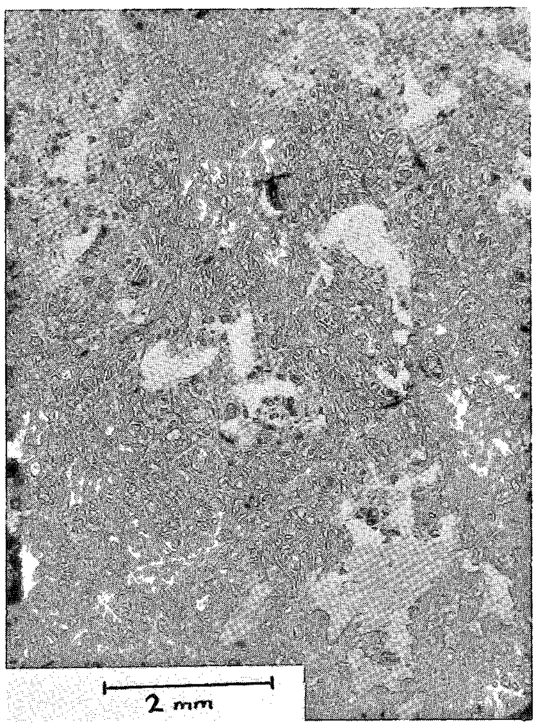

FIG. 3. Lepidoblastic texture of serpentinized harzburgite tectonite. Natural light. Sample G–16873, Quarry Hill, Black Lake.

TABLE 1. ELECTRON-MICROPROBE ANALYSES OF LIZARDITE FROM THETFORD MINES

Wt. %*	A	B	C	D	E	F	G	H	I	J	K	L
SiO_2	41.02	41.02	41.70	40.85	38.92	39.06	41.66	40.21	40.68	41.53	40.67	41.64
Al_2O_3	0.00	0.08	0.04	0.07	0.06	0.04	0.02	0.00	0.00	0.06	0.00	1.48
FeO_{TOT}	2.73	2.56	1.84	1.92	3.03	2.80	2.39	2.58	3.15	2.50	2.62	3.01
MgO	41.97	42.15	42.39	42.99	43.88	43.99	41.38	42.99	42.67	41.67	43.19	39.37
Cr_2O_3	0.78	0.57	0.49	0.69	0.51	0.62	0.29	0.17	0.00	0.07	0.02	0.94
NiO	0.00	0.02	0.04	0.00	0.10	0.04	0.76	0.55	0.00	0.67	0.00 /CaO	0.06
						Atomic proportions						
Si	.6979	.6840	.7214	.7082	.6078	.6163	.6719	.6281	.6526	.6843	.6776	.67
Al (X)	.0	.0030	.0014	.0030	.0022	.0014	.0008	.0	.0	.0022	.0	.05
Fe (X)	.0383	.0356	.0267	.0278	.0396	.0369	.0322	.0337	.0423	.0344	.0365	.04
Mg (X)	1.0489	1.0501	1.0929	1.1114	1.0213	1.0345	.9946	1.0007	1.0204	1.0234	1.0723	.95
Cr (X)	.0208	.0150	.0134	.0188	.0126	.0154	.0074	.0042	.0	.0020	.0004	.02
Ni (X)	.0	.0003	.0005	.0	.0014	.0005	.0099	.0070	.0	.0089	.0 / Ca	.00
TOTAL	1.1080	1.1025	1.1349	1.161	1.0771	1.0887	1.0449	1.0456	1.0627	1.0709	1.1092	1.08
X/Si	1.59	1.61	1.57	1.64	1.77	1.77	1.56	1.66	1.63	1.56	1.64	1.59
$\frac{Mg}{Mg+Fe}100$	96.5	96.9	97.6	97.6	96.3	96.6	96.9	96.7	96.0	96.7	96.7	75.3

