Peak conditions of kyanite-bearing quartz eclogites in the Sanbagawa metamorphic belt, central Shikoku, Japan

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Kyanite-bearing eclogitic assemblages occur in the highest-grade zone of the Sanbagawa metamorphic belt, central Shikoku, Japan. The eclogites consist mainly of garnet, omphacite, phengite, kyanite, epidote, quartz and rutile. Compositionally variable amphibole (glaucophane/barroisite/pargasite), phengite and paragonite occur as inclusions in garnet and other eclogite facies phases. Careful examination of garnet zoning in kyanite-eclogites suggests that (i) most garnet grains show complex zoning consisting of relatively Ca-rich/Mg-poor inner and Ca-poor/Mg-rich outer segments, (ii) the inner segment of the zoned garnet formed at the eclogite facies stage, and (iii) the Mg-rich outermost rim of garnet does not always represents a composition at peak eclogite stage but could form at lower-pressure conditions of subsequent epidote-amphibolite facies. The assemblage of inner segment of garnet, omphacite, phengite, kyanite and quartz points to equilibrium conditions of 2.3-2.4 GPa/675-740 °C. The metamorphic P-T conditions of the eclogite facies stage reported in literature have been estimated assuming that the outermost rim of garnet with Mg-rich composition was in equilibrium with other eclogite facies phases. Therefore, P-T estimations of the eclogite facies stage in the Sanbagawa metamorphic belt should be re-examined carefully on the basis of textural and compositional heterogeneities of constituent minerals.

Keywords: Sanbagawa belt, Besshi region, P-T conditions, Eclogite, Kyanite

INTRODUCTION

Eclogite assemblages sporadically occur in the Sanbagawa epidote-amphibolite facies area of the Besshi region, central Shikoku, Japan. Pressure (P)-temperature (T) conditions for the eclogite facies assemblages reported in literature imply large variations of P = 1.4-2.5 GPa and T = 500-800 °C (Takasu, 1989; Enami, 1996; Aoya, 2001; Ota et al., 2004). Ota et al. (2004) interpreted that (i) the P-T conditions are systematically variable in the eclogite-bearing area suggesting a sandwiched thermobaric structure characterized by the presence of the highest P-T zone at an intermediate structural level of the Sanbagawa metamorphic belt, and (ii) the peak metamorphic conditions vary continuously from the eclogite-bearing area to the surrounding lower-grade schistose rocks. Wallis and Aoya (2000), on the other hand, proposed a nappe structure consisting of eclogite and non-eclogite lithologies in the Besshi region, and suggested a large gap of the peak metamorphic conditions and the occurrence of tectonic discontinuities between them.

The sandwiched thermobaric model was mainly based on the inferred systematic variations of P-T estimates for the eclogite assemblages (Ota et al., 2004). The eclogitic rocks were, however, extensively re-equilibrated...
under lower pressure conditions during exhumation as suggested by many authors (e.g., Banno et al., 1976; Taka- 
su, 1989; Aoya, 2001; Banno, 2004; Ota et al., 2004), and their peak assemblages usually record multistage equilib-
ria evidenced by textural and chemical heterogeneities.

The previous petrological and mineralogical studies on 
the eclogitic rocks of the Besshi region might not have been necessarily accompanied by a careful choice of 
equilibrium mineral compositions. The thermobaric 
structure of the eclogite-bearing area should be reviewed
based on the peak P-T conditions re-estimated by a careful analytical approach of metamorphic phases and their textures.

Kyanite-bearing quartz-eclogite described in this paper contains useful mineral assemblages for metamorphic P-T estimates (Waters and Martin, 1993; Krogh Ravna and Terry, 2004). As a first step in a petrological and mineralogical review of the Sanbagawa eclogite facies metamorphism, we (i) report a new mineralogical dataset of the kyanite-eclogite, (ii) describe chemical and textural variations of minerals occurring at eclogite and subsequent epidote-amphibolite facies stages, and (iii) estimate the most probable P-T conditions of the peak eclogite facies stage.

Abbreviations for minerals and end-members described in the text, figures and tables generally follow Kretz (1983) and Miyashiro (1994). Mineral formulae used for description of reaction relations follow Holland and Powell (1998). Abbreviations for element sites are: [4], tetrahedral T-sites; [6], octahedral M2-sites; [B], B-site of amphibole and [A], A-site of amphibole.

