Canadian Mineralogist
Vol. 22, pp. 185-195 (1984)

DEFORMATION HISTORIES AS RECORDED BY SERPENTINITES. I. DEFORMATION PRIOR TO SERPENTINIZATION

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Abstract

The serpentine pseudomorphs that form during retrograde and some mild prograde serpentinization preserve the outline and some of the internal details of the solid-state deformation textures of olivine and pyroxene. Thus coarse, porphyroclastic, mosaic-porphyroclastic and granuloblastic textures of olivine and undulatory extinction, kink bands and elongation of enstatite can be recognized in spite of extensive serpentinization. An examination of the serpentinized peridotite in Glen Urquhart, Scotland, reveals that the plastic deformation textures of the olivine and enstatite can be recognized in the lizardite-1T ± brucite pseudomorphs. The addition of water to the ultramafic rock at high temperature at an early stage produced tremolite and then, successively with decreasing temperature, chlorite, talc and antigorite. The tremolite and chlorite have been involved in plastic deformation during emplacement, but in the final stages of emplacement solid-state plastic flow was replaced by brittle fracture along the tremolite and chlorite lenses and stringers. Minor shearing associated with emplacement was also taken up by talc and antigorite shear zones. The final pervasive serpentinization to lizardite-1T ± brucite, after olivine, enstatite, tremolite and talc, took place slowly over a long period of time, possibly with water supplied by the Great Glen fault system.

Keywords: plastic deformation, solid-state deformation, deformation textures, olivine, pyroxene, serpentinization, lizardite, chrysotile, antigorite, Glen Urquhart, Scotland.

Sommaire

La serpentine pseudomorphe formée au cours de la serpentinisation rétrograde et d'une faible serpentinisation prograde conserve les contours et certains caractères internes de l'olivine et du pyroxène déformé à l'état solide. Ainsi donc, la serpentinisation poussée n'oblitère ni les textures porphyroclastique, porphyroclastique en mosaïque et granuloblastique de l'olivine, ni l'extinction ondulante, les kink-bands et l'étirement de l'enstatite. Un examen de la péridotite serpentinisée de Glen Urquhart (Ecosse) montre que les textures de déformation plastique de l'olivine et de l'enstatite sont visibles dans les pseudomorphes de lizardite-1T ± brucite. L'addition d'eau à la roche ultramafique à haute température favorise, à un stade précoce, la cristallisation de trémolite et entraîne, au cours du refroidissement, l'apparition successive de chlorite, de talc et d'antigorite. La trémolite et la chlorite ont été impliquées dans la déformation plastique au cours de la mise en place, mais vers la fin de l'intrusion, c'est la fracturation cassante qui est devenue importante le long des lentilles et des filonnets de trémolite et de chlorite. Des zones de cisaillement à talc et antigorite ont également absorbé un faible cisaillement relié à la mise en place. La serpentinisation totale de l'olivine, enstatite, trémolite et talc en lizardite-1T ± brucite s'est imposée lentement, au cours d'une longue période de temps, en présence d'eau vraisemblablement amenée par le réseau de faille de Great Glen.

(Traduit par la Rédaction)

Mots-clés: déformation plastique, déformation à l'état solide, textures de déformation, olivine, pyroxène, serpentinisation, lizardite, chrysotile, antigorite, Glen Urquhart (Ecosse).

Introduction

Ultramafic rocks may be subjected to deformation at various times in their geological history, prior to, during and after serpentinization. Some of these deformation events are recorded by the serpentine-mineral grains that make up the ultramafic rocks. For example, deformation events that occur prior to serpentinization, such as the plastic deformation of olivine and pyroxene, may still be recorded after serpentinization by serpentine pseudomorphs that have replaced the deformed olivine and pyroxene. In this case, it is important to recognize that the serpentine minerals have passively recorded earlier deformation and have not themselves been subjected to intensive deformation. Deformation events that occur during and after serpentinization are recorded by the recrystallization, brittle failure and plastic deformation of the serpentine-mineral grains. In these cases, it is important to recognize that the serpentine minerals have been actively involved in the deformation and that the various features can be used to recognize the type of deformation and to roughly estimate the pressure and temperature of deformation.

In publications by Wicks *et al.* (1977), Wicks & Whittaker (1977) and Wicks & Plant (1979), a variety of serpentine-mineral textures from serpentinized ultramafic rocks in different geological environments have been described. The various features of deformation recorded by these textures were not specifically described in the papers, even though microbeam X-ray-diffraction and electron-microprobe data from these deformation features were included in the studies. It is the objective of this paper and the following companion papers (Wicks 1984a, b) to draw attention to these deformation features so that the events that they record can be recognized and thus provide the opportunity to carry out more comprehensive interpretation of serpentinites. The passive recording of earlier events of deformation by serpentine pseudomorphs is the subject of the present paper.

Experimental Methods

The serpentine minerals making up the textures described in this study were identified *in situ* in thin section with a Norelco microbeam X-ray-diffraction camera using the techniques described by Wicks & Zussman (1975). The chemical composition of serpentine in most textures have been determined by electron microprobe (Wicks & Plant 1979, 1983).

