FAULT-RELATED PHENOMENA ASSOCIATED WITH HYDRATION AND SERPENTINE RECRYSTALLIZATION DURING SERPENTINIZATION

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ABSTRACT

The distribution of serpentine minerals and textures in lizardite–chrysotile serpentinites can be explained with an emphasis on the role of fault-controlled flow of fluid in their formation. Variations in serpentine mineralogy and texture can be attributed to three subprocesses within serpentinization. These subprocesses are characterized by the different roles of water and heat. *Hydration* proceeds *via* exothermic, water-consuming reactions and produces retrograde lizardite or antigorite serpentinites with mesh textures. *Deserpentinization,* the prograde metamorphism of serpentinite, proceeds *via* endothermic, water-producing reactions. *Serpentine recrystallization,* the replacement of one serpentine mineral by another, proceeds *via* endothermic, water-conservative reactions, and produces serpentinites consisting of lizardite hourglass and lizardite + chrysotile + antigorite interlocking textures. A fluid is present during serpentine recrystallization, on the basis of changes in whole-rock $\delta^{18}O$ values. Serpentine recrystallization is not necessarily a pervasive process; it also can be fracture-controlled.

Keywords: serpentine, hydration, recrystallization, deserpentinization, serpentinite, fracture, fault.

SOMMAIRE

La distribution des minéraux du groupe de la serpentine et des textures dans les serpentinites à lizardite + chrysotile peut s'expliquer en considérant la distribution d'une phase fluide, souvent contrainte de circuler le long de fissures. Les variations dans les assemblages minéralogiques et les textures résultent de trois sous-processus du phénomène de serpentinisation, qui diffèrent tant dans le rôle de la phase fluide que dans le budget de chaleur. Une *hydratation* accompagne les réactions exothermiques, dans lesquelles l'eau sert de réactif; il en résulte des serpentinites à lizardite ou à antigorite, à texture en maille. La *déserpentinisation* accompagne le métamorphisme prograde d'une serpentinite; les réactions sont endothermiques, et libèrent l'eau. La *recristallisation* de la serpentine implique le remplacement d'un minéral par un autre, et procède par réactions endothermiques qui conservent l'eau. Les serpentinites qui en résultent contiennent la lizardite en texture de sablier, et lizardite + chrysotile + antigorite en intercroissances. Une phase fluide est présente au cours de cette recristallisation, d'après les rapports $\delta^{18}O$ des roches totales. La recristallisation de la serpentine n'est pas nécessairement un processus répandu; elle aussi peut être limitée aux zones faillées.

(Traduit par la Rédaction)

Mots-clés: serpentine, hydratation, recristallisation, déserpentinisation, serpentinite, fissure, faille.

INTRODUCTION

The formation of serpentinite from peridotite is considered one of the classic examples of low-temperature metamorphism, in which water gains access to the peridotite along faults and shear zones. As serpentinized peridotite contains 13 to 15 wt.% H_2O that is not present in the unaltered peridotite, serpentinization is best thought of as an example of infiltration metamorphism (Ferry 1988), in which anhydrous mineral assemblages (olivine and enstatite), indicative of fluid-absent conditions, are replaced by hydrous mineral assemblages (serpentines). This view stresses the importance of the fluid to serpentinization and its role in catalyzing chemical reactions that occur during serpentine recrystallization. In contrast, low-temperature metamorphism is best used to describe processes operating at relatively fixed bulk-composition, such that mineral assemblages and compositions are a function of P and T.

Based on the 13 to 15 wt.% H_2O added to a peridotite during its hydration to form serpentine, the relationship between faults and fluid flow is obvious once one has developed an intuitive understanding of serpentinization, which is the replacement of olivine, and other Mg-rich silicates, by serpentine. Although this may now seem to be obvious, it should be kept in mind that this intuitive understanding and the obvious nature of serpentinization were slow in coming. If the fault-controlled nature of serpentinization was obvious, then I think that Hess (1938) would not have promoted the hypothesis that the formation of serpentine represents the final stage in the crystallization of a peridotite magma. Setting aside consideration of hydration due to serpentinization, it is not at all clear that the replacement of one serpentine mineral by another, termed serpentine recrystallization, also is a fault-controlled process.

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This is especially true where a completely serpentinized peridotite is the protolith affected by serpentine recrystallization. In these examples as well, the fault provides a pathway for the fluid that either catalyzes reactions that change the serpentine mineral assemblage and its texture, or it causes a metasomatic alteration of the serpentinite (*i.e.*, addition of SiO_2 to the rock) that also results in a change in mineral assemblage and texture. In both cases, serpentine recrystallization produces mineral assemblages stable at the *P* and *T* at which it occurs.

Serpentine recrystallization should be greatest near the fault that served as the fluid conduit and diminish with distance from it. The implications of fault-controlled flow of fluid for serpentine recrystallization may seem obvious to anyone who has considered it in detail. However, an absence of proper sampling based on this knowledge has hampered understanding of stable isotope systematics (O'Hanley *et al.* 1989a) and density–susceptibility relationships (Toft *et al.* 1991) in serpentinites. It has also hampered understanding of the formation of chrysotile as a rock-forming mineral (Page 1967) and the origin of chrysotile asbestos veins (O'Hanley 1988a).

The main purpose of this paper is to illustrate the spatial patterns of rock-forming serpentine minerals. This will be done by using four asbestos deposits as examples. Each exhibits different patterns of serpentine minerals and textures. Detailed information concerning the deposits is published elsewhere (see below), and only the elements essential to this paper are discussed.

Another purpose of this paper is to define subprocesses within the serpentinization process that are associated with the formation of different types of serpentinite. These subprocesses are characterized by the roles of water and heat and serve to justify the distinction between regimes of serpentinization as defined by O'Hanley *et al.* (1989b) and the different serpentinites that result.

The terminology of serpentine textures developed by Wicks & Whittaker (1977) is used here. Pseudomorphic textures (mesh-rim and hourglass textures) preserve protolith textures, whereas nonpseudomorphic textures (interlocking and interpenetrating textures) do not. For the serpentinites discussed here, the serpentine textures were identified by optical microscopy, and the serpentine minerals were identified with a microbeam X-ray camera using the methodology of Wicks & Zussman (1975).

THE CLASSIFICATION OF SERPENTINITES AND SUBPROCESSES OF SERPENTINIZATION

Wicks & Whittaker (1977) defined eight types of serpentinite based on the presence or absence of antigorite and a schistose fabric and divided them into retrograde (characterized by pseudomorphic textures) and prograde serpentinites (characterized by nonpseudomorphic textures). Wicks & Plant (1979) augmented the study of Wicks & Whittaker with an electron-microprobe study of the same samples. An important distinction that resulted from this work is that lizardite–chrysotile serpentinites present in chrysotile asbestos deposits are dominated by lizardite hourglass and lizardite ± chrysotile ± antigorite interlocking textures that are transitional between pseudomorphic and nonpseudomorphic textures.

In these serpentinites, chrysotile is present as a rock-forming mineral, in an interlocking texture, in addition to its presence in asbestos veins. The chrysotile formed from lizardite rather than olivine. An interesting feature in these rocks is the presence of different types of lizardite hourglass textures and lizardite interlocking textures that represent recrystallization of lizardite before the formation of chrysotile.

In contrast to retrograde alteration of peridotite that results in partly serpentinized peridotite with lizardite mesh-rim textures, prograde metamorphism of serpentinite produces antigorite in interpenetrating textures. The formation of interlocking lizardite and chrysotile textures is attributed to a mild prograde metamorphism, sufficient to recrystallize lizardite to chrysotile with an interlocking texture but not sufficient to form antigorite (Wicks & Whittaker 1977).

There are two models for the serpentine phase diagram based on different reaction relationships between lizardite and chrysotile. In the system $MgO–SiO_2–H_2O$ (MSH), lizardite and chrysotile are polymorphs, and only one of them can form stably from forsterite during hydration at low $P(H_2O)$ (O'Hanley *et al.* 1989b, Fig. 7). In the system $MgO–Al_2O_3–SiO_2–H_2O$ (MASH), lizardite is more Al-rich than chrysotile, which removes their polymorphic relationship, and both lizardite and chrysotile can form stably from forsterite during hydration (O'Hanley *et al.* 1989b, Fig. 6). Electron-microprobe data for lizardite and chrysotile that replaces it (*e.g.*, Wicks & Plant 1979, Table 3) are virtually identical and confirm the progress of a solid–solid reaction during the replacement, indicating that lizardite and chrysotile are polymorphs.

