Magnesian staurolite in garnet-corundum rocks and eclogite from the Donghai district, Jiangsu province, east China

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ABSTRACT

Magnesian staurolite of $X_{Mg} = 0.68-0.74$ was found in garnet-corundum rocks and eclogite from the Donghai district, Jiangsu province, east China. The garnet-corundum rocks consist mainly of primary garnet, corundum, zoisite, and Na-rich phlogopite ($Na_2O = 2.7 \pm 0.2$ wt%), with secondary magnesian staurolite, chlorite, Al-rich pargasite ($Al_2O_3 = 22.4$ wt% maximum) and Mg-rich allanite ($MgO = 6.2$ wt% maximum). The eclogite is composed mainly of primary garnet, clinopyroxene, corundum, kyanite, and Cr-rich zoisite ($Cr_2O_3 = 1.6$ wt% maximum) with secondary magnesian staurolite and calcic amphibole. Equilibrium conditions of primary minerals were estimated at about 800-850°C and 11-30 kbar for the garnet-corundum rocks and 700-750°C and 11-25 kbar for the eclogite. The magnesian staurolite occurs as pseudomorphs after garnet, corundum, and kyanite. Equilibrium pressure of the magnesian staurolite is more than 11 kbar. Its equilibrium temperature is slightly lower than that of the primary minerals.

Cell dimensions of the magnesian staurolite of $X_{Mg} = 0.74$ are $a = 7.873(3)$ Å, $b = 16.557(7)$ Å, and $c = 5.637(3)$ Å. Its $b$ axis is distinctly shorter than that of Mg-poor staurolite. $Cr_2O_3$ content of the magnesian staurolite reaches 1.2 wt%. The Mg enrichment of staurolite is controlled by the Mg substitution for $V$Al and by the Mg = Fe substitution in the $V$Fe sites.

INTRODUCTION

Staurolite is a common constituent mineral of pelitic and other aluminous rocks metamorphosed under intermediate pressure and temperature conditions. Staurolite is characteristically lower in $X_{Mg} = [Mg/(Mg + Fe)]$ value than the coexisting silicate minerals: its $X_{Mg}$ value is usually less than 0.3 (e.g., Deer et al., 1982). Iron-free staurolite (i.e., the pure-Mg end member) was synthesized under the conditions of $T = 700-950$ °C and $P > 11$ kbar by Schreyer (1967) and Schreyer and Seifert (1969), Helfman and Green (1979) experimentally produced Mg-rich staurolite ($X_{Mg} = 0.53-0.57$) from olivine tholeiitic materials under the conditions of $T = 740-760$ °C and $P = 24-26$ kbar. These experimental works suggest that Mg-rich staurolite could occur in Mg- and Al-rich metamorphic rocks that formed at high temperature and pressure. Recently, Mg-rich staurolites have been found from various types of rock metamorphosed under high pressures ($X_{Mg} = 0.43-0.56$, Ward, 1984a; 0.49, Schreyer et al., 1984; 0.40-0.42, Grew and Sandiford, 1984; 0.52, Nicollet, 1986). These Mg-rich staurolites always coexist with corundum. A silica-undersaturated environment is also required for the formation of Mg-rich staurolites (e.g., Schreyer, 1967).

In the course of our petrologic study on eclogite and the associated rocks in the Donghai district, Jiangsu province, east China, magnesian staurolite ($X_{Mg} = 0.68-0.74$) was found in garnet-corundum rocks and eclogite. This is the most Mg-rich natural staurolite, as far as we know, among staurolites reported. The mode of occurrence, chemistry, crystallographic data and petrogenesis of the magnesian staurolite are described in the present paper.

