Petrology of the alpine-type serpentinites of asbestos and Thetford Mines, Quebec

Petrology of the Alpine-Type Serpentinites of Asbestos and Thetford Mines, Quebec

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With 9 figures and 3 tables in the text

Summary

The host rock of the large asbestos deposits of southern Quebec is a serpentinized alpine-type peridotite of harzburgitic composition. It occurs as a thick sole at the base of an ophiolitic complex and has the features of a metamorphic tectonite. This peridotite is characterized by structures and solid state deformation textures formed in lower crust or upper mantle pressure and temperature conditions.

Serpentinization developed in two main episodes. The first one was pervasive; olivine and enstatite were converted to lizardite, magnetite and awaruite at a temperature lower than 400° C and in highly reducing conditions. Sea water is assumed to be responsible for the first serpentinization.

The second episode of serpentinization led to the formation, by syntaxial and antitaxial growth, of chrysotile fibres in veins which occupy late-stage dilation fractures. The veins have formed by processes of diffusion and solution transport during the final stages of the emplacement of the ophiolites in their present setting. Lizardite was converted to clino-chrysotile, brucite and magnetite at a temperature lower than that of the first episode and in oxidizing conditions. Meteoric waters perhaps mixed with connate waters are assumed to be responsible for the second serpentinization.

After emplacement the serpentinites were partly altered to talc and carbonates by low temperature CO_2 and SiO_2-bearing meteoric ground waters.

Introduction

The serpentinites of southern Quebec, where are localized many of the largest mines of chrysotile fibre in the world, are part of a discontinuous belt of ultra-mafic bodies and associated rocks extending for almost the entire length of the Appalachian Mountains. In the Eastern Townships of Quebec this ultramafic belt reaches a width of several kilometers and covers a distance of more than 250 kilometers. At Asbestos, Black Lake and Thetford Mines (Fig. 1) large peri-

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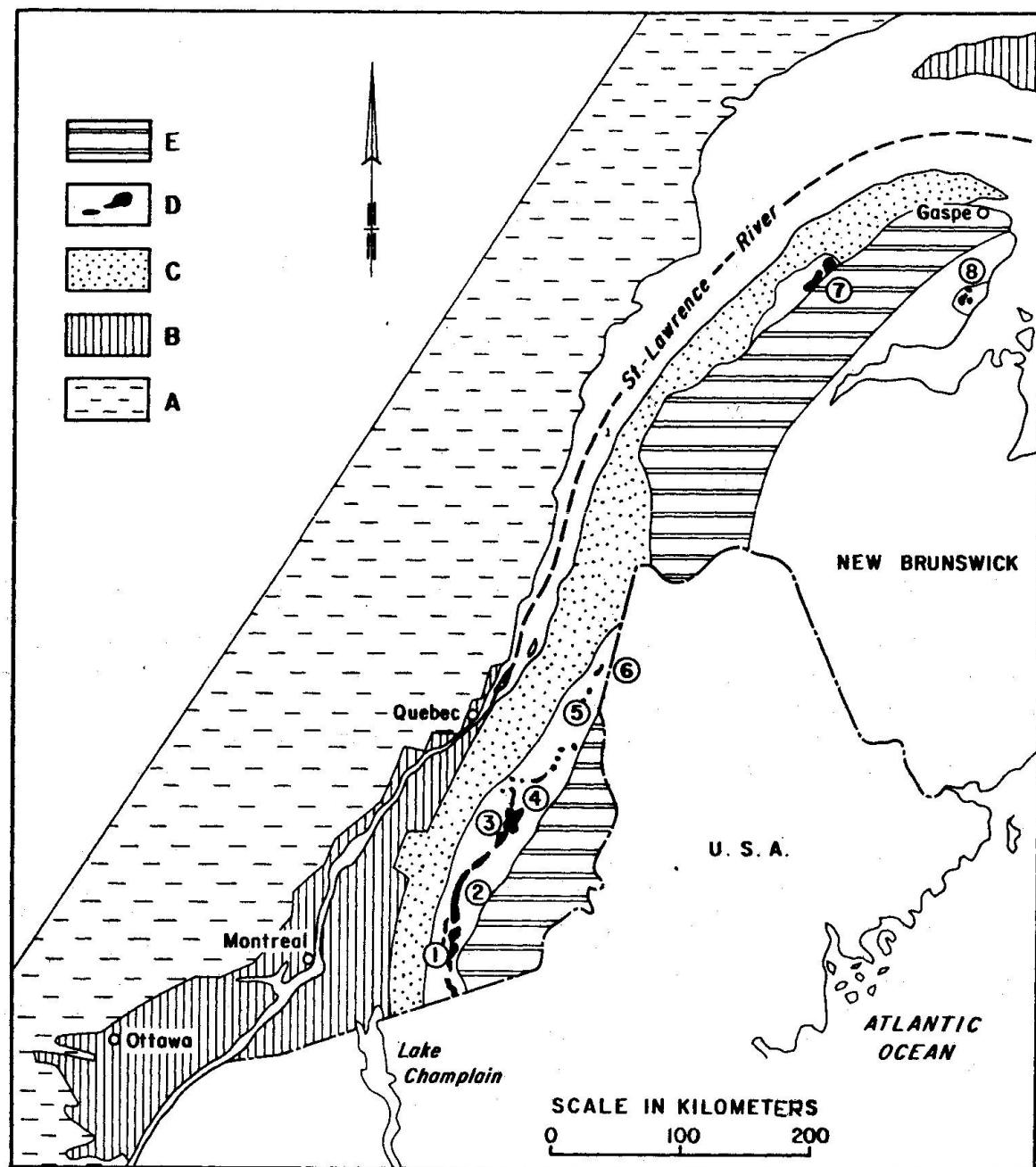
Fig. 1. Map of the Appalachians of southwestern Quebec showing the main structural zones and the major ophiolite localities: A, Precambrian crystalline basement; B, Sedimentary cover of the St. Lawrence Platform; C, Outer Zone or External Flysch Trough; D, Inner Zone or Notre Dame Trough; E, Siluro-Devonian belt of the Gaspé-Connecticut Valley Synclinorium. (1) Orford; (2) Asbestos, (3) Thetford Mines; (4) East Broughton; (5) St. Fabien; (6) St. Omer; (7) Mont Albert; (8) Rivière Port Daniel.

dotite bodies form the lower structural unit of a series of stratified allochthonous sheets. These sheets have been thrust over, and locally intruded into, the Cambrian formations of the Cambro-Ordovician Inner Zone of the Quebec Appalachians (St. Julien and Hubert, 1975; Laurent, 1975) and later folded with

the country rock. The serpentinites are overlain, in turn, by an upper structural unit consisting of gabbroic rocks, pillow lavas and cherty argillite. This suite of rocks is typical of ophiolitic complexes such as the Mesozoic Alpine ophiolites of the Mediterranean region (BEZZI and PICCARDO, 1971; MOORES and VINE, 1971) and the Early Paleozoic Appalachian ophiolites of Western Newfoundland (CHURCH and STEVENS, 1971; DEWEY and BIRD, 1971). Because complete ophiolites closely resemble rock sequences of present oceanic ridges and sea floor, they are regarded as tectonically emplaced fragments of the oceanic crust and the upper mantle (COLEMAN, 1971) and the remnants of oceanic basins that have long since vanished.

In two recent papers, I have described the occurrences and discussed the origin of the ophiolites of southern Quebec (LAURENT, 1975; SEGUIN and LAURENT, 1975). These ophiolites have the following five major features:

1. They are stratified sheets divisible in two structural and lithologic units, a lower and an upper unit. The lower unit consists of alpine-type peridotites, whose visible thickness varies between less than 1 km at Asbestos and about 4 km at Thetford Mines. The upper unit has a maximum thickness of less than 2 km and is stratiform. It consists of massive or layered chromite-bearing dunite cumulates at the base overlain by pyroxenite and gabbro. The gabbros locally are layered and cross-cut by diabase and plagiogranite dikes. At the summit of the sheet metabasaltic pillow lavas with associated pillow breccias and hyaloclastites form a volcanic cap.

2. The volcanic cap of the ophiolites is covered by a thin sedimentary layer of red cherty argillite which originally was similar to present deep sea red clays.

3. The ophiolites are bounded by fault and thrust planes. They occur as thrust sheets, which have been emplaced into their present setting as solid masses. These units are separated by tectonic dislocations; they are also internally deformed and folded with their Cambrian country rock. The regional metamorphism is of low grade; the ophiolites and their country rock are metamorphosed in the upper greenschist facies.

