LETTER

Petrology and phase equilibrium modeling of spinel-sapphirine-bearing mafic granulite from Akarui Point, Lützow-Holm Complex, East Antarctica: Implications for the P-T path

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We report new petrological and P-T data for spinel-sapphirine-bearing mafic granulite from Akarui Point in the upper amphibolite- to granulite-facies transitional zone of the Lützow-Holm Complex (LHC), East Antarctica, and provide unequivocal evidence for extreme crustal metamorphism possibly associated with the collisional orogeny during the Neoproterozoic. The reaction microstructures in the rock suggest the stability of the prograde pargasite + garnet + orthopyroxene + plagioclase + hematite assemblage followed by the formation of plagioclase + orthopyroxene + spinel + sapphirine symplectite after garnet. The application of mineral equilibrium modeling on the mafic granulite in the system NCFMASHTO yields a prograde condition of 11–12 kbar and ~ 900 °C, followed by decompression to the peak stage (Pgs + Pl + Opx + Spl ± H2O) of 5–6 kbar and 900–920 °C, and subsequent cooling to less than 890 °C, possibly along a clockwise P-T path. The high-temperature and possibly ultrahigh-temperature condition observed at Akarui Point might reflect an effect of a local thermal event or the presence of an exotic crustal block within the LHC, which are essentially associated with the complex collisional evolution of this region during the assembly of Gondwana.

Keywords: Granulite, Pseudosection, NCFMASHTO system, Neoproterozoic–Cambrian, East Antarctica

INTRODUCTION

The Lützow-Holm Complex (LHC) of East Antarctica (Fig. 1) is known for its exposures of regionally metamorphosed amphibolite- to granulite-facies rocks formed during the late Neoproterozoic to early Cambrian collisional orogeny, possibly related to the final phase of amalgamation of continental fragments within the Gondwana assembly (~ 0.55 Ga, e.g., Shiraishi et al., 1994, 2003, 2008). The dominant lithologies of this complex are felsic orthogneiss (charnockite and biotite gneiss) and various metasediments and metabasites, which increase in metamorphic grade from amphibolite-facies in the northeast to granulite-facies in the southwest (e.g., Hiroi et al., 1991). Owing to the continuous distribution of low- to high-grade metamorphic rocks, the LHC has been regarded as an excellent example that exposes the crustal cross section of a Pan-African orogenic belt. One of the characteristic features of the LHC is the presence of compositionally variable mafic to ultramafic rocks as isolated blocks, lenses, and layers within metasedimentary gneisses. Based on spatial distribution (occurring only in the southwestern part (high-grade zone) of the LHC), mode of field occurrence, bulk chemical compositions, mineral assemblages, and textures of ultramafic rocks, Hiroi et al. (1986) suggested that metamorphosed ultramafic rocks in the LHC were derived from various parts of layered gabbro probably constituting an ophiolitic complex. Recently, we performed a detailed geological field survey of this region during the 52nd Japanese Antarctic Research Expedition (JARE52), and examined granulites from Akarui Point, which is located in the transitional zone between the granulite- and amphibolite-facies regions (Fig. 1). Al-
though Akarui Point is a small (2.5 km × 2.3 km) rock exposure, metabasic rocks from the locality contain various reaction microstructures useful for the evaluation of the metamorphic $P$-$T$ evolution (e.g., Yanai et al., 1984; Hiroi et al., 1986). The peak $P$-$T$ condition at Akarui Point has previously been estimated to be 7.7–9.8 kbar and 770–790 °C using Grt-Bt geothermometers and GASP geobarometers for Bt-Grt gneiss (Kawakami et al., 2008), whereas the application of ternary-feldspar geothermometry gave slightly higher temperatures of 825–900 °C (Nakamura et al., 2013). In this study, we have employed for the first time, a pseudo-section approach on a spinel-sapphire-bearing mafic granulite, one of the most dominant lithologies at Akarui Point, and evaluated the $P$-$T$ evolution of this region. Our petrological studies on the metamorphic processes at Akarui Point provide valuable new information on the tectono-thermal evolution of the LHC.