* Recalculated to 86.5% assuming 13.5% H_2O content of serpentine. (A to J) pseudomorph of olivine in dunite cumulate; (K) pseudomorph of olivine in harzburgite tectonite; (L) bastite pseudomorph of orthopyroxene in harzburgite tectonite.

orthopyroxene that are about 1 cm in diameter. The texture of this matrix resulted from replacement concomitant with expansion. Evidence of expansion is afforded by lepidoblastic lizardite which fills dilation crystal fractures in spinels (Laurent 1975b, Fig. 4b). Orthopyroxene and olivine in the subunits are replaced in part by pseudomorphic lizardite. The orthopyroxene is altered to bastite along grain boundaries, fractures and cleavages (Wicks & Whittaker 1977, Figs. 2b, 2c), whereas olivine has lizardite mesh-rims that surround fresh relics in mesh centres (Wicks *et al.* 1977, Fig. 1a).

Microprobe analyses of lizardite pseudomorphs after olivine (A to J) in dunite and of lizardite after olivine (K) and orthopyroxene (L) in harzburgite are given in Table 1. The analyses were done with an ARL electron microprobe at 20 kV and 10 mA using natural olivine and diopside standards provided by the Geophysical Laboratory, Carnegie Institution of Washington. The results given are average values of a minimum of three selected spots in each lizardite analyzed; identification of the samples was made independently by X-ray diffraction using Guinier and Gandolfi cameras. Because mesh pseudomorphs are multiphase assemblages, the results obtained show chemical variations which, in part, may reflect the presence of (1) microscopic grains of magnetite or awaruite and (2) chrysotile and brucite intergrown with lizardite. Lizardite pseudomorphs have a higher Mg/Mg + Fe ratio than their parent olivine and orthopyroxene. The iron liberated by serpentinization has formed magnetite and minor amounts of awaruite. Some iron has also entered brucite that is intimately intergrown with lizardite; note that we have found no evidence of widespread formation of brucite during the first episode of serpentinization. Ideally, lizardite contains about 13.5% H_2O by weight and is enriched in SiO_2, or impoverished in MgO, with respect to olivine. With few exceptions, serpentinization textures provide strong evidence that the reactions run at constant volume (Thayer 1966, 1967) or that any increase in volume is minimal. Hence, it is more likely that magnesium was removed in solution than that silicon was added. Our data also suggest that the serpentinization of orthopyroxene in harzburgite released large amounts of silicon and smaller quantities of iron, aluminum and calcium. The following equation probably is a valid approximation of the major exchanges that took place during the first episode of serpentinization (modified from Coleman 1971): olivine + orthopyroxene + $H_2O \rightarrow$ serpentine ± brucite ± magnetite ± awaruite ± excess of Si, Al, Fe, Ca, Mg (removed).

The role of minor elements is complex. Lizardite after olivine is richer in chromium in the dunite cumulate than in the harzburgite tectonite. Also, chromium (as well as aluminum and calcium, Table 1) is higher in lizardite (bastite) after orthopyroxene than in lizardite after olivine (Wicks & Plant 1979). Nickel contents of the lizardite in tectonite peridotites define a range from 0.02 to 0.20% NiO (Nickel 1971, Table 1), which is narrower than the range of 0.0 to 0.76% found in the lizardite pseudomorphs after olivine from the dunite cumulate (Table 1).

The trends of both major and minor elements mobilized during the first episode of serpentinization can be ascertained. Aside from the iron and nickel retained in secondary magnetite and awaruite, calcium, magnesium and aluminum were, at least in part, taken up by the rodingitization of gabbro and diorite spatially associated with the serpentinized rocks (Cooke 1937, Faessler & Badollet 1947, De 1972). In an excellent review of the literature, Moody (1976b) pointed out that serpentinization can be either isochemical or allochemical, and that allochemical serpentinization (such as the first episode of serpentinization in the Québec Appalachians) implies the presence of an open system with a free exchange between circulating waters and the rocks. Studies of oceanic rocks provide ample evidence that seawater and oceanic crust interact and exchange chemical components (Bischoff & Dickson 1975, Hajash 1975, Wolery & Sleep 1976, Bloch & Hofmann 1978). Consequently, serpentinization in the oceanic environment takes place under the conditions of an open system.

