Fe–Mg–Ti domain-bearing garnet–sillimanite gneiss from Skallevikshalsen, Lützow-Holm Complex, East Antarctica: Implications for ultrahigh-temperature metamorphism

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The Lützow-Holm Complex (Fig. 1) is one of the Gondwana fragments and juxtaposed during the Gondwana era (Shiraishi et al 1992), when widely reported ordinary granulite-facies metamorphism was taken place as part of the Pan-African metamorphic event (Hensen Zhou 1997). The metamorphic grade of the Lützow-Holm Complex increases southwestwards from the upper amphibolite to the granulite facies of the intermediate pressure type (Hiroi et al 1987). Ultrahigh-temperature metamorphic rocks in the Lützow-Holm Complex have been reported from Rundvågshetta (Kawasaki et al 1993; Motoyoshi Ishikawa 1997; Kawasaki Motoyoshi 2006; Yoshimura et al 2008) and Skallevikshalsen(Yoshimura et al 2004; Kawakami Motoyoshi 2004).

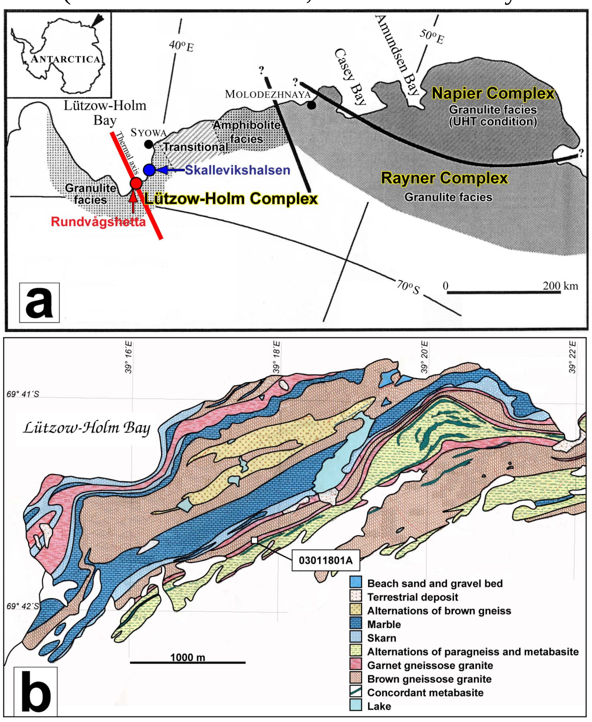

Figure 1. (a) Geological outline of the Lützow-Holm Complex of East Antarctica. Metamorphic zonation is based on Hiroi et al (1987) and Shiraishi et al (1984). The boundary between the Napier and Rayner complexes The boundary between the Napier and Rayner complexes is after Sheraton et al (1987). (b) Geological map of Skallevikshalsen after Yoshida et al (1976). The sampling point of the Fe–Mg–Ti domain-bearing garnet–sillimanite gneiss (sample no. 03011801A) is shown. Garnet–sillimanite gneiss corresponds to garnet gneissose granite category in the map.

A possible armalcolite pseudomorph has been identified in garnet–sillimanite gneiss (Fig. 2) from Skallevikshalsen collected during the summer operation (2002–2003) of the 44th Japanese Antarctic Research Expedition (JARE44). The gneiss constitutes of garnet with needle rutile, sillimanite, K-feldspar, plagioclase and quartz porphyroblasts and accessory minerals of apatite, ilmenite, monazite, rutile and zircon. Biotite is found only within garnet as inclusions. The pseudomorph occurs as an Fe–Mg–Ti compositional domain consisting of ilmenite, rutile and pseudorutile, partially mantled by rutile within ilmenite (Fig. 3). The domain yields 0.033–0.205 X_{Mg} with an average of 0.171 $\pm$ 0.036. Host ilmenite with 0.4 mole% hematite is in contact with prismatic sillimanite, quartz, plagioclase and K-feldspar.

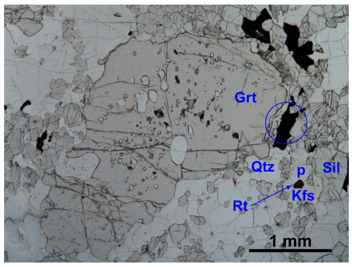

Figure 2. Photomicrograph of garnet–sillimanite gneiss from Skallevikshalsen, showing a garnet porphyroblast containing inclusions of quartz and biotite. Plane polarised light. The encircled ilmenite includes the Fe–Mg–Ti domain (possible armalcolite pseudomorph) partly wrapped by rutile. Rutile labelled “p” contains exsolution lamellae of hematite.

