Canadian Mineralogist
Vol. 22, pp. 197-203 (1984)

DEFORMATION HISTORIES AS RECORDED BY SERPENTINITES.
II. DEFORMATION DURING AND AFTER SERPENTINIZATION

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ABSTRACT

Serpentine minerals can be actively involved in deformation, and the form they take reflects the conditions under which the deformation occurred. By combining the results of published experimental studies on serpentine deformation with observations on naturally deformed samples, the types and conditions of deformation can be recognized. Naturally deformed antigorite serpentinites correspond well with the results of experimental deformation. Thus, at low confining pressures and low to intermediate temperatures, antigorite serpentinites fail by brittle fracture. At high confining pressures and low to intermediate temperatures, they fail by ductile solid flow; at low to high confining pressures and high temperatures, they fail by brittle fracture due to the dehydroxylation of antigorite. Naturally deformed lizardite and chrysolite serpentinites correspond with the experimental results in some cases only. In the other cases, the discrepancy with experimental results might simply indicate that the appropriate samples have not been obtained. But it must also be, in part, related to the fact that lizardite and chrysotile, before deforming by pure plastic flow or by dehydroxylation, will first alter to antigorite during the long time-spans in which deformation takes place in nature.

Keywords: deformation, brittle failure, ductile failure, tests of strength and ductility, serpentinization, lizardite, chrysotile, antigorite, dehydroxylation.

SOMMAIRE

Les minéraux de serpentine peuvent être activement impliqués dans la déformation; la forme qu'ils épousent reflète les conditions qui ont présidé à la déformation. On peut reconnaître les types de déformation et leurs conditions en intégrant les résultats publiés d'études expérimentales de la déformation de la serpentine aux observations faites sur des échantillons déformés naturellement. Les serpentinites à antigorite déformées correspondent bien aux résultats de déformations expérimentales. Ainsi, à faible pression lithostatique et à des températures basses à intermédiaires, les serpentinites à antigorite cèdent par rupture fragile. Aux mêmes conditions de température, mais à pression lithostatique élevée, elles cèdent par écoulement ductile. À des températures élevées et des pressions faibles à élevées, elles cèdent par rupture fragile due à la déshydroxylation de l'antigorite. Les serpentinites à lizardite et chrysotile déformées naturellement reflètent les résultats expérimentaux seulement dans certains cas. Dans les autres cas la divergence entre les faits observés dans la nature et les résultats expérimentaux peut indiquer simplement que l'on n'a pas obtenu les échantillons appropriés. Cependant, elle peut aussi, en partie, être attribuée au fait qu'avant de se déformer par écoulement plastique pur ou par déshydroxylation, la lizardite et la chrysotile dans la nature s'altèrent d'abord en antigorite au cours de la longue période de déformation.

(Traduit par la Rédaction)

Mots-clés: déformation, rupture fragile, rupture ductile, essais de contrainte et de ductilité, serpentinisation, lizardite, chrysotile, antigorite, déshydroxylation.

INTRODUCTION

The role of the serpentine minerals in deformation is not restricted to the passive recording through pseudomorphism of earlier deformation events as described in the preceding companion paper (Wicks 1984a). The serpentine minerals may also be actively involved in and be affected by deformation. The most systematic study of the experimental deformation of the serpentine minerals has been carried out by Raleigh & Paterson (1965), but no systematic study of the natural deformation of serpentine minerals has been performed. In this paper, the visible results of deformation in serpentine minerals are described as observed in thin section and correlated with the experimental results.

EXPERIMENTAL METHODS

The serpentine minerals making up the textures described in this study were identified either *in situ* in thin section with a Norelco microbeam X-ray-diffraction camera, using the technique described by Wicks & Zussman (1975) or using the criteria established by Wicks & Whittaker (1977). The chemical composition of the serpentine in many of the textures has been determined by electron microprobe (Wicks & Plant 1979, 1983).