Oceanic serpentinization is mostly of the lizardite–chrysotile type. Experimental and analytical evidence suggests that this paragenesis forms at temperatures below 350°C (Evans 1977, p. 434). Alteration of peridotites in the Québec Appalachians during the early phase of serpentinization has produced *lizardite ± magnetite*, an assemblage that is common in oceanic serpentinites.

Conditions of low oxygen-fugacities accompanying the oxidation reactions during the first episode of serpentinization are indicated by the presence of awaruite (Ni_3Fe) and nickel sulfides such as heazlewoodite and millerite (Nickel 1959, 1971, Chamberlain 1966), and by traces of N–alkanes with molecular weights between C_{16} and C_{36} (Gibbs 1971). On the basis of a detailed study of opaque minerals in serpentinites, Eckstrand (1975) has suggested that serpentinization may generate reducing conditions. Calculations by Moody (1976a) based on thermodynamic data confirm that the assemblages iron–magnetite and magnetite–awaruite define a very oxygen-deficient but hydrogen-rich environment.

[The presence of awaruite and other oxygen-poor compounds has led several researchers to describe this type of serpentinization as taking place in a reducing environment. In fact, it is a complex oxidation and reduction process in which 55 to 80% of the iron in the rock is *oxidized* at the expense of water, which is reduced to gaseous hydrogen. The hydrogen in turn is responsible for producing awaruite and related minerals by reduction. However, awaruite rarely occurs in amounts greater than 1% and is often absent. Magnetite occurs in amounts of up to at least 10% and is clearly the dominant iron-bearing phase. Thus, classifying the process as reducing puts too much emphasis on a minor, but important, phase. This has been discussed in detail in Wicks & Whittaker (1977): *Ed. note.*]

The cumulate dunites are wholly serpentinized, whereas the underlying harzburgite tectonite is not. This spatial distribution of the intensity of serpentinization implies that the source of water was located above rather than below the rocks and, therefore, that seawater was probably responsible for the first episode of serpentinization.

Eight different processes of serpentinization have been distinguished by Wicks & Whittaker (1977) on the basis of relative differences in temperature, regime of shearing and antigorite nucleation. The first episode of serpentinization corresponds to their process 3, characterized by the development of lizardite pseudomorphic textures in the absence of shearing and under falling or constant temperature conditions. The spreading axis is a dynamic, high-temperature environment that does not satisfy the above criteria. Furthermore, thermal models mitigate against widespread serpentinization of layer 3 at or near oceanic spreading axes (Fowler 1976). We are led to assume that the early episode of serpentinization occurred in the oceanic environment but at a distance removed from the spreading axis. Only after having cooled to below 350°C were the peridotites serpentinized under static conditions.