4. Preliminary K-Ar age determinations (LAURENT and VALLERAND, 1974) suggest that the ophiolitic rocks formed in Middle Cambrian time, about 550 m. y. ago. Structural and stratigraphic evidence (LAMARCHE, 1972; LAURENT, 1975) indicates that the ophiolites of southern Quebec were emplaced in Early Ordovician time. Therefore the emplacement of the ophiolites occurred early in the orogenic sequence of the Appalachians.

5. The ophiolites are overlain along their southeastern flank by breccias and phyllites, several hundreds of meters thick, of the St. Daniel Formation which is assumed to be of Early Ordovician age. The material of this formation is polygenic and consists of large and small unsorted blocks of Cambrian metasedimentary rocks and locally of rocks from the ophiolite suite, all in a black clayey or red and green siliceous matrix. This formation has the lithologic facies of

mélanges which presumably are originated in active oceanic trenches (MAXWELL, 1974). As recently stressed by GANSSER (1974) *mélanges* related to ophiolitic belts indicate major suture lines connected to plate boundaries. All these features clearly indicate an oceanic origin for the ophiolites of southern Quebec. Hence, if we assume that the chrysotile-rich serpentinites represent the base of a slice of upper mantle and oceanic crust, we must unravel a very complex history, whose salient stages are: firstly, the *formation* which took place in an oceanic spreading axis and involved processes of oceanic lithosphere accretion and sea floor spreading; secondly, the *tectonic emplacement* which took place at the margin of the oceanic basin and involved processes of oceanic crust fragmentation followed by the thrusting of some fragments (ophiolites) upon the continental margin; and thirdly, *transport and folding* of the ophiolites with the Cambro-Ordovician rocks of the Inner Zone of the Quebec Appalachians.

This model of the origin and evolution of ophiolites should not be regarded as an established fact but as a working hypothesis, which shall be modified and completed as knowledge accumulates. I examine in this paper the information provided by a detailed petrological study of the peridotite and its alteration products, and I find that this information agrees well with the model, which suggests that some aspects of the working hypothesis are correct.

Petrology of the harzburgite

The host rock of the asbestos deposits of southern Quebec is a spinel peridotite representative of the *harzburgite subtype* of alpine-type peridotites (JACKSON and THAYER, 1972). The average fresh harzburgite consists of dark green olivine (85%), brownish-golden orthopyroxene (more than 14%) and chromian spinel (less than 1%). According to the electron microprobe analyses given by KACIRA (1971) (see Table 1), the olivine is forsteritic ($Fo_{89.0-90.5}$) and rich in nickel (0.26 to 0.38% Ni), while the orthopyroxene is enstatitic ($En_{92.5-93.6}$) and frequently exhibits abundant exsolution lamellae of the clinopyroxene diopside. The chemical study of KACIRA has also shown that the chromian spinels in the harzburgite are richer in magnesium and aluminum and poorer in iron and chromium (10 to 34% Cr) than chromites in overlying dunite cumulates (33 to 41% Cr).

The most significant feature of the harzburgite is perhaps its tectonite fabric (Fig. 2) in which the orthopyroxenes form porphyroclasts 1 to 30 mm long, while the olivine grains, 0.5 to 5 mm in size, form a microblastic matrix. The orthopyroxenes are bent, show undulatory extinctions and present deformation lamellae parallel to (100) and kink bands. The olivine grains are granulated and strongly fractured and strained. Mosaics of unstrained much finer-grained olivine are frequently observed enclosing the orthopyroxene porphyroclasts (Fig.

Table 1. *Chemical and mineralogical composition of harzburgites* (in weight percent)

	1	2	3	4	5	$\overline{\mathrm{X}}$
SiO_2	43.47	43.84	44.51	45.88	43.52	44.22
Al_2O_3	2.02	0.20	0.41	0.34	0.31	0.65
FeO	8.32	7.87	8.38	8.01	12.77	9.06
MgO	43.80	47.47	45.27	44.49	41.96	44.57
MnO	nd	0.10	0.13	0.13	0.18	0.14
CaO	1.67	0.03	0.38	0.38	0.20	0.53
Na_2O	0.32	nd	0.07	0.07	0.07	0.13
K_2O	nd	nd	0.06	0.05	0.06	0.05
NiO	0.26	0.10	0.31	0.31	0.18	0.23
Cr_2O_3	0.14	0.39	0.48	0.34	0.75	0.42
MgO/SiO_2	1.008	1.083	1.017	0.969	0.964	1.008

These chemical analyses have been adjusted for effects of serpentinization. The data given in Table 2 have been normalized to 100 percent without H_2O. Fe_2O_3 has been entirely converted to FeO [Percentage of FeO_{total} = (%) $Fe_2O_3 \times 0.8998 + (\%)$ FeO].

Table 2 gives the key to specimen numbers. $\overline{X}$, average for the five analyses given here.

Average modal composition:

Forsteritic olivine:	85.0%	Clinopyroxene (in Opx):	1.0%
Enstatite orthopyroxene:	13.5%	Chromian spinel:	0.5%

Average normative composition:

Calculated from the average composition given here (X) normalized to 100 percent without Na_2O and K_2O:

Olivine Fo$_{90}$:	74.95%	Clinopyroxene diopside:	1.80%
Orthopyroxene En$_{90}$:	21.84%	Chrome-aluminum spinel:	1.41%

Chemical composition of mineral components in harzburgite (in cation percent) *)

Olivine (forsterite):   average of 6 samples

Mg	27.00	to	29.97	28.42
Fe	7.14		7.61	7.38
Ni	0.26		0.38	0.30
Si	18.44		19.60	18.97
Mole % Fo	89.0		90.5	89.9

Orthopyroxene (enstatite):   average of 6 samples

Mg	20.92	to	22.50	21.47
Fe	3.51		3.98	3.83
Si	26.66		27.73	27.22
Al	0.47		1.00	0.77
Ca	0.18		0.38	0.29
Cr	0.11		0.19	0.15
Ni	0.03		0.06	0.05
Mole % En	92.5		93.6	92.9

Clinopyroxene (diopside): exsolution lamellae in enstatite, 1 sample

Ca	19.15		Si	22.99
Mg	12.00		Al	0.80
Fe	1.49		Cr	0.41

Chromian spinel (chromite):   average of 9 samples

Cr	18.20	to	33.71	24.80
Fe	10.58		14.33	12.44
Mg	6.98		11.48	9.66
Al	10.62		21.97	16.67
Ti	0.02		0.14	0.06

*) Microprobe analyses from KACIRA (1971, p. 79, and Table 6, p. 86 to 88). I have selected samples A, B, C, D, E, F, G, H and I from Caribou Mountain (Black Lake), because they are well localized, and grouped and appear to form a representative sampling of the Alpine-type harzburgite.
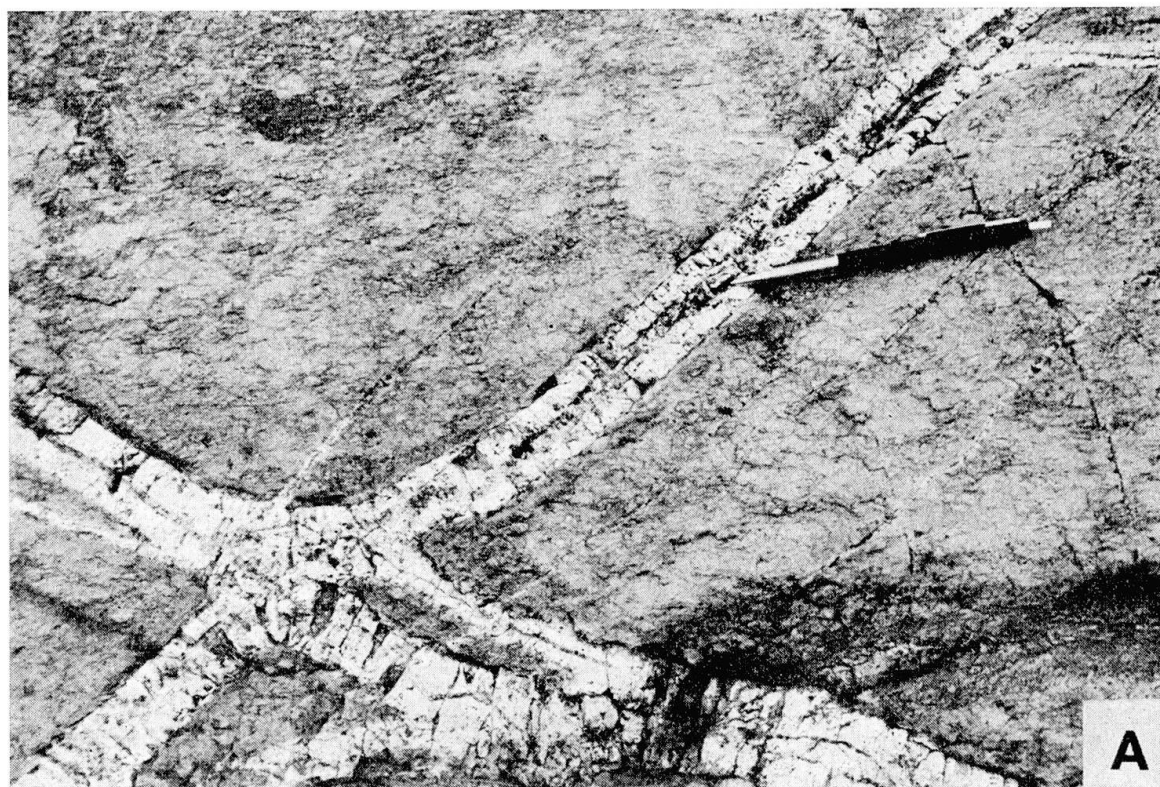
Fig. 2a. Tectonite fabric in serpentinized harzburgite at Vimy Ridge. The porphyroclasts of enstatite are in relief and set into a finer-grained matrix of olivine which is pervasively serpentinized. The foliation is parallel to the pencil used as a scale and to the bissextrix of the acute angle of the cross formed by the asbestos veins.