EXPERIMENTAL DEFORMATION

Raleigh & Paterson (1965) performed strength and ductility investigations on two types of serpentinites, the first composed of antigorite with minor chrysotile-$2M_{c1}$ in radial aggregates, the other composed of lizardite-$1T$ with chrysotile-$2M_{c1}$ + minor

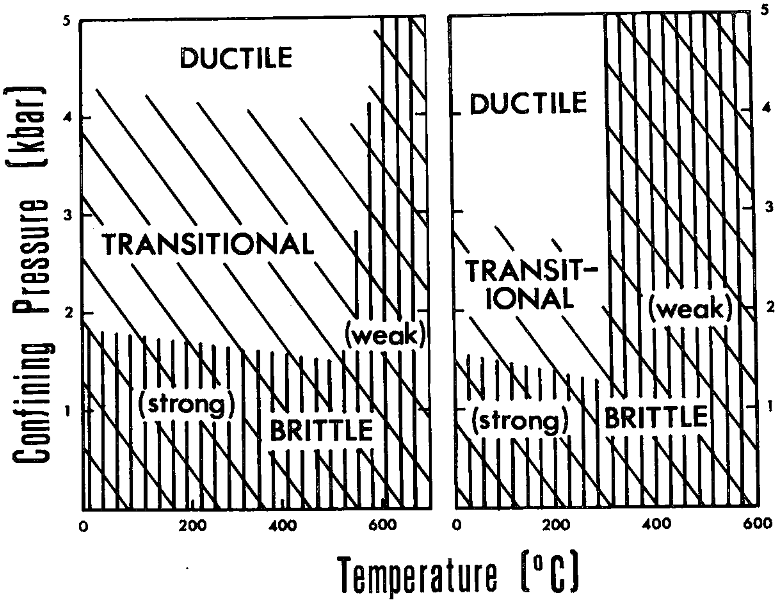

FIG. 1. Approximate pressure–temperature fields of brittle, transitional and ductile failure for antigorite serpentinites with minor chrysotile-$2M_{c1}$, on the left and for lizardite-$1T$ ± brucite mesh-texture serpentinites on the right (from Raleigh & Paterson 1965).

brucite in a mesh texture. Both completely and partly serpentinized samples of the second type were investigated. The strength and ductility experiments were performed on a high-pressure and high-temperature apparatus using serpentine cylinders 1 cm in diameter by 2.0 or 2.5 cm in length drilled from blocks of serpentinite. The cylinders were dried at 120°C for at least 24 hours prior to testing. The specimens were sealed in annealed to copper jackets and subjected to confining pressures of 0.5, 1, 2, 3.5 or 5 kilobars. They were then heated at temperatures between 25° to 700°C for up to 0.5, 1, 2 or 7 hours; then a load was applied so that the specimens were strained at a rate of 7×10^{-4} s^{-1} (Raleigh & Paterson 1965). The results of the experimental runs are summarized in Figure 1.

Below approximately 2 kilobars confining pressure and throughout the temperature range examined, the antigorite serpentinites displayed brittle failure (Fig. 1). Above 4 kilobars and up to 500° to 600°C antigorite serpentinites displayed ductile failure, with elements of both brittle and ductile failure between 2 and 4 kilobars. Above 500–600°C, at all confining pressures, antigorite displayed brittle failure owing to the breakdown of antigorite to form olivine and water. The water released by this reaction raised the pore pressure, reducing the effective confining pressure and producing brittle failure of the antigorite serpentinite samples.

The mesh-texture serpentinites of lizardite-$1T$ + chrysotile-$2M_{c1}$ + minor brucite displayed a similar pattern, but the brittle failure due to the breakdown of the serpentine and brucite to olivine and water occurred at 300–350°C. Below this temperature at confining pressures of over 3 kilobars, ductile failure occurred. Between 3 and 1.5 kilobars, both brittle and ductile features of failure developed, and below 1.5 kilobars only brittle failure occurred.

Raleigh's & Paterson's (1965) observations in thin section of the zone of failure in specimens that had undergone ductile failure revealed a broad zone of deformation containing bent and kinked grains of serpentine, evidence of plastic deformation. Those specimens that had undergone brittle failure displayed highly oriented grains of serpentine in a narrow zone adjacent to the fault. As the brittle failure occurred rapidly over a few minutes, Raleigh & Paterson concluded that the strong orientation was produced by rotation of grains during failure and not by recrystallization.