Textures in Unserpentinized Peridotites

The peridotite xenoliths found in kimberlites, alkali basalts and carbonatites display a variety of metamorphic textures that have been formed through processes of solid-state deformation, recrystallization and crystal growth. As the xenoliths are thought to have been carried up from the upper mantle, and as their textures are thought to have been produced there, the xenoliths present a unique opportunity to study upper-mantle material and to deduce mantle processes (Harte *et al.* 1975, Mercier & Nicolas 1975). Most alpine peridotites contain similar textures and are also thought to be mantle material; however, the plastic deformation they have undergone during their transport through the crust makes the interpretation of their textures more complex (Nicolas & Poirier 1976). Textural classifications have been developed by numerous researchers. Descriptions and reviews of these classifications can be found in Nicolas *et al.* (1971), Mercier & Nicolas (1975), Gueguen & Boullier (1976), Boullier & Nicolas (1975), Boullier & Gueguen (1975), Nicolas & Poirier (1976), Pike & Schwarzman (1977), Harte (1977), Carswell (1980) and Gueguen & Nicolas (1980). Harte (1977) has correlated the various classifications and developed a four-fold division of the rocks based essentially on the textures of the olivine grains: coarse, porphyroclastic, mosaic–porphyroclastic and granuloblastic. The coarse peridotites are composed of olivine grains greater than 2 mm. Porphyroclastic peridotites contain more than 10% of the olivine in the form of large, strained porphyroclasts surrounded by fine, unstrained, recrystallized olivine (neoblasts: Nicolas *et al.* 1971). Mosaic-porphyroclastic peridotites contain more than 90% of the olivine in the form of neoblasts with a mosaic texture and less than 10% as porphyroclasts. Granuloblastic peridotite is composed mainly of olivine grains less than 2 mm across in a granuloblastic texture with less than 5% of the olivine as porphyroclasts. The coarse and granuloblastic textures may be further divided according to whether the olivine grains are equant or tabular. Pike & Schwarzman (1977) have extended the classification to include igneous and cataclastic features.

Stress on olivine produces a variety of strain features that include undulatory extinction, deformation lamellae, kink bands, and the polygonalization and recrystallization of the coarse, strained grains in the porphyroclasts (Fig. 1a) into fine, strain-free grains, the neoblasts (Fig. 1a) that make up the enclosing matrix (Ragan 1963, Mercier & Nicolas 1975). The processes of plastic deformation, through the mechanisms of dislocation creep (Nicolas *et al.* 1971, 1973) associated with syntectonic recrystallization (Carter & Avé Lallemant 1970, Avé Lallemant & Carter 1970, Avé Lallemant 1975), impart a distinctive fabric to the olivine (Nicolas & Poirier 1976).

Enstatite is less abundant than olivine and maintains a coarser grain-size than olivine in the same stress-field, but the stress does produce undulatory extinction and kink bands (Fig. 1c), rotation, elongation and the pulling apart of grains (Nicolas *et al.* 1971), as well as polygonalization and reduction in grain size (Boyd 1975) and the development of a distinctive fabric (Nicolas *et al.* 1971). Clinopyroxene is usually less abundant and slightly more resistant to stress than orthopyroxene (Pike & Schwarzman 1977), but does display similar features of deformation. Spinel (Mercier & Nicolas 1975), chromite (Carswell 1980) or garnet (Harte *et al.* 1975) may be present as minor phases and are affected by stress (Nicolas & Poirier 1976), but as they are not subject to subsequent serpentinization, they need not be discussed further.

The deformation features discussed above can be readily observed in normal thin sections and represent a strain of 30% or more (Gueguen 1979). Through the application of a simple heating technique (Kohlstedt *et al.* 1976), dislocation structures, which represent strains of 1 to 5% (Gueguen 1979), can be decorated so that they too are readily observed in thin section. This technique displays all dislocations within a reasonably large volume in a thin section and provides further data on the mechanisms of deformation within olivine (Gueguen 1977, 1979). Dislocations have also been studied by transmission-electron microscopy (Green 1976) on both naturally deformed (Gueguen & Boullier 1976, Buiskool Toxopeus 1977, Boland & Buiskool Toxopeus 1977) and experimentally deformed olivine (Kohlstedt & Goetze 1974,