The absence of thermodynamic data for Al-free lizardite prohibits the calculation of its equilibria, so that the stability of lizardite with respect to chrysotile is uncertain. I prefer the topology given by O'Hanley *et al.* (1989b, Fig. 7) because it is easiest for me to accept lizardite forming metastably from forsterite at low $P(H_2O)$ and then lizardite being replaced by a stable chrysotile if serpentine recrystallization occurs. The alternative topology is lizardite forming stably from forsterite and then being

replaced by a metastable chrysotile during serpentine recrystallization. In addition, if the reaction forsterite + water = lizardite + brucite is stable at low $P(H_2O)$, then the reactions antigorite + brucite = forsterite + water, and antigorite = forsterite + talc + water are metastable at low $P(H_2O)$, and chrysotile is everywhere metastable. Mineral assemblages produced during prograde metamorphism of serpentinite suggest that antigorite-bearing assemblages are stable rather than metastable, and thermodynamic data for chrysotile and antigorite in the system MSH are consistent with antigorite being stable at higher temperatures than chrysotile (Berman *et al.* 1986).

As the crystal structure of lizardite and its thermal behavior are more similar to those of chrysotile than antigorite (Wicks & O'Hanley 1988), I expect the behavior of lizardite to be closer to that of chrysotile than to that of antigorite, such that lizardite should be a low-temperature mineral. For these reasons, the topology for the system MSH given by O'Hanley *et al.* will be used in this discussion, so that lizardite is metastable when it forms after forsterite.

O'Hanley *et al.* (1989b) defined four regimes of serpentinization in the $P(H_2O) - T$ plane. The eight types of serpentinites of Wicks & Whittaker can be
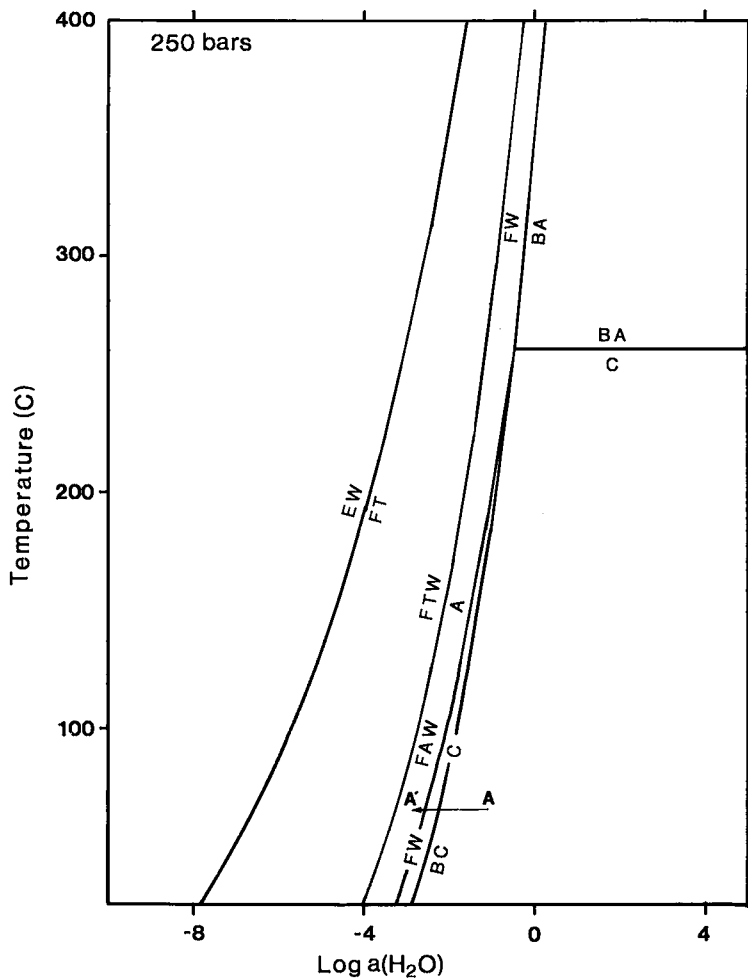

FIG. 1. Temperature – log $a(H_2O)$ diagram calculated at 250 bars H_2O pressure, illustrating the stable reactions among the phases forsterite (F), enstatite (E), brucite (B), antigorite (A), chrysotile (C), talc (T), and water (W). Lack of thermodynamic data for Al-free lizardite precludes calculation of its equilibria. It is assumed to be metastable; see text for discussion. Path A–A' represents a decrease in $a(H_2O)$ accompanying sealing of a rock containing water initially under hydrostatic conditions.

reduced to four with the following assumptions: first, the presence of a schistosity does not affect serpentine stability, and second, the presence or absence of antigorite is a function of temperature. These assumptions may not be appropriate at low $P(H_2O)$ for two reasons. First, the development of schistosity can affect the magnitude of $P(H_2O)$ with respect to geostatic pressure by changing porosity and permeability (Bruton & Helgeson 1983). If the rock becomes sealed, then $a(H_2O)$ may be reduced; if the change is of sufficient magnitude, then hydration could be stopped because the anhydrous mineral assemblage is stabilized as $a(H_2O)$ is reduced to a value below the equilibrium (Path A–A' in Fig. 1). Second, in the vast majority of partly serpentinized peridotites, hydration produces lizardite metastably rather than the stable assemblages brucite + chrysotile, or chrysotile + antigorite below 260°C or antigorite + brucite above this temperature (Fig. 1). The presence of lizardite without chrysotile or antigorite + brucite indicates only that T is less than 400°C [which is the highest T for the metastable reaction olivine + water = lizardite + brucite in the MSH model of O'Hanley et al. (1989b)] and that there could have been insufficient energy available to induce recrystallization to produce the stable assemblage.

The four-fold division leads to the distinction between retrograde lizardite ± chrysotile serpentinites, lizardite + chrysotile ± antigorite serpentinites found in asbestos deposits, and retrograde and prograde antigorite serpentinites (Table 1).

Most retrograde lizardite ± chrysotile serpentinites consist of lizardite only in mesh-rim textures.

TABLE 1. SUBPROCESSES OF THE SERPENTINIZATION PROCESS

Sub-process	Characteristics of reactions (Resulting Minerals & Textures)	Reactions[1]	Enthalpy Change[2] (kJ/mol H$_2$O)
Hydration			
	H$_2$O-consuming, heat-evolving (lizardite ± chrysotile or antigorite mesh-rim texture)	2F + 3W = C[3] + B	-71.69 -25.8[4]
Serpentine Recrystallization		L = C	
	H$_2$O-conservative, heat-consuming (lizardite hourglass & lizardite ± chrysotile ± antigorite interlocking textures)	C + 0.11SiO$_2$(aq)= A + 0.07W C = A + 0.16B	3507.0 17.32
Deserpentinization			
	H$_2$O-evolving, heat-consuming (antigorite ± brucite interpenetrating texture)	2OB + A = 34F + 51W A = 18F + 4T + 27W	70.98 78.0

[1]Symbols in reactions represent forsterite(F), steam(W), chrysotile(C), brucite(B), antigorite [Mg$_{48}$Si$_{34}$O$_{85}$(OH)$_{62}$(A)] and talc(T). [2]Calculated at 25°C, 1 bar using data in Berman (1988). [3]Chrysotile is used in the reactions instead of lizardite, although lizardite is more appropriate based on petrographic observations (Wicks & Whittaker 1977), because there are no enthalpy, entropy or free-energy data for Al-free lizardite. However, the results should not change dramatically when data for lizardite are obtained. [4]Calculated at 413°C, 30kbars by Peacock (1987b).

In the other examples, chrysotile occurs in two textures. First, millimeter-wide chrysotile veins occur in compound mesh rims where they can be identified optically. In this type of serpentinite, no serpentine recrystallization has occurred because chrysotile is found in fractures (serpentine recrystallization is the replacement of one serpentine mineral assemblage by another). Second, submicroscopic lizardite + chrysotile intergrowths occur in isotropic mesh centers, and it is not clear whether or not chrysotile formed from lizardite or from olivine. To the writer's knowledge, no one has documented at the thinsection scale the formation of chrysotile directly from olivine. The one sample that contains chrysotile only in a mesh center formed from olivine has been studied both optically (sample 18501: Wicks & Whittaker 1977) and by transmission electron microscopy (Cressey & Zussman 1976). It occurs in a serpentinite from an asbestos deposit that does not contain relict olivine, so that this chrysotile could have formed from lizardite rather than olivine. Neither the studies by Wicks & Zussman (1975), Wicks & Whittaker (1977) nor Wicks & Plant (1979) document a serpentinite in which chrysotile formed from olivine during hydration. Prichard (1979) concluded from her study of samples taken from ophiolites and from the ocean floor that chrysotile formed from lizardite rather than olivine and that chrysotile did not form until olivine had reacted out. Based on these observations, I conclude that chrysotile does not form microscopic textures after olivine. As lizardite is the sole serpentine mineral present in most retrograde lizardite serpentinites, there is no evidence for serpentine recrystallization in these rocks. However, the other serpentinites of this type contain chrysotile along with lizardite. Both types of retrograde lizardite serpentinites will be described as lizardite ± chrysotile serpentinites (Table 1).

