Formation of corundum in direct contact with quartz and biotite in clockwise $P$–$T$ trajectory from the Sør Rondane Mountains, East Antarctica

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We have found corundum in direct contact with quartz and biotite as inclusions within garnet porphyroblasts in the pelitic gneisses of the Sør Rondane Mountains (SRM), East Antarctica. Our samples, which include corundum-bearing gneisses, show petrographic features such as staurolite inclusions in garnet, compositional zoning of orthoamphibole with Al decreasing toward the rims, and late-stage cordierite formation, and these features are characteristic of a clockwise $P$–$T$ trajectory. The observations are consistent with the proposed regional clockwise $P$–$T$ evolution of the NE Terrane in the SRM. The corundum and other inclusions observed in the garnet porphyroblasts are interpreted to have formed owing to either staurolite breakdown or metastable crystallization relative to kyanite prior to the peak metamorphism. The close association of biotite and quartz surrounding corundum inclusions suggests fluid- or melt-related processes. These petrographic features imply that the corundum and quartz (rarely observed in high-grade metamorphic rocks) formed as a result of metastable crystallization during the prograde stage of the clockwise $P$–$T$ evolution of a continental collision zone.

Keywords: Corundum–quartz–biotite, High-$T$ metamorphism, Sør Rondane Mountains, Dronning Maud Land, Antarctica

INTRODUCTION

The corundum + quartz association is rare but usually found in high-grade metamorphic rocks (e.g., Motoyoshi et al., 1990; Guiraud et al., 1996; Shaw and Arima, 1998; Mouri et al., 2003, 2004; Tsunogae and van Reenen, 2006; Kihle et al., 2010; Kato et al., 2011; Nakano et al., 2018). Nevertheless, the tectonic settings and ages of occurrences vary and include both isobaric cooling and isothermal decompression terranes with Archean to Paleozoic ages, and previous researchers have commonly suggested peak metamorphism under high to ultra-high temperatures and dry conditions (e.g., Mouri et al., 2004 and references therein). There has also been a series of debates on the occurrence and mineral paragenesis of the stable or metastable ‘corundum + quartz’ assemblage. According to currently available thermodynamic data (e.g., Berman, 1988; Holland and Powell, 1998) and considering experimental constraints (e.g., Harlov and Newton, 1993; Harlov and Milke, 2002; Harlov et al., 2008), corundum + quartz is a metastable mineral assemblage relative to both sillimanite and kyanite (e.g., Harlov et al., 2008; Kato et al., 2011).

We have found corundum in direct contact with quartz and biotite as inclusions within garnet porphyroblasts in the pelitic gneisses of the Sør Rondane Mountains (SRM), East Antarctica. The area is thought to be part of a continental collision zone that formed during formation of the Gondwana Supercontinent during the Neoproterozoic-
Early Cambrian (e.g., Osanai et al., 2013). The studied samples show clear petrographic features that characterize a clockwise pressure-temperature (P-T) trajectory. The corundum + quartz assemblage in high-grade metamorphic rocks (Mouri et al., 2004; Kato et al., 2011; and references therein) has usually been described in anhydrous rocks; however, our newly found corundum + quartz inclusions are closely associated with biotite. Therefore, in this paper we describe the petrographic features of the corundum-bearing textures in our samples and discuss the reactions implied. In particular, we consider the implications for corundum + quartz formation and stability in high-grade metamorphic rocks in the presence of hydrous biotite, and in rocks where there is clear petrographic evidence for a clockwise metamorphic P-T trajectory.

GEOLOGICAL SETTING AND SAMPLE LOCALITY

The SRM is located within the Antarctica part of the Neoproterozoic–Cambrian collision zones between the E and W Gondwana continents (Fig. 1a; Meert, 2003). On Antarctica, exposures of rock are limited due to the thick ice sheet, but the SRM is one mountainous area where basement rocks are widely exposed (Fig. 1b). The SRM area is divided into Northeastern (NE) and Southwestern (SW) terranes by the Main Tectonic Boundary (MTB; Osanai et al., 2013; Fig. 1c). The NE and SW terranes present contrasting P-T evolutions, with a clockwise P-T trajectory in the NE Terrane and a counterclockwise P-T trajectory in the SW Terrane (Adachi et al., 2013a; Grantham et al., 2013; Higashino et al., 2013; Kawakami et al., 2017; and references therein). U-Pb zircon studies have shown that the NE Terrane contains crustal materials as old as 3200–640 Ma, whereas the SW Terrane contains crustal materials younger than ~1200 Ma. An exception is the Tvihøgda area, which is the southernmost exposure of the SRM, but the geology of this area remains poorly understood (e.g., Adachi et al., 2013b; Kitano et al., 2016; and references therein). Both the NE and SW terranes underwent high-grade metamorphism during 630–550 Ma.

