SERPENTINIZATION CONSIDERED AS A CONSTANT-VOLUME METASOMATIC PROCESS


ABSTRACT

The three classic arguments for major expansion of peridotite during serpentinization—(1) constant composition except for hydration, (2) internal deformation, and (3) lack of Mg- or Si-metasomatism in country rocks—are considered and found invalid in specific instances, and probably in general. Plots of about 350 analyses of fresh and serpentinized ultramafites show that major changes in the ratio of total bivalent oxides (MgO, FeO and CaO) to SiO₂ and oxidation of iron yield an end product essentially composed of serpentine and magnetite from either dunite or pyroxenite. Structural relations of serpentinized rocks with interlayered or included fresh rocks and minerals, such as serpentinized dunite with pyroxenite, anorthosite, and chromite, prove that no change in volume has accompanied serpentinization, on hand-specimen and outcrop scales. World-wide association of calcium-rich rodingite with serpentinite indicates that Mg-metasomatism of the kind that forms chloritic "blackwall" with talc does not occur in the serpentine mineral stability range; that Mg, Si, and alkalies in excess of the amounts needed to form serpentine are relatively fugitive elements; and that diffusion between ultramafite and country rock must be very minor compared to fluid or gas transfer of Mg and Si. Failure to recognize the chemical changes accompanying serpentinization has led to serious exaggeration of the original pyroxene content of alpine peridotite.

INTRODUCTION

Recently three papers (Hess and Otalora, 1964; Green, 1964; Hostetler et al., 1966) have given new impetus to the theory, also held by some Russians (Shteinberg, 1960), that serpentinization of ultramafic rocks is accomplished by minimal changes in composition except for addition of water, and is accompanied by major increase in volume. Decrease in density from about 3.2 to 2.6 g/cc and addition of 10-14 per cent water during the process present three alternatives: (1) removal of about 30 per cent of the original material in solution; (2) increase in volume by 35 to 40 per cent; (3) some combination of (1) and (2). Most geologists seem to argue either for alternative (1) or (2), with little inclination to compromise on (3). Because ultramafites of the alpine type commonly are more or less serpentinized and are widely believed to represent upper mantle material, possible changes in bulk composition during serpentinization have broader implications than many geologists realize.

The arguments for expansion during serpentinization arise primarily from the sheared nature of most serpentinite and from general absence of obvious related alteration in adjoining country rocks, but also, I believe, from inadequate study of critical rock relations and failure to consider fully available petrographic and chemical information. The aim of this

¹ Publication authorized by the Director, U. S. Geological Survey.
paper is to call attention to data that show serpentinization commonly does involve major changes in bulk composition and that, at least in some situations, constancy of volume can be proved. Volume-for-volume replacement of olivine and pyroxene by serpentine or other minerals requires movement of large quantities of water or other solvents in an open system, but this concept is fundamental in genesis of many kinds of ore deposits. Refusal to apply the same concept to serpentinization, even though it involves unsolved problems, seems inconsistent.

A paper of this kind grows, like Topsy, largely from discussions between the author and his colleagues, who may serve as consultants, provide alternative hypotheses as targets, or do both. R. G. Coleman and P. B. Hostetler very kindly reviewed this paper at an early stage, loaned me a copy of their manuscript to which this is in part a rebuttal, and called my attention to Shteinberg’s paper by providing a translation. C. Ervin Brown, C. L. Christ, G. T. Faust, P. W. Guild, Norman Herz, D. B. Stewart, and David Wones contributed critical advice and friendly counsel on many aspects of the complex problems touched upon in this paper. The San Jose Oil Company, Manila, kindly provided two analyses of combustible gas from seeps in the Zambales Complex, and permitted their publication.

**Normative Composition of Serpentinized Dunite and Serpentine Minerals**

One way to illustrate the chemical changes effected by serpentinization is to compare the known original modal composition of an ultramafite with the normative pyroxene-olivine ratio of its serpentinized equivalent. Dunites are ideal for such comparisons: “As the serpentinization process is one of replacement by pseudomorphism, the relative proportions of replaced olivine and pyroxene may be readily determined, and . . . the rocks may be referred to as serpentinized dunite or . . . peridotite” (Bailey and others, 1964, p. 81) and the essential original mineral in dunite is olivine, which varies mainly in Mg:Fe ratio. In Table 1 the normative pyroxene-olivine ratios for a highly serpentinized dunite and the average of four completely serpentinized dunites are compared with that for the average of 15 analyses of serpentine minerals (Faust and Fahey, 1962, p. 18). In column B of the table the sum of pyroxene and olivine has been recalculated to 100 per cent from the CIPW norm. In column C pyroxene and olivine are recalculated by assigning all MgO, CaO, FeO and SiO₂ in the analyses to these minerals and recalculating

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¹ In this discussion the serpentine-group minerals are referred to collectively as serpentine or serpentines, and rocks composed essentially of serpentine minerals are called serpentinite.
**Table 1. Chemical Analyses, Norms and Normative Pyroxene Content of Serpentinized Dunite, Serpentine Minerals, and Serpentinite**

<table>
<thead>
<tr>
<th></th>
<th>Chemical analyses and molecular equivalents</th>
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<tr>
<td></td>
<td>Chemical analyses and molecular equivalents</td>
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<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>SiO₂</td>
<td>40.12</td>
<td>669</td>
<td>33.10</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.98</td>
<td>10</td>
<td>0.72</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>2.28</td>
<td>2</td>
<td>0.38</td>
</tr>
<tr>
<td>FeO</td>
<td>6.52</td>
<td>4</td>
<td>5.54</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.21</td>
<td>17</td>
<td>2.30</td>
</tr>
<tr>
<td>MgO</td>
<td>35.78</td>
<td>895</td>
<td>40.37</td>
</tr>
<tr>
<td>CaO</td>
<td>0.12</td>
<td>2</td>
<td>0.31</td>
</tr>
<tr>
<td>Na₂O</td>
<td>24</td>
<td>4</td>
<td>0.31</td>
</tr>
<tr>
<td>H₂O⁺</td>
<td>12.17</td>
<td>—</td>
<td>14.46</td>
</tr>
<tr>
<td>Other</td>
<td>2.70</td>
<td>—</td>
<td>2.50</td>
</tr>
<tr>
<td>Total</td>
<td>100.12</td>
<td>—</td>
<td>99.99</td>
</tr>
</tbody>
</table>