GEOLOGIC SETTING AND PETROGRAPHY

Magnesian staurolite was found in two garnet-corundum rocks and an eclogite, from the Zhimafang and Mengzhong areas in the Donghai district, respectively. Figure 1 shows a geologic sketch map of east China. The Precambrian basement of east China is divided into two units by the Tancheng-Lujiang fracture zone, i.e., an eastern unit (the Jiaoliao massif, age 1300-2400 Ma), and a western unit (the Jilu massif, age >2400 Ma) (Tectonic map compiling group, Institute of Geology, Academia Sinica, 1974). The Donghai district is situated about 50 km east of the Tancheng-Lujiang fracture zone and belongs to the Jiaoliao massif. This district is underlain by pelitic and mafic gneisses and serpentinitized ultramafic rocks.

The garnet-corundum rocks and eclogite occur as subrounded blocks (diameter, 5-50 cm) in ultramafic rocks...
intruding the Precambrian pelitic gneisses. The ultramafic rocks in the Zhimafang area are serpentinized phlogopite-bearing garnet lherzolite. Equilibrium conditions of the garnet lherzolite are estimated at about $T = 750-850$ °C and $P = 20-30$ kbar (Zang et al., in prep.). The ultramafic rocks in the Mengzhong area are completely serpentinized. Bulk chemical analyses of the magnesian staurolite-bearing rocks are given in Table 1.

**Zhimafang samples**

The Zhimafang samples (TS-03 and TS-04) are composed of a corundum-rich pink part and garnet-rich white part. The samples contain garnet and corundum with subordinate amounts of Na-rich phlogopite, zoisite, pentlandite, and apatite as primary minerals. Aggregates of fine-grained diaspore, margarite, dolomite, and calcite (all <0.03 mm in size) were observed as inclusions in corundum crystals. Secondary minerals are magnesian staurolite, Al-rich pargasite, chlorite, clinozoisite, Mg-rich alalanite, and heazlewoodite (Ni,S$_2$).

Both garnet and corundum occur as anhedral crystals 0.1–2.0 mm in size. They are usually surrounded by aggregates of magnesian staurolite and chlorite. Garnet is partly replaced by Al-rich pargasite and clinozoisite around the crystal rim and along fractures. Phlogopite shows a subhedral and tabular form and is partly replaced by chlorite. Magnesian staurolite constitutes acicular and/or prismatic crystals and forms pseudomorphs after garnet and corundum with chlorite (Fig. 2).

The bulk chemistry of the garnet-corundum rock (TS-03) is characterized by an extremely high $\text{Al}_2\text{O}_3 / \text{SiO}_2$ value (1.0) and low $\text{Fe}_2\text{O}_3 + \text{FeO}$ content (4.7 wt%) and is similar to that of some diaspore bauxites (e.g., Valeton, 1972). This rock is also enriched in MgO and CaO. These components may have been derived from dolomite or dolomitic limestones, which are usually associated with bauxites. The garnet-corundum rocks are considered to be metamorphosed mixtures of bauxites and Mg-rich carbonate rocks, on the basis of the occurrence of diaspore and carbonate inclusions in the corundum crystals and the bulk chemistry of the garnet-corundum rock.

**Mengzhong sample**

The Mengzhong sample (TM-02) is massive and consists of a clinopyroxene-rich green part and garnet-rich brown part. The sample contains garnet, clinopyroxene, and subordinate amounts of corundum, kyanite, zoisite, dolomite, rutile, and apatite as primary minerals. Secondary minerals are magnesian staurolite, calcic amphibole, clinozoisite, and chlorite.

Garnet occurs usually as euhedral or subhedral crystals 0.1–0.5 mm in diameter. Large garnet crystals 1–2 cm in diameter are sometimes observed. The garnet crystals are usually replaced by calcic amphibole, chlorite, and clinozoisite around crystal rims and along fractures. Clinopyroxene occurs as rounded and subhedral crystals 0.1–0.5 mm in size in the matrix and as fine inclusions smaller than 0.05 mm in size in the garnet crystals. Corundum is smaller than 0.03 mm in size and is rimmed by chlorite. Kyanite forms anhedral crystals smaller than 0.02 mm in size and is replaced by magnesian staurolite and calcic amphibole. Zoisite shows prismatic forms 0.1–0.3 mm in length and occurs usually as inclusions in garnet. Some zoisite crystals contain fine-grained garnet inclusions smaller than 0.03 mm in size. Magnesian staurolite forms anhedral crystals smaller than 0.02 mm in size and