Fig. 2b. Blastomylonitic texture of the harzburgite at Vimy Ridge as seen under the microscope. The porphyroclasts of enstatite are bent and show deformation lamellae; the olivine grains are fractured and granulated and partly serpentinized (OL, olivine; EN, enstatite; S, serpentine; SP, spinel).

3a). Subhedral grains of spinel tend to occur as inclusions in orthopyroxene, while the anhedral spinels are interstitial between olivine grains. They are slightly fractured and are embayed by mosaics of fine-grained olivine (Fig. 3b). Kink bands and deformation lamellae result from intracrystalline gliding (RALEIGH, 1967), while mosaic textures result from syntectonic recrystallization (RAGAN, 1969). Both types of textures are considered to be caused by solid state deformation under lower crust or upper mantle pressure and temperature conditions (AVE'LALLEMANT and CARTER, 1970; NICOLAS *et al.*, 1972). Therefore the blastomylonitic fabric and mineral textures are metamorphic and of tectonic origin. They characterize a penetrative deformation that erased the primary fabric of the harzburgite.
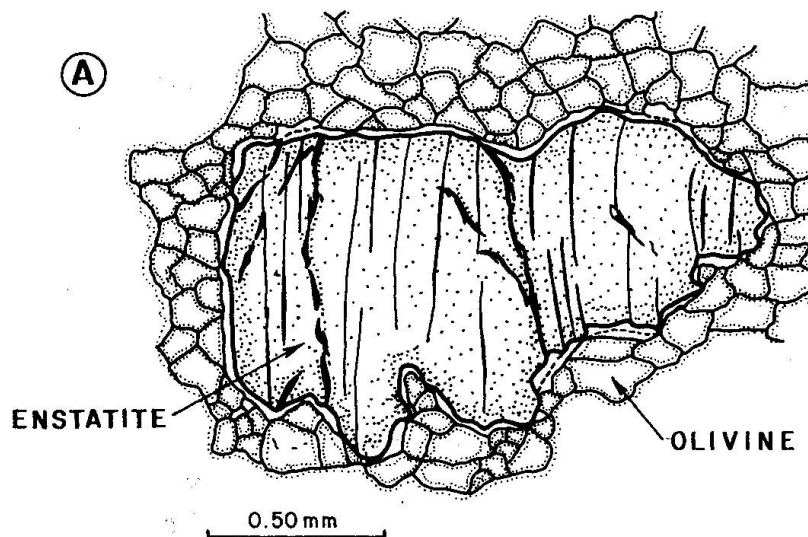

Fig. 3a. Mosaic of unstrained fine-grained olivine enclosing a porphyroclast of enstatite.
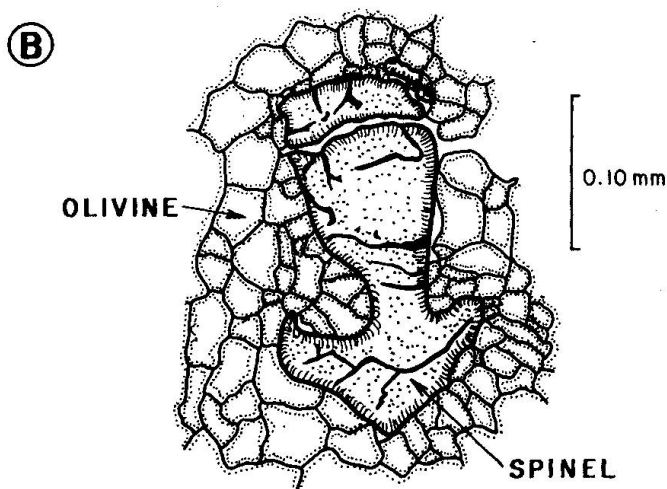

Fig. 3b. Corroded grain of spinel in a mosaic of unstrained fine-grained olivine.

The tectonite fabric of the harzburgite is expressed on the outcrops by a foliation which varies in direction but is everywhere vertical. The foliation is defined as the plane of preferential orientation of orthopyroxene porphyroclasts and recrystallization mosaics of olivine, and usually it appears to be parallel or subparallel to structures of crude banding, elongated lenses and occasional chromitite pods that occur locally in the peridotite. The banding results from visible changes in mineral content of the harzburgite, mainly through depletion of either orthopyroxene (dunite bands and lenses) or olivine (olivine orthopyroxenite bands and lenses). The feature possibly is the relic of a structure caused by one or several episodes of partial melting and high grade metamorphic differentiation. The bulk chemical composition of the rock, very low in aluminum and calcium (see Table 1), is characteristic of crystalline mantle residua left after extraction of basalt liquid (e.g. DICKEY, 1970). The banded structure and the primary fabric of the harzburgite could have formed synchronously through crystallization under non-hydrostatic stress deep in the mantle (DEN TEX, 1969). The harzburgitic assemblage where the clinopyroxene is in solution in the orthopyroxene is stable at higher temperature than the assemblages in which the clinopyroxene is exsolved in the orthopyroxene (O'HARA, 1967). Foliation, blastomylonitic fabric and mineral textures characteristic of solid state deformation must have formed later during the ascent of the mantle material towards the surface. With temperature lowering, subsolidus reactions would have caused exsolution of the clinopyroxene phase in the orthopyroxene as observed in the harzburgite. The structural, textural and mineralogical features of this harzburgite are very similar to alpine-type peridotites from the Circum-Pacific orogenic belt (e.g. RAGAN, 1967; LONEY et al., 1971; HIMMELBERG and LONEY, 1973; CHALLIS, 1965; WALLCOTT, 1969; YOSHINO, 1961) and the Alpine ranges (e.g. HIESSLEITNER, 1952; AYRTON, 1968; MOORES, 1969; GASS, 1967; JUTEAU, 1970; VUAGNAT and COGULU, 1967; REINHARDT, 1969), and from the Mid-Atlantic Ridge near 45° N (AUMENTO and LOUBAT, 1971).

Petrology of serpentinization

Fresh harzburgite is rare and most of the ultramafic rocks are partly or completely serpentinized. Previous workers (DRESSER, 1913; GRAHAM, 1917; COOKE, 1937; RIORDON, 1953) have recognized two main episodes of serpentinization: a first one resulting from the partial or complete replacement of the ferromagnesian silicates by the lizardite-bastite assemblage; and a second one leading to the formation of asbestos veins which occupy late stage dilation fractures cutting across all other peridotite structures and taking various orientations. Furthermore, several generations of antigoritic serpentine, picrolite, brucite and chrysotile slip-fibres mantle the fracture and fault surfaces, and are of

dynamometamorphic origin. The serpentine assemblage was first studied in transmitted light microscopy and then identified by X-ray diffraction in following the methods described by AUMENTO (1970).

1. The lizardite-bastite assemblage

The first episode of serpentinization postdates the primary structures and the solid state deformation textures described earlier. This is evident because the serpentine minerals replace olivine and enstatite to a variable extent and the serpentine replacement textures are generally not deformed.

A reticulate fabric characterizes the pervasive serpentinization. This fabric common to most alpine-type peridotites is controlled by the fracture pattern of the rock and mineral components (COLEMAN and KEITH, 1971). Five kinds of mineral grains are involved in the process of serpentinization: porphyroclasts of orthopyroxene, large and fractured olivine, fine-grained olivine resulting from intense granulation of larger grains, small unstrained recrystallized olivine grains forming a mosaic around the orthopyroxene porphyroclasts, and fractured chromian spinel.