**Normative Composition**

|   | A | B | C | D |   | A | B | C | D |   | A | B | C | D |   | A | B | C | D |
| fo | 41.6 | 47.7 | 43.6 | 47.4 | 82.5 | 95.1 | 88.0 | 85.3 | 47.7 | 51.3 | 52.8 | 51.7 | 52.2 | 61.7 | 56.8 | 56.3 |
| na | 52.3 | 53.5 | 37.8 | — | 3.7 | 4.3 | 6.7 | — | 45.5 | 48.7 | 44.6 | 39.4 | 32.4 | 38.3 | 37.4 | 26.2 |
| en | 52.3 | 53.5 | 37.8 | — | 3.7 | 4.3 | 6.7 | — | 45.5 | 48.7 | 44.6 | 39.4 | 32.4 | 38.3 | 37.4 | 26.2 |
| ls | 52.3 | 53.5 | 37.8 | — | 3.7 | 4.3 | 6.7 | — | 45.5 | 48.7 | 44.6 | 39.4 | 32.4 | 38.3 | 37.4 | 26.2 |
| wo | 52.3 | 53.5 | 37.8 | — | 3.7 | 4.3 | 6.7 | — | 45.5 | 48.7 | 44.6 | 39.4 | 32.4 | 38.3 | 37.4 | 26.2 |
| ab | 52.3 | 53.5 | 37.8 | — | 3.7 | 4.3 | 6.7 | — | 45.5 | 48.7 | 44.6 | 39.4 | 32.4 | 38.3 | 37.4 | 26.2 |
| an | 52.3 | 53.5 | 37.8 | — | 3.7 | 4.3 | 6.7 | — | 45.5 | 48.7 | 44.6 | 39.4 | 32.4 | 38.3 | 37.4 | 26.2 |
| mt | 52.3 | 53.5 | 37.8 | — | 3.7 | 4.3 | 6.7 | — | 45.5 | 48.7 | 44.6 | 39.4 | 32.4 | 38.3 | 37.4 | 26.2 |
| hm | 52.3 | 53.5 | 37.8 | — | 3.7 | 4.3 | 6.7 | — | 45.5 | 48.7 | 44.6 | 39.4 | 32.4 | 38.3 | 37.4 | 26.2 |
| c | 52.3 | 53.5 | 37.8 | — | 3.7 | 4.3 | 6.7 | — | 45.5 | 48.7 | 44.6 | 39.4 | 32.4 | 38.3 | 37.4 | 26.2 |

**Total pyroxene**

<p>| | | | | | | | |</p>
<table>
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<tr>
<th></th>
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<th></th>
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<tr>
<td>45.7</td>
<td>52.3</td>
<td>55.2</td>
<td>43.2</td>
<td>4.2</td>
<td>4.9</td>
<td>7.9</td>
<td>0</td>
</tr>
<tr>
<td>45.5</td>
<td>48.7</td>
<td>46.2</td>
<td>41.8</td>
<td>32.4</td>
<td>38.3</td>
<td>40.6</td>
<td>31.1</td>
</tr>
</tbody>
</table>

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1. Average of 10 determinations.
2. Includes 2.00 per cent H₂O⁺, average of 8 determinations.
3. Chromian spinel.
5. Average of 4 serpentinites, Mayaguez, Puerto Rico, Hess and Otalora, 1964, p. 158.
7. Average of 60 serpentinites containing more than 11 per cent H₂O⁺.
the total to 100 per cent. This approximate method minimizes the pyroxene content because no FeO is assigned to magnetite, and it ignores Al₂O₃, which in feldspar-free rocks is mostly in pyroxene, though some may occur in spinel. Calculation of Na₂O and K₂O as feldspar has two objections: no feldspar occurs in the mode, and determination of Na and K in ultramafic rocks seems to be uncertain (Steuber and Murthy, 1965; Hamilton and Mountjoy, 1965). In the CIPW calculation, Na₂O has a strong effect on the pyroxene-olivine ratio because one per cent of it ties up as much SiO₂ in albite as 3.9 per cent MgO in enstatite or 7.8 per cent MgO in forsterite; corresponding figures for FeO in ferrosilite and fayalite are 5.4 and 10.8 per cent, respectively. To avoid confusion, norms calculated by the simplified method will be referred to as proximate in this paper.

In column D the normative minerals have been calculated essentially by Shteinberg’s method (1960). This method calls for doubling the molecular amount of Fe₂O₃ and adding it to the total of bivalent oxides (RO); then an amount of RO equivalent to Al₂O₃ and Cr₂O₃ is subtracted as spinel. The resulting molecular figure is designated R₀ and used as the basis for chemical discussions. This method is followed in essence also by Hess and Otalora (1964, p. 159) and Green (1964, p. 143) to determine the original composition of serpentinites.

Examination of Tables 1 and 2 shows that the normative pyroxene content of serpentinized dunite ranges from almost zero to about 45 per cent even when calculated by Shteinberg’s method, and the normative pyroxene may exceed olivine. The proximate normative pyroxene in 15 serpentines from ultramafites (Faust and Fahey, 1962, p. 18) ranges from 20.8 to 81 per cent, but the average normative pyroxene:pyroxene plus olivine (100 px:px + ol) ratio of 48.7 (Table 1, no. 3B) (50.6 if Al₂O₃ is included) is remarkably close to the 50:50 ratio in theoretical serpentinite (H₄Mg₃Si₂O₈). The very low normative pyroxene in the Mayaguez dunites is attributable partly at least to presence of brucite (Table 2).

**Principal Chemical Changes Accompanying Serpentinitization**

The general trends of chemical variation with increasing serpentinization of ultramafites are shown in Fig. 1. There the silica and sums of the major bivalent constituents in 165 analyses of samples from widely scattered regions have been plotted against content of H₂O+, if determined, or total H₂O. About 125 of the analyses, or three-fourths, are of alpine ultramafites (Joplin, 1963; Green, 1964; Mattson, 1964; Wilson and Ingham, 1959); 35 are from stratiform complexes, mostly the Great Dyke (Worst, 1958); and five are from concentrically zoned complexes (Ruckmick and Noble, 1959, p. 984). Analyses containing more than 0.5
per cent CO₂ and about 6 per cent Al₂O₃, or so much SiO₂ as to suggest presence of much talc or quartz were excluded.

The data plotted in Fig. 1 indicate that serpentinization of the average ultramafite is essentially complete when H₂O⁺ reaches about 11 per cent, a figure that agrees fairly well with a theoretical mixture of 90–95 per cent serpentine and 5–10 per cent magnetite and chromite. Oxidation of Fe²⁺ in olivine and pyroxene somewhat in excess of the amount needed to form magnetite, shown by hematite in the norm, appears to be a consistent chemical change (Table 1, col. 4A). The great variability of the FeO:Fe₂O₃ ratio in serpentine minerals (Faust and Fahey, 1962, p. 18) and general absence of modal hematite imply that the excess Fe₂O₃ over that assignable to normative magnetite is in the serpentine structure, but some may also be in magnesioferrite in solid solution with magnetite. Native FeNi alloys such as awaruite or josephinite seem to be quantitatively minor, and apparently formed during the later stages of serpentinization under exceptional reducing conditions (Krishnarao, 1964).