<table>
<thead>
<tr>
<th>Table 1. Bulk chemical compositions of magnesian staurolite-bearing rocks</th>
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<tbody>
<tr>
<td><strong>TS-03</strong></td>
</tr>
<tr>
<td><strong>Wt%</strong></td>
</tr>
<tr>
<td><strong>SiO$_2$</strong></td>
</tr>
<tr>
<td><strong>TiO$_2$</strong></td>
</tr>
<tr>
<td><strong>Al$_2$O$_3$</strong></td>
</tr>
<tr>
<td><strong>Cr$_2$O$_3$</strong></td>
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<tr>
<td><strong>Fe$_2$O$_3$</strong></td>
</tr>
<tr>
<td><strong>FeO</strong></td>
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<tr>
<td><strong>MnO</strong></td>
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<tr>
<td><strong>NiO</strong></td>
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<tr>
<td><strong>CaO</strong></td>
</tr>
<tr>
<td><strong>Na$_2$O</strong></td>
</tr>
<tr>
<td><strong>K$_2$O</strong></td>
</tr>
<tr>
<td><strong>P$_2$O$_5$</strong></td>
</tr>
<tr>
<td><strong>H$_2$O$^+$</strong></td>
</tr>
<tr>
<td><strong>H$_2$O$^-$</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>

Note: Normative composition of TM-02 was calculated on the basis of Fe$^3+$/Fe$^{2+}$ ratio of 0.15.

* Total Fe as FeO.

† Analyzed by Shiguang Wang.
Magnesian staurolite

Chemistry. H$_2$O content of staurolite is variable and cannot be associated with a fixed stoichiometry (e.g., Juurinen, 1956; Lonker, 1983; Holdaway et al., 1986a). Li is sometimes concentrated in staurolite (Hietanen, 1969; Grew and Sandiford, 1984; Holdaway et al., 1986b; Dutrow et al., 1986). H$_2$O and Li$_2$O contents cannot be estimated by EPMA analysis, and so the chemical formula of the magnesian staurolite was calculated on the basis of Si + Al + Cr = 25.53 as recommended by Holdaway et al. (1986b). V$_2$O$_5$, ZnO, CoO, CaO, Na$_2$O, and K$_2$O contents of the magnesian staurolite are below the detection limits, i.e., less than 0.02 wt% for V$_2$O$_5$, and less than 0.01 wt% for the other elements.

The magnesian staurolite is faintly yellow in thin section and chemically homogeneous. $X_{Mg}$ values (Mg/ (Mg + Fe)) of the magnesian staurolite are 0.74 ± 0.01 and 0.69 ± 0.01 in the Zhimafang and Mengzhong samples, respectively. Average Si content per formula unit is 7.92 for the Zhimafang samples and 7.74 for the Mengzhong sample. Grew and Sandiford (1984) pointed out that lower Si content is characteristic of Mg-rich staurolite from silica-undersaturated environments. Although the present samples contain corundum, the Si contents of these magnesian staurolites are higher than the Si contents of Mg-rich staurolite from other corundum-bearing samples (e.g., 7.43–7.68; Ward, 1984a). The magnesian staurolite here occurs as pseudomorphs after corundum and/or kyanite, and so the relatively high Si contents are probably due to disequilibrium with the associated aluminous minerals. Cr$_2$O$_3$ contents of the magnesian staurolite are up to 0.70 and 1.17 wt% for the Zhimafang and Mengzhong samples, respectively.