NATURAL DEFORMATION

A petrographic examination of foliated antigorite serpentinites (types 2 and 8: Wicks & Whittaker 1977) and foliated chrysotile ± lizardite serpentinites (types 4 and 6: Wicks & Whittaker 1977) from a variety of geological environments reveal some parallels and

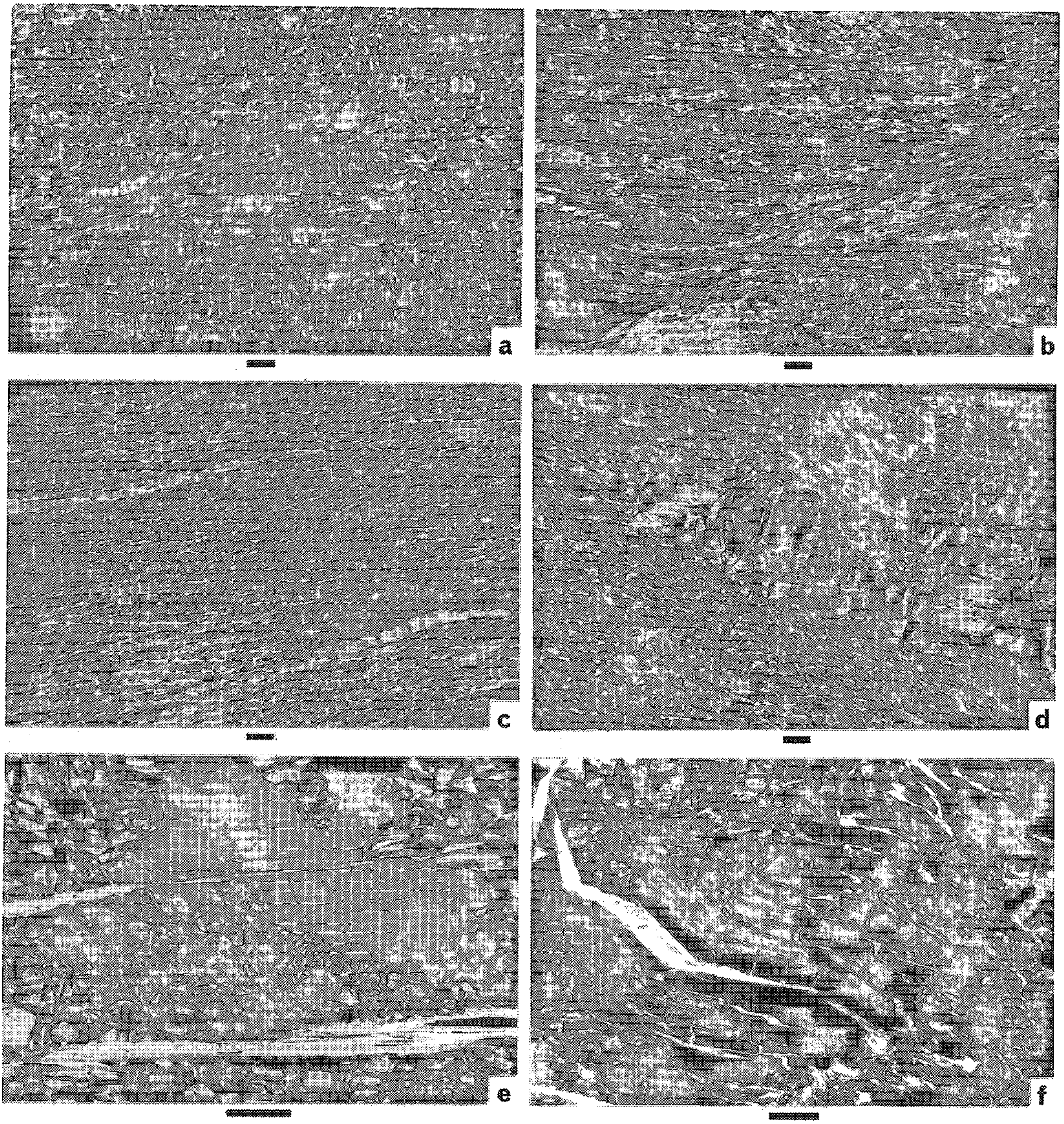

FIG. 2. (a) A zone of brittle failure, lined with parallel, coarse blades of antigorite and magnetite, passing through fine, weakly foliated antigorite grains. Sample W68–88, Torrente Ordagna, Lanzo massif, Italy. (b) Zone of brittle failure, lined with fine-grained olivine, titanian clinohumite and strain-free diopside grains, passing through strongly foliated blades of antigorite. Sample W68–71, Ponte del Diavolo, Lanzo massif, Italy. (c) Zone of ductile failure composed of strongly foliated blades of antigorite. Sample W68–63, Col del Lis, Lanzo massif, Italy. (d) A coarse grain of antigorite exhibiting ductile failure through kink banding, surrounded by fine, strongly foliated blades of antigorite. Sample W68–63, Col del Lis, Lanzo massif, Italy. (e) Zones of brittle failure lined with parallel chrysotile and brucite fibres and magnetite lenses. The lower fracture passes through undisturbed lizardite-1*T* hourglass texture, and the upper fracture passes through and offsets a lizardite-1*T* bastite after enstatite. Sample AG67-7a, Jeffrey mine, Quebec. (f) Brittle failure of lizardite-1*T* bastite after enstatite. The bending and shattering were caused by a fracture passing along a diagonal from the upper right to lower left. The fractures in the bastite have been occupied by chrysotile. Sample AG67-lb, Jeffrey mine, Quebec. All under crossed nicols. Bar represents 0.2 mm.

some differences with the experimental results of Raleigh & Paterson (1965).

Antigorite serpentinites

Two types of brittle failure are recorded in antigorite serpentinites, and both can be correlated with Raleigh's & Paterson's experimental results. In some weakly foliated antigorite serpentinites, simple fractures pass through randomly oriented or slightly oriented grains of antigorite without significantly disrupting them (Fig. 2a). Elongate blades of antigorite lie parallel to, and in a narrow zone adjacent to, the fracture plane (Fig. 2a), and form the slickensides observed on the fracture plane. The simple fracture-plane, with minimum disruption of the adjacent wallrock, represents brittle failure at low pressure and at temperatures below the dehydroxylation of antigorite (Fig. 1). Simple fractures also occur in some strongly foliated antigorite serpentinites but, in this case, the fractures are produced by the dehydroxylation of antigorite. The antigorite is very strongly