### GEOLOGICAL OUTLINE AND PETROGRAPHY

The late Cretaceous Sanbagawa high P/T metamorphic belt represents the deepest exposed parts of the Mesozoic accretionary complexes in the Outer Zone of the Southwest Japan, and extends for over 800 km through the Japanese Island arc. The Sanbagawa belt in central Shikoku is subdivided into four metamorphic zones: chlorite, garnet, albite-biotite and oligoclase-biotite zones in ascending order of metamorphic grade (e.g., Higashino, 1975; Enami, 1983; Higashino, 1990). The higher-grade albite-biotite and oligoclase-biotite zones are widely distributed in the Besshi region of central Shikoku (Fig. 1). The metamorphic grade of these mineral zones is equivalent to that of the epidote-amphibolite facies, and P-T peak conditions have been estimated to be 470-635 °C and 0.7-1.1 GPa, respectively (Enami et al., 1994; Wallis et al., 2000). Within these higher-grade zones there are numerous ultramafic (e.g., Higashihakaishi body) and mafic complexes (e.g., Western and Eastern Iroatsu, Seba and Tonaru bodies). These ultramafic-mafic complexes in the Besshi region underwent extensive recrystallization.

<table>
<thead>
<tr>
<th>Localities</th>
<th>Sample</th>
<th>Houo-Gongen shrine</th>
<th>Tokonabe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GE1501b</td>
<td>GE1502</td>
<td>GO1701a</td>
</tr>
<tr>
<td>SiO2 (wt%)</td>
<td>68.48</td>
<td>57.07</td>
<td>63.32</td>
</tr>
<tr>
<td>TiO2</td>
<td>0.47</td>
<td>1.06</td>
<td>0.51</td>
</tr>
<tr>
<td>FeO</td>
<td>6.95</td>
<td>10.74</td>
<td>7.84</td>
</tr>
<tr>
<td>MnO</td>
<td>0.13</td>
<td>0.18</td>
<td>0.14</td>
</tr>
<tr>
<td>MgO</td>
<td>2.46</td>
<td>6.16</td>
<td>4.73</td>
</tr>
<tr>
<td>CaO</td>
<td>4.18</td>
<td>6.33</td>
<td>5.30</td>
</tr>
<tr>
<td>Na2O</td>
<td>1.73</td>
<td>2.29</td>
<td>1.89</td>
</tr>
<tr>
<td>K2O</td>
<td>0.70</td>
<td>0.70</td>
<td>1.25</td>
</tr>
<tr>
<td>P2O5</td>
<td>0.10</td>
<td>0.14</td>
<td>0.08</td>
</tr>
<tr>
<td>Total</td>
<td>98.19</td>
<td>98.37</td>
<td>98.42</td>
</tr>
<tr>
<td>Al-index*</td>
<td>1.75</td>
<td>1.33</td>
<td>1.44</td>
</tr>
</tbody>
</table>

* Total iron as FeO.
† Kyanite-bearing sample.
‡ Al2O3/(CaO + Na2O + K2O) mole value.

**Table 1.** Representative bulk-rock compositions of quartz-eclogites from the Gongen area, Sanbagawa metamorphic belt.
under epidote–amphibolite facies conditions during exhumation (Banno et al., 1976; Ota et al., 2004). However, they also locally preserve evidence of a early stage of eclogite facies metamorphism (e.g., Takasu, 1989; Wallis and Aoya, 2000).

The Higashi-akaishi body is the largest ultramafic lens (5 × 2 km) in the Sanbagawa belt. Dunite, wehrlite and garnet clinopyroxenite are the dominant rock types in this body. Compositional layering is developed in the dunite and other rock types. The Higashi-akaishi body is thought to have formed as a cumulate under garnet-stable conditions of \( P > 1.8 \) GPa (Kunugiza et al., 1986), and re-equilibrated under subsolidus conditions in the garnet-lherzolite facies (2.9–3.8 GPa/700–810 °C: Enami et al., 2004). The protoliths of the Western Iruats body are possibly oceanic materials consisting mainly of basaltic volcaniclastic rocks, pelitic and siliceous sediments and limestones (Kugimiya and Takasu, 2002). In contrast, the protoliths of the Eastern Iruats, Seba and Tonaru bodies are layered gabbros that were derived from mantle wedge or lower crust (Banno et al., 1976). The Western Iruats and other basic bodies suffered prograde metamorphism from the blueschist facies and/or epidote–amphibolite facies to quartz-eclogite facies, and were retrogressively re-equilibrated under the epidote–amphibolite facies conditions during exhumation (e.g., Takasu, 1989; Miyagi and Takasu, 2005). Schistose basic rocks around the Seba body (Fig. 1) rarely contain eclogite assemblages, and are considered to share the same eclogite facies metamorphism with the Seba body (e.g., Naohara and Aoya, 1997; Aoya and Wallis, 1999). Equilibrium \( P-T \) conditions of the eclogite facies stage have been reported to be 1.4–2.5 GPa/550–790 °C for the Western and Eastern Iruats bodies (Ota et al., 2004), 1.2–2.4 GPa/610–640 °C (Aoya, 2001) and 1.8 GPa/520–550 °C (Zaw Win Ko et al., 2005) for the Seba body and >1.5 GPa/700–730 °C for the Tonaru body (Miyagi and Takasu, 2005). Petrologic characteristics of the Sanbagawa eclogitic rocks were briefly summarized by Tsujimori et al. (2000).