Antigorite does form mesh-rim textures after olivine without either lizardite or chrysotile, so that these serpentinites represent a second type of retrograde serpentinite.

All eight types of serpentinite defined by Wicks & Whittaker (1977) may be found in chrysotile asbestos deposits. The most common are lizardite hourglass textures and lizardite ± chrysotile ± antigorite interlocking textures. The paragenetic sequence is olivine to lizardite to chrysotile or antigorite (or both); chrysotile is never found with olivine. Although asbestos deposits are best known because they contain chrysotile asbestos veins, it is the presence of chrysotile as a dominant rockforming mineral that make them petrologically important. In some asbestos deposits, serpentinites consisting of antigorite interlocking or interpenetrating textures are present. They form from lizardite and may or may not contain coexisting chrysotile.

The discussion above indicates that chrysotile as

a rock-forming mineral forms after lizardite, and that it is most commonly found in interlocking textures. Thus, serpentinites in asbestos deposits contain lizardite mesh-rim and hourglass textures, lizardite ± chrysotile ± antigorite interlocking textures, and antigorite interpenetrating textures. These rocks will be referred to as lizardite ± chrysotile ± antigorite serpentinites (Table 1).

Prograde metamorphism of serpentinite produces first antigorite interpenetrating textures and then forsterite + talc. They represent a fourth type of serpentinite and have been discussed by Evans (1977); they will not be discussed here.

The formation of the four types of serpentinites can be related to three distinct subprocesses within serpentinization (Table 1). One subprocess, hydration of olivine to either antigorite or lizardite, produces retrograde serpentinites. It is accomplished by water-consuming, exothermic reactions. A second subprocess, recrystallization of lizardite to a different lizardite-bearing texture, or to either chrysotile or antigorite (or both), produces serpentinites found in chrysotile asbestos deposits. It is accomplished *via* solid–solid reactions that are weakly endothermic because there is little or no fluid or vapor involved (Table 1). A fluid is inferred to be present during this process on the basis of changes in whole-rock stable isotope values and changes in mineral composition (O'Hanley *et al.* 1989a); in most cases, H_2O is a catalyst rather than a reactant or product, so that reaction progress does not indicate the water–rock ratio during the process. The final subprocess, deserpentinization, which is the prograde metamorphism of serpentinite, represented by the formation of olivine from antigorite, is accomplished via H_2O-producing, endothermic reactions (Table 1).

It is possible that the heat released during hydration, which is equivalent to a rise in temperature of 200 to 250°C (MacDonald 1984, Frost 1985, Peacock 1987a), is sufficient to transform lizardite to chrysotile, so that both hydration and recrystallization occur during the same serpentinization event. If this is the case, then the distinction between the two subprocesses is not a useful one because these do not result in two distinct serpentinization events that affected the peridotite. Instead, the rate at which water gained access to the peridotite would be important in controlling whether or not chrysotile formed during hydration, because it would determine the rate at which heat was generated at the reaction front. Which parameters control the result are not well known, so that further discussion is not warranted; several authors have discussed qualitatively the influence of heat on hydration (Frost 1985, Peacock 1987a). The purpose of this discussion is to motivate the presentation of textural criteria that may distinguish hydration with recrystallization from

hydration followed at a later time by serpentine recrystallization.

If serpentine recrystallization accompanies hydration, then lizardite should be intimately mixed with chrysotile within the same texture, such as in the serpentinite at Burro Mountain (Coleman & Keith 1971). At Burro Mountain, chrysotile and lizardite occur in mesh textures, and there is no variation in patterns of serpentine weathering in outcrop to indicate that there are different types of serpentinite present; there are only different extents of hydration, based on increasing modal amounts of serpentine minerals.

The serpentinite at Woodsreef, New South Wales, contrasts greatly with that at Burro Mountain. At Woodsreef, most of the rock is partly serpentinized peridotite, consisting of lizardite mesh rims surrounding cores of unaltered olivine. Near a fault in the center of the partially serpentinized rock, veins of chrysotile asbestos, spaced one meter apart, with completely serpentinized zones on either side, cut the partly altered rock. In outcrop, the boundary between the completely and the partly serpentinized rock is very sharp, similar to that at Mt. Belvedere (Labotka & Albee 1979). At Woodsreef, these margins contain a series of serpentine textures consisting of different serpentine minerals. From the partly serpentinized peridotite toward the vein, these minerals and textures are lizardite ± brucite mesh rims with olivine mesh centers, lizardite + brucite mesh texture, lizardite hourglass texture, lizardite interlocking texture, and finally chrysotile interlocking texture; the chrysotile texture is not invariably present. Thus, the lizardite and chrysotile textures are distinct spatially both on the macroscopic and microscopic scales.

Using the evidence in outcrop and in thin section from both the Burro Mountain and Woodsreef serpentinites, hydration with recrystallization can be distinguished from hydration followed at a later time by recrystallization. In outcrop, hydration with recrystallization should produce one serpentinite, and in thin section only one texture in which the serpentine minerals are intimately mixed. The type-3 serpentinites of Wicks & Whittaker (1977), or the retrograde lizardite serpentinites in this study, which consist of lizardite ± chrysotile in mesh textures, fit this description. Hydration followed by recrystallization should produce at least two types of serpentinite in outcrop, and apparent cross-cutting relationships. In thin section, the serpentine minerals will not be intimately mixed in one texture but will form different textures composed of different minerals. Examples that have been described by Laurent & Hébert (1979) from the Thetford Mines area of Quebec, and others that are described in this paper, are composed of lizardite ± chrysotile ± antigorite serpentinites, or several types of serpentinite as defined

TABLE 2. PERTINENT DATA ON ASBESTOS DEPOSITS

	Woodsreef	Cassiar	Garrison	United
location	Woodsreef, N. S. Wales	Cassiar, B. C.	Matheson, Ont.	Matachewan, Ont.
geological setting	Tamworth terrane[1]	Sylvester allochthon[3]	Southern volcanic zone, Abitibi greenstone belt[6]	
serpentine protolith	peridotite tectonite[2] forearc basement[1]	peridotite tectonite[4] arc-related, suboceanic crust[5]	dunite cumulate, in differentiated mafic-ultramafic sill[7]	dunite cumulate, in differentiated mafic-ultramafic sill[8]

[1] Blake & Murchy (1988), [2] O'Hanley & Offler (1989), [3] Harms (1986), [4] O'Hanley & Wicks (1987),
[5] Nelson & Bradford (1989), [6] Ludden & Hubert (1986), [7] Wicks et al. (1983), [8] Kretschmar & Kretschmar (1986).

by Wicks & Whittaker.

For the remainder of this paper, serpentinites like the one found at Burro Mountain will be considered products of hydration, and those similar to Woodsreef will be considered products of multiple episodes of serpentinization involving hydration followed at a later time by serpentine recrystallization.

In an earlier, comprehensive study, Wenner & Taylor (1971, 1973, 1974) used serpentine–magnetite $\delta^{18}O$ thermometry to differentiate lizardite-chrysotile serpentinites ($85 < T < 185°C$) from antigorite serpentinites ($220 < T < 460°C$). The Cassiar asbestos deposit, British Columbia, was considered anomalous in their study because of its high calculated temperature ($260°C$). The results summarized in this paper suggest that asbestos deposits form as a result of fluid flow accompanied by deformation; the fluid is necessary to accomplish serpentine recrystallization, and fluid and deformation are necessary to form the chrysotile-filled fractures. Temperature estimates for these processes are 290 ± 40°C based on fluid inclusions in rodingite from the Bowman asbestos deposit in Ontario (Schandl et al. 1989), and 300 ± 50°C from serpentine-magnetite $\delta^{18}O$ thermometry from the Cassiar mine (O'Hanley et al. 1989a). The petrographic observations and the calculated temperatures of serpentine recrystallization indicate that asbestos deposits are a type of serpentinite distinct from retrograde lizardite and retrograde and prograde antigorite serpentinites.

SPECIFIC DEPOSITS

Four prototypes of cross-fiber asbestos deposits are discussed in this paper (Table 2). The examples include both serpentinized tectonite peridotites from Phanerozoic terranes (Woodsreef and Cassiar), as well as serpentinized dunite cumulates from an Archean greenstone belt (Garrison and United mines, Ontario). The chrysotile deposits of southeastern Quebec that formed during Ordovician time are similar to the Woodsreef deposit (Laurent & Hébert 1979, Cogulu & Laurent 1984). The Garrison and United deposits are very similar, both in terms of mineralization and serpentine protolith, to many asbestos deposits in southern Africa (e.g., Anhaeusser 1986).