The northern Austkampane area is located within the granulite-facies zone of the NE Terrane (Osanai et al., 2013; Fig. 1c), where our pelitic rock sample with corundum + quartz, along with two other pelitic samples described in this manuscript were collected. Felsic orthogneisses (hornblende + biotite ± orthopyroxene) and pelitic gneisses (garnet + biotite, garnet + biotite + sillimanite) are dominant in the area, together with layers, blocks, and lenses of amphibolite, mafic granulite, marble, and calc-silicate gneiss. Later-stage granitic and pegmatic intrusions are present throughout the area.

Figure 1. (a) East Antarctica and neighboring continents in a reconstruction of Gondwana at ~500 Ma (modified after Meert, 2003). (b) Major geographic and geological domains within Dronning Maud Land and Enderby Land of East Antarctica (Shiraishi et al., 2008; Dunkley et al., 2020), and location of the study area (dashed line box). (c) Distribution of outcrops and geological divisions in the SRM (modified after Osanai et al., 2013 and Mieth et al., 2014). The star indicates the location of the sample site. SRS, Sør Rondane Suture; MSZ, Main Shear Zone; MTB(O), the Main Tectonic Boundary after Osanai et al. (2013); MTB(M), the Main Tectonic Boundary modified by Mieth et al. (2014). The Main Tectonic Boundary separates the area into a CW Zone with a clockwise metamorphic P-T path and a CCW Zone with a counterclockwise metamorphic P-T path.
semblages are combinations of the following: quartz, plagioclase, K-feldspar, garnet, sillimanite, and cordierite (Fig. 3a). Spinel and corundum occur as inclusions in the garnet. Rutile, ilmenite, apatite, zircon, and monazite are minor constituents in the matrix. Porphyroblastic garnet grains in the gneiss show weak compositional zoning with increasing alm, grs, and sps and decreasing prp toward the rims (core alm0.64prp0.32grs0.02sps0.02 and rim alm0.73prp0.21grs0.03sps0.03; Fig. 4; see Table 2 for abbreviations). Quartz, biotite, sillimanite, rutile, ilmenite, spinel, and rare corundum occur as inclusions in garnet crystals, as will be discussed below. Sillimanite occurs either as prismatic grains or aggregates of fibrolite in association with biotite in the matrix. In many cases, cordierite is distributed around garnet porphyroblasts or in cracks within garnet. The garnet porphyroblasts contain rare inclusions of sillimanite-cordierite-spinel (Fig. 5b).

Two corundum-bearing inclusions were found in a single porphyroblastic garnet crystal (Fig. 5). The corundum-bearing inclusions occur in the prp-rich core of the garnet (Fig. 4). Quartz, biotite, rutile, ilmenite, sillimanite, and spinel inclusions occur in nearby areas of the garnet crystal. The corundum grains are in direct contact with quartz and biotite (Figs. 5c–5f). In one of the inclusion domains, euhedral corundum grains occur between quartz and biotite (Figs. 5d and 5f). Tiny quartz grains, as inferred from X-ray mapping, also occur in the euhedral corundum. The corundum contains minor amounts of Cr2O3 (<0.2 wt%) and Fe2O3 (<0.7 wt%). An aggregate of cordierite + sillimanite + spinel + biotite + quartz forms another peculiar inclusion (Fig. 5b) in the same garnet porphyroblasts, in which spinel is included in sillimanite but is not in direct contact with quartz. The corundum in this aggregate has an extremely Mg-rich composition ([Mg/(Mg + Fe) = 0.84–0.85], which is in marked contrast to other inferred retrograde cordierite grains ([Mg/(Mg + Fe) = 0.64–0.65]).

Biotite grains associated with the corundum and quartz in the garnet have relatively high Mg/(Mg + Fe) and F contents and low Ti contents [Mg/(Mg + Fe) =

The main constituent minerals of corundum-bearing pelitic gneiss AC07121801E are quartz, plagioclase, K-feldspar, biotite, garnet, sillimanite, and cordierite (Fig. 3a). Spinel and corundum occur as inclusions in the garnet. Rutile, ilmenite, apatite, zircon, and monazite are minor constituents in the matrix. Porphyroblastic garnet grains in the gneiss show weak compositional zoning with increasing alm, grs, and sps and decreasing prp toward the rims (core alm0.64prp0.32grs0.02sps0.02 and rim alm0.73prp0.21grs0.03sps0.03; Fig. 4; see Table 2 for abbreviations). Quartz, biotite, sillimanite, rutile, ilmenite, spinel, and rare corundum occur as inclusions in garnet crystals, as will be discussed below. Sillimanite occurs either as prismatic grains or aggregates of fibrolite in association with biotite in the matrix. In many cases, cordierite is distributed around garnet porphyroblasts or in cracks within garnet. The garnet porphyroblasts contain rare inclusions of sillimanite-cordierite-spinel (Fig. 5b).