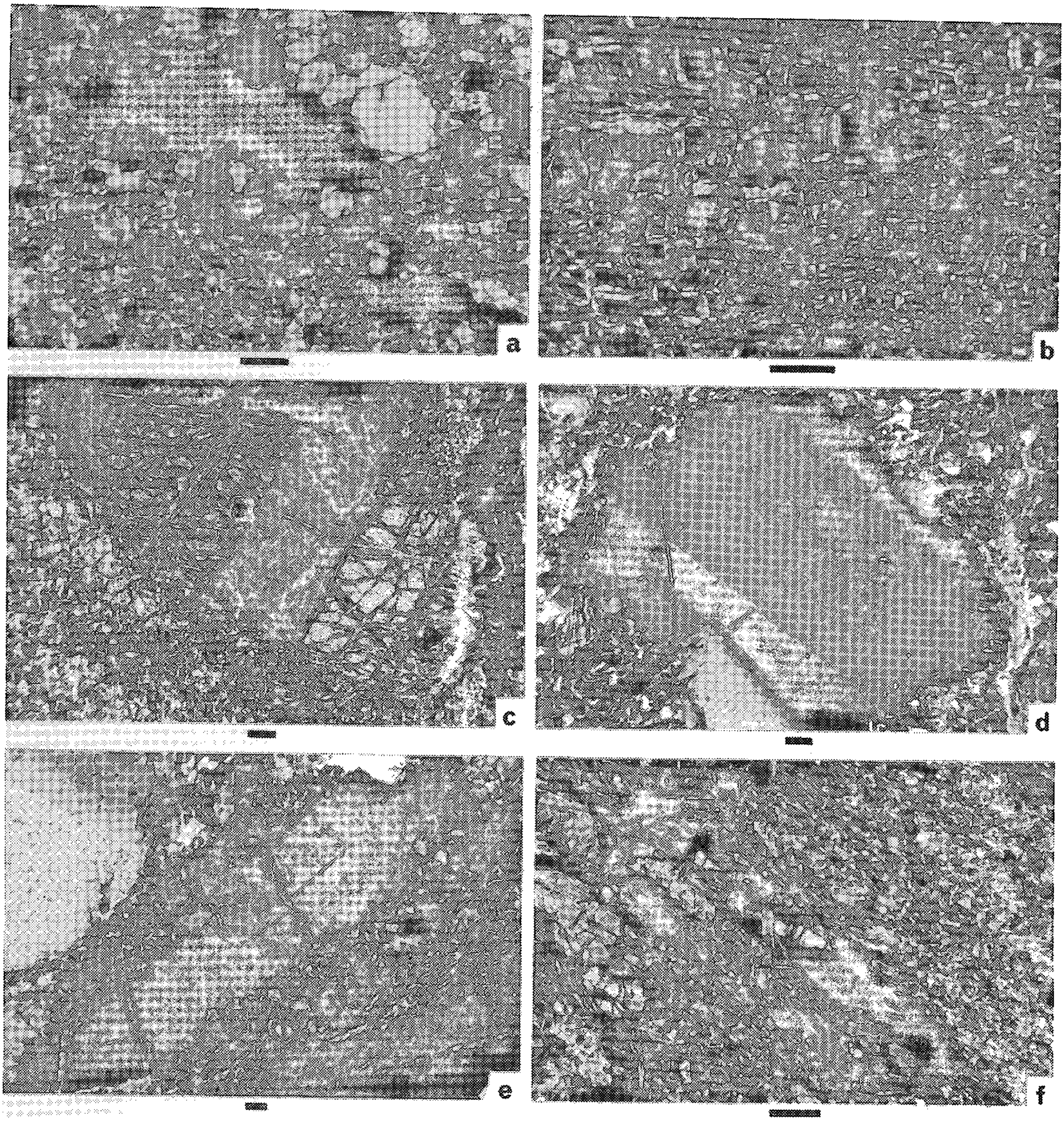

FIG. 1. (a) Porphyroclasts of strained olivine with deformation lamellae, surrounded by fine neoblasts of strain-free olivine. Sample SDM 57–593, Mount Albert, Quebec. (b) Porphyroclasts and neoblasts of olivine completely altered to lizardite-1T (as α-serpentine in mesh rims) ± brucite mesh-texture. Most neoblasts are now small, individual mesh-cells of serpentine. Sample 18508, Glen Urquhart, Scotland. (c) A strained grain of enstatite with a well-developed kink band and slight serpentinization along fractures. Sample SDM 57–56A, Mount Albert, Quebec. (d) A Povlen-type chrysotile $2M_{c1}$ and $2Or_{c1}$ (γ-serpentine) bastite pseudomorph after kink-banded enstatite. Sample 18540, Jeffrey mine, Quebec. (e) Lizardite-1T hourglass assemblage (α-serpentine in extinction) after an elongate olivine porphyroclast, surrounded by small lizardite-1T hourglass cells after olivine neoblasts. The small bright plates at the margin of the large kink-banded enstatite were small strain-free, recrystallized grains of enstatite. Both types of grains now consist of a pseudomorph of Povlen-type chrysotile $2M_{c1}$ + $2Or_{c1}$ (γ-serpentine). Sample 18540, Jeffrey mine, Quebec. (f) Coarse, elongate and strained grains of tremolite in the lower left half of the photomicrograph, with associated fine-grained, strain-free tremolite grains in the upper right half. Sample W66–83, Glen Urquhart, Scotland. All photomicrographs taken under crossed nicols. Bar represents 0.2 mm.

Durham *et al.* 1977) to reveal the fine details of the dislocations. Further details in solid-state flow can be found in the very useful book by Nicolas & Poirier (1976).

Pseudomorphic Textures in Serpentinized Peridotites

Many peridotites, either of alpine type or found as xenoliths in basalts or kimberlites, have been affected by serpentinization. Obviously, those that have been highly serpentinized are not suitable for the detailed textural studies referred to above, and in most cases have been passed over in favor of less-serpentinized peridotites. Limited studies of serpentinized peridotite have been carried out by Mercier & Nicolas (1975), who have noted the partial replacement of olivine by lizardite, by Borley (1976), who has described the pseudomorphic replacement of olivine in a granular polygonal texture by serpentine, by Boyd & Nixon (1979), who found that even in highly serpentinized olivine the outlines of the primary grain-boundaries were preserved, and by Laurent & Hébert (1979), who have observed the results of pseudomorphic replacement of olivine and enstatite by lizardite in harzburgite tectonites.

The pseudomorphic replacement of olivine and pyroxene by serpentine occurs during retrograde serpentinization (type 3: Wicks & Whittaker 1977) and is mineralogically characterized by lizardite-1*T* with or without brucite or magnetite (Wicks *et al.* 1977, Wicks & Whittaker 1977, Wicks & Plant 1979). Minor amounts of chrysotile do occur with lizardite-1*T*, particularly in some samples of pyroxene bastite (Cressey 1979), but it is not a major phase in pseudomorphs in the retrograde environment. Chrysotile does become a major phase in pseudomorphs after olivine and pyroxene during the mild prograde metamorphism (type 5) that produces chrysotile-asbestos deposits (Wicks & Whittaker 1977, Wicks & Plant 1979).