Woodsreef deposit

The Woodsreef deposit, located in New South Wales, Australia, consists mostly of partly serpentinized harzburgite tectonite as described earlier (Glen & Butt 1981; Table 2, Fig. 2). Within the middle of the serpentinite, southeast of the N10E fault, the partly serpentinized peridotite is dissected by serpentine veins bounded on either side by zones containing completely serpentinized peridotite. This combination is called a kernel pattern (O'Hanley & Offler 1989; Fig. 3a). The kernel pattern starts abruptly southeast of the N10E fault and dies out to the southeast, away from the fault. On Figure 2, the distribution of the kernel pattern coincides with that of massive serpentinite, a term used by Glen & Butt (1981) to describe this rock.

O'Hanley & Offler (1989) presented evidence for several episodes of hydrothermal alteration that affected the peridotite. Relict protogranular textures indicate that the host rock was a peridotite tectonite. In addition, fabrics consisting of recrystallized olivine grains, kinked olivine and orthopyroxene grains and cataclasites, were found in partly serpentinized peridotite near one fault in the Wunderlich pit (see Fig. 2 for locations of pits). Taken together, the protogranular textures record a pervasive annealing of the peridotite followed by a localized high-temperature ductile deformation and subsequent
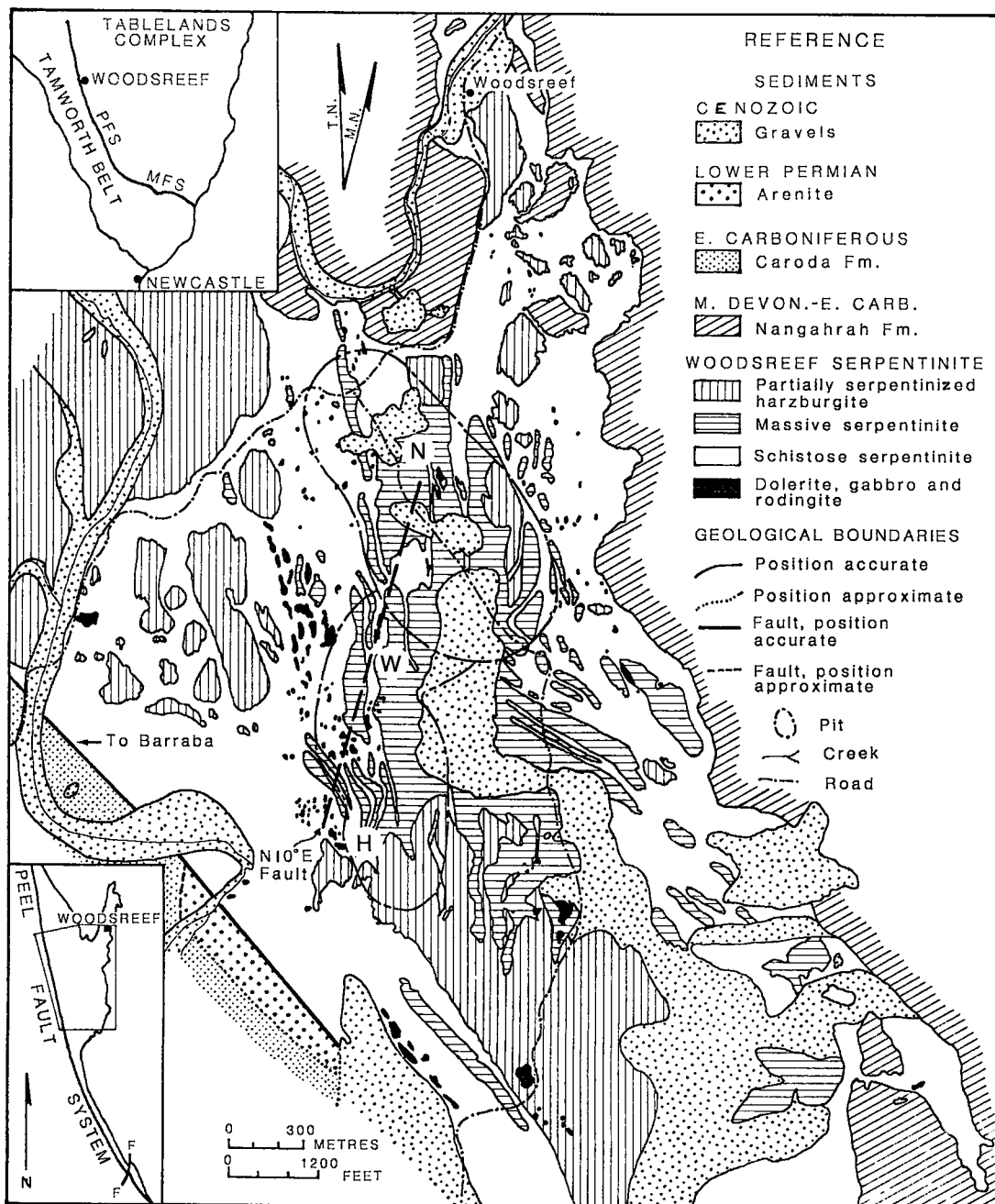
FIG. 2. Geology of the Woodsreef serpentinite in New South Wales. PFS: Peel fault system, MFS: Manning fault system. The inset in the lower left-hand corner shows the shape of the Woodsreef serpentinite and its setting with respect to the Peel fault system. The N10°E fault cuts across the northwestern parts of the open pits, labeled H (Hardee), W (Wunderlich) and N (North). Massive serpentinite consists of kernel pattern (shown in Fig. 3a), which occurs southeast of the N10°E fault.

brittle deformation. In contrast to the ductile deformation, tremolite, talc and chlorite are present in the Hardee and North pits in addition to the Wunder-lich pit. This alteration occurred before the brittle deformation because the amphibole is deformed. All of the above minerals are partly replaced by lizardite,
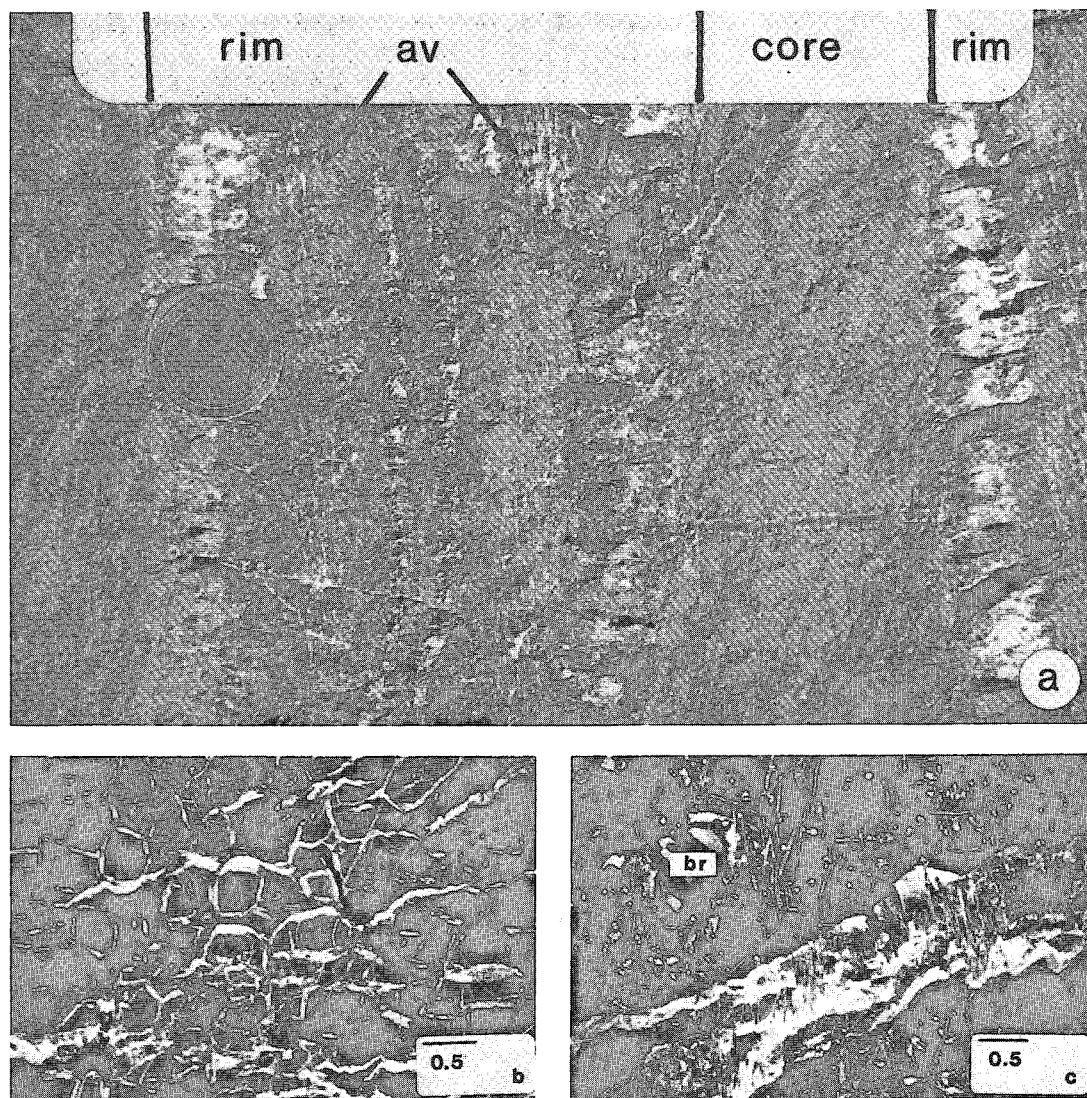
FIG. 3. a) Outcrop photograph from the Woodsreef mine, illustrating details of kernel pattern, which consists of partly serpentinized peridotite (in core) mantled by completely serpentinized peridotite (rim). Asbestos veins (av) are located in the rims. Lens cap is 6 cm wide. b) and c) Photomicrographs of serpentine textures from the United mine: scale bars in millimeters. b) Grain-boundary-controlled asbestos veins (white in photograph) in serpentinized dunite cumulate; veins occur between grains (sample DSO88-0001). c) Transgranular asbestos vein in lizardite + brucite interlocking texture (DSO88-0011).