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**PETROGRAPHY AND MINERAL CHEMISTRY**

The chemical compositions of the constituent minerals were measured using an electron microprobe JEOL JXA-8200 with five channel wavelength dispersive spectroscopy (WDS) at the National Institute of Polar Research, Tokyo, Japan. Synthetic oxides and natural minerals were used as standards for calibration. The analytical conditions for the quantitative analyses were a 15 kV accelerating voltage, a probe current of 12 nA, and a 2 µm probe diameter.

**Table 1. Constituent minerals in samples AC07121801E, I, K, and U**

| Sample No.                  | Lithology                  | Qtz | Pl  | Kfs | Bt  | Grt | Sil | Crd | Spl | Crn | Oam | St  | Accessory |
|-----------------------------|----------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----------|
| Corundum+quartz-bearing sample | AC07121801E                | ++  | +   | ++  | ++  | ++  | ++  | ++  | i   | i   |     |     | Zrn, Mnz, Ap, Rt, Ilm |
| Other samples               | AC07121801I                | ++  | +   | ++  | ++  | ++  | ++  |     |     |     |     |     | Zrn, Mnz, Ap, Rt, Ilm |
| AC07121801K                 | Grt-Bt-Crd-Oam gneiss      | ++  | +   | ++  | ++  | +   | ++  |     |     | i   |     |     | Zrn, Mnz, Ap, Rt, Ilm |
| AC07121801U                 | Pegmatite vein             | ++  | +   | ++  | ++  | ++  |     |     |     |     |     |     | Mnz       |

Mineral abbreviations follow Kretz (1983). ++, present; +, minor; i, inclusion.
of garnet and sillimanite. Most of the spinel crystals are included in garnet (Figs. 5b, 5d, and 5f), and they show a wide range of compositions [Fig. 7a; Mg/(Mg + Fe) = 0.44–0.51, ZnO = 8.4–18.2 wt%]. A few spinel crystals occur as inclusions in sillimanite, and they have relatively Fe-rich [Mg/(Mg + Fe) = 0.37–0.38] and extremely ZnO-rich compositions (ZnO = 22.8–24.2 wt%).

Other pelitic samples (AC07121801I and AC07121801K) that are interlayered with the corundum-bearing pelitic gneiss show orthoamphibole-bearing mineral assemblages and (in AC07121801K) staurolite inclusions in garnet (Table 1 and Fig. 8). Representative mineral compositions for these samples are listed in Table 2, and the compositions are similar to those in corundum-bearing sample AC07121801E. The staurolite inclusion (in garnet) in AC07120801K has ZnO = 0.9–1.4 wt% and Mg/(Mg + Fe) = 0.26–0.29 (Table 2). The orthoamphi-
boles in AC07121801I and AC07121801K show strong chemical zoning from high-Al cores (Al2O3 = 7–17 wt%) to low-Al rims (Al2O3 = 1–4 wt%; Fig. 7b).

METAMORPHIC P–T EVOLUTION AND CORUNDUM FORMATION

The NE Terrane of the SRM, where our samples were collected, is characterized by a clockwise P–T metamorphic evolutionary path that contrasts with the counter-clockwise P–T path of the SW Terrane (e.g., Adachi et al., 2013a; Baba et al., 2013; Osanai et al., 2013). Adachi et al. (2013a) evaluated the P–T evolution of pelitic samples from the northern Austkampane area, including a sample from our sampling location (AC07121801M of Adachi et al., 2013a), and they estimated the peak meta-
morphic conditions to have been 770–780 °C and 0.4–0.5 GPa. They inferred near-peak decompression followed by isobaric cooling and further late-stage decompression (Fig. 9).