The orthopyroxene is usually replaced without outgrowth by a variety of lizardite (bastite) which preserves the morphological features of the original grain (cleavages, deformation lamellae, and so on), and by minute crystals of magnetite arranged either along the cleavage planes or around the grain. From a chemical point of view, the serpentinization of the orthopyroxene corresponds to a gain of water and, since the reaction is apparently operated at constant volume, to a loss of silica, as well as smaller amounts of calcium and aluminum. A part of the silica released is probably incorporated by serpentines replacing the silica-undersaturated olivine, while another part may be combined with calcium and aluminum to form calcium-rich aluminosilicates which have been stored in rodingite dikes. These dikes show the diopside-grossularite-vesuvianite association (POITEVIN and GRAHAM, 1918; COOKE, 1937; DE, 1972).

In olivine grains the serpentinization has proceeded in two distinct steps that has led to the mesh-textured serpentinites. In specimens where serpentinization is not complete, we can distinguish a pale green lizardite, with low birefringence and undulatory extinctions, forming a network of veinlets which occupy the microfractures of olivine and enclose olivine remnants of various sizes. This lizardite, whose cell parameters have been determined by AUMENTO (1970, Table 6, p. 47), has a fibrous and braid or ribbon-like texture that is distinct from the longer fibres of occasional chrysotile and brucite. In specimens where serpentinization is complete, the remnants or cores of olivine are replaced by a colorless lamellar lizardite pseudomorph which is subisotropic to weakly birefringent and has wavy extinctions. The fine-grained olivine resulting from intense granulation of larger grains is first replaced by braid and ribbon textured

lizardite. The small olivine grains forming mosaic textures resist longer and are usually replaced by lamellar lizardite. The larger and less fractured olivine grains are replaced by both types of lizardite described before.

At the scale of the mineral components, the serpentinization textures of the replacement of olivine by lizardite apparently illustrate firstly a reaction operating with volume increase, and secondly a reaction at constant volume. Braid and ribbon textured lizardite fills expansion microfractures in olivine and chromite grains (Fig. 4). However, it is usually not possible to measure the increase
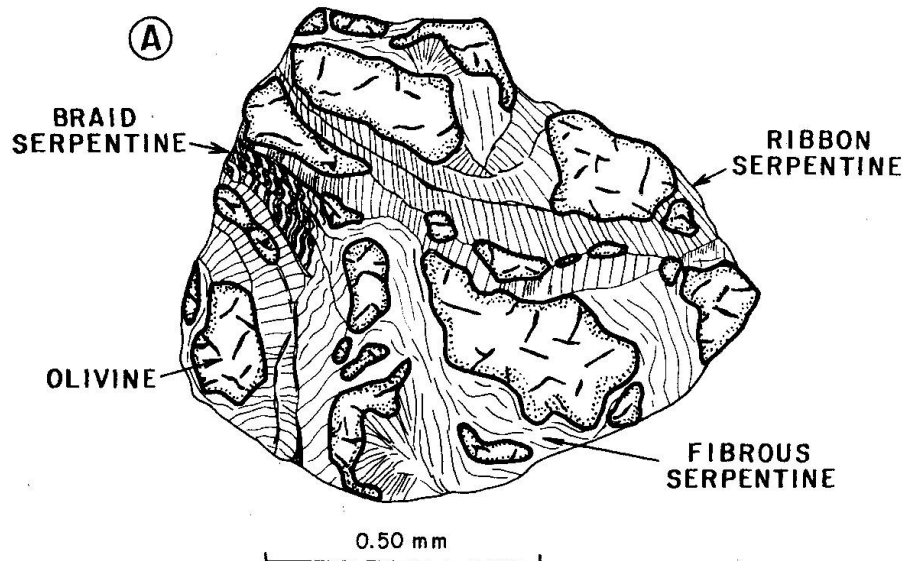

Fig. 4a. Large grain of olivine partly replaced by various types of serpentine. The ribbon and braid serpentines seem to fill expansion microfractures in the granulated olivine.
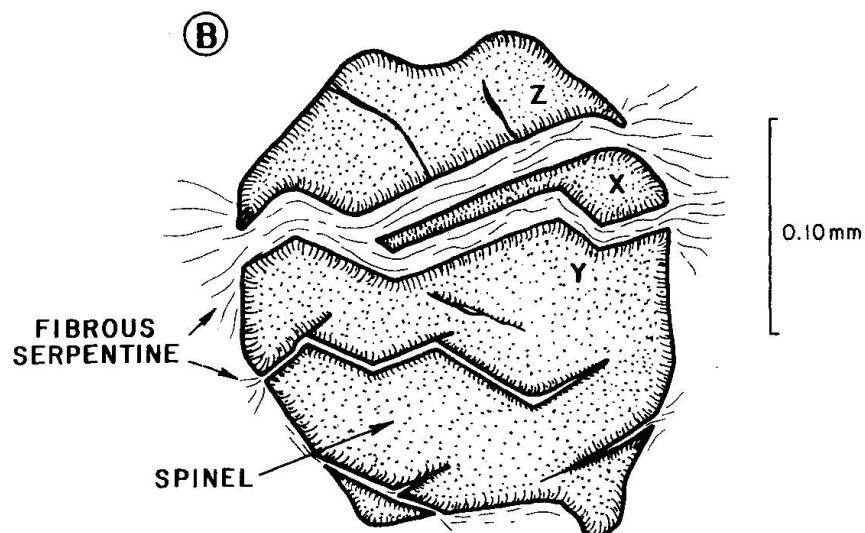

Fig. 4b. Grain of spinel showing microfractures filled with fibrous serpentine. The outline of fragment x matches perfectly the outline of fragment y, indicating that the microfracture between fragments x and y is an expansion fracture. The expansion in the fracture between fragments x and z was combined with partial replacement of the spinel during the process of serpentinization.

in volume because this type of serpentinization has combined replacement and expansion so that original grain boundaries and other possible markers have disappeared. Lamellar lizardite has replaced olivine without visible outgrowth, and the reaction must have operated at constant volume. From a chemical point of view, the serpentinization of olivine grains corresponds to a gain of water and to a slight loss of iron and nickel, and possibly to the loss of magnesium. Most of the original iron and nickel content of olivine is accommodated into the structure of lizardite (see chemical analysis No. 6, Table 2), the remainder has formed minute crystals of magnetite, awaruite (NICKEL, 1959) and

Table 2. *Chemical composition of serpentinized harzburgites and lizardite* (in weight percent)

	1	2	3	4	5	6
SiO_2	39.66	40.11	39.93	41.55	37.70	40.72
Al_2O_3	1.84	0.18	0.37	0.31	0.27	1.01
Fe_2O_3	4.07	3.05	4.43	3.96	9.71	4.07
FeO	3.92	4.46	3.49	3.65	2.23	0.63
MgO	39.96	43.43	40.62	40.29	36.35	39.30
MnO	nd	0.09	0.12	0.12	0.16	nd
CaO	1.52	0.03	0.34	0.34	0.17	0.32
Na_2O	0.29	nd	0.06	0.06	0.06	0.09
K_2O	nd	nd	0.05	0.05	0.05	nd
NiO	0.24	0.09	0.28	0.28	0.16	0.30
Cr_2O_3	0.13	0.36	0.43	0.31	0.65	0.42
H_2O^+	7.51	7.52	8.65	9.03	11.55	13.41
H_2O^-	0.38	0.22	0.82	0.45	0.50	0.43
Total	99.52	99.54	99.59	100.40	99.56	100.70

Key to samples:

Samples, from 1 to 5, have been arranged in order of increasing serpentinization.

1. Harzburgite, about 50 percent serpentinized, specific gravity 2.90. Locality: Vimy Ridge, Coleraine (COOKE, 1937, sample 11).
2. Dunite, about 50 percent serpentinized, specific gravity 2.91. Locality: Bell Mine, Thetford Mines (COOKE, 1937, sample 13).
3. Harzburgite, about 60 percent serpentinized. Locality: Lake Asbestos Mine, Black Lake (LAURENT, current research).
4. Harzburgite, about 70 percent serpentinized. Locality: Quarry Hill, Black Lake (LAURENT, current research).
5. Serpentinite (harzburgite 100 percent serpentinized). Locality: region of Thetford Mines (LAURENT, current research).
6. Lizardite. This serpentine forms the selvage of asbestos veins. Locality: Vimy Ridge, Coleraine (COOKE, 1937, sample 12).

heazlewoodite (CHAMBERLAIN, 1966). The original bulk chemical composition of the harzburgite was probably uniform as suggested by the minimal variation in composition of the olivines and orthopyroxenes (Table 1). However, when the analyses of serpentinized harzburgites (Table 2) are adjusted for effects of serpentinization and recalculated to 100 percent without water (Table 1), we observe a small but regular decrease of the MgO/SiO_2 ratio with increasing serpentinization. This must be caused by either a gain of silica or a loss of magnesia during the process of serpentinization. The formation of braid and ribbon tex-

tured lizardites must have resulted in some volume increase in order to accommodate about 13 percent of water per weight unit. In these conditions a loss of magnesia is more probable than a gain of silica to keep the increases in volume to a minimum (see HOSTETLER et al., 1966; THAYER, 1966). The loss of magnesia however is relatively small and apparently remains lower than 5 percent of the original content in completely serpentinized harzburgites. The serpentinization process is frequently viewed as isochemical (e.g. COLEMAN and KEITH, 1971), except for the introduction of water, but this appears to be unlikely in the case of the serpentinization of the Asbestos and Thetford Mines peridotites.