foliated and, in some samples examined, encloses coarse-grained, strained, kink-banded diopside with associated tails of fine-grained, strain-free, recrystallized diopside (Peters 1968, Trommsdorff & Evans 1974, Evans 1977) strung out along the foliation planes in the antigorite (Fig. 2b). All the features suggest intense plastic flow and recrystallization. Brittle fractures, occupied by olivine, titanian clinohumite and fine-grained, recrystallized diopside, occur both parallel to and at low angles to the foliation of the antigorite (Fig. 2b). The fractures were formed when the antigorite dehydrated at a high temperature to produce olivine, titanian clinohumite and water in association with the recrystallization of coarse-grained, strained diopside to fine-grained, strain-free diopside. This event marks the end of ductile failure in the antigorite and the establishment of brittle failure at high temperatures caused by the dehydroxylation of the antigorite (Fig. 1).

Ductile failure is recorded in intensely foliated antigorite schists; this too can be correlated with Raleigh's & Paterson's (1965) results. These rocks are composed of fine-grained, elongate blades of antigorite with a strong foliation (Fig. 2c), enclosing very coarse grains of antigorite that are complexly kinked (Fig. 2d). Simple brittle fractures are absent. This combination of features points to plastic deformation and, with reference to the results of Raleigh & Paterson (1965) (Fig. 1), fairly high confining pressures and intermediate temperatures below the temperature of dehydroxylation of antigorite.

Finally, specimens with both a strong foliation indicating ductile failure and fractures indicating brittle failure were observed in a number of cases. These represent the transitional type of failure of Raleigh & Paterson (1965), occurring at intermediate pressure and low to intermediate temperatures (Fig. 1).

Chrysotile and lizardite serpentinites

The observed modes of failure (type 4: Wicks & Whittaker 1977) that occur in association with retrograde lizardite pseudomorphic textures (type 3) and those (type 6) that occur in association with mild prograde chrysotile–lizardite pseudomorphic and nonpseudomorphic textures (type 5) indicate that in nature, some cases of failure occur in a manner similar to that observed by Raleigh & Paterson in their experiments; in other cases, the failure does not correspond to the experimental observations. Chrysotile is usually the dominant serpentine mineral in these shear zones; both retrograde (type 4) and prograde (type 6) foliated serpentinites display the same basic features and are essentially indistinguishable in thin section (Wicks & Whittaker 1977).