**Petrography and Interpretation of Microtexture**

The studied mafic granulite (sample Ts11021301D) is a coarse-grained layered rock, possibly reflecting the protolith’s compositional layering as layered gabbro, without any evidence of extensive partial melting (Fig. 2a). It is composed mainly of Ca-amphibole (50–60%), plagioclase (10–20%), orthopyroxene (10–20%), spinel (5–10%), garnet (2–3%), and sapphireine (1–2%), with accessory quartz, corundum, and hematite (Figs. 2b–2f). The matrix of the rock is composed of coarse-grained garnet (~4 cm) and medium-grained Ca-amphibole (~1.7 mm). The Ca-amphiboles are aligned sub-parallel to the layering of the metagabbro as reported in previous studies (e.g., Ikeda...
and Kawakami, 2004) and were probably formed during the prograde stage. It is pale greenish, subidioblastic, and compositionally classified as garnetite \(X_{Mg} = Mg/(Fe + Mg) = 0.82-0.83, Si = 6.31-6.37 \text{ pfu, (Na + K)}_a = 0.64-0.65 \text{ pfu}\). F and Cl contents of the garnetite are <0.01% and 0.07-0.08 wt%, respectively. Porphyroblast garnet is pyrope rich (Alm_{35-39}, Prp_{0-51}, Grs_{7-8} + Sp_{5-1}), and its granular component slightly decreases towards the rim (Alm_{79-90}, Prp_{90-99}, Grs_{7-5}, Sp_{5-4}). Medium-grained (0.3-1.2 mm) subidioblastic orthopyroxene \(X_{Mg} = 0.83-0.84, Al = 0.24-0.25 \text{ pfu}\) occurs along the grain boundaries of garnetite (Fig. 2e). Fine-grained quartz, corundum, plagioclase (An_{35-77}), and hematite are present only as rare inclusions in garnet (Fig. 2b). A possible prograde mineral assemblage of the rock is therefore inferred from the matrix and inclusion minerals as garnet + paragneissite + orthopyroxene ± quartz ± plagioclase ± corundum ± hematite. The corundum in Figure 2b shows a direct contact relationship with quartz without any reaction texture between them. Such a texture of corundum + quartz has been reported from several high-grade terranes as an evidence of high-T metamorphism (e.g., Shaw and Arima, 1998; Tsunogae and van Reenen, 2006), although most published studies favor their metastable relationship (e.g., Motoyoshi et al., 1990; Harlov and Milke, 2002).

The garnet is partly or completely replaced by plagioclase + orthopyroxene + spinel ± sapphireine symplectite (Figs. 2c and 2f), suggesting the progress of the following reaction:

\[
\text{Grt} \rightarrow \text{Pl} + \text{Opx} + \text{Spl} + \text{Spr} \tag{1}
\]

Similar reaction microstructures have been reported from many high-grade terranes as an evidence of decompression from the high-pressure stage (e.g., Thost et al., 1991). The symplectitic plagioclase is characterized by a higher anorthite content (Al_{43-89}) than that in the garnet (An_{35-77}). Spinel (0.05-0.4 mm) is Mg-rich \(X_{Mg} = 0.65\) and contains little Cr_{2}O_{3} (0.16-0.35 wt%) and ZnO (0.07-0.12 wt%). Although the spinel in the symplectite shows no evidence of exsolution (Fig. 2c), the spinel associated with plagioclase in the garnet-bearing portion is relatively coarse-grained (~3 mm) and contains numerous lamellae of magnetite (Fig. 2d), which is possibly an indicator of exsolution during post-paste cooling. Sapphirine (0.05-0.5 mm) intergrowing with orthopyroxene is also Mg-rich \(X_{Mg} = 0.85-0.86\). Symplectic orthopyroxene (0.2-0.6 mm) is slightly depleted in Al (0.20-0.22 pfu) and Mg \(X_{Mg} = 0.82-0.83\) than in the prograde phase. Summarizing the textural observations, we regard a probable peak granulite-facies mineral assemblage as An-rich plagioclase + orthopyroxene + spinel + garnetite ± sapphireine ± H_{2}O.

**PHASE EQUILIBRIUM MODELING**

Metamorphic conditions for the stability of the mineral assemblages discussed in the previous chapter were constrained using THERMOCALC 3.33 (Powell and Holland, 1988, updated October 2009) with an updated version of the internally consistent data set of Holland and Powell (1998; data set tcds55s, file created November 2003). Calculations were undertaken in the system Na_{2}O-CaO-FeO-MgO-Al_{2}O_{3}-SiO_{2}-H_{2}O-TiO_{2}-Fe_{2}O_{3} (NCF-MASHTO), which provides the most realistic approximation for modeling mineral assemblages in metabasites. The chemical composition (in wt%) of the sample analyzed by X-ray Fluorescence Spectrometry is SiO_{2} = 43.17, Al_{2}O_{3} = 19.06, Fe_{2}O_{3} = 3.25, FeO = 6.10, MgO = 17.27, CaO = 7.75, Na_{2}O = 0.98, K_{2}O = 0.09, TiO_{2} = 0.08, P_{2}O_{5} = 0.01, and Cr_{2}O_{3} = 0.06. The FeO/Fe_{2}O_{3} ratio was determined by titration. Mineral name abbreviations are listed in Figure 2 caption.