The MgO-FeO-CaO-SiO₂ part of the diagram may be divided into

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### Table 2. Comparison of Original Mineral Composition, Degree of Serpentinization, and Proximate Normative Pyroxene in Peridotite Samples from the AMSOC Core Hole near Mayaguez, Puerto Rico

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Rock Type</th>
<th>Per Cent serpentinized</th>
<th>Per Cent H₂O⁺</th>
<th>Original</th>
<th>Proximate normative²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>en</td>
<td>di</td>
</tr>
<tr>
<td>A2</td>
<td>Harzburgite</td>
<td>90-95</td>
<td>12.41</td>
<td>5</td>
<td>35.5</td>
</tr>
<tr>
<td>A3</td>
<td>Harzburgite</td>
<td>80</td>
<td>10.97</td>
<td>10</td>
<td>37.4</td>
</tr>
<tr>
<td>A6</td>
<td>Harzburgite</td>
<td>97</td>
<td>12.70</td>
<td>5</td>
<td>35.4</td>
</tr>
<tr>
<td>A7</td>
<td>Dunite</td>
<td>100</td>
<td>14.02</td>
<td>3</td>
<td>8.7 (1.9)</td>
</tr>
<tr>
<td>A8</td>
<td>Dunite</td>
<td>99-100</td>
<td>15.26</td>
<td>3</td>
<td>0 (2.7)</td>
</tr>
<tr>
<td>A10</td>
<td>Harzburgite</td>
<td>100</td>
<td>12.41</td>
<td>5</td>
<td>32.4</td>
</tr>
<tr>
<td>A11</td>
<td>Harzburgite</td>
<td>80</td>
<td>10.00</td>
<td>5-10</td>
<td>37.4</td>
</tr>
<tr>
<td>A13</td>
<td>Dunite</td>
<td>100</td>
<td>14.54</td>
<td>2</td>
<td>22.2</td>
</tr>
<tr>
<td>A14</td>
<td>Dunite</td>
<td>99-100</td>
<td>14.10</td>
<td>2</td>
<td>3.9 (3.3)</td>
</tr>
<tr>
<td>A18</td>
<td>Harzburgite</td>
<td>94</td>
<td>12.15</td>
<td>5</td>
<td>36.5</td>
</tr>
<tr>
<td>A19</td>
<td>Harzburgite</td>
<td>75</td>
<td>11.13</td>
<td>25-30</td>
<td>33.3</td>
</tr>
</tbody>
</table>

1 en, di: relict grains of and serpentine pseudomorphs after enstatite and diopside, respectively (Mattson, 1964, p. 17).
2 Calculated by method described in text.
3 Rock contains, or may contain, brucite.
4 Weight percent of brucite in rock (Hess and Otalora, 1964, p. 154).
Fig. 1. Variation in composition of 165 ultramafics with content of H₂O+. Above, total divalent oxides (MgO, FeO, CaO), and SiO₂; below, FeO, Fe₂O₃, and approximate normative magnetite. Large symbols indicate averages of 15 serpentine minerals (Faust and Faege, 1982) and 60 serpentinites containing more than 11 per cent H₂O+.
Fig. 2. Diagram showing molecular ratios of $\text{RO}':\text{SiO}_2$ and $\text{H}_2\text{O}:\text{SiO}_2$ in ultramafites of the Ural Mountains, after Shteinberg (1960). Trend lines for non-platiniferous dunites (D-D') and peridotites and serpentinites (P-P') added, with composition field of 15 serpentine minerals (Faust and Fahey, 1962) calculated by Shteinberg's method. Averages of 60 serpentinites shown by large crosses; upper cross calculated by Shteinberg method; lower cross, calculated with normative magnetite.
three segments according to $H_2O^+$ content: (1) 0–1 per cent, (2) 1–10 per cent and (3) 10–16 per cent. The wide variation of the oxides in the first segment reflects samples of fresh rocks that range from dunite to pyroxenite. The segment from 1–10 per cent $H_2O^+$ represents mixtures of primary and secondary minerals, in which the decrease of total MgO, FeO, and CaO is comparable to that of SiO$_2$ as the composition of serpentine is approached. The essentially horizontal trend of values between 10 and 14 per cent $H_2O$ results principally from mixtures of secondary minerals: magnetite, serpentines of various compositions, and small amounts of brucite, talc, amphibole and carbonate. The presence of brucite (69 per cent MgO, 31 per cent $H_2O$) accounts for the high content of water and total bivalent elements and the low SiO$_2$ in at least three and probably in seven of the eight samples that contain more than 14 per cent $H_2O$. For comparison, three lines have been added to show the effect of brucite on total composition. The sloping line indicates increase in MgO and $H_2O$ with increase in brucite; a reciprocal decrease in SiO$_2$ seems obvious. The lower horizontal line indicates the average bivalent oxide content of 15 serpentines (Faust and Fahey, 1962, p. 18); only one analysis deviates from this average by more than 2 percentage points. The upper line indicates the effect of adding 10 per cent brucite (6.9 per cent MgO) to the serpentine average. In most rock analyses much of the excess of the bivalent oxides over the serpentine average consists of FeO, probably combined in modal magnetite; only part of this excess is attributable to brucite. For example, subtraction of FeO in normative magnetite from the analyses of the brucite-bearing Mayaguez dunites (Table 2) gives calculated percentages (in parentheses) for brucite that compare with the determined values as follows: A-7, 1.9(1.2); A-8, 2.7(2.0); A-14, 3.3(2.4). Even though it may be coincidental, such close agreement indicates that very few of the serpentinites plotted contain as much as 5 per cent brucite. CaO and Al$_2$O$_3$ seem to decrease irregularly with increasing water content, but not in constant ratio: the average CaO content drops from 1.34 per cent (22 analyses) in the range 8–10.7 per cent $H_2O$ to 0.56 (56 analyses) with higher $H_2O$ content; Al$_2$O$_3$ averages 2.71 per cent (25 analyses) between 8 and 10.7 per cent $H_2O$, and drops to 1.70 per cent (33 analyses) above 12 per cent $H_2O$. Although CaO and Al$_2$O$_3$ may be leached during serpentinization or fixed in hydrogrossularite as Hess and Otalora (1964, p. 155) suggest, comparison of modes and analyses of the Mayaguez cores indicates that occurrence of relict clinopyroxene, which is notably resistant to serpentinization, is a more important factor in the distribution of these two oxides in serpentinite.

Two conclusions may be drawn from the data in the two tables and
Fig. 1: (1) completely serpentinized ultramafites are, as they theoretically should be, mixtures of serpentine and magnetite, with other minerals in accessory amounts; (2) the serpentinization process is not uniform, but forms serpentines that differ widely in composition and normative px:ol ratio. The chemical differences between the serpentinized dunites from Mayaguez and Lizard must be due largely to the serpentinizing processes, because the composition of the original olivine in them was essentially the same: Fo$_{89-91.2}$ in Mayaguez (Hess and Otalora, p.153) and Fo$_{89.7-91.0}$ in Lizard (Green, 1964, p. 148).

Major differences in chemical and physical conditions of alteration are implied by variations in stability of chromite in the verde antique and “bucksin-weathering” varieties of serpentinite. In the verde antique variety, well described by Chidester (1962) lamellar or platy serpentine and antigorite form a felted fabric which makes the rock tough. Concentration of the magnetite in grains of appreciable size commonly leaves the native green color of the serpentine unobscured when the rock is cut for ornamental use. In this rock chromite characteristically is attacked hydrothermally, and may be extensively replaced by chromian chlorite (Miller 1953; Thayer, 1956). The “bucksin-weathering” facies is named from its characteristic yellow-brown or brownish-red color on weathered surfaces and is very brittle. In this rock the serpentine forms a very characteristic mesh of minute cross-fiber veins along grain boundaries and fractures in olivine; much of the magnetite is extremely fine and dusty, imparts a sooty gray or black color on fresh fractures, and weathers readily to brown limonite. The magnetite in this kind of serpentinite commonly accretes on chromite to form simple sharply bounded rims (Du Rietz, 1956, fig. 25, 26; Thayer, 1956). In general, I believe that verde antique is associated with talc in foliated green-schist or amphibolite-facies country rocks and near younger dioritic or more silicic plutonic intrusions. The “bucksin-weathering” facies is preeminent in low-grade unfoliated country rock environments such as Cuba, Oregon, California, and Cyprus. Intermixing of both kinds of serpentinite in some places undoubtedly reflects a complex history of fluctuating conditions, as in the State Line district of Maryland and Pennsylvania. Little systematic work seems to have been done on this very interesting and promising problem.