indicating that the chemical alteration and deformation described above predate serpentinization.

The serpentine minerals and textures in the kernel rims were described earlier. However, near the shear zones, represented by schistose serpentinite, the chrysotile texture overprints earlier-formed asbestos veins, producing isolated lenses of asbestos fiber within "bastite", called "bastite fiber" by Glen & Butt (1981).

Oxygen isotope data from the lizardite + brucite texture in the kernel core ($3.9 \leq \delta^{18}O \leq 4.2\%_0$), representing hydration, is lighter isotopically than the kernel rims ($3.3 \leq \delta^{18}O \leq 8.6\%_0$), representing serpentine recrystallization. Serpentine–magnetite thermometry on ribbon fiber indicates temperatures of recrystallization of 300 and 350°C; there are no temperature estimates for serpentine hydration. These results indicate that oxygen isotope data do

not clearly differentiate the fluid accompanying hydration from that accompanying recrystallization.

The hydrothermal alteration that produced tremolite, talc, chlorite and lizardite is characterized by the addition of water to the peridotite and the operation of retrograde, exothermic reactions. The second alteration, which produced the kernel rims, involved serpentine recrystallization, which is characterized by prograde, endothermic, solid–solid reactions, such as lizardite reacting to produce chrysotile during recrystallization (Table 1).

The operation of retrograde exothermic reactions assists cooling of the peridotite by providing a mechanism for rapid removal of energy, in the form of heat, from the rock to the fluid involved in alter-

ing the rock. The origin of the energy associated with the endothermic reactions is not clear. It could be transferred from the fluid to the rock because the fluid needs only to supply sufficient heat to form chrysotile. As chrysotile occupies <6 to 7 cm out of every meter of peridotite, and only occurs east of the N10E fault, the fluid does not have to heat up the entire peridotite. Although fluids cannot provide enough energy to induce regional metamorphism, they can provide enough heat to induce thermal perturbations locally, in particular during non-steady-state conditions (Brady 1988).

The energy needed for recrystallization also could be provided by the peridotite, as it continued to cool. However, this process should produce serpentinites
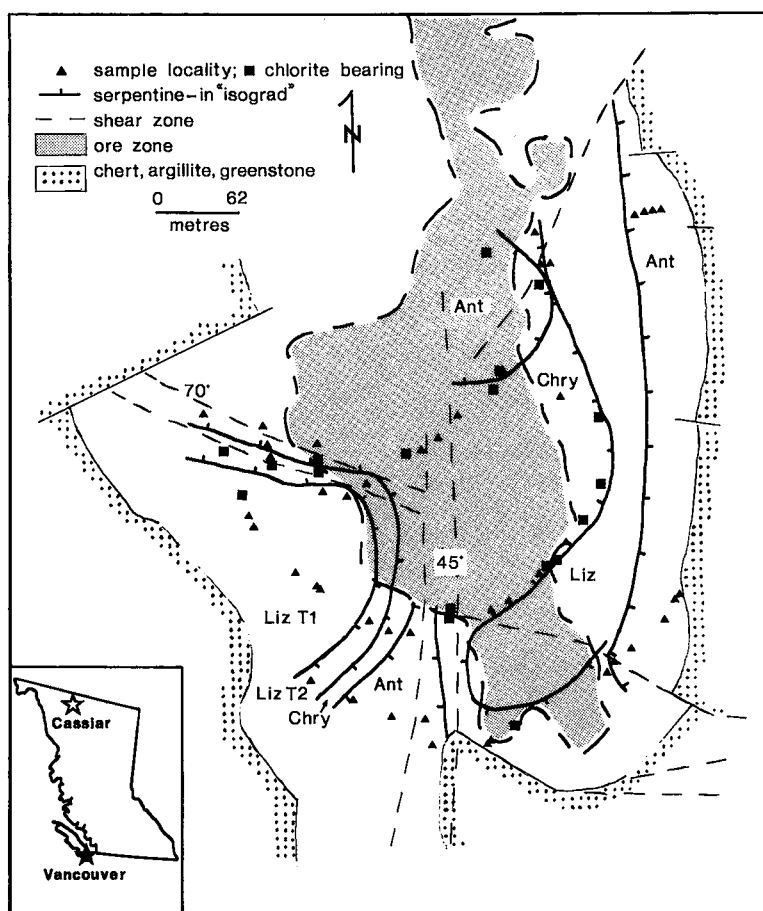

FIG. 4. Geology of the Cassiar serpentinite in north-central British Columbia. The ore zone lies in the center of the serpentinite, structurally above the 45 and 70° shears. Serpentine-in "isograds" and the ore-zone perimeter show an excellent geometrical relationship to the shear zones. The antigorite-in "isograd" at the eastern margin of the serpentinite is part of a zone of metasomatic alteration formed between serpentinite and greenstones and metasedimentary rocks. It is not associated with recrystallization in the ore zone.

such as those at Burro Mountain, described earlier. As the Woodsreef serpentinite is different from the one at Burro Mountain, I prefer the fluid as the heat source. Regardless of the energy source, the difference between evidence for hydration and serpentine recrystallization, as discussed earlier, is consistent with at least two distinct episodes of alteration, both possessing distinct characteristics in terms of the processes involved and their effects on the rock.

These observations document an extensive history of hydrothermal alteration and physical deformation of the peridotite. All deformation and alteration diminish with distance from the shear zones, which evolved from wide ductile to brittle zones that predate serpentinization, to narrower brittle zones of shear during serpentinization. It was the N10E fault, serving as a fluid conduit, and not the Peel fault, located further to the west (Fig. 2), that was the major control on serpentine recrystallization, in light of the distribution of the kernel pattern. Further, the asbestos veins are associated with the kernel pattern (Fig. 3a); it is thus deformation associated with minor faults east of the N10E fault that is responsible for the presence of the asbestos veins. The discussion above indicates that the Woodsreef deposit contains evidence for both fault-controlled hydration and fault-controlled serpentine recrystallization accompanied by deformation.

Cassiar deposit

The Cassiar serpentinite, located in north-central British Columbia, is a completely serpentinized peridotite tectonite (Table 2). The oldest textures consist of lizardite in hourglass textures containing up to 1 wt.% Al_2O_3. The absence of mesh-rim textures and unaltered olivine indicates that the Cassiar serpentinite does not record evidence of hydration. The ore zone, defined by the presence of >3% by volume asbestos fiber in fractures, is located in the center of the serpentinite, structurally above the 45 and 70° shears, both of which contain talc–magnetite pods (Fig. 4). Examination of samples taken on traverses perpendicular to both shear zones allowed serpentine-in "isograds" to be defined based on texture and mineralogy. Stable isotope studies documented a difference of 3‰ in $\delta^{18}O$ values between the least- and most-recrystallized samples (O'Hanley et al. 1989a).