The pseudomorphic replacement of olivine by serpentine has often been envisaged in terms of a large fractured olivine grain into which serpentinization advances uniformly, from all fractures and grain boundaries, to produce mesh textures or hourglass textures (Wicks *et al.* 1977). The serpentinization of coarse, fractured olivine grains found in the coarse peridotites, and of large strained and fractured porphyroclastic olivine grains found in porphyroclastic and mosaic–porphyroclastic peridotites (Fig. 1a), produces an assemblage of crystallographically interrelated mesh (Fig. 1b) or hourglass cells (Fig. 1e) that are directly related to the fractures in the olivine grains. Note that the morphological relationships of mesh and hourglass cells to one another and to the parent olivine have been described by Wicks *et al.* (1977), and the crystallographical relationships of the serpentine minerals within the various mesh and hourglass units have been described by Wicks & Whittaker (1977) using microbeam X-ray-camera techniques described by Wicks & Zussman (1975). In contrast, the fine-grained, unstrained, recrystallized neoblasts of olivine, which surround the porphyroclasts in porphyroclastic and mosaic–porphyroclastic peridotites and which make up granuloblastic peridotites, are usually unfractured (Fig. 1a) and serpentinize to individual mesh-cells crystallographically unrelated to the adjacent mesh-cells (Fig. 1b), or to single plates of serpentine the same size as the original grains of olivine (Fig. 1e). Thus the size, shape, fracture sites and grain-boundary relationships of the olivine grains are preserved by serpentine ± brucite pseudomorphs, and the various types of deformation textures can be recognized in spite of retrograde (type 3: Wicks & Whittaker 1977) and mild prograde serpentinization (type 5). In the case of retrograde serpentinization, the pseudomorphs are composed of lizardite (as α-serpentine in the mesh rims) ± brucite mesh-texture, as illustrated in Figure 1b; in the case of prograde serpentinization, the pseudomorphs are composed of lizardite (as α-serpentine) ± brucite in an hourglass texture (Fig. 1e), or chrysotile (as γ-serpentine) ± brucite or antigorite (as γ-serpentine) + brucite in a mesh or hourglass texture. However, the finer details, such as the deformation lamellae (the subgrain structures of Nicolas & Poirier 1976, p. 47, 114) and the dislocation structures, are lost. Secondary magnetite, associated with the serpentinization, commonly develops along (and emphasizes) the former olivine grain-boundaries and fractures. Some caution should be used because the serpentinization of olivine and the deposition of the magnetite does eliminate the finer details along the grain boundaries. Nevertheless, careful observation of the serpentine pseudomorphs can yield a great deal of data on the preserpentinization nature of the peridotite.

The pseudomorphic replacement of enstatite by serpentine progresses in from grain boundaries and fractures by following along cleavage planes (Wicks & Whittaker 1977). The resulting pseudomorph, usually called bastite, may vary in appearance from apparently fibrous to nearly featureless. Clinopyroxene may also be serpentinized in a similar way but usually is somewhat resistant to serpentinization and persists longer than does enstatite. Although it was not pointed out in the Wicks & Whittaker (1977) paper, some of the serpentine-bastites described are pseudomorphs after plastically deformed enstatite. Specifically, the pseudomorphic replacement of plastically deformed enstatite by lizardite (usually as γ-serpentine) has been documented in retrograde serpentinization (type 3: Wicks & Whittaker 1977),