Belief in essential immobility of Mg, Fe, Ca and SiO$_2$ during serpentinization seems to be founded on the common presence of brucite in partly or completely serpentinized dunite and on the assumption that recalculation of secondary magnetite back to FeO is a valid procedure. Shsteinberg (1960) has plotted more than 300 Russian analyses of ultra-
mafites, recalculated by his method, to show the mutual relations of R₆O:SiO₂:H₂O. His diagram (Fig. 2) shows that in approximately 150 dunites the average R₆O:SiO₂ mole ratio falls between 1.8:1 and 2.2:1, and the extremes range between about 1.6:1 and 2.25:1. A ratio of 1.6:1 is equal to about one-third pyroxene in the norm, whereas 2.25:1 indicates a deficiency of SiO₂ equivalent to about 9 per cent of forsterite. Calculation of Mayaguez analysis A8 (Table 2) by this method yields an R₆O:SiO₂ ratio of 2.2, or SiO₂ deficiency equivalent to 7.2 per cent forsterite or 6 per cent brucite. Ratios of R₆O:SiO₂ exceeding 2:1, that of R₆O:SiO₂ in olivine, obviously cannot be interpreted rationally in terms of original olivine and pyroxene.

Shteinberg, I believe, oversimplifies interpretation of his data (Fig. 2), when he draws a rather sharp distinction between dunites in the range 1.9–2.1 R₆O:SiO₂ and peridotites and serpentinites between 1.4 and 1.8:1, even though he recognizes some transitional rocks. To compare my diagram with Shteinberg's I have added to his the composition field of the 15 serpentines from Faust and Fahey, and the average of the 60 serpentinites from Table 2, all recalculated by his method. The peridotites, though scattered, clearly trend from about 1.75 R₆O:SiO₂ when fresh to about 1.55:1 when serpentinized, and cluster with other serpentinites around the serpentine composition point (1.5 R₆O:SiO₂; 1H₂O:1SiO₂). Of the 32 nonplatiniferous (alpine type) dunites, 28 follow a trend approximately parallel to the peridotites, from about 2.05 R₆O:SiO₂ and 0.4H₂O:SiO₂ to 1.75 R₆O:SiO₂ and 1.7H₂O:SiO₂. Similar relationships between dunite and pyroxene-bearing peridotites are suggested in my diagram by the upper staggered or double row of symbols for total bivalent oxides below about 8 per cent H₂O. Except for the platiniferous dunites, it seems to me that Shteinberg's and my diagrams, based on two different groups of analyses and different methods of calculation, agree surprisingly well. The platiniferous dunites, which are described as small bodies within coarse gabbro, appear to maintain essentially constant R₆O:SiO₂ ratios, and probably reflect a consistently different chemical environment related to their different occurrence. Support for this hypothesis is provided by two analyses of serpentinized dunite in Lizard (Green, 1964) which can be distinguished chemically from associated pyroxene-bearing peridotites only by 2–3 per cent more H₂O⁺, 1–3 per cent less Al₂O₃, and 1–2.5 per cent less CaO. These differences, of course, reflect variations in degree of serpentinization as well as original composition, and would be expected to decrease with further serpentinization of the mass as a whole.

Because oxidation of about two-thirds of the iron in silicates to form magnetite is a fundamental aspect of serpentinization, recalculation of all Fe₂O₃ as FeO is misleading. In the first place, it completely disregards the
actual mineralogic equilibria of the rocks and exaggerates the RÖ combined in the silicates. In fresh rocks the RÖ:SiO₂ ratio, when corrected for spinels, theoretically cannot exceed the 2:1 ratio in olivine. Ratios as high as 2.25:1 therefore indicate that the RÖ:SiO₂ ratio has been increased or that the method of calculation is invalid, or perhaps both. Correction for magnetite in the nonplatiniferous dunites in Shteinberg’s diagram would increase the slope of the RÖ:SiO₂ trend line (D-D’) by at least half, from about 2:1 in fresh rocks to 1.55:1 in the serpentinite equivalent, which is still higher than the 1.42:1 ratio in Lizard dunite. Similar adjustment of the peridotite and serpentinite analyses would bring many more into the composition field of the 15 serpentines. Application of the Shteinberg formula to the 60 serpentinite average (Table 1, 4D) has the same effect on total bivalent oxides as adding 7.8 per cent brucite. Shteinberg’s method of calculation, however, must be used to determine possible changes in the ratio of Fe and Mg during serpentinization. His data indicate little or no change in Fe:Mg ratio despite the shifts in RÖ:SiO₂, and therefore imply significant removal of Fe.

EVIDENCE OF VOLUME CHANGE DURING SERPENTINIZATION

Possible volume changes accompanying serpentinization must be determined by the physical evidence in the rocks themselves, regardless of theoretical arguments. I agree with Turner and Verhoogen’s conclusion (1960, p. 318) that “microscopic fabric and field relations of undeformed serpentinites show clearly . . . that serpentinization is commonly accompanied by little or no increase in volume.” Hostetler et al. (1966) argue that volume increases of 35 to 40 per cent are probably common even in rocks that originally contained essential pyroxene; Hess in 1955 (p. 403) suggested a 25 per cent volume increase in dunite, although earlier (1933) he had cited evidence of constant volume as an argument for hydrous ultramafic magma and autometamorphic origin of serpentine.

Volume increases of 35 to 40 per cent are equivalent to linear expansion of 11 to 12 per cent, and should be readily detectable in rocks under suitable conditions. The most obvious evidence for expansion consists of radial fractures in fresh feldspar surrounding serpentinized olivines in troctolite (Smith, 1958, pl. 5); in Cuba I have seen troctolites that weather to resemble cup corals because of this phenomenon. The freshness of the feldspar, however, suggests limited movement of solutions, and very slight expansion could cause the fractures. The highly sheared nature of most serpentinite is cited also, but this is at best questionable evidence in view of the notoriously unstable tectonic environments of alpine ultramafites; even large masses of associated gabbros normally are highly faulted and sheared. The real answer to the question must be found in
structural relations between serpentinized ultramafites and unaltered but related contemporaneous rock units, such as interlayered dunite and chromite or fresh pyroxenite, or disruption of features in large exposures. Most olivine-rich peridotites do not provide this kind of unequivocal evidence. Complete serpentinization of olivine lenses and layers in massive chromite and of olivine-rich peridotite interbanded with centimeter-thick layers of fresh anorthosite without any visible disruption of chromite or anorthosite, as specimens in Geological Survey collections show, is conclusive evidence of volume-for-volume replacement. Fragile chromite structures such as the nodules and crystals from the Guillermmina mine in Cuba (Thayer, 1942, pl. 4; 1964, Fig. 3) would be completely disrupted by any significant expansion; on the contrary, they characteristically are found intact even though the olivine matrix is thoroughly serpentinized. Original features of peridotites, such as schlieren banding in chromite deposits, commonly are so well preserved and intact over distances of several feet in large outcrops (Smith, 1958, pl. 6, 7) that one cannot tell anything about the degree of serpentinization from inspection of the weathered surface; such undisturbed preservation after even 10 per cent of volume increase seems out of the question.