Simple brittle fracture most closely corresponds to the results of Raleigh & Paterson (1965). Observations in thin section reveal that the fractures contain strongly oriented serpentine, usually chrysotile, that has passed through lizardite mesh (type 3) and lizardite and chrysotile hourglass-textures (types 3 and 5) without deforming or greatly disturbing the textural units immediately adjacent to the fracture (Fig. 2e). This is also the case in lizardite or Povlen-type chrysotile bastite where a fracture lies at a low angle to the parting planes of the bastite (Fig. 2e). The two halves of the bastite are simply offset with no visible deformation. However, bastite responds to stress differently along different structural directions. This occurs because the pseudomorphic replacement of pyroxene by serpentine is in part topotactic so that some of the features of the original pyroxene, such as partings and some cleavage planes, are preserved in the bastite (see Wicks 1984b). Thus where a fracture intersects a bastite grain at an angle nearly coincident with the partings, the bastite fails easily along the parting as illustrated in Figure 2e, but where a fracture intersects a bastite grain at a high angle to the partings, the bastite yields by bending and shattering (Fig. 2f). The bending produces undulatory extinction that could be mistaken for the pseudomorphosed undulatory extinction of plastically deformed enstatite, but the shattering represents brittle failure of the bastite and is uncharacteristic of plastic deformation in unserpentinized enstatite. Thus it would appear that when a retrograde or mild prograde serpentinite fails by brittle fracture, the bastite grains also fail by brittle fracture or by slip along cleavage planes.

Examples of the transitional failure with both brittle and ductile features (Fig. 1) are fairly abundant. These vary from samples dominated by brittle failure to those dominated by ductile failure. The former represent failure at lower confining pressures than the latter. In specimens dominated by brittle failure, simple fractures lined with nonfibrous chrysotile with the x axis parallel to the fracture surface (Fig. 3a) pass through massive undeformed serpentinite (type 3). Ductile failure occurs only in areas between two closely spaced fractures and takes the form of kink-banded grains and recrystallization (Fig. 3a).

Specimens dominated by ductile failure occur in the most intensely sheared zones (types 4 and 6) within or at the contacts of massive lizardite mesh-texture serpentinites (type 3) and massive prograde chrysotile and lizardite serpentinites (type 5). Strongly foliated nonfibrous chrysotile with the x axis aligned parallel to the foliation indicates strong ductile failure of the serpentine in these shear zones. Brittle failure also occurs as simple, sinuous fractures filled with strongly oriented nonfibrous chrysotile (Fig. 3b). This chrysotile forms the slickensides and occurs in successive generations of slightly different orientations. In some cases, strongly oriented chrysotile slip-fibre has been formed. An examination of these shear zones reveals that even in cases of intense shearing, small nodules of relict massive serpentinite, bounded by shears, have survived and can be examined to elucidate the deformation process. The nodules of relict massive serpentine may appear to be unaffected by shearing, but usually recrystallization is evident, particularly in zones adjacent to shear planes or between two closely spaced shear-planes (Fig. 3b). The recrystallization, leading to poorly and strongly oriented chrysotile that replaces the host pseudomorphic textures, has destroyed the earlier pseudomorphs (Fig. 3b), including bastite. In one case studied in detail (Wicks & Plant 1979, W70–74), even an earlier generation of antigorite was recrystallized to chrysotile. This mode of deformation, with a combination of shears, fractures and recrystallization, displays both brittle and ductile failure and represents the higher-pressure regions of the transitional zone (Fig. 1).

No clear examples of pure ductile failure in the high confining pressure and low to intermediate temperature region were found. Similarly, no examples of brittle failure caused by the breakdown of lizardite or chrysotile to olivine, analogous to the antigorite-bearing example discussed above (Fig. 2b) and as produced experimentally by Raleigh & Paterson (1965), were found in an examination of many thin sections.