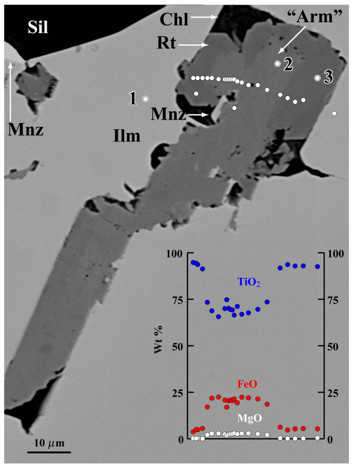

Figure 3. Backscattered electron image of an Fe–Mg–Ti domain partly wrapped by rutile within ilmenite in garnet–sillimanite gneiss from Skallevikshalsen and compositional profile showing variations in Wt% TiO_2, FeO and MgO (analysed on the white spots in the figure) traversing the rutile–Fe–Mg–Ti domain–rutile. Secondary chlorite formed in the space between rutile and ilmenite. Note that the Fe–Mg–Ti domain is chemically and physically heterogeneous.

The Raman spectroscopic data of the point 2 in the Fe–Mg–Ti domain of Figure 3 are assigned to rutile and ilmenite (Fig. 4a). A broad peak at around 3360 cm^{-1} wavenumber (Fig. 4b) corresponds to an O–H bond, indicating that the domain contains pseudrutile in addition to rutile and ilmenite.

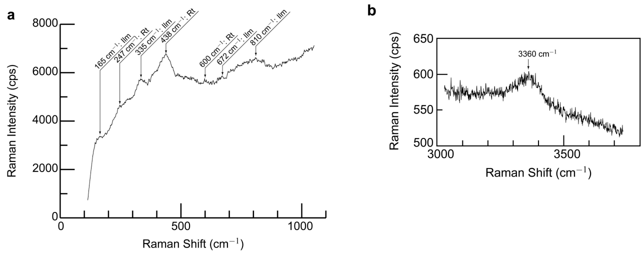

Figure 4. Raman spectra of the point 2 in the Fe–Mg–Ti domain of Figure 3 in garnet–sillimanite gneiss from Skallevikshalsen. (a) Profile for 114–1053 cm^{-1}. (b) Profile for 3030–3730 cm^{-1}.

The metamorphic conditions estimated using various methods based on the mineral chemistry are listed in Table 1. The peak or near-peak metamorphic conditions are 803–946 °C (average, 897 $\pm$ 23 °C) recorded in rutile inclusion using Zr-in-rutile thermometers (Zack et al 2004; Watson et al 2006; Tomkins et al 2007; Ferry Watson 2007), 0.88 GPa and 935 °C for garnet core using the Ti-in-garnet thermobarometer (Kawasaki Motoyoshi 2007), 0.7–1.1 GPa and 1050 °C by comparison between the measured Fe_2O_3 content in sillimanite and experimental data

Table 1. *Metamorphic conditions of possible armalcolite-bearing garnet-sillimanite gneiss estimated from various methods.*

Method	*T*, °C		*P*, GPa		Remarks
	Average	Range	Average	Range	
Zr-in-rutile*	897(23)	803-946			inclusion
	828(29)	723-912			core
	780(65)	659-854			rim
	692(70)	631-761			wrapping domain
Ti-in-garnet†	891(91)	723-1088	0.76(39)	0.38-1.19	79 analyses
	935(97)		0.88(36)		core
	840(84)		0.61(34)		rim
Fe-in-sillimanite	< 1050		1.1		comparison of data
Ti-in-quartz‡	1016(73)	871-1085			inclusion (group I)
	869(61)	772-970			core (group II)
	717(76)	606-859			rim (group III)
	571(34)	498-623			rim (group IV)
Annealed eclogite		> 940			$P = 1$ atm
		> 1100			$P = 0.5$ GPa
		> 1290			$P = 1.0$ GPa