In thin-section studies, many features like granulation in olivine and kink-banding in enstatite, which actually are relict from earlier magmatic stages and are quite distinctive, have been wrongly attributed to deformation resulting from expansion during serpentinization. Hostetler et al. (1966) with regard to other microscopic criteria state:

"Preservation of olivine grain boundaries in mesh-structure serpentines and the presence of bastite-type pseudomorphs after enstatite is often cited as evidence for 'serpentine' replacement at constant volume. This evidence is ambiguous. Interconnecting 'serpentine' veins and the innumerable fine veinlets of 'serpentine' cutting through parent olivine grains which show optical continuity are, in the manner of septarian concretions, plausible evidence for expansion. Buse and Watson ... noted a volume increase due to a 'spreading apart' of olivine grains along fractures during serpentinization."

The characterization of the evidence as "ambiguous," I would say, is conservative; other relations indicate that it may be delusive. The partly serpentinized matrix of chromite ore such as that from the Guillermmina mine (Thayer, 1964, Fig. 3) shows all the features mentioned in mesh-structure serpentinites, but the continuity of structure in the chromite shows that there can have been no volume change whatever. A photomicrograph by Diller (1921, Pl. 1B) of chromite from Shasta County, California, shows an intact anastamosing network of chromite grains in partly serpentinized dunite that has an apparent "expansion" pattern. Such situations show that the accepted criteria for determining spatial relationships between cross-fiber chrysotile and olivine may be completely misleading.
Diapiric movement during or after serpentinization has been proposed to account for the lack of Mg-metasomatism or silicification around some serpentinite masses (Hostetler et al., in press), and has been appealed to as the solution of the volume problem. As Chidester (1962, p. 89) summarized the situation:

"The general lack of evidence for either increase in volume or expulsion of Mg and Si into the surrounding schist supports the idea that serpentinization did not occur while the ultramafic rocks were in their present positions."

It can be demonstrated, however, that no significant movement has accompanied the principal serpentinization of some large ultramafic masses. In the Canyon Mountain Complex (Thayer, 1963) the peridotite, as distinct from highly sheared marginal serpentinite, is probably 75 per cent serpentinized, and the gabbro is extensively altered to saussurite and rodingite. Post-gabbro dikes that cut the serpentinite are also extensively rodingitized. Perfect pseudomorphic preservation of igneous-intrusion features, absence of faults between gabbro and country rock, and interfingering of gabbro and peridotite eliminate the possibility of significant tectonic transport during or after serpentinization. As described by C. H. Smith (1958), relationships between country rock, gabbro, and ultramafites in the Bay of Islands Complex are essentially the same as those in the Canyon Mountain Complex; despite 60–99 per cent serpentinization of dunite (p. 29), layering in dunite and peridotite (pl. 6) and in interbanded peridotite and gabbro (pl. 7) is preserved perfectly. Clear distinction between border serpentinization during emplacement and later alteration probably is impossible in most masses, but I do not believe that we can seriously debate the evidence for large-scale constant-volume replacement of peridotite by serpentine in situ.

**REACTIONS DURING SERPENTINIZATION AND MOVEMENT OF MATERIALS**

The main argument for volume increase during serpentinization seems to be the need, otherwise, for removal in solution of MgO and SiO₂ equal to 31 per cent of original dunite, according to the equation presented by Turner and Verhoogen (1960, p. 319):

\[5\text{Mg}_2\text{SiO}_4 + 4\text{H}_2\text{O} \rightarrow 2\text{H}_2\text{Mg}_2\text{Si}_2\text{O}_6 + 4\text{MgO}_{aq} + \text{SiO}_2 \]

(1)

Olivine Added Serpentine (Removed)

\[(704 \text{ g}; 219 \text{ cc}) (72 \text{ g}) (552 \text{ g}; 220 \text{ cc}) (160 \text{ g}) (60 \text{ g})\]

The equivalent constant-volume equation for enstatite is

\[7\text{Mg}_2\text{SiO}_4 + 4\text{H}_2\text{O} \rightarrow 2\text{H}_2\text{Mg}_2\text{Si}_2\text{O}_6 + \text{MgO}_{aq} + 3\text{SiO}_2 \]

(2)

\[(700 \text{ g}; 219 \text{ cc}) (72 \text{ g}) (552 \text{ g}; 220 \text{ cc}) + (40 \text{ g}) (180 \text{ g})\]

Addition of 10 per cent fayalite as in natural olivine changes equation (1) at atmospheric pressure to
The comparable equation for natural enstatite is

\[ 7(\text{Mg}, \text{Fe})_2 \text{SiO}_4 + 4\text{H}_2\text{O} \]

\[ \rightarrow 1.9(\text{H}_2\text{Mg}_2\text{Si}_2\text{O}_6)_c + 0.23 \text{Fe}_3\text{O}_4 + 0.6 \text{MgO}_aq + 3.2 \text{SiO}_2_aq + 0.2 \text{H}_2 \]

\[(524 \text{ g}; 209 \text{ cc}) \quad (54 \text{ g}; 10 \text{ cc}) \quad (24 \text{ g}) \quad (192 \text{ g}) \quad (4,480 \text{ cc}) \quad (4) \]

The four equations show that the weight of material that must be removed in solution during constant-volume serpentinization is about 30 per cent in both natural olivine and enstatite, and that, although presence of Fe reduces the amount of MgO to be removed in solution, it increases the SiO₂ reciprocally. From the solubility of brucite and SiO₂ in pure water some believe that unreasonable volumes of water would be required for their solution and transportation. However, as Bowen and Tuttle said (1949, p. 456), "The aqueous medium coming into the mass in nature would not be pure water."