As described above, the mineral assemblages in the matrix of our pelitic samples are garnet + sillimanite + biotite + cordierite (in AC07121801E) and garnet + orthoamphibole + biotite + cordierite (in AC07121801I and AC07121801K). Rare staurolite inclusions (in AC07121801K) and abundant Zn-bearing spinel inclusions in garnet (in AC07121801E, I, and K) suggest early stage staurolite decomposition through the following re-

Table 2. Representative analyses of constituent minerals in samples AC07121801E, I, and K

| Sample        | AC07121801 E | AC07121801 I | AC07121801 K |
|---------------|--------------|--------------|--------------|
| Mineral       | Crn | Crn | Grt | Grt | Spl | Spl | Crd | Crd | Bt | Bt |
| Spot 1        | 16  | 23  | 24  | 1   | 14  | 8   | 25  | 7   | 10 |
| SiO₂           | 0.09 | 0.03 | 38.99 | 37.94 | 0.00 | 0.05 | 49.62 | 48.84 | 40.17 | 38.81 |
| TiO₂           | 0.03 | 0.04 | 0.02 | 0.07 | 0.03 | 0.00 | 0.05 | 0.00 | 1.33 | 1.77 |
| Al₂O₃          | 99.95 | 99.24 | 22.06 | 21.96 | 62.26 | 58.00 | 33.51 | 33.17 | 17.99 | 17.81 |
| Cr₂O₃          | 0.08 | 0.12 | 0.01 | 0.05 | 0.44 | 2.74 | 0.04 | 0.00 | 0.00 | 0.19 |
| FeO*           | 0.46 | 0.37 | 30.17 | 33.73 | 16.60 | 12.28 | 3.77 | 7.88 | 9.66 | 10.07 |
| MnO            | 0.14 | 0.00 | 0.77 | 1.89 | 0.00 | 0.11 | 0.04 | 0.16 | 0.01 | 0.00 |
| MgO            | 0.00 | 0.00 | 8.32 | 3.68 | 7.61 | 4.21 | 11.44 | 8.54 | 18.62 | 17.96 |
| ZnO            | n.d. | n.d. | n.d. | 13.95 | 22.78 | n.d. | n.d. | n.d. | n.d. | n.d. |
| CaO            | 0.00 | 0.02 | 1.05 | 1.11 | 0.00 | 0.03 | 0.02 | 0.01 | 0.01 | 0.00 |
| Na₂O           | 0.00 | 0.00 | 0.00 | 0.00 | n.d. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| K₂O            | 0.01 | 0.02 | 0.02 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 8.41 | 8.80 |
| F               | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | 0.50 | 0.53 |
| Cl              | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | 0.34 | 0.37 |
| (–O)           | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | –0.29 | –0.31 |
| Total (wt%)    | 100.77 | 99.83 | 101.39 | 100.43 | 100.89 | 100.17 | 98.68 | 98.81 | 97.31 | 96.42 |
| Number of O    | 3   | 3   | 12  | 12  | 4   | 4   | 18  | 18  | 22  | 22  |
| Si              | 0.002 | 0.000 | 2.990 | 3.008 | 2.900 | 4.998 | 4.995 | 5.661 | 5.573 |
| Ti              | 0.000 | 0.001 | 0.001 | 0.004 | 0.001 | 0.000 | 0.004 | 0.000 | 0.141 | 0.191 |
| Al              | 1.989 | 1.991 | 1.994 | 2.052 | 2.003 | 1.951 | 3.971 | 3.998 | 2.988 | 3.014 |
| Cr              | 0.001 | 0.002 | 0.000 | 0.003 | 0.009 | 0.062 | 0.003 | 0.000 | 0.000 | 0.021 |
| Fe*             | 0.007 | 0.005 | 1.935 | 2.237 | 0.379 | 0.293 | 0.317 | 0.674 | 1.139 | 1.209 |
| Mn              | 0.002 | 0.000 | 0.050 | 0.127 | 0.000 | 0.003 | 0.003 | 0.013 | 0.002 | 0.000 |
| Mg              | 0.000 | 0.000 | 0.951 | 0.435 | 0.309 | 0.179 | 1.714 | 1.303 | 3.911 | 3.843 |
| Zn              | n.d. | n.d. | n.d. | n.d. | 0.281 | 0.480 | n.d. | n.d. | 0.000 | 0.000 |
| Ca              | 0.000 | 0.000 | 0.086 | 0.094 | 0.000 | 0.000 | 0.003 | 0.002 | 0.001 | 0.000 |
| Na              | 0.000 | 0.000 | 0.000 | 0.000 | n.d. | 0.000 | 0.033 | 0.041 | 0.155 | 0.199 |
| K               | 0.000 | 0.000 | 0.002 | 0.000 | 0.000 | 0.002 | 0.000 | 0.000 | 1.511 | 1.613 |
| F               | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | 0.220 | 0.236 |
| Cl              | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | 0.080 | 0.089 |
| Total cation    | 2.001 | 2.000 | 8.009 | 7.960 | 2.983 | 2.970 | 11.038 | 11.025 | 15.809 | 15.908 |
| X(Mg)           | 0.330 | 0.163 | 0.449 | 0.379 | 0.844 | 0.659 | 0.774 | 0.761 |
| X(Zn)           | 0.290 | 0.504 |
| Alm             | 0.640 | 0.773 |
| Sps             | 0.016 | 0.044 |
| Prp             | 0.315 | 0.150 |
| Grs             | 0.029 | 0.033 |
Mineral abbreviations follow Kretz (1983):

St + Qtz = Grt + Sil ± Spl + H₂O.