Note: Standard error in parenthesis refers to the last decimal place.
*Zr-in-rutile thermometer (Zack et al 2004; Watson et al 2006; Tomkins et al 2007; Ferry Watson 2007)
†Ti-in-garnet thermobarometer (Kawasaki Motoyoshi 2007)
‡Ti-in-quartz thermometer (Kawasaki Osanai 2008)

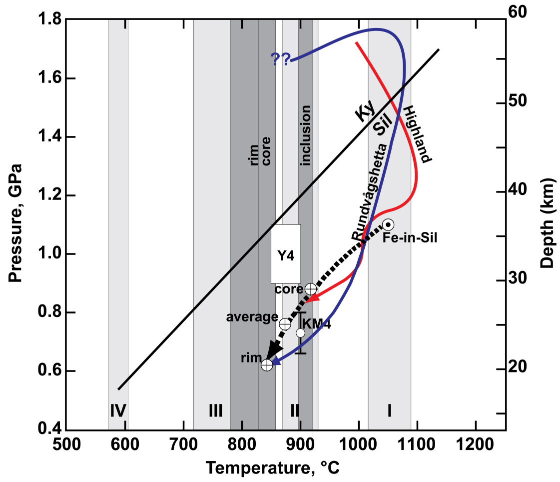

Figure 5. Metamorphic pressure–temperature path of Skallevikshalsen (dashed arrow) and Rundvågshetta, East Antarctica (Kawasaki et al 2011b) and Highland Complex of Sri Lanka (Osanai et al 2006). Estimated temperature ranges using the Zr-in-rutile thermometer (Zack et al 2004; Watson et al 2006; Tomkins et al 2007; Ferry Watson 2007) are indicated by grey areas labelled "inclusion", "core" and "rim". The Ti-in-quartz thermometer (Kawasaki Osanai 2008) yields the results shown by light grey areas labelled "I", "II", "III" and "IV". The pressure–temperature condition estimated from the Fe-in-sillimanite experiments (Kawasaki et al 2011a) is indicated by the circled dot. Result evaluated from the Ti-in-garnet thermoborometry (Kawasaki Motoyoshi 2007) is given by circled plus. The peak metamorphic condition of 9.0–1.1 GPa and 850–950 °C (Yoshimura et al 2004) is shown by a box labelled "Y4". The metamorphic pressure of 0.65–0.80 GPa (Kawakami Motoyoshi 2004) is given by a vertical bar with small circle labelled "KM4". The sillimanite–kyanite phase boundary (Holdaway 1971) is shown in this figure.

(Kawasaki et al 2011a), 871–1085 °C (average, 1016 ± 73 °C) for a quartz inclusion in garnet (group I) and 772–970 °C (average, 869 ± 61 °C) for the cores of quartz porphyroblasts (group II) using the Ti-in-quartz thermometer (Kawasaki Osanai 2008).

From these data, we propose that the peak (or near-peak) metamorphic conditions at Skallevikshalsen were 0.88–1.1 GPa and 970–1050 °C. The calculated pressure–temperature conditions of 659–854 °C (average, 780 °C) from the Zr-in-rutile thermometers (Zack et al 2004; Watson et al 2006; Tomkins et al 2007; Ferry Watson 2007) applied to rutile rims, 0.38 GPa/723 °C from the Ti-in-garnet thermobarometer (Kawasaki Motoyoshi 2007) applied to the garnet rim, and 606–859 °C (average, 717 ± 76 °C) from the Ti-in-quartz thermometer applied to rim quartz (group III), suggest that the subsequent retrograde metamorphic conditions were around 0.6 GPa and 780 °C. The latest-stage metasomatic events, involving alteration, probably occurred at about 630 °C, as indicated by the temperature of 631–761 °C (average, 692 °C) obtained using the Zr-in-rutile thermometers (Zack et al 2004; Watson et al 2006; Tomkins et al 2007; Ferry Watson 2007) applied to rutile partly wrapping the Fe–Mg–Ti domain in ilmenite, and of 498–623 °C (average, 571 °C) obtained using the Ti-in-quartz thermometer applied to quartz rims (group IV).

Combining the finding of a possible armalcolite pseudomorph, and pressure–temperature estimates using the published thermobarometers based on mineral chemistry, the metamorphic path for Skallevikshalsen yields: peak or near-peak conditions, 0.88–1.1 GPa and 970–1050 °C; subsequent retrograde metamorphism, 0.6 GPa and 780 °C; and finally metasomatic alteration occurred at about 630 °C (Fig. 5).

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