These eclogitic bodies have been regarded as tectonic blocks with diverse protoliths and metamorphic \( P-T \) trajectories (Kunugiza et al., 1986; Takasu, 1989; Takasu et al., 1994). In contrast, Wallis and Aoya (2000) proposed that the Seba body and the surrounding schistose basic rocks (Seba eclogite unit) and Iruats body are two parts of a single eclogite facies nappe at the highest structural levels of the Sanbagawa belt. This idea is based on structural and petrological data that show the Seba eclogite unit to overly lower-grade non-eclogitic schists and to occupy the hinge zone of a kilometer-scale synform. Structural data suggests that the base of the Seba unit can be traced to the southern boundary of the Western Iruats body, which may also occupy a similar structural position in a large-scale fold (Hara et al., 1992). Ota et al. (2004), on the other hand, suggested a sandwiched thermobaric structure in which the highest \( P-T \) volume is situated in an intermediate structural level, i.e., in the upper part of the Higashi-akaishi body near the boundary with the Iruats body. The proposed model implies that (i) the eclogitic bodies and the surrounding lower-grade schistose rocks both join the sandwiched structure, and (ii) presumes metamorphic and tectonic continuity between the two lithologies.

A quartz-rich eclogitic lithology (denoted as quartz-eclogite hereafter), that includes the kyanite-bearing assemblages discussed in this paper, occurs as a small (20–100 × 750 m) unit (Fig. 2) along the northeastern margin of the Higashi-akaishi body (Takasu, 1989; Kugimiya and Takasu, 2002). This unit locally contains quartz-free
### Table 2. Mineral assemblages of kyanite-quartz eclogites from the Gongen area, Sanbagawa metamorphic belt

<table>
<thead>
<tr>
<th>Sample</th>
<th>Grt</th>
<th>Omp</th>
<th>Sam</th>
<th>Cam</th>
<th>Ky</th>
<th>Phn</th>
<th>Pa</th>
<th>Ep</th>
<th>Rt</th>
<th>Ab</th>
<th>Kfs</th>
<th>Qtz</th>
<th>Apt</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE1501a</td>
<td>++</td>
<td>+</td>
<td>i, m, s</td>
<td>s</td>
<td>+</td>
<td>++</td>
<td>i, s</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>13-A-17a</td>
<td>++</td>
<td>+</td>
<td>s</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>s</td>
<td>++</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14-A-7</td>
<td>++</td>
<td>+</td>
<td>i, s</td>
<td>i</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>s</td>
<td>s</td>
<td>++</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GO12Y10</td>
<td>++</td>
<td>+</td>
<td>i, s</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>s</td>
<td>++</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>ME75043008</td>
<td>++</td>
<td>+</td>
<td>i, s</td>
<td>s</td>
<td>+</td>
<td>++</td>
<td>i, s</td>
<td>++</td>
<td>s</td>
<td>++</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations are: Grt, garnet; Omp, omphacite; Sam, sodic amphibole; Cam, subcalcic amphibole; Ky, kyanite; Phn, phengite; Pa, paragonite; Ep, epidote; Rt, rutile; Ab, sodic plagioclase; Kfs, K-feldspar; Qtz, quartz; Apt, apatite; ++, at eclogite and epidote-amphibolite facies stages; +, at eclogite facies stage; i, inclusion in eclogite facies phase; m, isolated phase in matrix; s, pseudomorph after eclogite facies phase.