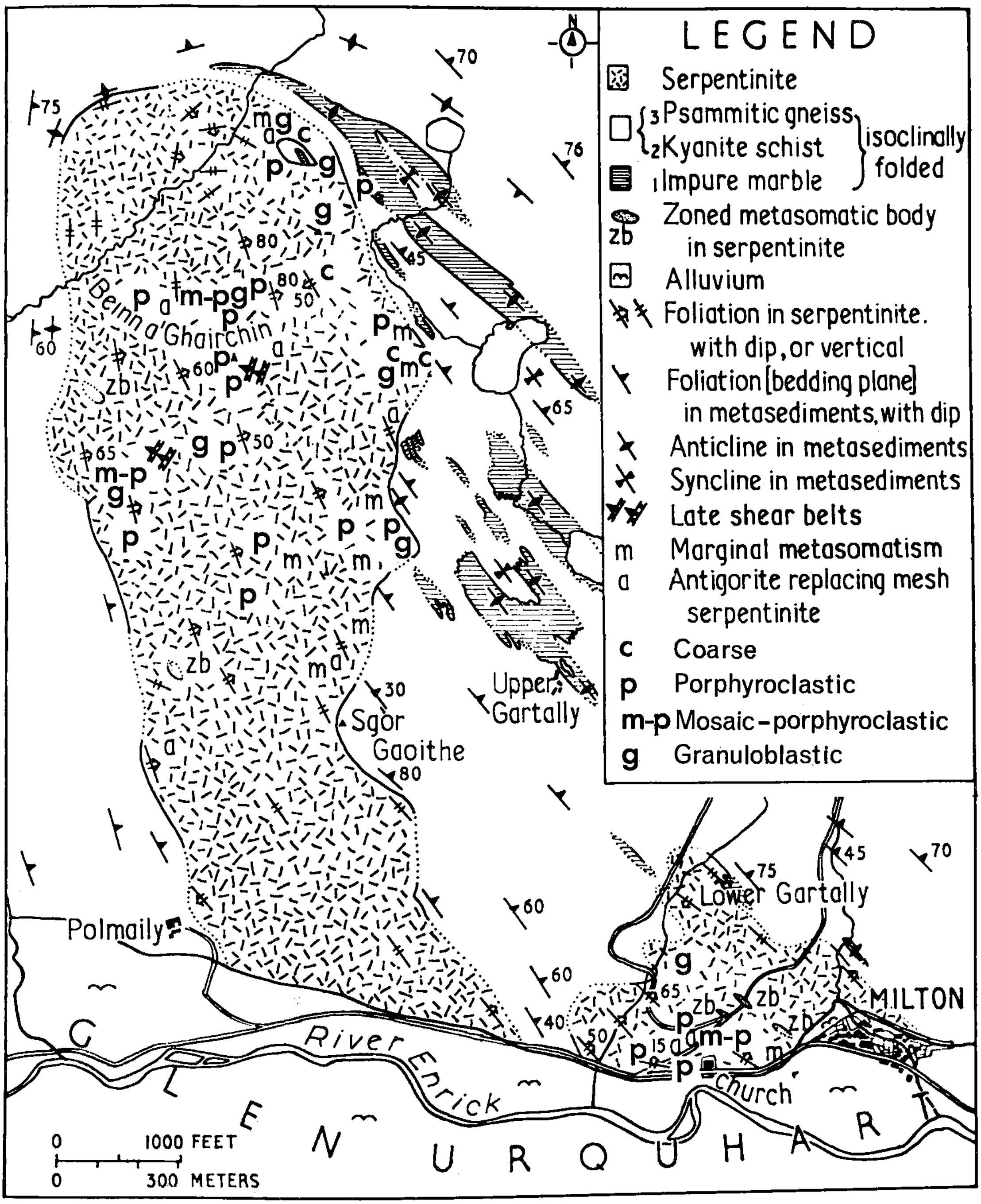

FIG. 2. Geological sketch map of the ultramafic rocks in Glen Urquhart, showing the distribution of the types of solid-state deformation-induced textures of the olivine grains (modified after Francis 1956).

and by chrysotile, both normal and Povlen-types (as γ-serpentine), in some cases of mild prograde serpentinization (type 5) and the antigorite + brucite assemblage (type 7: Wicks & Plant 1979). In all cases, both the large deformed grains of enstatite (Fig. 1d) and the small, strain-free, recrystallized grains at the margins of large grains (Fig. 1e) are pseudomorphically replaced by serpentine. Where bastite forms after an enstatite grain that contains kink bands, it faithfully records the kink bands in the serpentine pseudomorph (Fig. 1d). Thus, in contrast to the serpentine pseudomorphs after olivine, in which the internal structure of subgrains (deformation lamellae) is lost, serpentine pseudomorphs after pyroxene record the internal evidence of the early plastic deformation of the pyroxene, as well as the external morphology.

Application to the Glen Urquhart Serpentinite

Description

Francis (1956) found the ultramafic mass at Glen Urquhart (Fig. 2) to be composed mainly of a serpentine mesh-texture after olivine, that was later identified as lizardite-1*T* ± brucite mesh-texture (Wicks & Whittaker 1977), with minor amounts of lizardite-1*T* bastite. Isolated grains of olivine occur scattered throughout the rocks as relics in some mesh centres, but only the occasional grain of enstatite occurs in the interiors of the lizardite–bastites. Although lizardite-1*T* is the most abundant serpentine mineral, antigorite occurs infrequently, appearing to have replaced mesh-texture lizardite-1*T*, and in places formed an antigorite schist (Francis 1956).

A pronounced foliation is imparted to the rock by lenses and stringers of chlorite and magnetite (Fig. 3a). Tremolite, in the form of large elongate crystals (Fig. 1f) or as trains and clusters of fine-grained prisms, occurs on its own or in association with the chlorite–magnetite lenses and stringers (Fig. 3b) and contributes to the foliation. Talc occurs as selvages around bastite (Fig. 3c) or as large plates (Fig. 3d). Minor amounts of carbonate and several other minor accessory minerals were also identified by Francis (1956).