Figure 3 explores the variation of cation contents in the staurolite monolayer, except for Al ($FM$ content = Fe + Mn + Mg + Zn + Co + Ni + Li + Ti), for staurolites reported in the literature. Figure 3 clearly shows that the $FM$ content of staurolite increases with increase in $Y_{Mg}$ value (= Mg/$FM$). The $FM$ content of Mg-rich staurolites ($Y_{Mg} \approx 0.4$) is higher than 4.0, and its average is 4.6. The $FM$ content of Mg-poor staurolites ($Y_{Mg} \approx 0.2$) is mostly lower than 4.2, and its average is 3.9. Two Mg-poor staurolites with $FM > 4.6$ were reported by Griffen and Ribbe (1973) (specimens 4 and 10), and the latter has a high ZnO content of 6.86 wt%. Staurolites with $Y_{Mg} = 0.2–0.4$ have compositions intermediate between the above two groups (average $FM$ content is 4.2), except for the unusually Zn-enriched staurolites with ZnO = 7.44 and 6.73 wt% reported by Juurinen (1956) and Miyake (1985), respectively. The compositional variation seen in Figure 3 may have some uncertainties because of the absence of H$_2$O and/or Li$_2$O data in most analyses. Thirty complete analyses of staurolite, excluding one analysis (specimen 6-3), believed to be inaccurate owing to variability in Li content (Dutrow et al., 1986).
The present study corresponds well to those of Fe-free staurolites synthesized by Schreyer and Seifert (1969) and Borg and Smith (1969). Diffractions with d > 6.6 Å could not be observed, since 2d of the microdiffractometer ranged from 20° to 140° in the present study. Preliminary X-ray powder-diffraction analysis of a mixture of the magnesian staurolite and garnet crystals showed a weak peak at d = 8.34 Å, corresponding to the 020 reflection of the magnesian staurolite. Observed peaks and their intensities are different between the two selected areas, because of the limited oscillation angles around φ and χ axes of the microdiffractometer. Peak positions of the present study correspond well to those of Fe-free staurolite synthesized by Schreyer and Seifert (1969). An or-

**FM** content increases with increasing Y<sub>Mg</sub> value in staurolite: average FM content of nine staurolites with Y<sub>Mg</sub> ≥ 0.2 is 4.5 and that of three staurolites with Y<sub>Mg</sub> ≤ 0.1 is 3.8. High FM content of some staurolites can be possibly explained by substitution of "IAl by Fe"<sup>III</sup>, which would be seen as part of the FM components (Holdaway et al., 1986b). Most of Mg-rich staurolites with Y<sub>Mg</sub> ≥ 0.4, however, coexist with zoisite or Fe<sup>III</sup>-poor clinozoisite (Fe<sub>2</sub>O<sub>3</sub> = 2.33–4.2 wt%) and probably have little Fe<sup>III</sup>. Staurolite of high Y<sub>Mg</sub> tends to be lower in "IAl content and vice versa: Average "IAl contents are 17.3 and 17.6 for staurolites with Y<sub>Mg</sub> ≥ 0.2 and Y<sub>Mg</sub> ≤ 0.1, respectively (Holdaway et al., 1986b). Thus the high FM content of Mg-rich staurolite suggests the preferential Mg substitution for "IAl. Alternative explanations for the "IAl = Mg substitution are 2"IAl = 3 Mg (see Ward, 1984a) or "IAl = Mg + H.

Lonker (1983) showed the negative correlation between "IAl and (Fe + Mg) + OH contents. This negative correlation implies that the second substitution scheme better explains Mg enrichment in staurolite. The present magnesian staurolite has lower FM (4.0–4.4) and lower Fe (1.1–1.3) concentrations than those of other Mg-rich staurolites. This fact suggests that the Fe = Mg substitution in the "IFe sites also affects the high Mg content of the magnesian staurolite concerned. The Mg substitution in the "IFe sites is attributed to the extremely high X<sub>Mg</sub> values of host rocks (0.84 for TS-03 and 0.77 for TM-02).