The garnets are commonly surrounded by cordierite coronae (Fig. 4a), indicative of the following reactions:

Grt + Sil + Qtz + H₂O = Crd

### Table 2. (Continued)

|       | AC07121801 |       | AC07121801 |       |
|-------|------------|-------|------------|-------|
|       | I          | K      |            |       |
| Bt    | Bt         | Grt   | Grt        | Oam   |
| 61    | 27         | 37    | 40         | 14    | 3     | 16    | 38 | 9 | 55 | 60 |
|       | in Grt     | in matrix |       | in matrix |       | in Grt | in Grt | in Sil | in matrix |
|       | 37.76      | 35.80  | 38.81      | 39.18  | 49.29  | 49.82  | 45.25 | 26.44 | 0.05 | 0.01 | 49.23 |
|       | 1.36       | 2.25   | 0.02       | 0.03   | 0.00   | 0.25   | 0.02  | 0.42  | 0.02 | 0.00 | 0.00  |
|       | 18.74      | 18.91  | 22.01      | 21.99  | 33.06  | 8.14   | 2.52  | 55.17 | 62.49 | 59.51 | 33.23 |
|       | 0.12       | 0.11   | 0.07       | 0.07   | 0.01   | 0.02   | 0.00  | 0.08  | 0.33 | 0.85 | 0.00  |
|       | 14.00      | 19.38  | 31.24      | 31.38  | 5.66   | 21.55  | 22.37 | 11.39 | 23.56 | 23.26 | 5.40  |
|       | 0.00       | 0.07   | 1.90       | 1.77   | 0.06   | 0.37   | 0.33  | 0.00  | 0.00 | 0.12 | 0.02  |
|       | 15.01      | 10.27  | 6.20       | 5.14   | 10.10  | 16.49  | 18.52 | 2.50  | 8.46  | 4.31  | 10.42 |
|       | n.d.       | n.d.   | n.d.       | n.d.   | n.d.   | n.d.   |       | 1.15  | 5.48  | 12.04 | n.d.  |
|       | 0.00       | 0.00   | 1.01       | 1.30   | 0.00   | 0.31   | 0.18  | 0.00  | 0.00 | 0.01 | 0.03  |
|       | 0.45       | 0.38   | 0.02       | 0.02   | 0.17   | 0.86   | 0.22  | n.d.  | n.d. | n.d. | 0.07  |
|       | 8.74       | 9.19   | 0.01       | 0.00   | 0.00   | 0.00   | 0.00  | 0.01  | 0.00 | 0.02 | 0.02  |
|       | 0.45       | 0.18   | n.d.       | n.d.   | n.d.   | 0.12   | 0.15  | n.d.  | n.d. | n.d. | n.d.  |
|       | 0.38       | 0.38   | n.d.       | n.d.   | n.d.   | 0.02   | 0.01  | n.d.  | n.d. | n.d. | n.d.  |
|       | −0.28      | −0.16  | n.d.       | n.d.   | n.d.   | −0.05  | −0.06 | n.d.  | n.d. | n.d. | n.d.  |
|       | 96.73      | 96.75  | 101.28     | 100.88 | 98.35  | 97.882 | 98.499| 97.16 | 100.38 | 100.12 | 98.41 |