### Table 3. Representative analyses of garnet in kyanite-eclogites from the Gongen area, Sanbagawa metamorphic belt

<table>
<thead>
<tr>
<th>Sample</th>
<th>GE1501a</th>
<th>13-A-17a</th>
<th>14-A-7</th>
<th>GO12Y10</th>
<th>ME75043008</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ISc</td>
<td>ISc</td>
<td>ISc</td>
<td>ISc</td>
<td>ISc</td>
</tr>
<tr>
<td>Si</td>
<td>3.01</td>
<td>3.00</td>
<td>3.00</td>
<td>3.01</td>
<td>3.01</td>
</tr>
<tr>
<td>Ti</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Al</td>
<td>1.98</td>
<td>1.99</td>
<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>Cr</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Fe²⁺</td>
<td>1.63</td>
<td>1.55</td>
<td>1.52</td>
<td>1.57</td>
<td>1.51</td>
</tr>
<tr>
<td>Mn</td>
<td>0.07</td>
<td>0.05</td>
<td>0.02</td>
<td>0.14</td>
<td>0.08</td>
</tr>
<tr>
<td>Mg</td>
<td>0.62</td>
<td>0.78</td>
<td>0.96</td>
<td>0.79</td>
<td>0.80</td>
</tr>
<tr>
<td>Ca</td>
<td>0.68</td>
<td>0.65</td>
<td>0.48</td>
<td>0.54</td>
<td>0.59</td>
</tr>
<tr>
<td>Total</td>
<td>7.99</td>
<td>8.02</td>
<td>7.98</td>
<td>8.01</td>
<td>7.99</td>
</tr>
</tbody>
</table>

*Total iron as FeO.

Abbreviations are: ISc, center of inner segment; ISe, edge of inner segment; OSm, outermost margin of outer segment.
A. Miyamoto, M. Enami, M. Tsuboi and K. Yokoyama

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Maﬁc clots and layers. Bulk-rock compositions of the quartz-eclogite layer (cf., Table 1) are variable in SiO$_2$ (52.9–68.5 wt%), Al$_2$O$_3$ (12.5–15.1 wt%), FeO$^+$ + MgO (8.3–18.1 wt%) and Na$_2$O + K$_2$O (2.4–4.4 wt%), and are similar to those of some Si-poor wacke types (Fig. 3). Okamoto et al. (2004) reported SHRIMP U-Pb ages of 1899 ± 79 Ma and 148134 Ma for the detrital core and 132112 Ma for the metamorphic rim of zircon grains from the quartz-eclogite samples, and interpreted that the eclogite facies metamorphism peaked at 120–110 Ma. The trend of bulk-rock compositions and the presence of detrital zircon grains suggest that the protolith of the quartz-eclogite is a sedimentary mixture of pelitic and basic volcaniclastic materials as proposed by Takasu (1989). Aluminous portions of the quartz-eclogite with Al-index [= Al$_2$O$_3$/(CaO + Na$_2$O + K$_2$O) in mole] over 1.5 show kyanite-bearing assemblages (Table 1).

This study focuses on the kyanite-bearing quartz-eclogites collected from the outcrops near the Houo-Gongen shrine (33°52′44″N, 133°23′12″E: Fig. 2a: sample GE1501a) and along the upper reaches of the Tokonabedani stream (Fig. 2b: samples 13-A-17a, 14-A-7, GO12Y10 and ME75043008) in the Gongen area. Petrological and mineralogical characteristics of samples GE1501a, 14-A-7 and ME75043008 and their equilibrium conditions were briefly discussed by Enami (1996). The peak assemblage of the kyanite-quartz eclogite is garnet, omphacite, kyanite, epidote, phengite, quartz and rutile (Table 2). Glauco- phane/barroisite/pargasite, paragonite and phengite are included in garnet and other eclogitic phases (Figs. 4a and 4b). Omphacite and kyanite are rimmed by aggregates of symplectic barroisite and sodic plagioclase (Fig. 4c) and fine-grained paragonite and phengite (Fig. 4d), respectively. Matrix phengite is usually rimmed by fine-grained

Figure 4. Photomicrographs showing the textural relationships of major phases in kyanite-quartz eclogites from the Gongen area. (a) Garnet porphyroblast including abundant quartz and amphibole grains (ME75043008), (b) glaucophane inclusion partly replaced by barroisite (ME75043008), (c) omphacite rimmed by symplectic aggregates of barroisite and albite (ME75043008), (d) kyanite replaced by a fine-grained aggregate of paragonite and phengite (ME75043008), (e) and (f) garnets partly wrapped by omphacite in samples GO12Y10 and ME75043008, respectively. Abbreviations are: Bar, barroisite; Gln, glaucophane; Sm, symplectic consisting of barroisite and albite. Others are defined in Table 2.
aggregates of paragonite. These pseudomorphs are post-eclogite facies products during exhumation. Possibly secondary K-feldspar occurs as fine-grained aggregate with quartz, amphibole, phengite and albite in 14-A-7.

MINERAL CHEMISTRY

Quantitative analyses and X-ray mapping of major phases were carried out using a JEOL JXA-8800R (WDS + EDS) electron probe micro analyzer at Petrological Laboratory of Nagoya University. Accelerating voltage and specimen current for quantitative analyses were 15 kV and 12 nA on the Faraday cup, respectively. Beam diameter of 5 µm was used for mica and feldspar analyses, and 2–3 µm for analyses of all other phases. Well-characterized natural and synthetic phases were used as standards. The ZAF method was employed for matrix correction. Representative analyses of major phases are listed in Tables 3, 4 and 5.