DISCUSSION

The experimental deformation studies of serpentinites carried out by Raleigh & Paterson in 1965 have provided a very useful framework with which to interpret the modes of failure observed in natural serpentinites. The types of failure observed in natural antigorite correspond most closely to the results of the experimental deformation (Fig. 1). The types of failure observed in lizardite and chrysotile serpentines correspond less closely to the experimental results, as no examples of purely ductile failure or of brittle failure due to dehydroxylation were found. This may be due to a failure to collect the appropriate

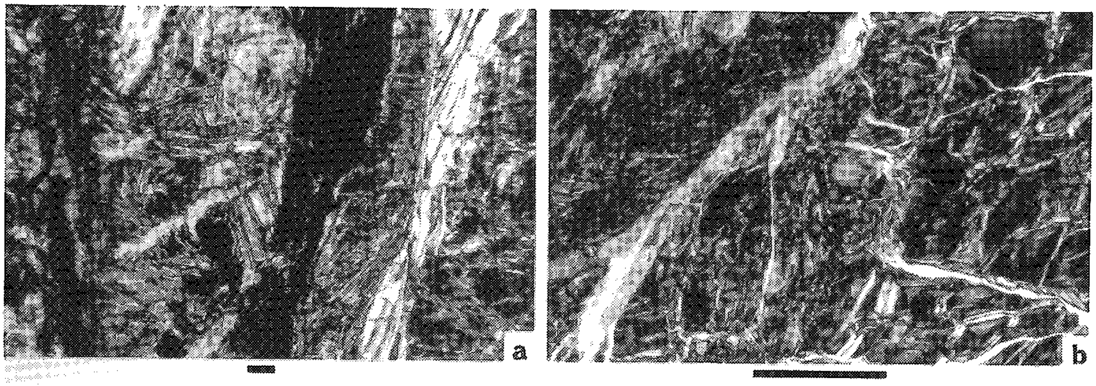

FIG. 3. (a) Transitional failure with brittle failure and minor ductile failure. A zone of brittle fracture lined with nonfibrous chrysotile, with the x axis parallel to the fracture, and magnetite stringers. A lens of host serpentinite between the fractures displays the effect of ductile failure in the form of kink-banded and recrystallized grains (centre) and recrystallization of the host lizardite mesh-texture to foliated chrysotile. Sample 13242-650, Fox River sill, Manitoba. (b) Transitional failure with ductile and minor brittle failure. A brittle fracture (lower left corner up to the middle of the top edge), filled with parallel Povlen-type chrysotile-$2M_{c1}$ fibres, occurs along the edge of a relict nodule of massive serpentinite composed of chrysotile-$2M_{c1}$ + lizardite-$1T$ mesh-texture. The zone within the nodule to the right of the fracture has been partly recrystallized to chrysotile-$2M_{c1}$. The area in the upper left corner is composed of strongly foliated chrysotile-$2M_{c1}$ and chrysotile-$2Or_{c1}$ produced by ductile failure (see also Figs. 11e, f, Wicks & Plant 1979). Sample W70–74, Normandie mine, Quebec. All under crossed nicols. Bar represents 0.2 mm.

specimens but, as a large number of serpentinites have been examined, other reasons may also play a part.

Some of the specimens characterized by both ductile and brittle failure, and classified as transitional, may represent an early stage of ductile deformation at high confining pressure followed by a later stage of brittle failure at low confining pressure. Another possibility is that at the higher pressures and temperatures, at which ductile failure would occur, lizardite and chrysotile are unstable and give way to antigorite that undergoes ductile failure. There is some field evidence for this progression. The chrysotile shear-zone that contains specimen W70–74 described above occurs in the Normandie open pit in the Asbestos Belt of the Eastern Townships, Quebec, but the adjacent ore-deposit to the southwest, the Vimy Ridge open pit, contains strongly foliated antigorite in the shear zones. Detailed field and laboratory studies are required to solve this problem.

Although brittle failure at high temperature due to dehydroxylation of chrysotile or lizardite was not found in the present study, Dungan (1977) has described olivine developing directly from lizardite mesh-textures. However, the olivine described by Dungan (1977) developed through thermal metamorphism in the absence of shearing or deformation. Although it is possible to form olivine directly from lizardite or chrysotile through thermal metamorphism and probably through dynamic metamorphism, its occurrence appears to be rare. The more common path of reaction, particularly in regional metamorphism, is the recrystallization of lizardite and chrysotile to antigorite (Wicks & Whittaker 1977) and then the recrystallization of antigorite to olivine. Further studies of this problem also are required.

Raleigh's & Paterson's discussion of the significance of their results centred on the importance of the dehydroxylation of serpentine as a mechanism of failure, to the exclusion of other mechanisms. Dehydroxylation of serpentine, as pointed out by Raleigh & Paterson (1965), will be important in the lower-crust and upper-mantle environments but, at higher levels in the crust, other factors must be considered.