|       | 22         | 22     | 12         | 12     | 18     | 23     | 23     | 46   | 4    | 4     | 18    |
|       | 5.497      | 5.382  | 3.010      | 3.049  | 5.011  | 7.222  | 7.788  | 7.348 | 0.001 | 0.000 | 4.994 |
|       | 0.149      | 0.254  | 0.001      | 0.002  | 0.000  | 0.027  | 0.002  | 0.087 | 0.000 | 0.000 | 0.000 |
|       | 3.217      | 3.351  | 2.012      | 2.018  | 3.962  | 1.391  | 0.427  | 18.070| 1.997 | 1.981 | 3.973 |
|       | 0.014      | 0.013  | 0.004      | 0.004  | 0.001  | 0.002  | 0.000  | 0.018 | 0.007 | 0.019 | 0.000 |
|       | 1.705      | 2.437  | 2.026      | 2.043  | 0.481  | 2.613  | 2.685  | 2.646 | 0.534 | 0.549 | 0.458 |
|       | 0.000      | 0.009  | 0.125      | 0.117  | 0.005  | 0.045  | 0.041  | 0.000 | 0.000 | 0.003 | 0.001 |
|       | 3.257      | 2.300  | 0.717      | 0.596  | 1.531  | 3.564  | 3.963  | 1.036 | 0.342 | 0.182 | 1.575 |
|       | 0.000      | 0.000  | n.d.       | n.d.   | n.d.   | n.d.   | 0.236  | 0.110 | 0.251 | n.d.  |       |
|       | 0.000      | 0.000  | 0.084      | 0.108  | 0.000  | 0.048  | 0.027  | 0.000 | 0.000 | 0.000 | 0.004 |
|       | 0.127      | 0.110  | 0.003      | 0.003  | 0.033  | 0.242  | 0.061  | n.d.  | n.d. | n.d. | 0.014 |
|       | 1.623      | 1.762  | 0.001      | 0.000  | 0.000  | 0.000  | 0.000  | 0.003 | 0.000 | 0.001 | 0.002 |
|       | 0.206      | 0.085  | n.d.       | n.d.   | n.d.   | 0.05   | 0.07   | n.d.  | n.d. | n.d. | n.d.  |
|       | 0.093      | 0.095  | n.d.       | n.d.   | n.d.   | 0.00   | 0.00   | n.d.  | n.d. | n.d. | n.d.  |
|       | 15.888     | 15.798 | 7.983      | 7.940  | 11.024 | 15.21  | 15.06  | 29.444| 2.992 | 2.987 | 11.022 |
|       | 0.656      | 0.486  | 0.261      | 0.226  | 0.761  | 0.577  | 0.596  | 0.281 | 0.390 | 0.248 | 0.775 |
|       | 0.686      | 0.713  | 0.042      | 0.041  | 0.243  | 0.208  |       | 0.028 | 0.038 |       |       |

n.d., not determined.

* total Fe as FeO.

X(Mg) = Mg/(Fe + Mg), X(Zn) = Zn/(Fe + Mg + Zn).

Alm = Fe/(Fe + Mn + Mg + Ca), Grs = Ca/(Fe + Mn + Mg + Ca), Sps = Mn/(Fe + Mn + Mg + Ca), Prp = Mg/(Fe + Mn + Mg + Ca).

action [Mineral abbreviations follow Kretz (1983); nae (Fig. 4a), indicative of the following reactions:
Grt + Kfs + H₂O = Crd + Bt.

The variation of Al in the orthoamphibole (decreasing from cores to rims; Figs. 7b and 8b) of Grt-Bt-Crd-Oam gneiss AC07121801I is consistent with the commonly described decreasing pressure in cordierite-orthoamphibole rocks (Diener et al., 2008). These lines of evidence are consistent with the $P$-$T$ evolution of near-peak decompression proposed by Adachi et al. (2013a), and they provide an additional prograde heating path in the sillimanite-stability field (Fig. 9).

Corundum-bearing domains are enclosed within garnet porphyroblasts, which suggests either that corundum crystallization occurred in the prograde stage prior to garnet formation, or that the corundum represents recrystallization within the garnet porphyroblast after garnet for-
mation. Considering the following corundum–forming reaction, breakdown of muscovite is a candidate for the formation of the corundum (e.g., Chatterjee, 1974):

\[ \text{Ms} = \text{Crn} + \text{Kfs} + \text{H}_2\text{O}. \]

However, this reaction is restricted to silica–undersaturated whole-rock compositions. Moreover, muscovite is essentially absent, even as relic inclusions within the garnets of our samples, and K-feldspar was not observed in any of the nearby corundum–bearing domains. Hence, this reaction is not likely to have been responsible for the formation of the corundum, either during the prograde stage or as a result of recrystallization within the garnets.

Figure 6. Plots showing the chemical compositions of biotites in Grt-Sil-Bt-Crd gneiss specimen AC07121801E. (a) Mg/(Mg + Fe) versus TiO2. (b) Mg/(Mg + Fe) versus F. (c) Mg/(Mg + Fe) versus Cl.