Our petrographical observations of the sample suggest that the prograde mineral assemblage is Grt + Pgs + Opx ± Pl + Qtz ± Crn ± Hem or Ilm. Figure 3a is a P-T pseudosection constructed at M(H_{2}O) (mole H_{2}O in the rock) = 2.0 mol%. The figure demonstrates that a probable prograde mineral assemblage (Grt + Pgs + Opx + Pl + Hem) is stable at a wide P-T range of 8-12 kbar and 700-1200 °C. The upper-T stability limit of the assemblage is defined by the Spl-out line, while the lower-T limit is defined by the Cpx-out line. The upper-P stability limit is constrained by the absence of rutile. Lack of corundum and quartz in the pseudosection assemblage is probably related to the low modal abundance of the minerals in the sample (totally less than 1%). We further constrained the condition using isopleths of anorthite content in plagioclase (An_{35-77}) and obtained a prograde P-T condition of 11-12 kbar and 900 °C (830-950 °C). We adopted the An isopleth because the plagioclase occurs as isolated inclusions in garnet and possibly underwent little compositional modification during peak metamorphism.

As garnet in the sample is replaced by Pl + Opx + Spl ± Spr symplectite, the metamorphic condition of the rock should have shifted to the stability of the Pgs + Pl + Opx + Spl ± Spr assemblage, which probably corresponds to the stability field of Pgs + Pl + Opx + Spl ± H_{2}O in Figure 3a at 0-6 kbar and 890-1050 °C. We further constrained the P-T ranges by applying the isopleth of Al content in orthopyroxene \(y(\text{Opx}) = A/2 = 0.10-0.11\) and the orthopyroxene-spinel geothermometry of Sato et al. (2008) to the symplectite assemblage, and obtained a P-T condition of 900-920 °C and 5-6 kbar (Figs. 3a and 3b),
which probably corresponds to the condition at peak metamorphism. We subsequently constructed a \( T-M(H_2O) \) pseudosection calculated at a fixed pressure value of 5 kbar (Fig. 3c) and confirmed that the peak assemblage is stable at a \( M(H_2O) \) range of >1.9 mol\%, which supports the assertion that although the \( M(H_2O) \) value adopted in this study (2.0 mol\%) corresponds to the minimum \( M(H_2O) \) of the rock, it is reasonable.

As sapphirine is absent in the pseudosections (Fig. 3a), we constructed several different \( P-T \) pseudosections using the composition of garnet and local compositions based on modal abundances of the symplectitic minerals to find out the stability of sapphirine. However, this attempt was unsuccessful. The lack of sapphirine in the pseudosection might reflect the low modal content of the mineral (1-2\%).

Although magnetite is absent in the symplectitic assemblage (Fig. 2c), it occurs as lamellae in coarse-grained spinel adjacent to garnet (Fig. 2d), suggesting exsolution during post-peak cooling. Therefore the Mag-free Pgs + Pl + Opx + Spl assemblage was probably retrogressed to form a Pgs + Pl + Opx + Spl + Mag assemblage after the peak metamorphism.

**DISCUSSION**

This study examined the stability of mineral assemblages in mafic granulite from Akarui Point based on the phase equilibrium modeling approach in the system NCF-MASHTO, and obtained prograde and peak conditions of 11-12 kbar at ~ 900 °C and 5-6 kbar at 900-920 °C, respectively. Such decompressional \( P-T \) paths inferred from the conditions is consistent with the occurrence of Pl + Opx + Spl ± Spr symplectite after garnet. The peak event was followed by cooling to less than 890 °C, as inferred from the magnetite lamellae in the coarse-grained spinel, possibly along a clockwise \( P-T \) evolution (Fig. 3b). The peak condition is slightly higher in temperature than previous reports for Akarui Point based on conventional geothermobarometry (770-790 °C and 7.7-9.8 kbar; Kawakami et al., 2008) and ternary-feldspar geothermometry (825-900 °C; Nakamura et al., 2013) which suggests ex-