**Table 4. Representative analyses of omphacite and phengite in kyanite-eclogites from the Gongen area, Sanbagawa metamorphic belt**

<table>
<thead>
<tr>
<th></th>
<th>Omphacite</th>
<th>Phenolite</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GE15</td>
<td>13-A</td>
</tr>
<tr>
<td>SiO₂</td>
<td>55.1</td>
<td>55.5</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.06</td>
<td>0.19</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>11.8</td>
<td>12.6</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>FeO⁺</td>
<td>8.56</td>
<td>8.00</td>
</tr>
<tr>
<td>MnO</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>MgO</td>
<td>5.42</td>
<td>5.65</td>
</tr>
<tr>
<td>BaO</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>CaO</td>
<td>9.36</td>
<td>10.0</td>
</tr>
<tr>
<td>Na₂O</td>
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</tr>
<tr>
<td>K₂O</td>
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<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>99.35</td>
<td>100.51</td>
</tr>
</tbody>
</table>

*Total iron as FeO.
†Calculated values assuming pyroxene formula and charge balance (see text).
Abbreviation is: n.d., not determined.

**Garnet**

All iron of garnet was assumed to be ferrous and end-member proportion (Xᵢ) was calculated as i/(Fe + Mn + Mg + Ca). Garnets belong to the almandine-pyrope series and are Mn-poor (less than 0.05 Xₛₚₚ) and Ca-rich (up to 0.27 Xₐᵣₑ). They show zonal structure with roughly increasing Xₐᵣₑ and decreasing Xₛₚₚ from the crystal center towards margin, are commonly divided into relatively Ca-rich/Mg-poor inner and Ca-poor/Mg-rich outer segments (Figs. 5 and 6). Garnet partly surrounded by a single crystal of omphacite (Figs. 4e and 4f) shows asymmetric zonal structure with the outer segment preserved only towards the matrix-facing side (Figs. 5a, 5b, 5e and 5f). The Xₑᵣₑ value at the edge of the inner segment is variable even in a garnet grain (Figs. 5c and 5d and Figs. 6b and 6c), suggesting discontinuous crystal growth between the formation of inner and outer segments. Chemical compositions are variable from Xₐᵣₑ(0.50–0.55)Xₛₚₚ(0.01–0.03)
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X_{Prp}(0.19-0.28)X_{Grs}(0.21-0.27) in GE1501a to X_{Alm}(0.40-0.55)X_{Sp}(0.01-0.02)X_{Prp}(0.25-0.41)X_{Grs}(0.16-0.22) in 14-A-7 for the inner segment and X_{Alm}(0.51-0.59)X_{Sp}(0.01-0.02)X_{Prp}(0.23-0.30)X_{Grs}(0.16-0.20) in ME75043008 to X_{Alm}(0.46-0.53)X_{Sp}(0.01-0.02)X_{Prp}(0.31-0.36)X_{Grs}(0.14-0.17) in GO12Y10 for the outer segment (Fig. 7 and Table 3). TiO$_2$ and Cr$_2$O$_3$ contents are usually less than 0.1 wt%.

**Phengite**

Phengite occurs as inclusion in omphacite and epidote and as isolated grain in matrix. The inclusion has relatively Si-poor and Na-rich composition with Si = 3.20-3.34 per formula unit (pfu, O = 11) and X$_{Na} = [Na/(Ba + Na + K)] = 0.05-0.19$ compared to that of the matrix phase with Si = 3.26-3.39 pfu and X$_{Na} = 0.04-0.16$ (Fig. 11 and Table 4). Matrix phengite shows zonal structure with relatively celadonite-poor core and celadonite-rich mantle (Fig. 12). Celadonite-rich composition is commonly observed along cracks and cleavages of the matrix phengite implying a secondary enrichment of celadonite component. Phengite pseudomorph after kyanite has distinctly celadonite-poorer (Si = 3.13-3.17 pfu and X$_{Na} = 0.07$) composition than the inclusion and matrix phases. TiO$_2$, Cr$_2$O$_3$ and BaO contents are usually less than 0.9 wt%, 0.2 wt% and 0.3 wt%, respectively.