Because ultramafites commonly are more highly serpentinized in low-grade geosynclinal rocks than in high-grade metamorphic terrains, connate water is now widely regarded as a probable major source of serpentinizing solutions. Of 24 oil-field waters and deep-well brines rich in CaCl₂ and NaCl listed by White and others (1963, p. F30–F33), 15 contained more than 500 ppm Mg, averaged 2,340 ppm, and ranged as high as 9,960 ppm of Mg. In the same samples Na averaged 46,420 ppm and Cl 83,000 ppm. None of the Mg-rich brines analysed for SiO₂ contained as much as 50 ppm of it. Connate waters of such compositions moving into a hot peridotite mass which is being serpentinized could be very effective carriers of Mg and Si. The contact zone would be marked by two opposite gradients: (1) rising temperature toward the intrusion: (2) decreasing water vapor or fluid pressure due to progressive combination of water in serpentine. The rising temperature in the contact zone would lead to formation of albite by reaction of NaCl in water moving toward the intrusion with kaolinite or other clay minerals at temperatures down to 300° C. or less (Hemley and others, 1961, p. D339). With a molar ratio of NaCl: HCl in the range of 1000:1 at 300° and 100:1 at about 450° C., solutions containing 50,000 ppm NaCl should be very active in serpentinizing peridotite. Magnesium would be highly soluble as MgCl₂. The mobility of silica in such an open system, after being freed in ionic form by decomposition of olivine or pyroxene, can be determined only by experiment, but Na₂O·nSiO₂ might offer some interesting possibilities.
The hypothesis outlined is supported by presence of chlorine in serpentinites in Canada, and an unusual spring in California may be related to the problem. Earley (1958, p. 151) found that Precambrian serpentinitized dunite in three drill holes in Ontario, at the corners of a triangle approximately 50 miles long and 30 miles across, averaged between 0.16 and 0.30 per cent Cl over intercepts of 150 to 650 feet; one sample from a depth of 1150 feet contained 0.7 per cent Cl. Associated unserpentinized peridotite and pyroxenite contained about 0.04 per cent Cl. Part of the chlorine is soluble in water, and most of it is readily soluble in cold H₂SO₄; the way in which the chlorine is held is not known. Kuroda and Sandell (1953) also reported 0.24 per cent Cl in serpentinized dunite from Newfoundland and 0.13 per cent in a serpentinized harzburgite. Earley suggests (1958, p. 148) "that the readily soluble chlorine was introduced into the rock during serpentinization by chloride-rich solutions from adjacent sediments and tuffs."

The relationship to this problem of a cold spring of unusually high pH and SiO₂ content is problematical but of interest. Water from Aqua de Ney spring, which appears to issue from highly sheared serpentinite along a fault zone in metavolcanic rocks near Mount Shasta, California (Feth et al., 1961, p. 76) contains 3400–3970 ppm SiO₂, 8710–10,900 ppm Na, 4790–5560 ppm CO₂, 5950–7180 ppm Cl, and much smaller amounts of nitrogen in ammonia, SO₃, SO₄, Br, I, and B. The pH of the water is 11.6. The solutions are attributed to alteration of a mixture of entrapped sea water, from a thick sedimentary sequence believed to underlie the volcanic rocks, and a calcium-magnesium-sulfate-rich ground water.

The discussion of connate waters is not intended to imply that water or solutions of other origin are not equally important as agents of serpentinization. Serpentinization of large volumes of peridotite in high-grade metamorphic terrains and in large, apparently deep-seated plutons must require solutions from magmatic or deep crustal sources. A large pipelike serpentinized zone in the heart of the Troodos Complex, Cyprus (Wilson and Ingham, 1959), which intrudes sediment-free meta-volcanic rocks, is an example of this problem. The partial serpentinization of dunitic ultramafites in the southern Appalachians (Miller, 1953) probably occurred during the later stages of a metamorphic episode which in its earlier stages formed amphibole, corundum, talc and related minerals.

The source of oxygen for oxidation of the iron in silicates to form magnetite, or even in excess of the amount needed for that reaction, is an interesting aspect of serpentinization. Equations (3) and (4) imply generation of substantial amounts of hydrogen gas by decomposition of water and, accordingly, the presence of hydrogen in serpentinite would be evidence against serpentinization by meteoric water containing
dissolved oxygen. Serpentine from Leupoldsgrün was found by Hahn-Weinheimer and Rost (1961) to contain 2–20 cc of hydrogen per 5 g of rock; they related the hydrogen to the formation of awaruite. Serpentinization now in progress is believed to be the source of hydrogen and methane gas that seeps from peridotite of the Zambales Complex in the Philippines; Stoll (1953, p. 167) described seeps about 5 miles east of the Coto mine, known by the local people as “los fuegos eternos,” as follows:

“In an area of a few square rods there are about 18 separate orifices with yellow-orange flames ... extending from 6 to 12 inches above. The flames are fed by a combustible natural gas escaping ... with a slight whispering, rustling noise. There is no smoke. The orifices, where visible, coincide with tiny, tight cracks in the rock, which is pyroxene-peridotite. Where the flames are partly enclosed ... the rocks are orange-hot ... The origin of the natural gas is obscure, as the country rocks for miles around are peridotites and gabbros insofar as is known.”

Analyses by the San Jose Oil Company, Manila (personal communication, 1965) of two samples of gas from similar seeps in peridotite of the same complex, but south of Mt. Lanat several miles to the west, gave the following results, in mole per cent:

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Hydrogen</th>
<th>Oxygen</th>
<th>Nitrogen (by difference)</th>
<th>Methane</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>41.4</td>
<td>0.5</td>
<td>5.5</td>
<td>52.6</td>
</tr>
<tr>
<td>1B</td>
<td>45.6</td>
<td>0.2</td>
<td>0.4</td>
<td>53.8</td>
</tr>
</tbody>
</table>

Reaction of juvenile CO₂ with hydrogen would produce methane, and could form graphite like that Krishnarao (1964) found associated with most natural NiFe alloys, and Cady and others (1963, p. B39, B42) describe in Vermont. According to equations (3) and (4) the hydrogen released, at 400°C and 1,000 atm., would equal about 10 and 5 per cent, respectively, of the volumes of olivine and pyroxene that were serpentinized.

**Irreversibility of Serpentinization as a Process**

Complete reversibility is a corollary of the hypothesis that, except for hydration, serpentinization is an isochemical process. Field evidence, however, shows that high-temperature metamorphism of serpentine does not reproduce the primary mineralogy or textures of ultramafic rocks. Regenerated olivine as described by Durrell (1940), Gabrielse (1963) and Leech (1953) consistently contains much powdery magnetite, extinguishes uniformly, may have a granoblastic to porphyritic texture, and forms stringers and chains in serpentine. Talc, tremolite, hornblende, clinochlore and similar metamorphic minerals are associated with the
olivine, which in some instances appears to be nearly pure forsterite (Gabrielse, 1963). Gabrielse (p. 82) summarizes the mineralogic relations as follows:

"The unique texture and composition of the olivine, the unusual texture of the serpentine, and the environment in which these rocks are found, point to a metamorphic origin. . . . The widespread presence of dust magnetite in the regenerated olivine indicates that ferrous iron, released upon serpentinization of the original rock and subsequently oxidized, was not reincorporated into regenerated olivine. The extremely low iron content of the metamorphic olivine supports this belief.

". . . the lack of talc in the regenerated dunites may be the result of reactions having taken place in an open system."