Serpentine recrystallization at Cassiar, which did not go to completion, can be described by reactions such as lizardite = chrysotile and lizardite + SiO_2 = antigorite + H_2O (Table 1); brucite was not produced during recrystallization. H_2O is stoichiometrically low in the latter reaction, so that these reactions are essentially solid–solid, endothermic ones. The formation of antigorite without brucite from lizardite requires a change in bulk composition; the presence of talc in the shear zones suggests that SiO_2 was added to the serpentinite during recrystallization.

Serpentine recrystallization at Cassiar requires a heat source, albeit a small one, to accompany the change in bulk composition. Thermally driven metamorphism associated with intrusion of igneous rocks is ruled out for several reasons. First, there are no igneous rocks nearby that can produce recrystallization in the center of the serpentinite but not in the margins (drilling done to acquire data for estimates of ore reserves did not locate any). Second, the $\delta^{18}O$ values of each texture are distinct, and the Fe^{3+}_{total}/Fe^{2+} ratios in lizardite decrease continuously with recrystallization, suggesting equilibration with a fluid emanating from the shear zones. In the absence of alternatives, it is logical to make the fluid the energy source. As with the Woodsreef deposit, not much energy is needed to cause the amount of recrystallization observed; its localization in proximity to a shear zone makes the fluid a feasible source.

Inspection of Figure 4 indicates a good geometric fit between the "isograds", the ore-zone perimeter and the shear zones. The "isograds" are defined by an increasing extent of recrystallization based on the serpentine minerals. In contrast, the ore zone is defined by the presence of asbestos veins, which are the result of physical deformation (O'Hanley 1988a). There is no a priori reason why serpentine recrystallization and physical deformation should affect the same volume of rock unless they are the result of related processes. Serpentine recrystallization and the formation of the ore zone both are due to fault-controlled processes: for serpentine recrystallization,

TABLE 3. REPRESENTATIVE CHEMICAL COMPOSITION (ELECTRON-MICROPROBE[1] DATA) OF COEXISTING LIZARDITE AND CHRYSOTILE FROM THE GARRISON ASBESTOS DEPOSIT

	Lizardite					Chrysotile				
	71-242 (3)	71-242 (3)	71-242 (6)	70-564 (3)	70-564 (3)	71-242 (5)	71-242 (4)	82-25 (3)	70-568 (3)	71-293 (3)
SiO₂	39.77	40.08	39.93	40.13	40.18	40.20	40.27	41.51	40.71	41.25
TiO₂	0.08	0.08	0.08	0.08	0.06	0.10	0.10	0.07	0.08	0.07
Al₂O₃	0.41	0.49	0.45	0.37	0.47	0.80	0.81	0.97	1.00	0.84
Cr₂O₃	0.31	0.32	0.32	0.18	0.21	0.34	0.34	0.38	0.57	0.27
FeO*	1.85	1.85	1.85	1.29	1.48	1.83	1.97	1.28	1.58	3.89
MnO	0.08	0.12	0.10	0.05	0.04	0.08	0.08	0.09	0.05	0.01
MgO	42.06	42.14	42.10	43.21	43.18	21.41	42.55	42.00	42.51	39.67
CaO	0.00	0.02	0.01	0.02	0.00	0.00	0.00	0.01	0.00	0.01
Na₂O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K₂O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	84.57	85.11	84.84	85.34	85.62	85.76	86.12	86.31	86.51	86.01
Si	3.838	3.842	3.840	3.827	3.822	3.824	3.818	3.899	3.832	3.934
Al	0.047	0.055	0.051	0.042	0.052	0.09	0.090	0.107	0.111	0.094
Fe	0.150	0.149	0.149	0.103	0.118	0.146	0.156	0.101	0.125	0.310
Cr	0.024	0.024	0.024	0.014	0.016	0.026	0.026	0.028	0.042	0.020
Mn	0.006	0.010	0.008	0.004	0.003	0.006	0.006	0.007	0.004	0.001
Mg**	6.050	6.023	6.037	6.143	6.124	6.014	6.013	5.880	5.965	5.639

[1]Atomic proportions, based on 14 oxygen atoms, calculated using unpublished electron microprobe data obtained by F. J. Wicks: see Wicks & Plant (1979) for operating conditions. Numbers in parentheses under the sample numbers represent number of analyses averaged together to obtain the reported values.
*Total Fe as FeO. ** Excess Mg is probably related to brucite, which is common in some thin sections.

fault-controlled flow of fluid, and for the ore zone, fault-controlled deformation.

Garrison deposit

The Garrison asbestos deposit, located near Matheson, Ontario, has been studied by Wicks *et al.* (1983). It is within the completely serpentinized basal dunite cumulate of a differentiated mafic–ultramafic sill (Table 2). The presence of two types of serpentine minerals and textures (a lizardite mesh-rim and hourglass texture that is overprinted by a chrysotile interlocking texture) suggests that the dunite was affected by two episodes of alteration. The compositions of both lizardite and chrysotile are very similar, confirming the progress of a solid–solid reaction relationship between the two minerals (Table 3).

A search was made for spatial patterns involving the serpentine minerals by plotting sample locations on a map of the deposit and noting the presence of either lizardite or chrysotile (Fig. 5). The chrysotile-in "isograd" is poorly defined because the samples represent one traverse oblique and parallel to the rock contacts. Nonetheless, chrysotile dominates the rock near the basal fault, whereas lizardite dominates the rock near the clinopyroxenite. Stable isotope data from samples of both textures indicate that lizardite ($3 < \delta^{18}O < 5‰$) and chrysotile (5 to 7‰) are isotopically distinct, such that a fluid is inferred to have been present during serpentine recrystallization.

The isotope data and the distribution of the serpentine minerals and textures and mineral chemistry indicate that recrystallization occurred *via* a solid–solid reaction (Table 1) in the presence of a fluid; they are consistent with recrystallization increasing toward the basal fault. As heat is necessary for recrystallization and as there are no igneous rocks nearby to provide a heat source for recrystallization (the diabase dike is oriented perpendicular to the "isograd"), I conclude that the Garrison deposit contains evidence for serpentine recrystallization caused by a fluid that gained access to the serpentinite along the basal fault.

United deposit

The United deposit, located approximately 26 km west of Matachewan, Ontario, is in the completely serpentinized basal dunite cumulate of a sill (Table 2). There are two orebodies within the dunite, near the contact with a wehrlite and separated from each other by serpentinite barren of asbestos (Kretschmar
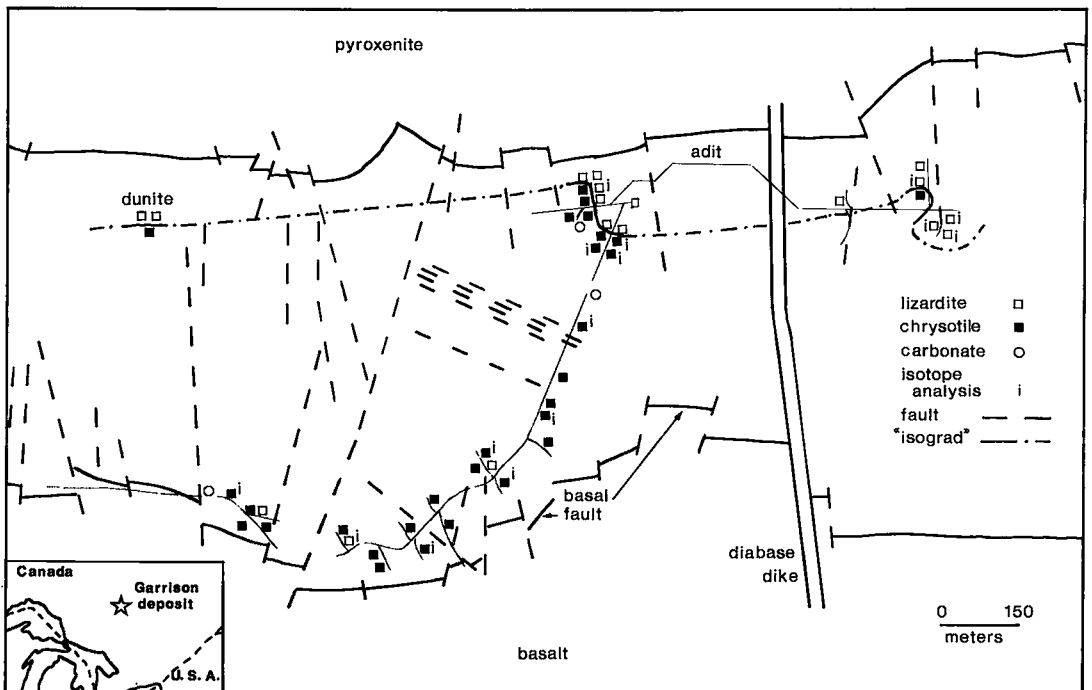

FIG. 5. Geology of the Garrison serpentinite, in east-central Ontario, on the 210-meter level. Sample locations are marked with a solid (for chrysotile) or open circle (for lizardite), depending on the presence or absence of chrysotile. The chrysotile-in "isograd" is dashed where it separates samples with and without chrysotile, and dotted where it is constrained by samples on one side only.