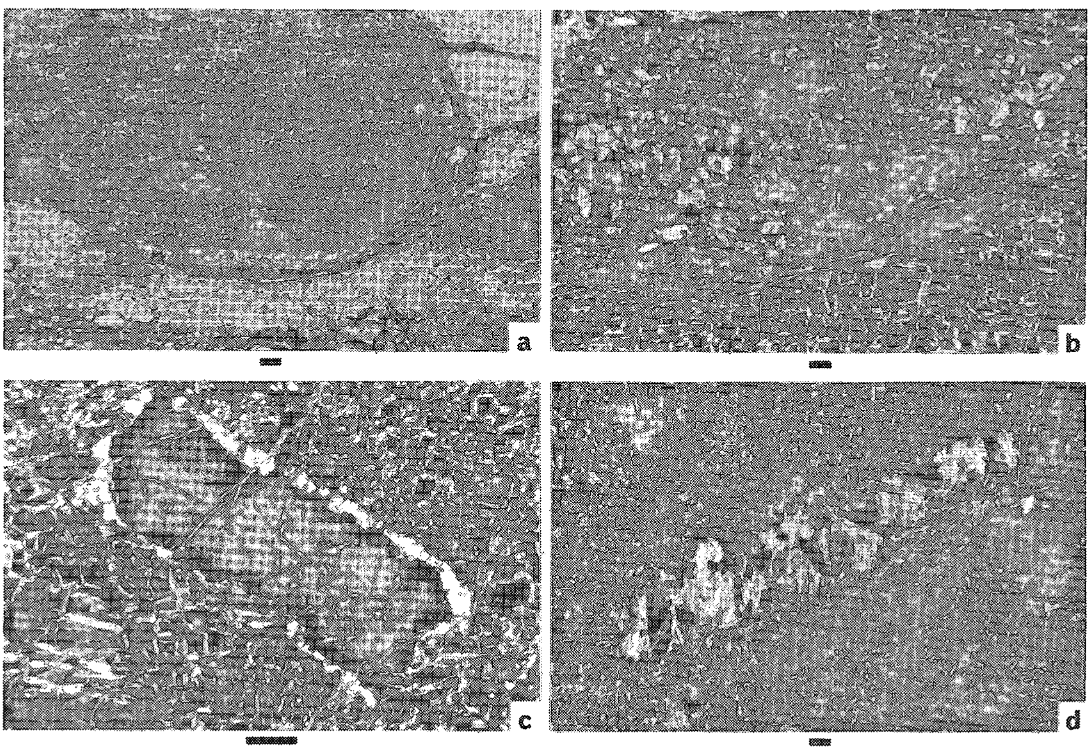

FIG. 3. (a) A chlorite and magnetite lens with a chlorite-lined brittle fracture passing beneath the lens along the chlorite–olivine (now lizardite-1*T* ± brucite mesh-texture) interface. Sample W66–68. (b) A complex lens of tremolite toward the top and chlorite and magnetite toward the bottom with a chlorite-lined brittle fracture along the chlorite–olivine (now lizardite-1*T* ± brucite mesh-texture) interface. Sample W66–69. (c) Elongate grain of enstatite with a talc alteration rim, both serpentinized to lizardite-1*T* (γ-serpentine). Sample W66–39. (d) Coarse flakes of talc after an elongate enstatite grain. Sample W66–68. All samples from Glen Urquhart, Scotland; (a) under plane-polarized light, and all others under crossed nicols. Bar represents 0.2 mm.

There is a second small body to the southeast of the main body, and a very small sheet of ultramafic rock 50 m east of the northeast end of the main body (Fig. 2). Francis (1956) felt all three are probably joined at depth. The ultramafic bodies have intruded into and have disturbed isoclinally folded metasediments, but have not produced any contact metamorphism. At the north end of the main body, the isoclinal folds in the metasediments have been overturned by the intrusion, on the west side the folds and foliation of the metasediments are subparallel to the contact, and on the east side the folds in the metasediments are truncated by the intrusive body. The contact to the south is not exposed. A block of metasediments whose folds and foliation are parallel to the adjacent country-rock has been caught up in the ultramafic mass near its northeastern contact with the metasediments.

Francis's interpretation

Francis (1956) noted several problems in the interpretation of the sequence of events, among them the apparent lack of a source of water to produce the serpentine. The water content of the metasediments is low (the total water of the kyanite schist is 0.73%, and of the paragneiss, 0.40%: Francis 1956, p. 217), so that they do not appear to have been a ready source of water. Francis's preferred interpretation is that intrusion of a mush of olivine and enstatite crystals occurred with enough interstitial water of "unknown provenance" to cause serpentinization once the body cooled. Intrusion must have occurred after the height of metamorphism of the metasediments but while they were still able to deform plastically and to produce the overturned isoclinal folds at the northern end of the intrusive body. A foliation unrelated to that of the host metasediments was imparted to the ultramafic rock during intrusion. Once movement ceased and the cooling intrusive body crossed into the stability field of serpentine, serpentinization of the olivine and enstatite took place, and the talc rims developed around bastite. Francis suggested that some of the coarse crystals of tremolite were slightly serpentinized at this time (Fig. 1f), but that the development of some of the fine-grained prisms of amphibole was associated with the serpentinization process.

A final major alteration was caused by the Older Granite metasomatism which also affected all the metasediments with the exception of the block included within the ultramafic body. According to Francis (1956), the metasomatism took three forms: the injection alteration of the serpentinite, the marginal hydrothermal bodies and the zoned hydrothermal bodies within the intrusion (Francis 1955). The discussion of the latter two is beyond the scope of this paper. The injection alteration of the serpentinite took the form of the development of chlorite and magnetite lenses and stringers of fine-grained prisms of tremolite (Fig. 3b).

Francis (1956) placed the development of antigorite after the Older Granite metasomatism. However, he found it difficult to satisfactorily account for the development of the antigorite after lizardite mesh-texture, as it was not clearly associated with thermal metamorphism or shearing that is commonly the cause of the alteration of mesh-texture lizardite to antigorite. Francis did attribute strongly foliated antigorite to shearing, but this was formed by the recrystallization of coarse-grained, randomly oriented antigorite, not directly by the recrystallization of lizardite mesh-texture. The final episode in Francis's interpretation was the development of a series of late veins of chrysotile, chalcedony and carbonate.