**X-ray data.** The magnesian staurolite was examined on a Rigaku RAD-"YB X-ray microdiffractometer with position-sensitive proportional counter (PSPC/MDG system), using V-filtered CrKa radiation (λ = 2.29092 Å, 40 kV, 200 mA). X-ray diffraction data were obtained from the two selected areas of about 30 μm in diameter for two crystals in a thin section. Average chemical compositions of the selected areas obtained by EPMA analyses are shown in Table 2. The X-ray diffraction data are summarized in Table 4. Peaks were indexed with respect to Schreyer and Seifert (1969) and Borg and Smith (1969). Diffractions with d > 6.6 Å could not be observed, since 2φ of the microdiffractometer ranged from 20° to 140° in the present study. Preliminary X-ray powder-diffraction analysis of a mixture of the magnesian staurolite and garnet crystals showed a weak peak at d = 8.34 Å, corresponding to the 020 reflection of the magnesian staurolite. Observed peaks and their intensities are different between the two selected areas, because of the limited oscillation angles around φ and χ axes of the microdiffractometer. Peak positions of the present study correspond well to those of Fe-free staurolite synthesized by Schreyer and Seifert (1969). An or-

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**Table 2. Chemical compositions of magnesian staurolites**

<table>
<thead>
<tr>
<th>Element</th>
<th>Zhimafang</th>
<th>Mengzong</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>TS-03</td>
<td>TS-04</td>
</tr>
<tr>
<td></td>
<td>n = 17†</td>
<td>n = 20†</td>
</tr>
<tr>
<td>SiO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>29.8(0.3)</td>
<td>29.8</td>
</tr>
<tr>
<td>TiO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>55.9(0.4)</td>
<td>55.8</td>
</tr>
<tr>
<td>MgO</td>
<td>5.0(0.08)</td>
<td>5.05(0.07)</td>
</tr>
<tr>
<td>FeO&lt;sup&gt;**&lt;/sup&gt;</td>
<td>4.69(0.21)</td>
<td>4.70</td>
</tr>
<tr>
<td>MnO</td>
<td>0.07(0.03)</td>
<td>0.09</td>
</tr>
<tr>
<td>MgO</td>
<td>7.38(0.07)</td>
<td>7.37</td>
</tr>
<tr>
<td>NiO</td>
<td>0.16(0.05)</td>
<td>0.14</td>
</tr>
<tr>
<td>CaO</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Na&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>K&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>98.5</td>
<td>98.4</td>
</tr>
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</table>

**Formulae (Si + Al + Cr = 25.53)**

<table>
<thead>
<tr>
<th>Element</th>
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<tbody>
<tr>
<td>Si</td>
</tr>
<tr>
<td>Al</td>
</tr>
<tr>
<td>Fe&lt;sup&gt;**&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mn</td>
</tr>
<tr>
<td>Mg</td>
</tr>
<tr>
<td>Ni</td>
</tr>
<tr>
<td>Ca</td>
</tr>
<tr>
<td>Na</td>
</tr>
<tr>
<td>K</td>
</tr>
<tr>
<td>X&lt;sub&gt;Mg&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

**Note:** Values in parentheses are the standard deviations.
* Total Fe as FeO.
† n, number of analytical points; C-1 and C-2, crystals 1 and 2 for the X-ray analysis, respectively; Cr, most Cr-rich composition.
‡ X<sub>Mg</sub> = Mg/(Mg + Fe). 

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ENAMI AND ZANG: MAGNESIAN STAUROLINE
<table>
<thead>
<tr>
<th>Table 3. Chemical compositions of other constituent minerals</th>
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<tbody>
<tr>
<td><strong>TS-03</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Phi</td>
</tr>
<tr>
<td>n = 5</td>
</tr>
<tr>
<td>SiO₂</td>
</tr>
<tr>
<td>TiO₂</td>
</tr>
<tr>
<td>Al₂O₃</td>
</tr>
<tr>
<td>Cr₂O₃</td>
</tr>
<tr>
<td>FeO*</td>
</tr>
<tr>
<td>MnO</td>
</tr>
<tr>
<td>MgO</td>
</tr>
<tr>
<td>NiO</td>
</tr>
<tr>
<td>CaO</td>
</tr>
<tr>
<td>Na₂O</td>
</tr>
<tr>
<td>K₂O</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Formule