& Kretschmar 1986; Fig. 6). Both rock contacts and the ore zones strike east, so that sampling was done on north-striking traverses. The results discussed here are based on observations from the North orebody (O'Hanley 1988b,c).

The North orebody, bounded by two shear zones, each one meter wide (Fig. 6), lies within serpentinized dunite that consists of lizardite + brucite in an interlocking texture. It also contains magnetite-free asbestos veins that, under the microscope, are observed to zig-zag across the thin section as they follow the grain boundaries of grains of serpentinized olivine (Fig. 3b). Near the dunite–wehrlite contact, asbestos + magnetite veins are spatially associated with late-stage faults. These veins cut across grains of serpentinized olivine (and are therefore called transgranular veins; Fig. 3c).

There are no rock-forming serpentine minerals in the mine that can be attributed to fault-controlled processes. The origin of the grain-boundary asbestos veins is uncertain at this time, but O'Hanley (1988c) attributed their formation to strain accumulation during folding of the sill, because the veins are in the fold plane, and no evidence of slip along the veins was found. The asbestos + magnetite veins are fault-related, mode-1 fractures (Pollard & Aydin 1988). They can be modeled as pinnate fractures associated with fault displacement based on the angle between the veins and the faults (28° and 35° for two examples; O'Hanley 1988b). In summary, no evidence for either fault-controlled hydration or serpentine recrystallization was found in the United mine.

DISCUSSION

Lizardite–chrysotile serpentinites

The examples used to illustrate the role of fault-controlled processes in serpentine recrystallization exhibit spatial patterns to varying degrees. Such variation supports the hypothesis that serpentine recrystallization is a fault-controlled process because one would expect variations in vertical and horizontal flow of fluid and deformation in orogenic belts. The absence of spatial patterns related to faults does not rule out fault-controlled flow of fluid because serpentine recrystallization could have gone to completion; the fluid affected the entire serpentine protolith. From this view the absence of spatial patterns involving textures is moot in deciding for or against fault-controlled flow of fluid. This may be the case with the serpentinite in the United mine, in which the rock-forming texture is uniform.

The model for the serpentine phase diagram and the petrographic observations presented above indicate that hydration of peridotite to form serpentine proceeds *via* a metastable reaction in most cases because lizardite forms from olivine. It is driven by the addition of water to the peridotite within the stability field of hydrous minerals, such as chrysotile or antigorite.

Serpentine recrystallization occurs in the presence of a fluid, although H_2O may not be consumed or produced during the process. The fluid is a catalyst only in the Garrison and United deposits, but it was
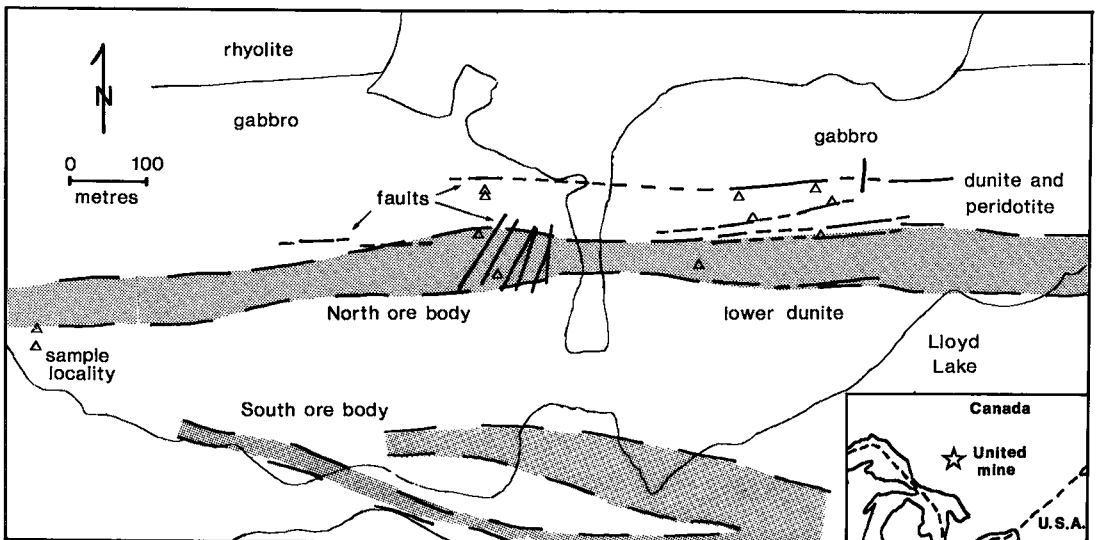

FIG. 6. Geology of the United serpentinite, in east-central Ontario, showing the orebodies and faults identified. Ore zones correspond to occurrence of fiber; asbestos is absent from the dunite – peridotite layers, and sparse to absent in dunite between the two orebodies. At the scale of the map, several faults coincide with lithologic contacts (although in fact they are distinct).

also a source of SiO_2 at Cassiar. H_2O was consumed during hydration reactions at Woodsreef, but it was a catalyst only during serpentine recrystallization.

In all these cases, the fluid gained access to the serpentinite protolith along faults; the changes in the peridotite or the pre-existing serpentinite are manifest as variations in serpentine mineralogy and textures with respect to them. Serpentine recrystallization is not necessarily pervasive; it can be fracture-controlled, as it was in the Woodsreef serpentinite, or it can be pervasive, as it was in the Cassiar and Garrison serpentinites.

Antigorite serpentinites

Antigorite serpentinites cut by chrysotile asbestos veins associated with emplacement-related thrust faults (Chidester *et al.* 1978, Peacock 1987b) also offer examples of rocks altered by fault-controlled flow of fluid and deformation, in which dehydration reactions in the footwall supply fluid for hydration reactions in the hanging wall. In these examples, the asbestos veins are attributed to retrograde alteration rather than to prograde metamorphism because chrysotile is stable at lower temperatures than antigorite. Lizardite may also be associated with the chrysotile veins, where it seems to replace previously unaltered olivine grains (Peacock 1987b).

Regional and contact-metamorphosed greenschist-grade and blueschist-grade antigorite serpentinites are not dependent upon structural elements in the same manner as are the other types of serpentinites (Springer 1974, Frost 1975, Evans 1977, and references therein), so that they are probably not related to fault-controlled processes. Instead, thermally induced metamorphism is the controlling process, in which diffusion of heat away from the igneous rock initiates reactions (Evans 1977).

Given the distinction between lizardite–chrysotile and antigorite serpentinites, it is prudent to keep in mind that prograde metamorphism affects pre-existing lizardite–chrysotile serpentinites as well as fresh peridotite (Wicks & Whittaker 1977, Wicks & Plant 1979). Therefore, the distribution of lizardite and chrysotile formed during hydration or serpentine recrystallization may influence the subsequent prograde metamorphism of the serpentinite. Evidence of such an influence has been reported from two peridotite bodies.

Contact metamorphism of the Blue River serpentinite affected both serpentinized and unserpentinized peridotite. Prior to prograde metamorphism, serpentinite was produced along shear zones, such as the Nickel Creek thrust, whereas peridotite farther from the faults was virtually unaffected. Prograde metamorphism occurred *via* different reactions in each rock: at the highest grade, metamorphosed ser-

pentinite contains olivine + enstatite assemblages but no anthophyllite, whereas metamorphosed peridotite contains olivine + anthophyllite but no enstatite (Pinsent & Hirst 1977). Regional metamorphism of the Agnew ultramafic sill produced mineral assemblages that were dependent on the H_2O–CO_2 ratio of the rock, inherited from a prior low-temperature infiltration metamorphism (Gole *et al.* 1987).

CONCLUSION

Serpentine minerals and textures are not randomly distributed in lizardite–chrysotile serpentinites. Their spatial patterns reflect ordered processes based on fault-controlled flow of fluid. The formation of lizardite–chrysotile serpentinites can be attributed to either hydration or serpentine recrystallization. Each process produces serpentinites with distinct characteristics at both the mesoscopic and microscopic scales.

REFERENCES

ANHAEUSSER, C.R. (1986): The geologic setting of chrysotile asbestos deposits in southern Africa. *In* Mineral Deposits of Southern Africa II (C.R. Anhaeusser & S. Maske, eds.). Geol. Soc. S. Africa, Johannesburg (359-375).