INTRUSIVE ROCKS

Three groups of rootless intrusive rocks, em-

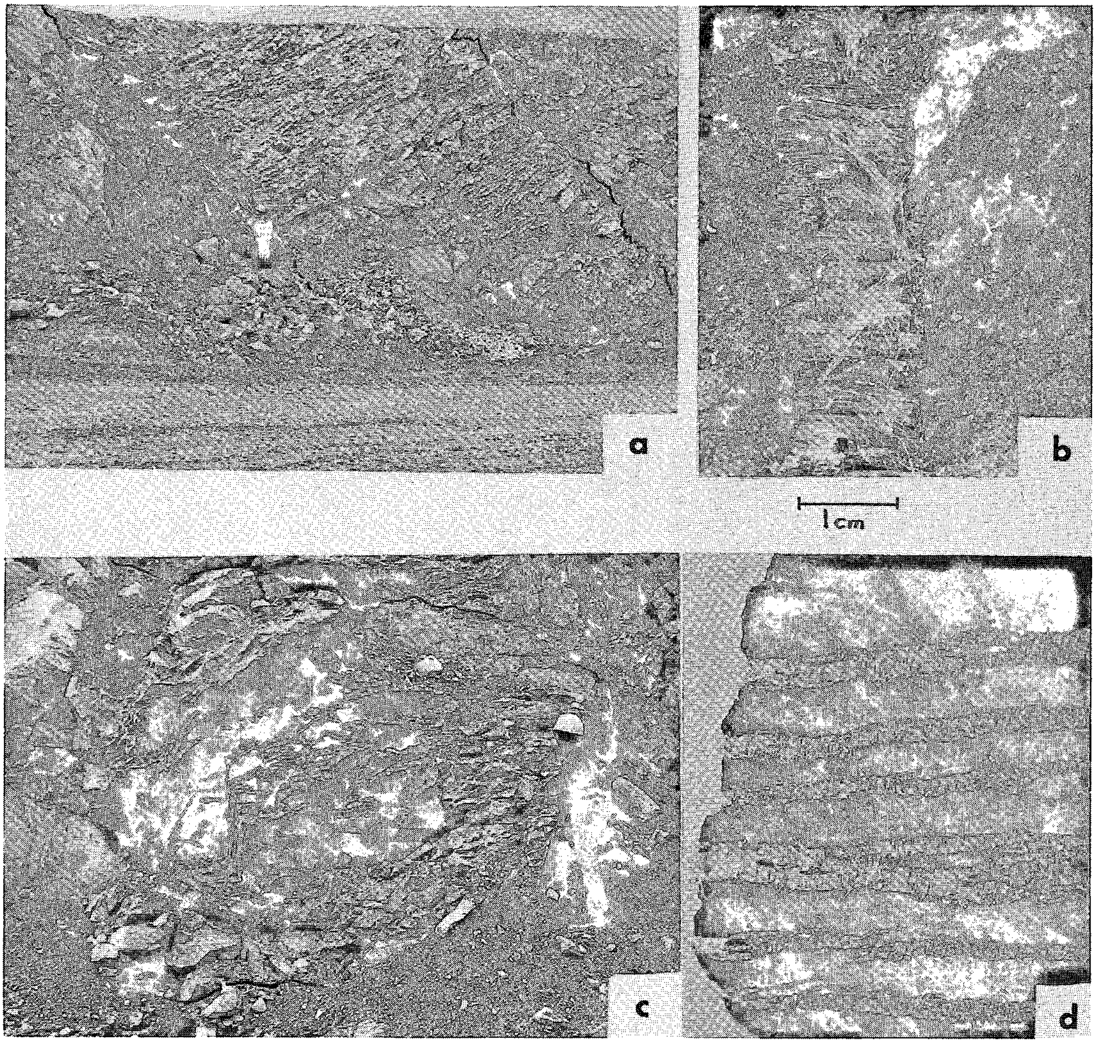

FIG. 4. (a) Quartz monzonite dyke in serpentinized harzburgite tectonite, Jeffrey mine, Asbestos. (c) Lens-like body of strongly deformed and altered hornblende diorite in serpentinized harzburgite tectonite, Jeffrey mine, Asbestos. (b) and (d) Asbestos veins composed of chrysotile cross-fibres, in serpentinized harzburgite tectonite from Thetford Mines.

placed chiefly in the harzburgite tectonite, can be distinguished on the basis of differences in composition, alteration and deformation (Laurent 1975a, b). The oldest group consists of isolated lenses of massive rodingite a few metres in length. The rodingite preserves relics of gabbroic texture, but all primary phases have been replaced by calc-silicate minerals (Olsen 1961). The second group is made up of irregular bodies, up to 100 m thick, of strongly deformed, foliated, altered and partly rodingitized hornblende diorite (Fig. 4c). The primary mineral assemblage of the diorite is andesine, poikilitic hornblende, sphene, apatite and zircon (De 1972). These first two groups are consanguineous with the ophiolite assemblage and were emplaced in the peridotites prior to the first episode of serpentinization. They went through several phases of alteration including two distinct episodes of rodingitization (Table