In applying Raleigh's & Paterson's results to naturally occurring serpentinites, it is important to note that all their samples were dried at 120°C for a minimum of 24 hours. This removed the pore water, so that the mechanical properties of the serpentine itself could be determined without the complicating factor of pore water decreasing the strength of the samples. Whereas this procedure is required if the fundamental dry strength of the rock is to be determined, the results cannot be directly applied to the natural environment without considering the water content of the natural rocks. Antigorite serpentinites are usually formed under dewatering, prograde metamorphic conditions (Evans & Trommsdorff 1970, Evans 1977; types 7 and 8 of Wicks & Whittaker 1977) and thus have a low porosity and, hence, a low capacity for pore water. They will tend to behave as a fairly uniform group, and their strength will be less affected by variations in porosity and content of pore water than retrograde lizardite serpentinites. Lizardite pseudomorphic serpentinites are usually formed under retrograde metamorphic conditions (type 3: Wicks & Whittaker 1977) where water is abundant. They have a variable and often high porosity (Robertson 1964) and, because of the water-rich environment, a high content of pore water. The effect of these conditions on the strength of serpentinite is demonstrated by compression-strength experiments at confining pressures of 0.75, 1.25 and 1.75 kilobars and at temperature of 25°, 100° and 200°C (Handin 1964) on lizardite-1*T* ± brucite mesh-texture serpentinites from the AMSOC drill-core from Mayaguez, Puerto Rico (Wicks & Whittaker 1977, Wicks & Plant 1979). Three samples with 0.6, 1.5 and 5.0% porosity (Robertson 1964) were tested as received (*i.e.*, with the water content at the time of collection in the field) in strength tests at the confining pressures and temperatures listed above. In all cases, the rocks with high porosity have lower strength. Samples tested in open sample-jackets from which the pore water could escape were found to be stronger than the same samples run in closed sample-jackets. Thus the decrease in strength would appear to be due to two factors, the porosity and the reduction in effective confining pressure produced by the trapped pore-water. The presence of the excess water may also help to promote recrystallization in the natural condition. Similar results can be expected for mild prograde chrysotile serpentinites (type 5: Wicks & Whittaker 1977) and deformed chrysotile ± lizardite serpentinites (types 4 and 6).

Raleigh & Paterson (1965) based their discussion of the geological significance of their tests on the dry strength of the serpentinites, and only discussed the effect of water in terms of the water produced at high temperature by the dehydroxylation of serpentine to produce olivine. These conditions would apply most directly to antigorite serpentinites in fairly intense metamorphic conditions. It is perhaps not surprising that the observations on antigorite serpentinites correspond most directly with Raleigh's & Paterson's experimental results. Lizardite and chrysotile serpentinites usually have somewhat different physical properties, occupy a different, more water-rich, environment and should be considered as a distinct group. Based on Handin's (1964) and Robertson's (1964) work, porosity and pore-water content play an important role and must also be considered. Wet lizardite and chrysotile serpentinites probably fail more easily under stress than their dry strengths would suggest.

Regardless of these points, Raleigh's & Paterson's experiments are an important contribution to our understanding of the deformation of serpentinites. The coupling of these types of experiments with field and laboratory studies provides a fruitful area for new research.

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. My thanks are extended to Dr. R.F.J. Scoates of the Manitoba Mineral Resources Division and Dr. R.Y. Lamarche, formerly of the Quebec Department of Natural Resources, for discussions from which part of this work developed. Discussions with Andrew MacDonald, University of Western Ontario, on fracturing in serpentinized ultramafic rocks were most helpful. Asbestos Corporation and Canadian Johns-Manville Co. Ltd., provided access to their mines in Quebec. Dr. R.F.J. Scoates provided thin sections from the Fox River sill, Manitoba, and the samples from the Lanzo massif, Italy were collected with the help of Dr. A. Nicolas. The assistance of all is gratefully acknowleged. The permission to use Figure 1, given by the Journal of Geophysical Research, is greatly appreciated. Mrs. Gloria Nelson is thanked for her careful work on the various versions of the manuscript. A part of the research reported in this paper was supported by research grants from the Geological Survey of Canada, Energy, Mines and Resources Canada, and from the Ontario Geological Survey, Ministry of Natural Resources.

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