**Omphacite**

Omphacite shows no systematic compositional zoning other than that in GO12Y10 and ME75043008. In these two samples, the core part is fairly but evidently Si-poorer and jadeite-richer than the mantle part, implying presence of measurable amount of Tschermarkite component (Figs. 8 and 9). Thus Fe$^{3+}$/Fe$^{2+}$ value of omphacite was calculated assuming four cations and six oxygens, and their end member proportions were calculated as follows: $X_{Alm} = \frac{1}{2}Al - \frac{1}{2}Al$, $X_{Sp} = Fe^{3+}$ and $X_{Sp} = 1 - (X_{Alm} + X_{Aeg})$. Chemical compositions are variable from $X_{Alm}(0.24-0.34)$ $X_{Sp}(0.56-0.64)$ $X_{Aeg}(0.07-0.16)$ and Mg$^+$ = [Mg/(Mg + Fe$^{2+}$): 0.75-0.87] in 14-A-7 and $X_{Alm}(0.40-0.53)$ $X_{Sp}(0.32-0.43)$ $X_{Aeg}(0.04-0.25)$ and Mg$^+$ = [Mg/(Mg + Fe$^{2+}$): 0.63-0.83] in ME75043008 (Fig. 10 and Table 4). TiO$_2$ and Cr$_2$O$_3$ contents are usually less than 0.3 wt% and 0.1 wt%, respectively.

**Table 5.** Representative analyses of amphibole in kyanite-bearing quartz eclogites from the Gongen area, Sanbagawa metamorphic belt

<table>
<thead>
<tr>
<th></th>
<th>GE1501a</th>
<th>14-A-7</th>
<th>GO12Y10</th>
<th>ME75043008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>5.74</td>
<td>7.30</td>
<td>6.50</td>
<td>6.16</td>
</tr>
<tr>
<td>Ti</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Al</td>
<td>1.59</td>
<td>1.65</td>
<td>1.99</td>
<td>2.93</td>
</tr>
<tr>
<td>Cr</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>Fe$^{3+}$</td>
<td>0.22</td>
<td>0.08</td>
<td>0.47</td>
<td>0.51</td>
</tr>
<tr>
<td>Fe$^{2+}$</td>
<td>0.97</td>
<td>0.27</td>
<td>0.96</td>
<td>0.57</td>
</tr>
<tr>
<td>Mg</td>
<td>2.66</td>
<td>2.97</td>
<td>2.86</td>
<td>3.44</td>
</tr>
<tr>
<td>Ca</td>
<td>1.02</td>
<td>0.78</td>
<td>1.59</td>
<td>1.61</td>
</tr>
<tr>
<td>Na</td>
<td>1.01</td>
<td>0.34</td>
<td>0.86</td>
<td>0.87</td>
</tr>
<tr>
<td>K</td>
<td>0.05</td>
<td>0.04</td>
<td>0.13</td>
<td>0.14</td>
</tr>
<tr>
<td>Mg#</td>
<td>0.73</td>
<td>0.92</td>
<td>0.78</td>
<td>0.72</td>
</tr>
<tr>
<td>Total</td>
<td>15.07</td>
<td>15.15</td>
<td>15.57</td>
<td>15.62</td>
</tr>
<tr>
<td>Mg$^+$</td>
<td>0.73</td>
<td>0.92</td>
<td>0.78</td>
<td>0.72</td>
</tr>
</tbody>
</table>

1 Total iron as FeO.
2 Calculated values (see text).
Abbreviations are: ICo, inclusion in omphacite; Mx, matrix; Smp, symplectite; ICg, inclusion in garnet.

* $X_{Alm}(0.40-0.55)$ and $X_{Sp}(0.01-0.02)$ in GE1501a to $X_{Alm}(0.40-0.55)$ and $X_{Sp}(0.01-0.02)$ in 14-A-7 for the inner segment and $X_{Alm}(0.51-0.59)$ and $X_{Sp}(0.01-0.02)$ in ME75043008 to $X_{Alm}(0.46-0.53)$ and $X_{Sp}(0.01-0.02)$ in GO12Y10 for the outer segment (Fig. 7 and Table 3). TiO$_2$ and Cr$_2$O$_3$ contents are usually less than 0.3 wt% and 0.1 wt%, respectively.