TABLE 2. SUMMARY OF EVENTS AND PARAGENESES

Ophiolite formation	Peridotites	Dykes of gabbro and diorite
First metamorphism: oceanic episode of static serpentinization	Pseudomorphic replacement of primary minerals *lizardite* ± *chrysotile* ± *brucite* ± *magnetite* *and awaruite*	*clinozoisite* + *diopside* + *hydrogrossularite*
Deformation	Emplacement of quartz monzonite dykes and development of biotite (K metasomatism)	
Second metamorphism: continental episode of dynamic serpentinization	Formation of the chrysotile-asbestos-rich ore a) foliated textures with *antigorite* + *brucite* + *magnetite* b) asbestos veins with *chrysotile* + *brucite* + *magnetite*	veins of *zoisite*, *grossularite*, *prehnite*, *diopside*, *vesuvianite*, *etc.*
Late alteration (post-emplacement)	*talc* + *chlorites* + *carbonates* + *quartz*	

2). The first produced clinozoisite, diopside and hydrogrossular as pseudomorphs after the primary minerals, whereas the second episode of rodingitization produced veins of such calc-silicate minerals as zoisite, grossular, prehnite, diopside, vesuvianite, wollastonite and margarite (Olsen 1961). The two episodes were separated by a period of deformation that was accompanied by the emplacement of the youngest intrusive rocks and a widespread development of biotite through potassium metasomatism.

The third group of intrusive rocks consists of relatively undeformed and unfoliated dykes of quartz monzonite 1 to 10 m thick (Fig. 4a) with potassium feldspar, oligoclase, quartz, biotite and muscovite as the main constituents (De 1972). The older, foliated intrusive rocks have sharp boundaries, whereas the youngest dykes show progressive, uneven contacts with the enclosing serpentinites. Quartz monzonitic material penetrates the serpentinite to distances that vary from a few millimetres to several centimetres, and xenoliths of serpentinite displaying a reaction rim of *serpentine–talc–anthophyllite* are found within the intrusive rock. These observations provide evidence that the youngest dykes were emplaced in peridotites that already had been serpentinized. The presence of antigorite within the serpentinite at the contact with these dykes was reported by Olsen (1961). De (1972) described thermal aureoles 10 to 50 cm wide in which lizardite has been dehydrated to antigorite–chlorite. No recrystallized olivine has been observed, because either this mineral never formed or it was replaced subsequently during the late episode of serpentinization. Although we cannot yet confirm the identification of antigorite, the work of Olsen and De suggests that the most widespread and characteristic reaction in the aureoles was the replacement of lizardite by antigorite. Studies of progressively metamorphosed serpentinites combined with a theoretical analysis of the serpentinite multisystem by Evans *et al.* (1976) indicate that antigorite is the high-temperature serpentine phase. It replaces lizardite as a result of prograde metamorphism at temperatures corresponding to the onset of the greenschist facies (300–350°C), and is stable to the onset of the amphibolite facies (Evans 1977). Serpentinite within contact aureoles of the dykes is cut by chrysotile fibres formed in the late episode of serpentinization (see below); therefore, the monzonitic dykes were emplaced between the two episodes of serpentinization. The only age deter-