\[
\begin{align*}
    \text{O} &= 22 \\
    \text{Si} &= 5.478 \\
    \text{Al} &= 3.187 \\
    \text{Ti} &= 0.000 \\
    \text{Cr} &= 0.028 \\
    \text{Fe}^{2+} &= 0.020 \\
    \text{Fe}^{3+} &= 0.000 \\
    \text{Mn} &= 0.000 \\
    \text{Mg} &= 4.936 \\
    \text{Ni} &= 0.000 \\
    \text{Ca} &= 0.000 \\
    \text{Na} &= 0.712 \\
    \text{K} &= 1.269 \\
    \text{Ce}^{4+} &= 0.96 \\
\end{align*}
\]

\[
\text{REE} = 0.945 \quad \text{and} \quad X_{\text{Fe}} = 0.30
\]

Note: Abbreviations are Phi, phlogopite; Mar, marcllrite; Grt, garnet; Cm, corundum; Cam, calcic amphibole; Chl, chlorite; Ala, alandite; Cpx, clinopyroxene; Ky, kyanite; Zo, zoisite; n, number of analytical points; Cr, most Cr-rich composition; Al, most Al-rich composition; Mg, most Mg-rich composition; n.d., not determined.

* Total Fe as Fe₂O₃.
** Total Fe as Fe₂O₃.
† \(X_{\text{Fe}} = \text{Mg}(\text{Mg} + \text{Fe})\).
‡ Includes La₂O₃, 9.45; Ce₂O₃, 12.3; Pr₂O₃, 2.83; Nd₂O₃, 1.95; Sm₂O₃, 0.11; and Ge₂O₃, 1.36 wt%.
§REE (La, 0.318; Ce, 0.410; Pr, 0.094; Nd, 0.063; Sm, 0.003; Gd, 0.057).
∥ \(X_{\text{Fe}} = \text{Fe}^{2+}/(\text{Fe}^{3+} + \text{Al})\).
Thornton's cell was assumed, and unit-cell dimensions calculated on the basis of 30 reflection data with 44° < 2θ < 120° (excluding 0k0 reflections) are as follows: a = 7.873(3) Å, b = 16.557(7) Å, and c = 5.637(3) Å. The a and c axes are similar to those of staurolites in the literature (a = 7.850–7.891 Å and c = 5.635–5.667 Å). Griffith et al. (1982) showed that the b axis of staurolite decreases systematically with decreasing mean ionic radius (MIR) of cations in the monolayer. The b axis of the magnesian staurolite (TS-03) lies close to the regression line of that against the MIR value (Fig. 4).

**Garnet, clinopyroxene, and calcic amphibole**

The garnet is mostly homogeneous and belongs to a grossular-rich pyrope-almandine series with very low MnO content (less than 0.3 wt%). Average compositions in terms of garnet end members are Prp54,Alm50,Gr535,Sp52, Prp54,Alm50,Gr545,Sp50,3, and Prp50,Alm57,Gr53,Sp55 for TS-03, TS-04, and TM-02, respectively (abbreviations after Kretz, 1983). The Cr2O3 content of TM-02 garnet reaches 2.9 wt% in the crystal core. The clinopyroxene is pale green in hand specimen, considering its substantial Cr2O3 content (0.63 wt% maximum), and is sodian augite (Na2O : 2.0 + 0.3 wt%, XAl2O3 : 0.94) of Essene and Fyfe (1967). The amphibole varies in composition from flake to flake. In the TM-02, the amphibole replacing garnet is magnesiohornblende with Al2O3 : 12.0 + 2.1 wt% and, that replacing the magnesian staurolite is tschermakite with maximum Al2O3 of 18.8 wt%, according to the nomenclature of Leake (1978). The amphibole in the Zhi- maifang samples is Al-rich pargasite, and its Al2O3 content is up to 22.4 wt%.
Corundum and kyanite

Corundum is a pink variety owing to its high Cr$_2$O$_3$ content, up to 1.1 wt% in the Zhimafang samples and 0.9 wt% in the Mengzhong sample. Its Fe$_2$O$_3$ content is less than 0.4 wt%. Kyanite is also enriched in Cr$_2$O$_3$ (1.2 wt% maximum), and its Fe$_2$O$_3$ content is 0.4 ± 0.1 wt%.