* $X_{Alm}(0.24-0.34)$ and $X_{Sp}(0.56-0.64)$ in 14-A-7 and $X_{Alm}(0.40-0.53)$ and $X_{Sp}(0.32-0.43)$ in ME75043008 (Fig. 10 and Table 4). TiO$_2$ and Cr$_2$O$_3$ contents are usually less than 0.3 wt% and 0.1 wt%, respectively.
Amphibole

Amphibole nomenclature follows Leake et al. (1997) and $\text{Fe}^{3+}/\text{Fe}^{2+}$ values were calculated with total cations = 13 excluding Ca, Na and K ($O = 23$). This is based on the fact that $(\text{Fe}^{3+} + \text{Mn} + \text{Mg})$ contents in the B-sites of amphibole are usually low in high P/low T metamorphic rocks (Deer et al., 1997). Amphiboles included in garnet were found in sample ME75043008, and most of them are sodic amphiboles with $X_{\text{Al}} [= \frac{[6]\text{Al}}{[6]\text{Al} + \text{Fe}^{3+}}] = 0.64-0.73$ and Mg$\#$ = 0.84-0.90. The sodic amphibole inclusions are usually associated with cracks and are partly replaced by secondary barroisite (Figs. 4b and 13d and Table 5). Omphacite usually includes winchite/barroisite/kataphorite with Si = 6.64-7.54 pfu, $[\text{Na}] = 0.59-1.09$ pfu and $[\text{Al}](\text{Na} + \text{K}) = 0.07-0.60$ pfu (Figs. 13a-13c). In sam-

Figure 5. X-ray mapping images of garnet in kyanite-quartz eclogites from the Gongen area. (a) and (b): garnet partly wrapped by omphacite in 13-17a, (c) and (d): garnet porphyroblast in GO12Y10, and (e) and (f): garnet partly wrapped by omphacite in GO12Y10 and ME75043008, respectively. Abbreviations are: IS, inner segment; OS, outer segment. Others are defined in Table 2.
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Figure 6. Composition profiles of garnet in kyanite-quartz eclogites (a: 13-A-17a; b and c: GO12Y10) from the Gongen area. Positions of step-scan analyses are shown in Fig. 5. Abbreviations are: Alm, almandine; Sps, spessartine; Prp, pyrope; Grs, grossular.

P-T ESTIMATES AND DISCUSSION

Choice of equilibrium compositions

Garnet in the kyanite-bearing quartz eclogites shows composite zoning with chemically and texturally distinct inner and outer segments. The inner segment is sub-rounded with irregular embayments, and edge of the inner segment shows variable composition from one point to another. These chemical and textural characteristics suggest the inner segment was resorbed before overgrowth of the outer segment. The development of outer segment is common in the matrix-facing side of garnet, and is weak and/or absent in omphacite-facing side (Fig. 5). Thus we considered that (i) the inner segment has formed in equilibrium with omphacite during eclogite facies metamorphism, and (ii) the outer segment was a product after resorption of the inner segment during exhumation. The presumed two stages of garnet growth are consistent with the P-T trajectory proposed by Aoya (2001) and Zaw Win Ko et al. (2005) that the Sanbagawa eclogite lithologies were (i) juxtaposed with subducting non-eclogite lithologies during exhumation and then (ii) progressively recrystallized under the epidote-amphibolite facies together with the surrounding non-eclogite lithologies. Thus we assume that (i) the Mg-richest composition at the edge of inner segment represents the climax of eclogite facies stage, and (ii) the outer segment formed during the epidote-amphibolite facies stage.

Omphacite grains in samples GE1501a and 14-A-7 show no systematic chemical zoning, and average composition in each sample is employed for the P-T estimation. In the case of zoned omphacite in samples GO12Y10 and ME75043008, the Si-poor core is in direct contact with the inner segment of garnet that formed during the eclogite facies stage (Figs. 8e and 8f). Thus we consider that the Si-poorer core of zoned omphacite in these two samples represents the climax of the eclogite faces metamorphism and the Si-richer mantle indicate compositional modification during an early stage of exhumation.

Phengite in the matrix is compositionally zoned with relatively Si-richer and X_{Na}\_poorer rim, and has higher celadonite content than that included in garnet, omphacite and epidote. A local increase of celadonite
content is also observed along cracks and/or cleavage (Fig. 12). Similar relationship between the mode of occurrence and chemical composition of phengite has been reported from an eclogite in the Kotsu area, eastern Shikoku (Matsumoto et al., 2003). In the Kotsu eclogite phengite grains lying within the schistosity show a distinct chemical zonation with the celadonite-rich rim composition close to the composition of the phengite replacing the garnet and a more celadonite-poor core. Thus we infer that the celadonite-rich part records reequilibration during exhumation and/or subsequent epidote-amphibolite facies stage, and relatively celadonite-poorer core of matrix phase and inclusions in garnet and other phases preserve the composition of the eclogite facies stage.

Geothermobarometry

Waters and Martin (1993) presented a geobarometer for the common eclogitic mineral assemblage of garnet + clinopyroxene + phengite via the reaction

$$\text{6diopside} + 3\text{muscovite} = 2\text{grossular} + \text{pyrope} + 3\text{celadonite}$$

(1).