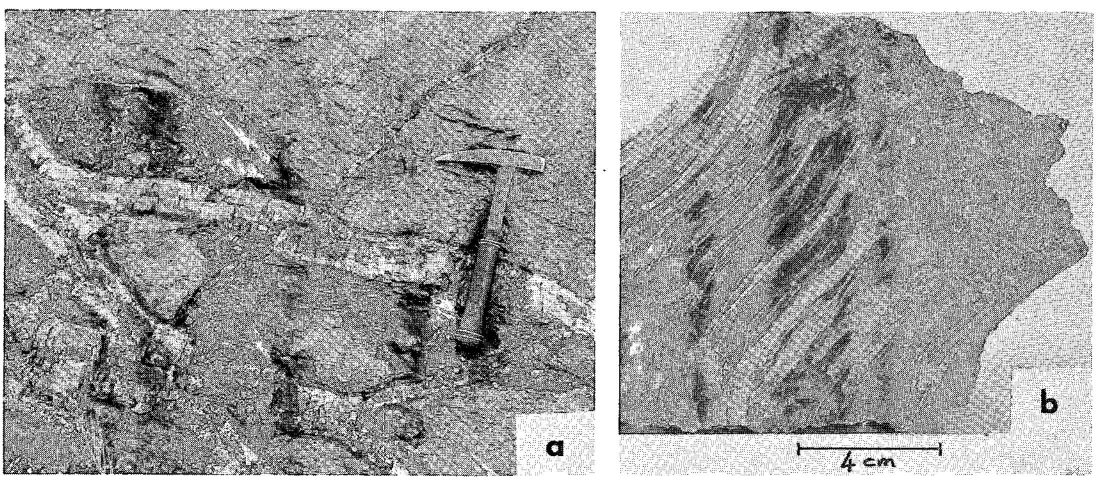

FIG. 5. (a) Stockwork of fractures filled with chrysotile cross-fibres in harzburgite tectonite, Vimy Ridge, Thetford Mines. (b) Deformed and recrystallized(?) antigorite cross-fibres filling a fracture in serpentinized harzburgite tectonite, Jeffrey mine, Asbestos.

minations on the monzonite are two early Ordovician muscovite K–Ar ages, 477 and 481 m.y. (Poole *et al.* 1963); these, we believe, correspond approximately to the time of tectonic emplacement of the ophiolites. We interpret the dyke intrusion as having occurred during fragmentation of the oceanic lithosphere immediately prior to, or concurrent with, obduction of the ophiolites onto the continent.

Continental Serpentinization

The late episode of serpentinization produced the commercial chrysotile fibres that fill a stockwork of expansion fractures from 0.5 to 2.5 cm thick, mainly within the harzburgite tectonite (Fig. 5a). The late serpentinization was controlled by several systems of fractures, and in many cases only narrow zones of wall rock along the fractures were deeply serpentinized for the second time. Selvages along margins of the chrysotile-asbestos veins (Fig. 4b) consist of cryptocrystalline banded fibrous lizardite that resulted from colloidal deposition; this in turn grades towards the wall rock into coarser grained lizardite associated with chrysotile and brucite. Chrysotile forms cross-fibres in the centres of the veins, with magnetite concentrated along the contact between fibres and vein selvages and, in smaller amounts, with chrysotile and brucite in the veins (Cooke 1937, Riordon 1955, 1975, Riordon & Laliberté 1972, Laurent 1975b, Fig. 9). To explain the mechanism of fibre growth, Laurent (1975b) applied the principles of incremental strain analysis developed by Durney & Ramsay (1973). Tensile and shear fractures commonly are filled synchronously (as they progressively open) with crystals of fibrous habit derived by solution or diffusion of material from the wall rock. The orientation of the growing fibres in the veins is controlled not by the position of the wall rock but by the direction of minimum shear stress; expansion causes fibre growth, and changes in the orientation of the minimum shear stress are expected to produce changes in the direction of fibre growth. Such changes are recorded by kinked fibres. Different generations of veins exhibit cross-cutting relationships. Chrysotile fibres in early veins are bent, kinked, broken and often replaced by fibrous antigorite or brucite or both (Fig. 5b), whereas late veins are not deformed (Fig. 4d). From shear zones in the Jeffrey mine at Asbestos, we have collected serpentine vein samples of strongly deformed fibrous antigorite up to 20 cm long, cut by undeformed and unaltered veins of chrysotile fibres 1 cm long. These observations suggest that "chrysotilization" is syntectonic and that it developed in a dynamic regime. The veins cement fractures caused by tectonic movements that occurred at a high level in the crust. Regional metamorphism at this level did not exceed low-greenschist facies, as shown by the mineral composition of pillow lavas from the Cambrian Caldwell Formation adjacent to the peridotites (Séguin & Laurent 1978).