Spinels are commonly rimmed by magnetite or partly replaced along fractures and grain boundaries by an iron-rich opaque chromite, and their microfractures are filled with lizardite.

2. The chrysotile fibres

The second episode of serpentinization has produced flexible fibres of green and silky chrysotile that have filled the stockwork of straight, irregular and curved fractures forming the asbestos ore (Fig. 5). Some asbestos veins attain a width of 10 cm or more but the majority are less than 25 mm in width (COOKE, 1937). Their selvages, which are aphanitic and homogeneous with the aspect and color of jade stones, consist of cryptocrystalline, banded fibrous lizardite resulting from colloidal deposition (RIORDON, 1962). This serpentine grades towards the wall rock into coarser-grained lamellar lizardite associated with brucite fibres and into a mesh-textured serpentinite. The asbestos forms cross-fibres in the centre of the veins. These fibres are of remarkably pure clinochrysotile (WHITTAKER, 1956), although they are locally associated with a small amount of brucite. We observed three main types of veins:

a) Simple veins, in which the fibres are either straight or bent and oriented at right angle or obliquely to the walls (Fig. 6).

b) Veins with a median suture marked by an irregular line of aggregates of magnetite and inclusions of serpentinite (Fig. 7).

c) Composite veins (Fig. 8).

Some magnetite is distributed along the contact between the fibres and the selvages of the veins and, in smaller amounts, in the veins parallel to the chrysotile fibres.

The process of formation of the chrysotile fibres has initiated many controversial hypotheses (summarized in DRESSER and DENIS, 1944), but recently it has been attributed to a combination of fissure filling and wall rock replacement by RIORDON (1962). This conclusion however does not explain the mechanism of fibre growth. In my opinion, the best explanation probably resides in the
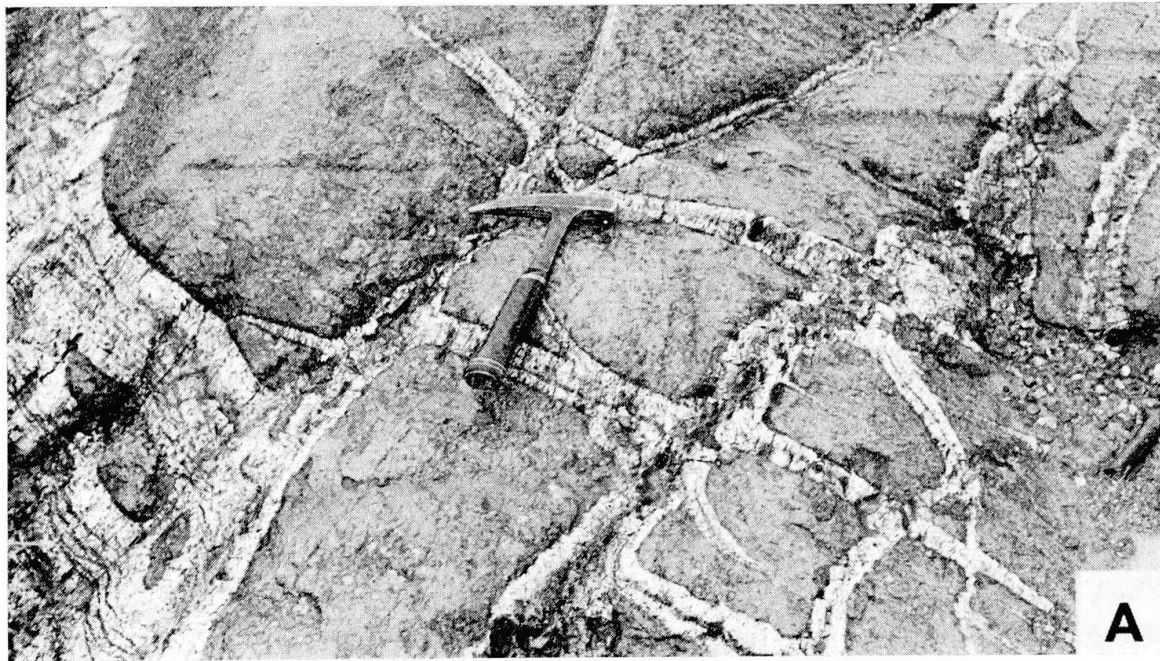
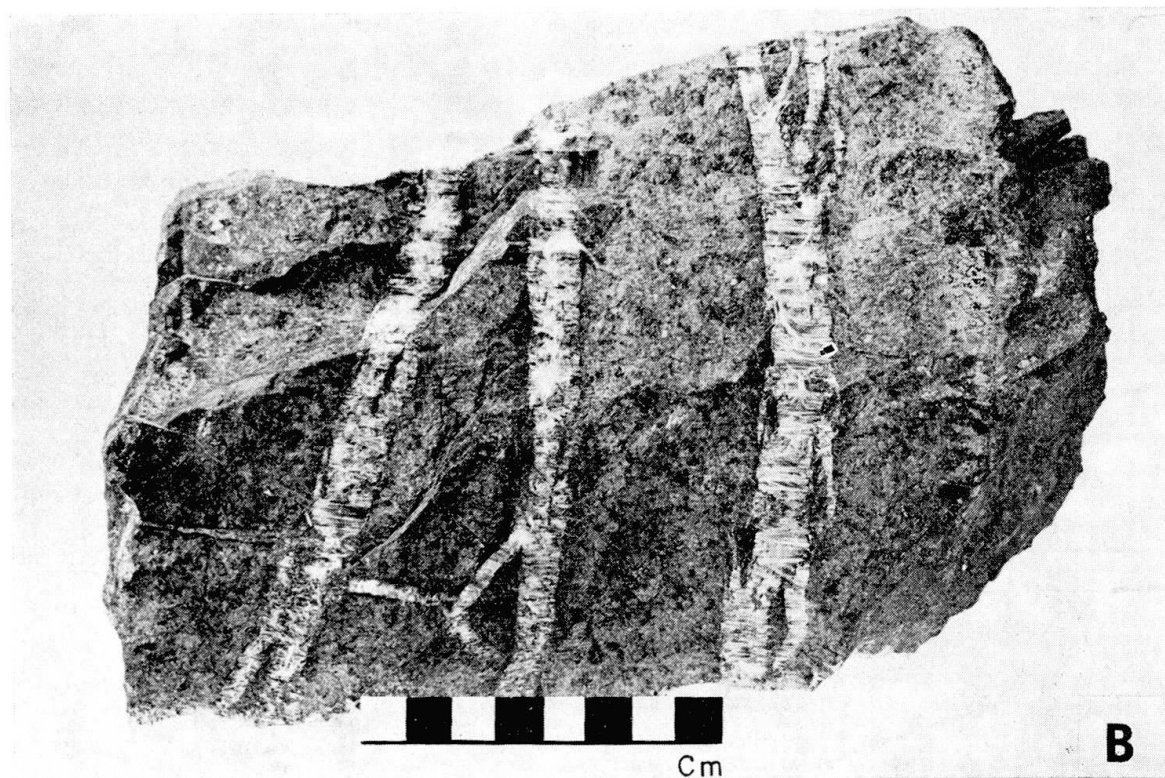Fig. 5a. Stockwork of composite veins of chrysotile fibres in harzburgite at Vimy Ridge.