Phlogopite, chlorite, and margarite

Both phlogopite and chlorite have high $X_{Na}$ values of about 0.96 and are colorless in thin section. Phlogopite is unusually enriched in Na$_2$O (2.7 ± 0.2 wt%). NiO contents of phlogopite and chlorite in the Zhimafang samples are up to 1.0 and 1.1 wt%, respectively. Margarite is depleted in both Na$_2$O + K$_2$O (0.18 wt%) and FeO + MgO (0.1 wt%).

Epidote group minerals

Both zoisite and clinozoisite are colorless in thin section. $X_{Fe^{3+}}$, values (=[Fe$^{3+}$/Fe$^{3+}$ + Al]) of Zhimafang and Mengzhong zoisites are 0.030 and 0.035, respectively. Cr$_2$O$_3$ content of the latter reaches 1.6 wt%. Clinozoisite is depleted in Fe$^{3+}$, and $X_{Fe^{3+}}$ values are about 0.10 and 0.11 for the Zhimafang and Mengzhong samples, respectively. Allanite in the Zhimafang sample is pale brown and shows a weak compositional zoning consisting of REE-rich cores and Ca-rich rims. CaO and REE contents are 10.9 and 28.0 wt% in the crystal core and 12.5 and 24.5 wt% in the crystal rim, respectively. MgO content of allanite reaches 6.2 wt%, and total Fe as FeO is less than 2.1 wt%, suggesting the substitution Ca + Al = REE + Mg.

Other minerals

Diaspore is enriched in Cr$_2$O$_3$ (1.0 wt%), and its Fe$_2$O$_3$ content is less than 0.6 wt%. Dolomite is homogeneous, and its average composition in terms of carbonate end members is Ca$_{1.5}$Mg$_{0.5}$Sd$_{3}$ for the Zhimafang samples and Ca$_{1.5}$Mg$_{0.5}$Sd$_{3}$ for the Mengzhong sample. Fe, Mn, and Mg components in calcite were not detected. Heazlewoodite is depleted in Fe (less than 0.1 wt%) and has a formula of Ni$_{10}$S$_2$.

FORMATION OF MAGNESIAN STAUROLITES

Textural and chemical evidence shows that the magnesian staurolites in these rocks are all retrograde products. The Zhimafang staurolite occurs as a pseudomorph after garnet and corundum and forms an aggregate with chlorite. The Mengzhong staurolite occurs as a pseudomorph after kyanite. Suggested reactions for the magnesian staurolite formations are as follows:

\[
197(Mg,Fe)_{3}Al_{3}Si_{2}O_{12} + 340AlrO_3 + 432H_2O \rightarrow 48(Mg,Fe)_{3}Al_{3}Si_{2}O_{12}(OH)_4 + 42(Mg,Fe)_{3}Al_{3}Si_{2}O_{12}(OH)_{16}
\]

for the Zhimafang samples and

\[
8(Mg,Fe)_{3}Al_{3}Si_{2}O_{12} + 25AlrO_3 + 21Al_2SiO_5 + 12H_2O \rightarrow 6(Mg,Fe)_{3}Al_{3}Si_{2}O_{12}(OH)_4 + 12H_2O
\]

for the Mengzhong sample. Grossular component in garnet was probably consumed for the formation of calcic amphibole and clinozoisite.

For the Zhimafang samples, the equilibrium temperature of the primary garnet + corundum stage was estimated at about 800–850 °C by the garnet-biotite geothermometer (methods of Indares and Martignole, 1985, and Hoinkes, 1986). The temperature calculated using the Ferry and Spear (1978) calibration for the Ca- and Mn-free system is 680 °C. The lower temperature estimates with the latter calibration may result from high grossular.