This barometer has a shallow $dP/dT$ slope, and has shown to be successful for phengite-bearing high pressure (HP) and ultrahigh-pressure (UHP) eclogites. Sharp et al. (1992) and Nakamura and Banno (1997) applied the equilibrium

$$\text{3diopside} + 2\text{kyanite} = \text{grossular} + \text{pyrope} + 2\text{SiO}_2$$

(2) to constrain the pressure for kimberlite xenoliths and UHP metamorphic rocks, respectively. Krogh Ravna and Terry (2004) proposed a set of net transfer reactions as a new geothermobarometer for kyanite-phengite-quartz/coesite eclogite, combining reactions (1) and (2) with

$$\text{pyrope} + 3\text{muscovite} + 4\text{SiO}_2 = 3\text{celadonite} + 4\text{kyanite}$$

(3).

They pointed out that this method could possibly minimalize the effect of uncertainties of $\text{Fe}^{2+}/\text{Fe}^{3+}$ estimations in clinopyroxene on the $P-T$ calibrations and give the most reliable results. We applied the garnet-clinopyroxene-kyanite-phengite-SiO$_2$ (GCKPQ) geothermobarometer to the Sanbagawa kyanite-quartz eclogites together with the garnet-clinopyroxene (Grt-Cpx) geothermometer (Krogh Ravna, 2000).

The GCKPQ geothermobarometer yields a narrow $P-T$ range of 2.3-2.4 GPa/675-740 °C as peak conditions using dataset listed in Tables 3 and 4 (Fig. 14). This $P-T$ estimations are consistent with the occurrence of paragonite inclusion in garnet and omphacite. The combination of the reaction (1) and Grt-Cpx geothermometer (GCPQ), that has been extensively employed for the $P-T$ estimation of HP rocks (e.g., Carswell et al., 1997; Cuthbert et al., 2000; Nowlan et al., 2000), gives slightly more scattered
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**CONCLUSIONS**

Enami (1996) and Ota et al. (2004) reported \( P-T \) conditions of 1.9-2.6 GPa/700-760 °C for the kyanite-quartz eclogite and 1.4-2.5 GPa/550-790 °C for eclogite assemblages from the Western and Eastern Iratsu bodies, respectively. These \( P-T \) estimates are on average slightly lower than the present \( P-T \) estimations (Fig. 14). The former authors assumed that the pyrope-richest outermost rim of garnet represents the climax of the eclogitic facies stage. However, in this paper it is shown that (i) garnet in the kyanite-quartz eclogite usually has complex zoning, and (ii) outer segment of garnet was produced after the

\( P-T \) conditions of \( 2.2-2.5 \) GPa/665-830 °C than the GCKPQ geothermobarometer.

*Figure 8.* X-ray mapping images of omphacite in kyanite-quartz eclogites (a-d: ME75043008; e and f: GO12Y10) from the Gongen area. Numbers in Figure 8e indicate Si content (pfu for O = 6). Abbreviations are defined in Table 2.
Figure 9. Composition profile of zoned omphacite in a kyanite-quartz eclogite (ME75043008) from the Gongen area. Positions of step-scan analyses are shown in Figure 8. Abbreviations are: Aug, augite; Jd, jadeite; Aeg, aegirine.

Figure 10. Chemical compositions of omphacite in kyanite-quartz eclogites from the Gongen area. Abbreviations are defined in Figure 9.

Figure 11. Chemical compositions of phengite in kyanite-quartz eclogites from the Gongen area.

eclogite facies stage and is therefore not in equilibrium with omphacite and other eclogitic phases. Such a multiple growth of garnet is common in eclogites from the Western and Eastern Iratsu bodies (Takasu and Kohsaka, 1987; Miyamoto, 1999; Inui and Toriumi, 2002; T. Ohama and S. Endo, personal communication 2006) and Seba body (Zaw Win Ko et al., 2005). As concerning samples studied in this paper, using the outermost rim composition for the P-T estimations would yield results 0.1-0.5 GPa/15-130 °C lower than those actually considered as the most reliable. Thus, former P-T estimates ranging towards the lower P-T side may be caused by the dataset including inappropriate garnet composition. We cannot deny the possibility of a systematic and areal P-T change of the eclogite assemblages in the Besshi region proposed by Ota et al. (2004). The thermobaric structure in the high grade area of the Sanbagawa metamorphic belt, however, should be carefully reviewed including systematic checks of compositional heterogeneities of garnet and other peak phases.
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SUPPLEMENTARY MATERIAL

Color versions of Figures 4, 5, 8 and 12 are available online from http://www.jstage.jst.go.jp/browse/jmps.
REFERENCES


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