New interpretation

Francis's interpretation was based on careful study and observation and was as advanced as was possible in 1956. In the light of the work that has been carried out in the following 28 years, particularly on deformation textures and serpentinization, and in the light of observations made on 65 thin sections of samples collected from Glen Urquhart, it is possible to make a new interpretation that answers some of the questions left unanswered by Francis (1956).

In spite of serpentinization, it can be seen that the peridotite clearly displays deformation textures of olivine and enstatite as well as a temperature-controlled series of mineral - water reactions that culminated in pervasive serpentinization. A careful examination of the lizardite-1T ± brucite mesh-textures reveals that the olivine possessed different textures in different part of the peridotite, including coarse (both equant and tabular), porphyroclastic, mosaic–porphyroclastic and granuloblastic textures (Fig. 2). The occurrence of minor relict olivine in some thin sections provides the opportunity to observe undulatory extinction and subgrains (deformation lamellae) in the olivine, which helps to verify indentifications and gives confidence to the interpretation of thin sections in which olivine is absent. The lizardite-1T bastite grains after enstatite are elongate, with aspect ratios of up to 7 to 1 (Fig. 3c). Kink bands are not present. These features indicate that fairly extensive slip occurred in the enstatite (Nicolas & Poirier 1976) prior to the serpentinization. The porphyroclastic and mosaic–porphyroclastic textures in olivine, with numerous strain-free polygonal neoblasts of olivine and the slightly elongated grains of enstatite, point to intrusion by plastic, solid-state flow.

It is very unlikely that during intrusion the hot ultramafic rock contained the 14 wt.% interstitial water required for serpentinization, as has been suggested by Francis (1956); however, the presence of hydrous minerals indicates that some water was in contact with the intrusive body throughout its cooling history. The effect of the water can be seen by the series of mineral reactions that can be followed with decreasing temperature on the pressure–temperature diagram of O'Hara (1967) and on the composition–temperature diagram of Evans (1977). There are also changes in the type of deformation of the minerals and the mechanics of intrusion related to decreasing temperature and the development of new minerals.

Solid-state flow, as identified in the olivine and enstatite textures, was the intrusive mechanism during the early and intermediate stages of intrusion. At this time, the rock was most likely composed of olivine, enstatite, diopside and a spinel phase, although it may also have contained pargasite (Evans 1982). No trace of diopside or of pseudomorphs after diopside is present at Glen Urquhart, but tremolite is abundant (Fig. 1f). An explanation for the alteration of diopside to tremolite can be found on Evans's (1977) composition–temperature diagram. The (MgO + FeO)/(MgO + FeO + SiO_2) ratio of the Glen Urquhart ultramafic rocks is between 0.50 and 0.53 (Francis 1956, Tables 4, 6). Thus with cooling in the presence of water, diopside will alter to tremolite and tremolite will remain a stable phase to low temperatures. (Evans's diagram is based on observations and calculations from prograde metamorphic rocks, but the diagram also works well for the sequence of retrograde alteration except in the low-temperature region, where tremolite is replaced by lizardite.)

The tremolite also shows the effects of solid-state deformation. Elongate coarse grains deform first by internal distortions revealed by undulatory extinction and twinning (Nicolas & Poirier 1976), and then evolve, through a type of polygonalization, into small elongate grains with slight misorientation between adjacent grains (Fig. 1f). Continued deformation produced lenses and stringers of fine-grained, strain-free, stubby prisms of tremolite through recrystallization (Fig. 3b). The development of strained tremolite means that water was available in sufficient quantities to replace any diopside and that the rocks were still hot enough to deform plastically.

At slightly lower temperatures, with the continued availability of water, chlorite became a stable phase through the reaction forsterite + 2 enstatite + 4 H_2O = clinochlore (Chernosky 1974), to form lenses and stringers of chlorite and magnetite. The chlorite stringers are commonly (but not always) closely related to the tremolite stringers, and the two features in part define the foliation (Fig. 3b) visible in the outcrops of ultramafic rock.

With a continued decrease in temperature, talc developed as rims on enstatite (Fig. 3c) through the metastable reaction 5 enstatite + H_2O = talc + forsterite (Chernosky 1976). An alternate interpretation would be that first anthophyllite developed as rims on enstatite and that the anthophyllite then reacted, with falling temperature, to produce talc. As no relict anthophyllite has been observed and as anthophyllite is difficult to nucleate, at least in experimental studies (Chernosky 1976), the most direct interpretation is for enstatite to alter directly to talc. In places where water was particularly abundant, the enstatite was completely replaced by an elongate mass of talc flakes conforming to the original form of the enstatite grains (Fig. 3d). At the same time, some talc formed along zones of minor slip in response to minor structural shifts of the ultramafic mass.

The antigorite that Francis (1956) found difficult to explain now can be considered as part of the series of temperature-related reactions with water. Antigorite replaced tremolite and chlorite (Wicks & Whittaker 1977, Fig. 5a) but has not replaced talc. The antigorite that appears to have formed after the lizardite-1$T \pm$ brucite mesh-textures may actually have formed after olivine before it was affected by the lizardite-1$T \pm$ brucite serpentinization. This development of antigorite represents a lower temperature of formation than the talc alteration, but talc would not be affected by antigorite because talc and antigorite would both be stable phases (Evans 1977). However, tremolite, chlorite and forsterite would be unstable and would alter to antigorite (Wicks & Whittaker 1977). This is an important observation, as it is an example of the retrograde type-1 serpentinization of Wicks & Whittaker (1977) that has been observed only infrequently. Minor structural adjustments associated with the late stages of intrusion would recrystallize the randomly oriented antigorite formed after olivine to foliated antigorite.