Fig. 4. Relationship between mean ionic radius (MIR) of cations in the monolayer and $b$ axis of staurolite. Regression line plotted was calculated using ten data of synthetic staurolites. Ionic radii were taken from Griffen (1981) for Zn and from Shannon (1976) for the other elements; $r$: correlation coefficient. Data are from Cech et al. (1981), Enami and Zang (this study), Griffen and Ribbe (1973), Juurinen (1956), Miyake (1985), Schreyer and Chinner (1966), Smith (1968), Takeuchi et al. (1972), von Knorring et al. (1979), and Ward (1984a) for natural staurolites and from Griffen (1981), Richardson (1966), and Schreyer and Seifert (1969) for synthetic staurolites.
component of the primary stage is about 11–14 kbar on the basis of the garnet + corundum assemblage (cf. Droop and Bucher-Nurminen, 1984) and the stability field of pyrope garnet (Schreyer and Seifert, 1969). Its upper pressure limit is probably defined by the equilibrium pressure of the host garnet-sterilolite of about 20–30 kbar. For the Mengzhong sample, the equilibrium conditions of the primary stage were estimated at \( T = 700-750 \, ^\circ\text{C} \) and \( P = 11-25 \, \text{kbar} \) (Enami et al., 1986). The estimated conditions of the primary stage may define the upper \( T \) and \( P \) limits of magnesian staurolite formation. The lower \( T \) and \( P \) limits of magnesian staurolite formation are estimated at about 730–770 \( ^\circ\text{C} \) and 11 kbar from the stability range of the magnesian staurolite + chlorite assemblage (cf. Schreyer and Seifert, 1969; Grew and Sandiford, 1984). Equilibrium conditions of the magnesian staurolite of this study are similar to those of other Mg-rich staurolites in the literature.

In the present study, magnesian staurolite occurs in two characteristic rock types. The Zhimaifang magnesium staurolite occurs in highly aluminous and silica-undersaturated rocks. The Mengzhong magnesian staurolite, on the other hand, occurs as a pseudomorph after kyanite in an eclogite without normative corundum. Schreyer (1967) suggested that the lack of natural magnesian staurolite was due to the absence of rocks having highly aluminous bulk compositions in the upper mantle where \( T \) and \( P \) conditions necessary for the formation of magnesian staurolite may prevail (i.e., higher than 11 kbar). He also pointed out that magnesian staurolite and quartz are incompatible by virtue of the stable tie lines between kyanite and other magnesian silicates. The Zhimaifang samples, as well as most of Mg-rich staurolites in the literature, occur in metamorphosed peraluminous rocks such as sapphire-garnet rock (Schreyer et al., 1984), corundum-bearing phlogopite-chlorite schist (Grew and Sandiford, 1984), and meta-anorthosite (Nicoll et al., 1986). These samples suggest that Mg-rich staurolite is formed in rocks having restricted bulk chemistry under limited \( T \) and \( P \) conditions. Mg-rich staurolite formation in typical mafic rocks may require much higher pressure reaching 24–26 kbar as shown by Hellman and Green (1979). The Mengzhong sample, however, clearly shows that Mg-rich staurolite can occur in common eclogite. Ward (1984a) reported Mg-rich staurolite in a reaction zone between plagioclase and orthopyroxene crystals in a metatzoite. The Mengzhong sample and that of Ward thus suggest that Mg-rich staurolite can be formed in common metamabases by local reactions of aluminous and magnesian minerals.

The Mengzhong sample has bulk and mineral compositions similar to those of eclogite xenoliths in kimmerites (Enami et al., 1986). Kyanite and other aluminous minerals are common in high-pressure eclogites (e.g., Dawson, 1980), and local breakdown of these minerals with decreasing temperature may be expected to form Mg-rich staurolite. Hellman and Green (1979) suggested that staurolite may be widespread in mafic rocks metamorphosed at high pressures, as, for example, in the subducted lithosphere. We also emphasize that careful petrographic examinations will probably reveal wide occurrence of Mg-rich staurolite as an accessory mineral in common metabasites formed under high pressures, especially in eclogites.

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**References Cited**


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