Rodingite, a Paradox of Serpentinization

The association of rodingite, a suite of rocks composed essentially of hydrous calcium and calcium-aluminum silicates, with serpentinite is a paradox whose implications have not been fully recognized. The relationships of these two radically different suites of rocks, I believe, show that Ca-metasomatism of wall rocks on a very small scale, not Mg-metasomatism of the type that forms “blackwall” during steatization (Chidester, 1962; Cady et al., 1963), accompanies serpentinization. In other words, it seems likely that those who postulate extensive Mg-metasomatism and silicification in country rocks as a corollary of serpentinization at constant volume look for something that does not exist. Phillips and Hess (1936), like Chidester, described “blackwall” as associated with and related to steatite; extrapolation of the reaction to the serpentinization process is pure inference. Perhaps we should consider two distinct but probably overlapping metamorphic or hydrothermal mineral facies: a low-temperature serpentine-rodingite facies and an intermediate-temperature, steatite-carbonate-blackwall facies. Definitions of these two facies are beyond the scope of this paper. Contact metamorphism of the kind described near Dillon, Montana by Heinrich (1963), in which serpentine forms during the last stages of a process that involves falling temperatures, would be in the intermediate-temperature facies of this classification.

Since its first identification as a distinct kind of rock by Marshall in New Zealand (Bell and others, 1911, p. 31), rodingite and similar rocks called by other names have been described in serpentinite, and only in serpentinite, practically all over the world. Rodingite consists essentially of the Ca-rich minerals hydrogarnet, prehnite, idocrase, zoisite and clinzoisite, diopside, edenite and xonotlite, with chlorite as the principal magnesium mineral. Rodingite occurs mainly as selvages on dikes and irregular inclusions and as border zones of country rocks against serpen-
tinite. Because of gradational relations, all students now agree that rodingite is an alteration product of many kinds of rocks ranging from keratophyre (Coleman, 1961) to dolerite (Bilgrami and Howie, 1960; Suzuki, 1953) and quartz-sericite-albite-chlorite schist (Cady et al., 1963, p. B41). The width of altered zones ranges from an inch or two to several feet, but most commonly is between 6 inches and 3 feet.

The essential workings of the serpentinization process in forming rodingite, and the differences and similarities between it and the black-wall-forming process, are suggested by two diagrams from Cady, Albee

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**Fig. 3.** Diagrammatic sections illustrating the relations of rodingite (lime-silicate rock) to serpentine (A), and “blackwall” (chlorite rock) to steatite (B) in Vermont. After Cady, Albee, and Chidester, 1963.
and Chidester (1963, Fig. 2). (See Fig. 3.) They describe lime-silicate rock (rodingite) as gradational with the country rock schist, and antigorite-chlorite rock in turn replacing the lime-silicate rock, with a generally sharp irregular contact. In the field the contact between dark antigorite-chlorite rock and light-colored calc-silicate rock is much more prominent than the other two. We get the impression from Fig. 3A, accordingly, of two well-defined fronts, the outer one rich in Ca, the inner one rich in Mg, moving out from the serpentinite in the absence of talc. In the presence of talc, only a narrow zone of chlorite-rich “blackwall” develops along the country rock. Mutual incompatibility between rodingite and “blackwall” is implied in their discussion of genetic relations (Cady et al. p. B46) and the following statements (p. B36):

“The chlorite rock (‘blackwall’) appears to be restricted principally to places in which the calc-silicate rock is absent. It is invariably succeeded inwardly by steatite a few inches to a few feet thick.”

Coleman (1963) has characterized development of rocks very similar to rodingite at contacts with serpentinite as due to “a relative enrichment of sodium accompanied by a Ca-Mg invasion from the serpentinites.” Coleman’s (1961) discussions of zoning in pods of jadeite and jadeite-albite schists in serpentinite in California indicate relations like those described by Cady, Albee and Chidester, but with the addition of local concentrations of Na and Al in jadeite ahead of the calc-silicate rocks. A jadeite zone of this kind would be analogous to the discontinuous albite-porphyroblast zones formed in schist outside of the “blackwall” zone around talc deposits in Vermont (Chidester, 1962). Coleman’s analyses (1961, p. 231) of specimens taken 3 or 4 feet apart in an inclusion about 10 feet across show, from jadeite rock at the center to calc-silicate rock near the margin, the following changes (in weight per cent): decrease in SiO₂ from 57.1 to 37.2, in Al₂O₃ from 20.9 to 13.8, and in Na₂O and K₂O from 13.4 to 3.3; increase in MgO from 1.4 to 2.6, in CaO from 2.6 to 25.9, and in H₂O⁺ from 0.35 to 6.3. The contrast between doubling the small amount of MgO and a ten-fold increase in CaO, though extreme, is characteristic (Bilgrami and Howie, 1960; Grange, 1927, p. 165) of rodingite-type alteration. To form rodingite from normal Franciscan graywacke or metagraywacke (Coleman, 1961, Table 8) the only essential changes are addition of 23–25 per cent CaO and 3 to 4 per cent H₂O⁺, and a concomitant decrease of 30–35 per cent in SiO₂ but only minor or insignificant changes in other oxides. In general, analyses (Baker, 1960, p. 29; Bilgrami and Howie, 1960, p. 795) indicate that rodingitization of dolerite and gabbro involves replacement of feldspar by calcium minerals, with removal of
alkalis and silica to balance; chloritization of mafic minerals may or may not be accompanied by some enrichment in magnesium.

The restriction of rodingite exclusively to serpentinites or closely related gabbroic rocks and its uniform mineralogy I regard as prima facie evidence of a close genetic kinship to serpentine minerals. Hydrogarnet pseudomorphs after bytownite in olivine gabbro apparently were formed by a single process together with serpentine after olivine and bastite after enstatite. Rodingitization of basaltic and dioritic dikes which have chilled margins against serpentinite and development of hornblende and pyroxenic metamorphic rocks around ultramafic plutons (Smith and MacGregor, 1960; MacKenzie, 1960), show that rodingite cannot be magmatic or contact-metamorphic, as some geologists have suggested (Cady et al., 1963; Turner and Verhoogen, 1960). The phenomenal enrichment of calcium in rodingite during serpentinization can have only one meaning: magnesium in excess of that needed to form serpentine, the alkalis, and excess SiO₂ are fugitive compared to calcium combined in hydrous silicates under identical conditions. Also, the narrowness of the zones in albitite-jadeite-rodingite inclusions and their sharp boundaries led Shido (1958, p. 599) to conclude that “the diffusion of silica appears to have been very limited within the concentric structure.” Finally, the compositional contrasts and very limited thicknesses of rodingite indicate that diffusion and activity gradients of Mg and Si between ultramafites and other rocks are unimportant in comparison with fluid or gaseous transport during serpentinization.

**Original versus Normative Pyroxene Content of Serpentined Alpine-type Peridotites**

Determination of the average primary composition of alpine peridotites is of major geologic interest because of the general belief that they constitute the upper part of the mantle and may be a source of basaltic magma. The ratio of pyroxene to olivine would be the principal limiting factor in possible generation of basaltic magma by direct fractional melting of peridotite. Because of the scarcity of fresh rocks, methods for determining the original composition of peridotites from their serpentinized equivalents should be rigorously tested. The following statement by Hess and Otalora (1964, p. 159) about the Mayaguez cores epitomizes the problem (italics added):

“Mattson’s . . . estimates of the olivine-pyroxene ratio in the serpentinized rocks is considerably higher than ours. His is based on examination of thin sections and ours on the norms of the chemical analyses. Before the chemical analyses were available we agreed with Mattson’s estimate when we too were only examining the thin sections. The water-free chemical
analyses of type C [harzburgite] are nearly identical to the olivine nodules. In the latter case the true mineral composition can be determined and agrees exactly with the norm; so there can be little doubt that the estimates based on chemical analyses are accurate and should be used in preference to the visual estimate."