(a)

(b)

(c)

Figure 7. (a) Zn-Fe-Mg diagram for spinels in Grt-Sil-Bt-Crd gneiss specimen AC07121801E and Grt-Bt gneiss specimen AC07121801K. (b) Plots showing the chemical compositions of orthoamphiboles in Grt-Bt-Oam gneiss specimen AC07121801I. (c) Ternary diagrams showing the chemical compositions of garnets in Grt-Sil-Bt-Crd gneiss specimen AC07121801E and Grt-Bt-Oam gneiss specimen AC07121801I.

One plausible corundum + quartz–forming reaction involves metastable kyanite decomposition in the sillimanite–stability field, as suggested by experiments under dry conditions (Harlov et al., 2008). The key implication of the Harlov et al. (2008) experiments is that corundum + quartz can form metastably relative to kyanite in the sillimanite–stability field (Fig. 9). Even though no kyanite grains have been identified in our samples, the occurrence of early–stage kyanite has been reported from other localities in the NE Terrane of the SRM (e.g., Asami et al., 1992; Shiraishi et al., 1997). We infer, therefore, that metastable corundum + quartz formation from kyanite is one possible process.

In our samples, garnet, spinel, and quartz are minerals commonly observed near corundum, and relic staurolite occurs in other rocks from the same locality. Earlier researchers suggested forming corundum + quartz
through the staurolite breakdown reaction (e.g., Tsunogae and van Reenen, 2006), as follows:

\[ \text{St} = \text{Grt} + \text{Cm} + \text{Qtz} + \text{H}_2\text{O} \]  

(1).

Thus, the breakdown of staurolite is one of the plausible corundum–forming reactions for our samples. In specimen AC07121801E, no reactant staurolite inclusions were found near the corundum + quartz–bearing inclusions, but one staurolite inclusion was found in sample AC07121801K. There have been several staurolite–breakdown reactions reported in the literature (e.g., Spear, 1993; Grapes and Li, 2010; Kihle et al., 2010), including:

\[ \text{St} + \text{Spl} = \text{Grt} + \text{Cm} + \text{H}_2\text{O} \]  

(Kihle et al., 2010),

\[ \text{St} = \text{Spl} + \text{Sil} + \text{Crd} \pm \text{H}_2\text{O} \]  

(Grapes and Li, 2010),

\[ \text{St} = \text{Spl} + \text{Sil} + \text{Qtz} + \text{H}_2\text{O} \]  

(Grapes and Li, 2010),

and

\[ \text{St} = \text{Grt} + \text{Sil} \pm \text{Spl} + \text{H}_2\text{O} \]  

(Spear, 1993; Grapes and Li, 2010; Kihle et al., 2010).

Although the complexity of staurolite–bearing phase rela-
tions makes it difficult to identify a specific reaction, all of these staurolite-breakdown reactions commonly take place at temperatures greater than 650–700 °C, depending on the staurolite chemical composition and H2O activity (e.g., Koch–Müller, 1997). Spinel-cordierite-sillimanite inclusions in garnet (Fig. 5b) are possibly the product of staurolite breakdown. Cordierites [Mg/(Mg + Fe) = 0.84] in these inclusion domains presumably formed earlier than the retrograde cordierites [Mg/(Mg + Fe) = 0.64–0.66] that often form coronae around garnet porphyroblasts, which is consistent with the P–T evolution inferred for our samples (Fig. 9).

If we assume the corundum + quartz was also produced by the breakdown of staurolite, the corundum + quartz-forming reaction could have taken place either before entrapment in the garnet (the decomposition of staurolite occurred in the matrix) or after staurolite entrapment (the decomposition of staurolite occurred within the garnet). We consider that both cases are possible. In the case of the former, the corundum + quartz in the matrix would have decomposed during the subsequent metamorphic recrystallization. In the case of the latter, the staurolite entrapped within the garnet porphyroblast would have decomposed to form corundum + quartz + garnet by reaction (1).

Above discussion ignores the presence of biotite in the corundum-bearing inclusions for simplicity. However, the corundum inclusions in our samples are actually in direct contact with quartz and biotite. There is the possibility that the biotite is unrelated to the corundum + quartz crystallization. However, we infer that the close relationship shown by corundum-bearing inclusions in direct contact with biotite requires consideration of the possibility that biotite formation was associated with fluid- or melt-related reactions. Therefore, our next step is to explain the close association of the biotite with the corundum and quartz in the garnet. The composition of the biotite in the corundum-bearing inclusions is similar to that of other biotite inclusions in the garnets that contain those corundum-bearing inclusions, but the composition shows no obvious relationship with the composition of other biotite inclusions or outside the garnet porphyroblasts. From a textural point of view, the corundum occurs closer to the garnet cores than do quartz and biotite inclusions (Fig. 5f), and this implies the later formation of quartz and biotite relative to corundum, or perhaps their synchronous formation. Considering the metamorphic conditions involved temperatures higher than 700 °C, one possible biotite-forming reaction is crystallization from a partial melt. Corundum can be formed by the following melt-related reaction:

\[ \text{St} + \text{H}_2\text{O} = \text{Spl} + \text{Crn} + \text{melt} \] (Grapes, 2011).