BERMAN, R.G. (1988): Internally-consistent thermodynamic data for minerals in the system Na_2O–K_2O–CaO–MgO–FeO–Fe_2O_3–Al_2O_3–SiO_2–TiO_2–H_2O–CO_2. *J. Petrol.* **29**, 445-522.

————, ENGI, M., GREENWOOD, H.J. & BROWN, T.H. (1986): Derivation of internally-consistent thermodynamic data by the technique of mathematical programming: a review with application to the system MgO–SiO_2–H_2O. *J. Petrol.* **27**, 1331-1364.

BLAKE, M.C., JR. & MURCHY, B.L. (1988): A California model for the New England fold belt. *New South Wales Geol. Surv., Quarterly Notes* **72**, 1-9.

BRADY, J.B. (1988): The role of volatiles in the thermal history of metamorphic terranes. *J. Petrol.* **29**, 1187-1213.

BRUTON, C.J. & HELGESON, H.C. (1983): Calculation of the chemical and thermodynamic consequences of differences between fluid and geostatic pressure

in hydrothermal systems. *Am. J. Sci.* **283-A**, 540-588.

CHIDESTER, A.H., ALBEE, A.L. & CADY, W.M. (1978): Petrology, structure and genesis of the asbestos-bearing ultramafic rocks of the Belvidere mountain area in Vermont. *U.S. Geol. Surv., Prof. Pap.* **1016.**

COGULU, E. & LAURENT, R. (1984): Mineralogical and chemical variations in chrysotile veins and peridotite host-rocks from the asbestos belt of southern Quebec. *Can. Mineral.* **22**, 173-183.

COLEMAN, R.G. & KEITH, T.E. (1971): A chemical study of serpentinization – Burro Mountain, California. *J. Petrol.* **12**, 311-328.

CRESSEY, B.A. & ZUSSMAN, J. (1976): Electron microscopic studies of serpentinites. *Can. Mineral.* **14**, 307-313.

EVANS, B.W. (1977): Metamorphism of alpine peridotite and serpentinite. *Ann. Rev. Earth Planet. Sci.* **5**, 397-447.

FERRY, J.M. (1988): Infiltration-driven metamorphism in northern New England. *J. Petrol.* **29**, 1121-1159.

FROST, B.R. (1975): Contact metamorphism of serpentinite, chloritic blackwall and rodingite at Paddy-Go-Easy Pass, central Cascades, Washington. *J. Petrol.* **16**, 272-313.

————— (1985): On the stability of sulfides, oxides and native metals in serpentinite. *J. Petrol.* **26**, 31-63.

GLEN, R.A. & BUTT, B.C. (1981): Chrysotile asbestos at Woodsreef, New South Wales. *Econ. Geol.* **76**, 1153-1169.

GOLE, M.T., BARNES, S.J. & HILL, R.E.T. (1987): The role of fluids in the metamorphism of komatiites, Agnew nickel deposit, western Australia. *Contrib. Mineral. Petrol.* **96**, 151-162.

HARMS, T.A. (1986): *Structural and Tectonic Analysis of the Sylvester Allochthon.* Ph. D. thesis, Univ. Arizona, Phoenix, Arizona.

HESS, H.H. (1938): A primary peridotite magma. *Am. J. Sci.* **235**, 321-344.

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

LABOTKA, T.C. & ALBEE, A.L. (1979): Serpentinization of the Belvidere Mountain ultramafic body, Vermont: mass balance and reaction at the metasomatic front. *Can. Mineral.* **17**, 831-845.

LAURENT, R. & HÉBERT, Y. (1979): Paragenesis of serpentine assemblages in harzburgite tectonite and

dunite cumulate from the Quebec Appalachians. *Can. Mineral.* **17**, 857-869.

LUDDEN, J. & HUBERT, C. (1986): Geologic evolution of the Late Archean Abitibi greenstone belt of Canada. *Geology* **14**, 707-711.

MACDONALD, A.H. (1984): *Water Diffusion Rates Through Serpentinized Peridotite: Implications for Reaction Induced Dynamic and Chemical Effects in Ultramafic Rocks.* Ph.D. thesis, Univ. Western Ontario, London, Ontario.

NELSON, J. & BRADFORD, J. (1989): Geology and mineral deposits of the Cassiar and McDame map areas, British Columbia (104P/3,5). *B.C. Min. Ener. Mines & Petrol. Res., Geol. Fieldwork* 1988, 323-338.

O'HANLEY, D.S. (1988a): The origin of alpine peridotite hosted, cross fiber, asbestos deposits. *Econ. Geol.* **83**, 256-265.

————— (1988b): Field investigations at the United asbestos deposit, Midlothian Township, District of Timiskaming. *Ont. Geol. Surv., Misc. Pap.* **141**, 219-221.

————— (1988c): A reconnaissance study at Lloyd Lake, Midlothian Township, District of Timiskaming. *Ont. Geol. Surv., Unpubl. Report.*

—————, CHERNOSKY, J.V., JR. & WICKS, F.J. (1989b): The stability of lizardite and chrysotile. *Can. Mineral.* **27**, 483-493.

—————, KYSER, T.K. & WICKS, F.J. (1989a): Evidence from lizardite chrysotile serpentinites for proton exchange without recrystallization. *Geol. Soc. Am., Abstr. Program* **21(6)**, A12.

————— & OFFLER, R. (1989): Fault-controlled fluid flow associated with serpentinization, Woodsreef, New South Wales, Australia. *Geol. Assoc. Can. – Mineral. Assoc. Can., Program Abstr.* **14**, A6.

————— & WICKS, F.J. (1987): Structural control of serpentine textures in the Cassiar Mining Corporation's open pit mine at Cassiar, British Columbia. *Geol. Assoc. Can. – Mineral. Assoc. Can., Program Abstr.* **12**, 77.

PAGE, N.J (1967): Serpentinization at Burro Mountain, California. *Contrib. Mineral. Petrol.* **14**, 321-342.

PEACOCK, S.M. (1987a): Thermal effects of metamorphic fluids in subduction zones. *Geology* **15**, 1057-1060.

————— (1987b): Serpentinization and infiltration metasomatism in the Trinity peridotite, Klamath province, northern California: implications for subduction zones. *Contrib. Mineral. Petrol.* **95**, 55-70.

PINSENT, R.H. & HIRST, D.M. (1977): The metamorphism of the Blue River ultramafic body, Cassiar, British Columbia, Canada. *J. Petrol.* **18**, 567-594.

POLLARD, D.D. & AYDIN, A. (1988): Progress in understanding jointing over the past century. *Geol. Soc. Am. Bull.* **100**, 1181-1204.

PRICHARD, H.M. (1979): A petrographic study of the processes of serpentinization in ophiolites and the ocean crust. *Contrib. Mineral. Petrol.* **68**, 231-241.

SCHANDL, E.S., O'HANLEY, D.S. & WICKS, F.J. (1989): Rodingites in serpentinized ultramafic rocks of the Abitibi greenstone belt, Ontario. *Can. Mineral.* **27**, 579-591.

SPRINGER, R.K. (1974): Contact metamorphosed ultramafic rocks in the Western Sierra Nevada foothills, California. *J. Petrol.* **15**, 160-195.

TOFT, P.B., ARKANI-HAMED, J. & HAGGERTY, S.E. (1990): Petrophysics of retrograde serpentinization. *Phys. Earth Planet. Interiors* **65**, 137-157.

WENNER, D.B. & TAYLOR, H.P., JR. (1971): Temperatures of serpentinization of ultramafic rocks based on O^{18}/O^{16} fractionation between coexisting serpentine and magnetite. *Contrib. Mineral. Petrol.* **32**, 165-185.

_____ & _____ (1973): Oxygen and hydrogen isotope studies of the serpentinization of ultramafic rocks in oceanic environments and continental ophiolite complexes. *Am. J. Sci.* **273**, 207-239.

_____ & _____ (1974): D/H and O^{18}/O^{16} studies of serpentinization of ultramafic rocks. *Geochim. Cosmochim. Acta* **38**, 1255-1286.

WICKS, F.J. & O'HANLEY, D.S. (1988): Serpentine minerals: structures and petrology. *In* Hydrous Phyllosilicates (exclusive of micas) (S.W. Bailey, ed.). *Rev. Mineral.* **19**, 91-168.

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

_____, SCHANDL, E.S., OZORAY, J. & WAN PU (1983): Mineralogy and geochemistry of the chrysotile asbestos deposits in Ontario. *Ont. Geol. Surv., Misc. Pap.* **121**, 99-110.

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

_____ & ZUSSMAN, J. (1975): Microbeam X-ray diffraction patterns of the serpentine minerals. *Can. Mineral.* **13**, 244-258.