Mattson's (1964) data indicate that the average pyroxene content of the Mayaguez core, including dunite, is about 8.9 per cent; Hess and Ota-lora's normative data with Fe₂O₃ recalculated to 1 per cent give a figure of 16.7 per cent; and the CIPW figures calculated feldspar-free are: magnetite-chromite 10 per cent, pyroxene 29 per cent, olivine 61 per cent.

Comparison of the original mineral composition with normative composition of most serpentinized ultramafites is uncertain because of lack of modal data. Although pseudomorphs after pyroxene generally are readily recognizable in unsheared peridotite (Bailey et al., 1964), in reporting modes most authors do not distinguish them from serpentine after olivine. Mattson's estimates (1964, p. 17) of the original pyroxene content of several Mayaguez core samples, as listed in Table 2, show that except for three samples which contain significant amounts of brucite, proximate normative pyroxene greatly exceeds the original mode. The Mayaguez rocks, it is generally agreed, are characteristic alpine peridotites, in which as a class over-all pyroxene content ranges from about 10 to 25 per cent (Bailey et al., 1964, p. 81; Gabrielse, 1963, p. 69; Leech, 1953, p. 29; Smith, 1958, p. 29; Thayer, 1960, p. 251); the dunites, as usual, contain only traces of pyroxene. In Fig. 4 the situation appears to be similar; although most of the analyses containing more than about 10 per cent H₂O+ are of alpine-type serpentinites, very few of the proximate norms even approach the modal composition range of average alpine peridotite as indicated by the shaded strip. The average normative px:px+ol ratio in 60 serpentinites that contain more than 11 per cent H₂O+ ranges

Fig. 4. Proximate normative pyroxene content of 165 ultramafites based on data shown in figure 1, in weight per cent; large dot indicates average of 60 serpentinites containing more than 11 per cent H₂O+. Composition field of 15 serpentine minerals (Faust and Fahey, 1962) indicated by small X's and average by large X. Probable average range of primary pyroxene in alpine peridotites (10–30 per cent) indicated by shaded strip.
somewhere between the CIPW figure 37.7 and 41.5, if CaO, Al₂O₃, and excess Fe₂O₃ are assigned to pyroxene as they would be in the fresh rock. Both figures are well within the range of norms for serpentine minerals and, therefore, are completely in accord with theory. The proximate normative pyroxene content (40.6 per cent) of the 60 serpentinites (Table 1, no. 4C), however, is about twice the original modal pyroxene of the average alpine peridotite. To reduce the proximate normative pyroxene to the alpine modal average of about 20 per cent would require addition of 5.4 per cent MgO in 7.3 per cent brucite, which would increase the H₂O+ to 13.7 per cent. These data confirm the findings of Hostetler et al. (1966), who identified brucite in only 31 of 102 samples of serpentinized alpine peridotites. Hostetler and others and Shteinberg all seem to have discounted the possibility that in open systems brucite forms in the presence of olivine as a more or less transitory phase during early stages of serpentinization, and may or may not be removed entirely by the time serpentinization is completed. Conversely, the presence of brucite in dunite is not in itself proof that no material has been removed from the system because, as in the Mayaguez cores, rocks other than dunite show that the original Mg:Si ratios may be changed significantly.

Exaggeration of apparent pyroxene content and the need for more accurate data on composition of alpine peridotites are exemplified by the figures cited by Ringwood et al. (1964) for pyroxene pyrolite as average upper mantle peridotite. Their figures are based on the average of 4 analyses of Green’s “primary,” “recrystallized anhydrous,” and “recrystallized hydrous” facies of the Lizard peridotite (Green, 1964, table 1), and one analysis of fresh peridotite from Tinaquillo, Venezuela. The Lizard samples average 9.88 per cent H₂O+, so are about 80 per cent serpentinized;¹ their normative composition, calculated feldspar-free, is about 52 per cent pyroxene, 38 per cent olivine and 10 per cent magnetite, chromite, and spinel. Calculation of the norm on an Fe₂O₃-free anhydrous basis reverses the proportions of pyroxene and olivine, to about 56 per cent olivine and 42 per cent pyroxene. The Tinaquillo peridotite, whose analysis apparently was matched with the Lizard average on a water- and Fe₂O₃-free basis, consists of about 38 per cent normative pyroxene, 58 per cent olivine, and 3 per cent chromian spinel. These norms differ markedly from Green’s statement (1964, p. 137) that the Lizard rock “is a true peridotite rarely having less than 20 per cent or more than 40 per cent pyroxene” and MacKenzie’s description (1960, p. 303) of the Tinaquillo

¹ Theoretically, complete serpentinization of a rock containing 40 per cent SiO₂ would require 12 per cent H₂O.
peridotite as "more than 90 per cent . . . unserpentinized dunite . . . [which] . . . contains up to 10 per cent lamellae-bearing enstatites." On an overall basis, it would appear that the original modal composition of the Mayaguez and Tinaquillo ultramafites was very similar, with about 90 per cent olivine. It seems possible that even my estimate of 20 per cent, which is based largely on visual examination of outcrops where pyroxene weathers in relief, may be too high for the original pyroxene content of average alpine peridotite.

Conclusions

The available chemical and physical evidence leaves little room for argument, I believe, but that serpentinization is essentially a constant volume metasomatic process which requires removal of about 30 per cent by weight of the original bivalent oxides and SiO₂ in peridotite. The final equilibrium products of the process are dominantly magnetite and serpentine minerals whose composition varies widely and presumably reflects differences in temperature, pressure and pH. Brucite probably occurs in less than a third of partly serpentinized peridotites and serpentinites, and is quantitatively significant in very few serpentinites; it seems most likely to be an early transient phase formed in the presence of olivine or a late phase deposited from solutions of unusually high pH. Oxidation of Fe²⁺ in olivine and pyroxene during serpentinization probably releases significant amounts of H₂ as gas, making the process one of dehydrogenation as well as hydration. The association of rodingite with serpentinite shows that serpentinizing solutions remove alkalis and SiO₂ from feldspathic rocks, that calcium instead of magnesium is introduced into adjoining rocks during serpentinization, and that diffusion between serpentinite and country rocks or inclusions is limited to a few inches commonly, and at most to a few feet.

Surely, very large volumes of water must pass through ultramafites during serpentinization, but this problem is not new to geology. The wide differences of opinion now current show that laboratory investigations of the system olivine (Fo₉₆Fa₁₄)-serpentine-magnetite-NaCl-H₂O are urgently needed for even a rudimentary understanding of the equilibria involved in serpentinization. Connate waters rich in Cl⁻ from geosynclinal sediments probably are an important source of solutions, but magmatic or other deep-seated sources must be at least as important quantitatively. The belief in major volume increase during serpentinization, it seems likely to me, has grown more from absence of information on a number of related problems than from positive data that can be obtained from the rocks involved.
**References**


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