Fig. 5b. Harzburgite with simple veins of chrysotile fibres grading or branching into veins with a median suture. Locality: Lake Asbestos Mine, Black Lake.
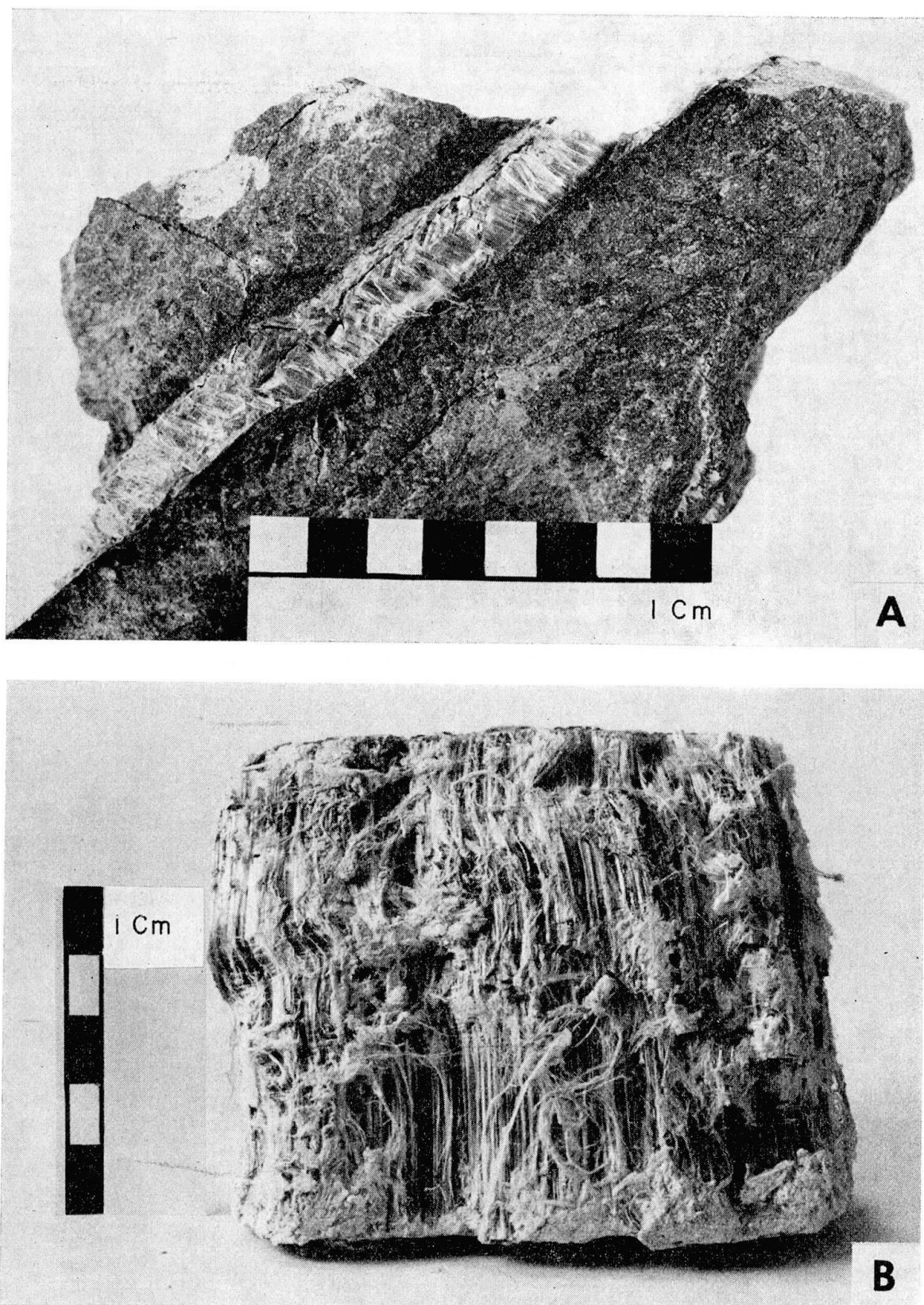
Fig. 6. Simple veins ("type a") of chrysotile fibres from the Thetford Mines region. A. Simple vein with straight fibres grown obliquely to the harzburgite walls. B. Simple vein with bent fibres grown perpendicular to the wall.
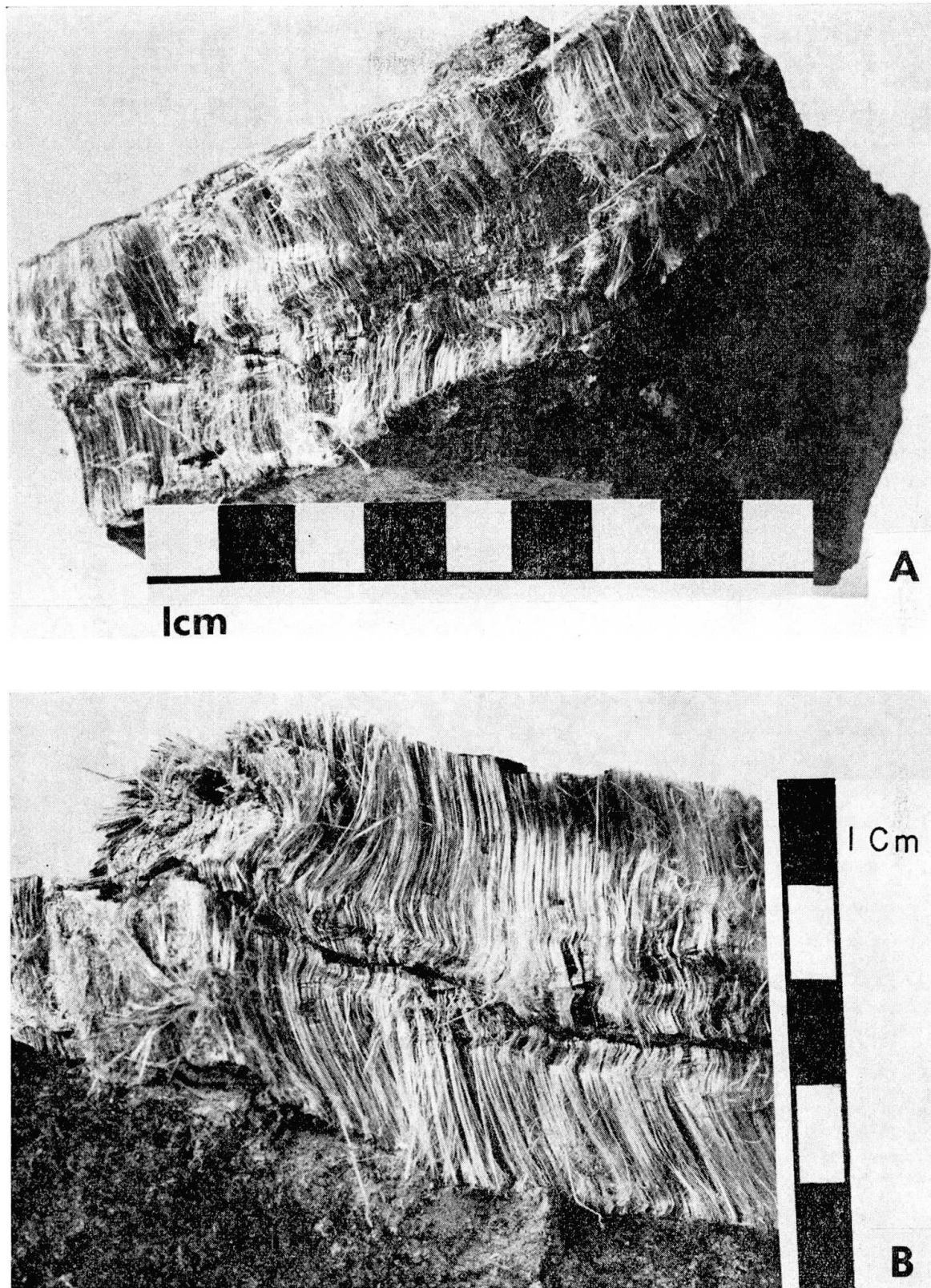
Fig. 7. Veins of chrysotile fibres with a median suture ("type b") from the region of Thetford Mines. In examples A and B, the fibres are bent and have grown obliquely to the harzburgite walls. Note the conspicuous median suture marked by an aggregate of magnetite.
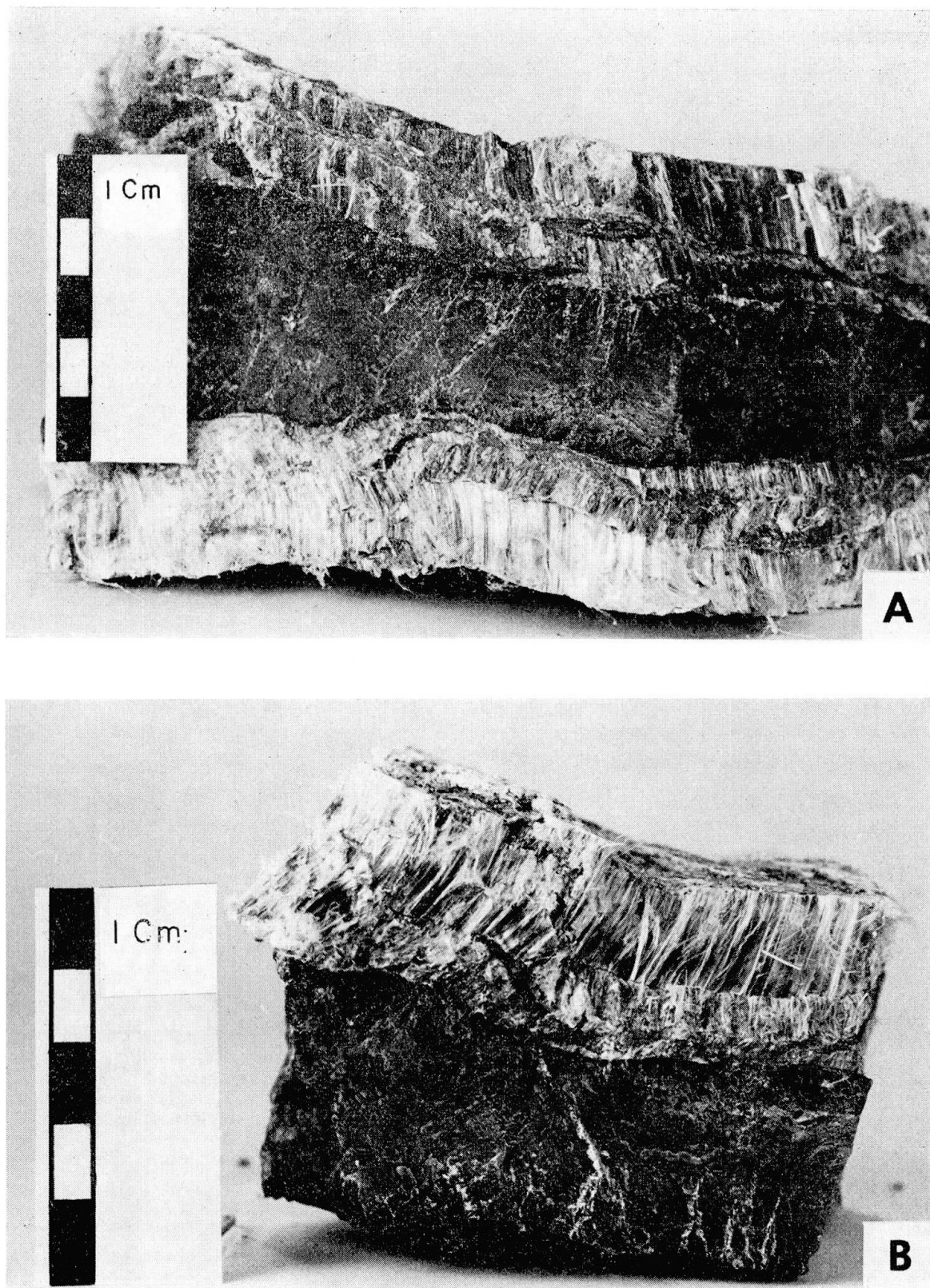
Fig. 8. Composite veins ("type c") of chrysotile fibres from the region of Thetford Mines. The veins are formed by a combination of simple veins and veins with a median suture. In both figures A and B, one can see examples of serpentinite inclusions along the median suture of some veins.