Although the available petrographic information is limited, crystallization of corundum, either after kyanite or staurolite, took place possibly somewhere around the prograde to near-peak metamorphic stage (700-800 °C and 0.4–0.8 GPa in Fig. 9). The melt (which possibly contained corundum, with both melt and corundum possibly trapped within garnet porphyroblasts) could subsequently have crystallized after the peak metamorphic stage as follows:

\[ \text{melt} = \text{Qtz} + \text{Bt} + \text{(other phases?)} \].

Because the above inferred reactions are not supported by reliable evidence or observations, they are speculative. The garnet porphyroblast could have crystallized later to the inclusions of corundum + quartz + biotite possibly formed through the melt crystallization process. Another possibility is that small melt inclusions, trapped within the garnet porphyroblasts, precipitated the late-stage quartz + biotite around corundum included within the garnet porphyroblasts. In either case, we assume that melt-related local processes controlled the formation and preservation of the disequilibrium association of corundum + quartz + biotite inclusions in garnet. A further possibility is that the late-stage infiltration of fluids through cracks in the garnet was responsible for the formation of biotite. We could not exclude this possibility, but the preservation of garnet compositional zoning around these inclusions (Fig. 4) implies that such fluid-infiltration from outside the garnet is not very evident.

**IMPLICATIONS FOR CORUNDUM + QUARTZ CRYSTALLIZATION AND STABILITY**

Occurrences of the corundum + quartz association and its stability and metastability have been discussed in numerous papers (e.g., Kihle et al., 2010; Kato et al., 2011; and references therein), but experiments and thermodynamic constraints have not yet allowed the corundum + quartz stability field to be located in P–T space (Harlov et al., 2008). However, the natural occurrences of corundum in direct contact with quartz in various high-grade metamorphic rocks with different P–T conditions worldwide imply that corundum and quartz can be present metastably over a range of P–T conditions. The formation of such a metastable assemblage of corundum and quartz relative to sillimanite and kyanite has been confirmed experimentally (Harlov and Milke, 2002; Harlov et al., 2008). What we should now consider is how such a metastable assemblage can be preserved and survive. Important observations on the occurrence of corundum + quartz have been reported mostly in rocks that contain anhydrous mineral assemblages. Hence the metastable preservation of co-
Corundum + quartz must normally be indicative of more-or-less fluid-absent conditions (e.g., Kihle et al., 2010). Our samples, however, include a hydrous phase associated with the corundum and quartz, and this could provide important new information on the formation and preservation of corundum associated with quartz.

First, the textures in our specimens indicate that the biotite and quartz assemblage postdated or was synchronous with the corundum. The biotites adjacent to corundum have the highest Mg/(Mg + Fe) and F compositions (Fig. 6) relative to other biotites that occur as inclusions in garnet or in the matrix, and this suggests that the biotites adjacent to corundum formed at a relatively high T, probably coexisting with a melt phase. One possible explanation of corundum formation in such a silica–saturated rod is that the formation of a partial melt and the selective incorporation of SiO2 into the melt phase generated a local deficiency in SiO2, which may have facilitated the crystallization of corundum. Following the formation of corundum, the melt should have undergone processes of both segregation and crystallization with the biotite and quartz (and perhaps other phases not currently visible in nearby domains) probably being precipitated from the melt trapped inside the garnet porphyroblasts. In any case, the major problem is that melt-related components such as Na– and Ca–bearing phases are not observed in the same inclusion domains.

CONCLUSIONS

1. Corundum in direct contact with quartz and biotite is found as inclusions in the garnets of the pelitic gneisses of northern Austkampane, in the NE Terrane of the Sør Rondane Mountains (SRM), East Antarctica.

2. Petrographic features are consistent with the rock having undergone a clockwise P–T path of metamorphism. The corundum-bearing and other inclusions observed in the garnet porphyroblasts are interpreted as having formed through staurolite–breakdown reactions and/or metastable crystallization relative to kyanite prior to the peak metamorphism, and these inclusions could have been formed through fluid– or melt-related processes.

3. Our study provides insights into a corundum + quartz association that formed through hydrous and melt-related conditions in a setting of continental collision characterized by a clockwise P–T metamorphic evolutionary path.

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