Thus in this new interpretation, the observed assemblages of minerals can be accounted for without an appeal to "the Older Granite metasomatism" (Francis 1956). The only phase added to the ultramafic body was water during critical stages of its cooling.

The plastic deformation of the metasediments noted by Francis (1956) at the northern end of the main body and the plastic-deformation textures of the olivine and enstatite indicate that plastic flow was the main mode of intrusion. However, the cooling of the ultramafic body, the addition of water and the related mineral reactions brought about a gradual change in the mode of deformation. Flow gradually passed from the olivine and enstatite to tremolite and chlorite, producing some of the observed foliation. With continued cooling, plastic flow ceased and brittle failure occurred, passing along the chlorite stringers and around the margins of large tremolite–chlorite–magnetite lenses (Figs. 3a,b), producing a stronger foliation. This would occur because at lower temperatures, the more competent unaltered forsterite, enstatite and tremolite would resist deformation, and the less competent chlorite, talc and antigorite would yield to deformation. Thus, although solid-state deformation of olivine, enstatite, tremolite and probably some chlorite has been extensive during the emplacement of the Glen Urquhart intrusive complex, the final emplacement was accomplished by shearing along specific planes, mainly of chlorite, but also of talc and antigorite, distributed throughout the body. This change in the mode of deformation would explain why coarse-grained olivine textures occur preserved near the eastern contact (Fig. 2), where one would expect intense reduction in grain size if intrusion was accomplished by solid-state flow alone (Nicolas & Poirier 1976).

The final major episode of alteration was the pervasive retrograde serpentinization (type 3: Wicks & Whittaker 1977) of most of the olivine to a lizardite-1$T\pm$ brucite mesh-texture (Fig. 1b), and all the enstatite (Wicks & Whittaker 1977, Fig. 3a), most of the talc (Wicks & Whittaker 1977, Fig. 4c) and some of the tremolite (Wicks & Whittaker 1977, Fig. 4b) to lizardite-1T bastite. Chlorite remains unaffected. During this serpentinization, which probably took place over a considerable period of time, fractures, particularly within chlorite stringers, were filled with fine veins of chrysotile asbestos. Minor amounts of carbonates developed in veins and in some of the mesh textures.

There is one remaining major problem: what is the source of the water that produced the series of minerals? All the reactions require water but, with the exception of the final pervasive serpentinization, not much water is required for formation of tremolite, chlorite or talc, and the antigorite is not abundant or widely distributed, suggesting that the supply of water to the intrusive body was constant but limited during intrusion. Once the ultramafic body reached its present position, the pervasive lizardite-1$T\pm$ brucite serpentinization probably took place over a long period of time at low temperatures as water slowly reached it (Wenner & Taylor 1971, Barnes & O'Neil 1969). The scattered but not uncommon relics of olivine and high-relief 14 Å intermediate structures between olivine and lizardite in some mesh-centres (Wicks 1969) indicate that serpentinization is still not complete. The ultramafic body is close to a major fault, the Great Glen fault, and may have slowly acquired water from the fault system over a long period of time.

Application to Studies of Serpentinites

In the past, serpentinized ultramafic rocks have been shunned as material in which to study solid-state deformation of olivine and pyroxene. The results of the present study illustrate that some details of solid-state deformation of olivine, enstatite, diopside and tremolite can be gathered in spite of extensive retrograde pseudomorphic serpentinization (type 3: Wicks & Whittaker 1977) and mild prograde pseudomorphic serpentinization (type 5). Although unserpentinized rocks are required to obtain the fine details of solid-state deformation, some completely serpentinized rocks can still yield a significant amount of detail on the earlier deformation. Thus it may not be necessary to abandon a study just because the rocks are serpentinized.

The restudy of the Glen Urquhart serpentinized peridotite in particular illustrates the potential of this type of study. Not only can the nature of the solid-state deformation of the former olivine and enstatite and of the relict tremolite be recognized, but the gradual change in the mode of deformation can also be documented. Deformation changes from early plastic, solid-state flow in olivine and enstatite, to later plastic, solid-state flow in tremolite and chlorite and finally to brittle fracture through chlorite along the margins of the tremolite–chlorite lenses, as the emplacement proceeds and as temperature and pressure decrease.

Further work is in progress to refine this interpretation of the Glen Urquhart intrusive complex. At this point, it stands as a good example of the understanding that can be gained if an effort is made to look through the effects of pseudomorphic serpentinization to the original textures of olivine, enstatite and tremolite.

Acknowledgements

The thoughtful comments of Dr. A. Nicolas, Université de Nantes, and Dr. J.V. Chernosky, University of Maine, on the original version of this manuscript are greatly appreciated. The Geological Survey of Canada provided thin sections from the Mount Albert intrusive complex, Quebec, and Canadian Johns-Manville Co., Ltd., provided access to the Jeffrey mine, Quebec. Their assistance is gratefully acknowledged. I thank the American Journal of Science for their permission to use Figure 2. Both Mrs. Gloria Nelson, who typed the final manuscript, and Miss Margaret Coutinho, who typed an earlier version of the manuscript, are thanked for their careful work. A part of the research incorporated into this paper was supported by a research grant from the Geological Survey of Canada, Energy, Mines and Resources Canada.

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Received January 11, 1983, revised manuscript accepted September 7, 1983.