principles of incremental strain analysis of DURNEY and RAMSAY (1973), which are based on field observations, theoretical fabric analysis as well as the experimental work of BREHLER (1951). Tensile and shear fractures are often synchronously filled – as they are progressively opening – with crystals of fibre habit derived by solution or diffusion from material of the wall rock. In the veins the orientation of the growing fibres is not controlled by the position of the wall rock but by the direction of minimum shear stress; expansion causes fibre growth and the growing fibres cause dilation. FAESSLER and BADOLLET (1947, p. 5) had noted that the "... veins became wider and wider as if they had had the power to push away the wall rock." Significant changes in the direction of minimum shear stress are expected to produce changes in the direction of fibre growth. Such changes actually are recorded by fibre bends.

A comparison between the previously defined a, b and c types of asbestos veins and the various types of crystal growth distinguished by DURNEY and RAMSAY (1973) suggests that the chrysotile fibres have formed by a process of diffusion and solution transport during the progressive opening of dilation fractures. The fractures were caused by tectonic movements that occurred late in the history of the peridotite and at high levels in the crust. The simple asbestos veins have formed by syntaxial growth, the veins with a median suture have formed by antitaxial growth, and composite veins have formed by a combination of syntaxial and antitaxial growth. This is illustrated in Fig. 9.

From a chemical point of view, the chrysotile fibres are almost entirely composed of magnesia, silica and water, or the ideal composition of serpentine (Table 3). Chrysotile itself is rarely observed as pseudomorph of olivine in the harzburgite, and I believe that it was not derived from unserpentinized olivine remnants but from the dissolution of lizardite. In the process of the dissolution

Table 3. *Chemical composition of chrysotile fibres* (in weight percent)

	1	2	3	4
SiO_2	43.41	42.00	42.36	41.32
Al_2O_3	1.41	0.64	tr	0.80
Fe_2O_3	0.60	0.80	0.96	1.01
FeO	2.35	1.89	0.39	0.58
MgO	39.44	42.41	43.64	43.47
CaO	0.12	0.14	0.05	0.03
H_2O^+	12.67	12.12	12.60	12.79
MgO/SiO_2	0.908	1.009	1.030	1.052

Samples have been arranged in order of increasing fibre quality from 1 to 4.
These chemical analyses have been normalized to 100 percent without H_2O^-.

Origin of samples:
1. Asbestos vein from Johnson Mine, Thetford Mines. Quality: very harsh (COOKE, 1937, sample 4).
2. Asbestos vein from British Canadian Mine, Black Lake. Quality: harsh (COOKE, 1937, sample 9).
3. Asbestos vein from King Mine, Thetford Mines. Quality: high (COOKE, 1937, sample 3).
4. Asbestos vein from Beaver Mine, Thetford Mines. Quality: very high (COOKE, 1937, sample 7).
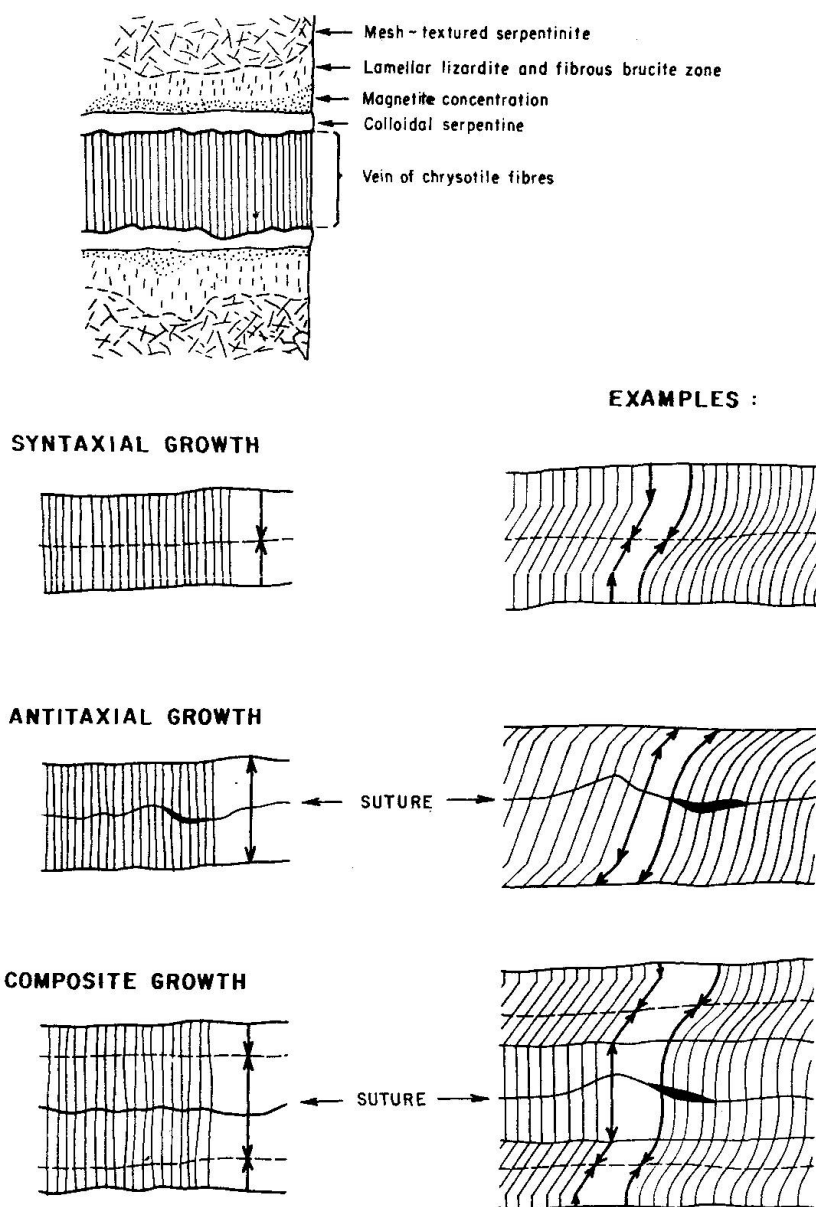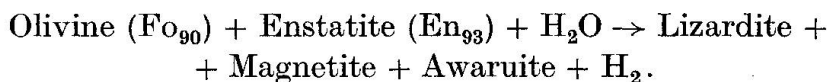
Fig. 9. Idealized sections through veins of chrysotile fibres. This interpretation is based on the work of DURNEY and RAMSAY (1973).