Although chrysotile pseudomorphs after olivine are commonly observed in the harzburgite (Wicks & Whittaker 1977, Fig. 8c), the observed relations of wall rock to asbestos veins suggest that vein chrysotile was derived from lizardite rather than from fresh olivine. During the processes of solution, transport and chrysotile growth, most of the iron accommodated in lizardite was expelled to form additional magnetite. The observed paragenesis is the following: lizardite + H_2O + O_2 $\rightarrow$ clinochrysotile + magnetite $\pm$ brucite $\pm$ excess Si (removed).

The chemical data of Hahn-Weinheimer &

FIG. 6. Foliated texture of serpentinized dunite cumulate, showing replacement of lizardite of the early episode of serpentinization by antigorite of the late episode of serpentinization. Crossed nicols. Sample 1a–28578, Red Hills, Thetford Mines.

Hirner (1975) show that the chrysotile is characterized by a higher Mg/Mg + Fe ratio than the coexisting lizardite and that it has a composition near that of ideal serpentine.

During the same episode of serpentinization, antigorite ± brucite developed extensively in shear zones within the harzburgite tectonite and dunite cumulate. Nonpseudomorphic platy antigorite replaced lizardite, producing foliated textures (Fig. 6) and locally forming antigorite schists.

The formation of chrysotile veins corresponds to serpentinization process 5 of Wicks & Whittaker (1977), defined by the recrystallization of pseudomorphic lizardite to form nonpseudomorphic chrysotile ± brucite, and process 7, to form nonpseudomorphic antigorite ± brucite under a regime of rising temperature. The occurrence of vein antigorite has been reported from Mont Adstock near Thetford Mines (Wicks & Whittaker 1977, Table 3) and from the British Canadian mine at Black Lake (Hahn-Weinheimer & Hirner 1975, Table 1), suggesting that temperatures had risen above the stability field of lizardite and chrysotile in major shear zones. However, temperature alone does not control the development of chrysotile at the expense of lizardite, since lizardite and chrysotile commonly occur together in serpentinites. It is known that lizardite and chrysotile, because of their different crystal structures, have distinct properties of nucleation. Lizardite usually grows on an olivine or pyroxene substrate but does not nucleate easily, whereas in synthetic systems chrysotile is favored by crystallization from gels and oxides (Dungan 1977). Lizardite was dissolved along tensile and shear fractures and was synchronously reprecipitated as chrysotile fibres. This chemical process and the variations of the physical parameters defining the stress applied to the peridotite bodies, as well as favorable temperatures ranging between 150 and 350°C, seem to have been the key factors that promoted the development of chrysotile veins. Antigorite formed in the same regime but at higher temperatures, in shear zones where we can assume that frictional energy was converted to heat.

Cumulate dunites do not display extensive arrays of asbestos veins. More often, chrysotile formed (with some magnetite and brucite) during the late serpentinization in sparse patches disseminated through the rock. Fracturing may have been inhibited in this peridotite, as it was wholly serpentinized prior to tectonic emplacement; consequently, the rock did not undergo brittle deformation during the late episode of serpentinization.

After emplacement in their present setting, the serpentinized peridotites were further altered at ambient temperatures by CO_2- and SiO_2-bearing groundwater. Serpentine minerals were altered locally to talc and magnesite; extensive alteration occurred along faults between the peridotites and the country rocks, where broad zones of talc–carbonate–chlorite rock were developed.

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