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**Figure 3.** Pseudosections calculated for sample Ts11021301D from Akarui Point. \( P-T \) fields surrounded by thick lines indicate stability fields of the prograde/peak mineral assemblages. (a) \( P-T \) diagram showing a calculated pseudosection for prograde (Grt + Pgs + Pl + Opx + Hem) and peak (Pgs + Pl + Opx + Spl ± H\(_2\)O) assemblages. Isotherms of anorthite content in plagioclase (An) and Al content in orthopyroxene \( y(Opx) = Al/2 \) are also shown. PG and PK indicate prograde and peak \( P-T \) conditions, respectively, inferred from the assemblages. T(Opx-Spl): Temperature range calculated using Opx-Spl geothermometer of Sato et al. (2008). (b) \( P-T \) diagram showing a clockwise \( P-T \) path inferred from the sample. (c) \( T-M(H_2O) \) diagram, calculated at \( P = 5 \) kbar, showing the stability field of peak Pgs + Opx + Pl + Spl ± H\(_2\)O assemblage at \( M(H_2O) \) >1.9 mol\%. Color version is available online from http://japanlinkcenter.org/DN/JST/JSTAGE/jmps/130621a.
extreme crustal metamorphism close to the ultrahigh-temperature (UHT) condition even though the peak metamorphic condition of the transitional zone has been regarded as ca. 750 °C (e.g., Hiroi et al., 1983).

It is interesting to note that such local occurrences of high-temperature metamorphic rocks (>900 °C) in ordinary granulite-amphibolite-facies terranes (~700–850 °C) have been reported from many metamorphic complexes worldwide. For example, the Rajapalaiyam area in the Madurai Block, southern India, exposes Mg-Al-rich and pelitic granulites with diagnostic UHT mineral assemblages such as Spr + Qtz and high-Al Opx + Sil + Grt (Tateishi et al., 2004; Tsunogae and Santosh, 2010). However, the surrounding orthogneiss records the peak temperature at ~820 °C (Endo et al., 2012) which is approximately 200 °C lower than the peak condition. Even in the LHC, ~1040 °C UHT metamorphic rocks in Rundvågshetta (Fig. 1) (Motoyoshi et al., 1985; Yoshimura et al., 2008; Kawasaki et al., 2011) is juxtaposed against massive charnockite that records the peak temperature condition at ~870 °C (Tsunogae et al., 2013). Such local high-temperature metamorphism might be related to local thermal input (for example, infiltration of metamorphic fluid) or lack of appropriate mineral assemblage that could buffer temperature during the high-grade stage. Therefore, it is possible that the spinel-sapphire-bearing metabasites at Akarui Point could have undergone higher-T metamorphism as compared to the surrounding low-grade metasedimentary gneisses in the transitional zone of the LHC.

An alternative explanation for the high-temperature metamorphism at Akarui Point may be related to the presence of major crustal breaks within the LHC. Although the metamorphic grade of the LHC has been thought to increase continuously from amphibolite-facies in the northeast to granulite-facies in the southwest (e.g., Hiroi et al., 1991), the high-temperature to possibly ultrahigh-temperature metamorphic condition obtained from the transitional zone suggests that the LHC might be separated into several crustal blocks by shear/suture zones, and that there could be gaps in metamorphic P-T conditions within the complex. Recently, Tsunogae et al. (2013) argued based on SHRIMP dating of the Vesleknasen area in the granulite-facies zone of the LHC, that the southwestern Lützow–Holm Bay region which corresponds to the Neoarchean magmatic block, was tectonically mingled with other fragments (such as metasedimentary units in the northern Lützow–Holm Bay region) by subduction/collision events during the assembly of the Gondwana supercontinent, and subsequently underwent granulite-facies metamorphism in the final collisional event during the Neoproterozoic. Therefore, the Akarui Point area could also consist of a discrete crustal block with a different P-T history. Based on geophysical data, Nogi et al. (2013) recently traced several geological structures within the LHC, and separated the complex into four blocks possibly bounded by NE-SW–trending right lateral strike-slip faults. They also argued for the presence of crustal gaps between the granulite-facies zone and the transitional zone, and between the transitional zone and the amphibolite-facies zone of the LHC. They further inferred that the transitional zone could be a remnant of the western Rayner Complex (a reworked Mesoproterozoic orogeny; Fig. 1). Therefore, based on the high-temperature condition observed at Akarui Point, it can be inferred that the transitional zone could be an exotic crustal block juxtaposed against the amphibolite-facies and granulite-facies zones by a complex collisional event during the Gondwana assembly, although we have no geological data so far to confirm this hypothesis. Further detailed petrological, structural, and geochronological investigations in high-temperature granulites from Akarui Point and the surrounding areas are necessary to fully understand the evolution of the Neoproterozoic orogenic event in the LHC.

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SUPPLEMENTARY MATERIALS

Color version of Figures 1–3 is available online from http://japanlinkcenter.org/DN/JST/JSTAGE/jmps/130621a.

REFERENCES

study from Rajapalaiyam, Madurai Block, southern India. Geoscience Frontiers, 3, 801–811.


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