of lizardite, its solution transport and chrysotile growth, most of the iron accommodated in the structure of lizardite was expelled from this silicate to form aggregates of magnetite grains mainly along the vein selvages. Although various factors can affect the nature of the fibres, their quality appears to be primarily related to their residual amount of iron and aluminum replacing magnesium in octahedral coordination. The magnitude of the magnesium substitution by iron and aluminum is reflected by the MgO/SiO_2 ratio which increases with fibre quality, as iron and aluminum decrease (see the examples given in Table 3).

3. Conditions of formation

The observed reaction during the first episode of serpentinization is:

$$\text{Olivine (Fo}_{90}) + \text{Enstatite (En}_{93}) + H_2O \rightarrow \text{Lizardite} + {} + \text{Magnetite} + \text{Awaruite} + H_2.$$

The formation of magnetite and awaruite is controlled by the serpentinization reactions through Fe-related redox mechanisms. ECKSTRAND (1975) gave good evidence that the hydration of olivine to form serpentine is, itself, a reaction that generates a highly reducing environment by the dissociation of H_2O to provide the oxygen required to form magnetite, thereby releasing H_2. Awaruite can exist in equilibrium with magnetite for high fH_2 and very low fO_2. Under the same conditions carbon monoxide and hydrogen may have reacted in presence of nickel as catalyst to form hydrocarbons. N-alkanes with molecular weights generally between C_{16} and C_{36} have been found in trace amounts by GIBBS (1971) in the serpentinites of Asbestos and Thetford Mines. This provides definite physical constraints and shows that the first episode of serpentinization occurred in highly reducing conditions.

Temperatures of serpentinization are difficult to ascertain and may vary from about 400° to less than 100° C depending on various factors such as the physical environment and the composition of the phases involved in the reactions. For example, O^{18}/O^{16} fractionation data between coexisting serpentine and magnetite indicate relatively cold conditions and suggest that the isotopic composition of lizardite-chrysotile assemblages is equilibrated in a temperature range from about 85° to 185° C (WENNER and TAYLOR, 1971). On the other hand AUMENTO and LOUBAT (1971, p. 660), on the base of mineralogical, chemical and isotopic evidence, concluded that most of the serpentinization of the ultramafic rocks from the Mid-Atlantic Ridge took place under relatively hot (480° C), deep-seated conditions. By combining the available experimental data of BOWEN and TUTTLE (1949) and YODER (1952), HOSTETLER et al. (1966) estimated that serpentinization of olivine of Fo_{90} composition may begin around 400° C at a water vapour pressure of 1000 atmospheres. Since under the same P_{H_2O} but at higher temperature olivine is converted to talc and later to anthophyllite (GREENWOOD, 1963), and since these minerals did not form we must conclude that hydration and pervasive serpentinization of the peridotite occurred at a temperature lower than 400° C. The mineral paragenesis observed indicates that water was not a primary component of the peridotite but was added after the rock had cooled to the temperature of serpentinization which, I assume, was probably lower than 374.2° C, the critical temperature of water. It is also known that olivine as an isolated phase is stable down to 380° C in equilibrium with pure water (JOHANNES, 1969, p. 1098). As no carbonates were formed, the water responsible for the first episode of serpentinization probably

was very low in carbon dioxide and contained no dissolved oxygen. It was a water quite unlike meteoric waters. In the oceanic floor environment, meteoric water is known to be absent.

In the case of the asbestos veins, the observed reaction is as follows:

$$\text{Lizardite} + H_2O + O_2 \rightarrow \text{Clinochrysotile} + \text{Brucite} + \text{Magnetite}.$$

BRINDLEY and ZUSSMAN (1957) have shown in their studies of the thermal transformations of serpentine polymorphs that chrysotile is stable at lower temperatures than lizardite and antigorite. HOSTETLER and CHRIST (1968), in turn, have demonstrated experimentally that chrysotile dissolves congruently in water at 90° C. Their data strongly suggest that chrysotile is presently being formed at temperatures less than 100° C as observed by DE CHÉTELAT (1947) and BARNES et al. (1967). On the other hand, a brucite-forming reaction must run close to 400° C or less according to HOSTETLER et al. (1966), and the mineral assemblage of asbestos veins must therefore have formed between 400° and less than 100° C.

The formation of large amounts of magnetite, without awaruite, during the growth of chrysotile fibres indicates higher fO_2 and lower fH_2 than the conditions of lizardite formation. Consequently, it appears that the reaction-forming chrysotile probably occurred at slightly lower temperatures than the reaction-forming lizardite and did not generate a reducing environment. Meteoric and/or connate waters containing dissolved oxygen but no carbon dioxide could be responsible for the dissolution of lizardite and the transport of dissolved silica and magnesia in dilation fractures where these components reacted to form the chrysotile fibres.

Granite emplacement and later alterations

The peridotite masses contain a varied assemblage of rootless intrusive rocks. Three groups can be distinguished on the base of differences in composition, stage of alteration and deformation. The oldest group consists of isolated lenses and pods of massive rodingite without any relic of primary minerals. Detailed petrographic studies of this calcium-rich metasomatic material could perhaps reveal some remnants (ghosts) of gabbroic or pyroxenitic fabrics. The second group consists of lensoid dikes of hornblende-biotite diorite strongly foliated, altered and partly rodingitized (DE, 1972). These two first groups are probably genetically associated with the ophiolite suite. The third group consists of a younger complex of intrusive dikes of quartz monzonite (DE, 1972) still relatively fresh and massive, although their margins are rodingitized. The peridotite was already serpentinized at the time of the dioritic and monzonitic intrusions

since the serpentinite at their contacts was dehydrated and converted into chlorite, diopside, talc and anthophyllite (COOKE, 1937; DE, 1972). The only significant age determinations we have on these rocks are two K-Ar ages, 477 and 481 m. y. (POOLE et al., 1963), obtained from muscovites of the younger granitic rocks. They both suggest an Early Ordovician age for the younger granites, corresponding approximately to the time of tectonic emplacement of the ophiolites.

After emplacement into their present setting, the asbestos serpentinites were altered at low temperatures by CO_2-bearing meteoric ground waters draining some silica from the country rock. Serpentine minerals were locally altered to talc and magnesite but the main alteration developed in shear zones and along the contact between the peridotites and their country rock, forming extensive talc-carbonates-chlorite zones.

Conclusion and hypothesis

The petrological study of the harzburgite has shown that this rock has primary mineral assemblages, structures and solid state deformation textures characteristic of ultramafic rocks formed in upper mantle pressure and temperature conditions. Several hypotheses can be formulated regarding the tectonic mechanism that brought this mantle material to the surface. Among several choices (see e.g. the discussion of VUAGNAT, 1968; or the review by WYLLIE, 1967), we prefer the hypothesis of an oceanic origin since the asbestos serpentinites are part of an ophiolitic complex (LAMARCHE, 1972; LAURENT, 1975). I will assume that the peridotite was brought close to the surface through diapiric rise amid an active oceanic ridge and was eventually welded to the spreading oceanic crust of the proto-Atlantic ocean. In that position and after having cooled to a temperature lower than 400° C, the peridotite was hydrated and serpentinized in highly reducing conditions. Alternatively, serpentinization may have taken place during low grade regional metamorphism at the time of transport and folding of the ophiolites. This, however, is unlikely since all granitic dikes predate the tectonic emplacement of the ophiolites and have intruded a peridotite already serpentinized. In Early Ordovician time the oceanic crust was fragmented at the margin of the oceanic basin. Some fragments were obducted on the Cambrian rocks deposited along the Appalachian continental margin. Both Cambrian rocks and ophiolites were transported northwestwards, and deformed and folded in mid-Ordovician time. Near the end of these tectonic movements, asbestos veins started growing in dilation fractures throughout the peridotite, and through the action of oxygen-rich waters. Finally, low temperature meteoric ground waters partly altered the peridotite to talc and carbonates.

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