Polar Geosci., **17**, 1–11, 2004

Timing of ductile deformation and peak metamorphism in Skallevikshalsen, Lützow-Holm Complex, East Antarctica

Tetsuo Kawakami[1]* and Takeshi Ikeda[2]

[1] *Department of Earth Sciences, Faculty of Education, Okayama University, Tsushima-naka 3-chome, Okayama 700-8530*
[2] *Department of Earth and Planetary Sciences, Graduate School of Science, Kyushu University, 33 Hakozaki, Fukuoka 812-8581*
**Corresponding author. E-mail: tetsuo@cc.okayama-u.ac.jp*

(Received January 30, 2004; Accepted April 5, 2004)

Abstract: The geological structures of Skallevikshalsen, Lützow-Holm Complex, East Antarctica are mainly controlled by two stages of ductile deformation, D_{m-1} and D_m. The D_{m-1} stage is characterized by the development of isoclinal F_{m-1} folds with fold axes gently plunging ENE or SWS, and axial planes parallel to the compositional layering (S_{m-1}) of the metamorphic rocks. The D_m stage is characterized by the development of tight folds with axes parallel to F_{m-1} and almost vertical axial planes. An axial planar foliation, S_m, defined by the alignment of biotite and hornblende, is formed in the hinges of F_m folds. No change in direction of elongation took place between D_{m-1} and D_m. Microstructural study and field observations show that a stretching lineation on S_{m-1} defined by the alignment of sillimanite was formed during D_{m-1}. The alignment of sillimanite inclusions in garnet rims probably corresponds to an older schistosity formed during D_{m-2}, which had a different orientation of principal strain axes than those of D_{m-1} and D_m. Peak metamorphic mineral assemblages are preserved in garnet cores, and their formation is considered to predate D_{m-2}. Absence of the alignment of inclusions in garnet cores suggests that peak metamorphism was attained under conditions without strong deformation.

key words: deformation, fold, interference pattern, Lützow-Holm Complex, Skallevikshalsen

1. Introduction

Structural and microstructural analysis of metamorphic rocks provides us with important information on the relative timing of mineral growth and deformation during metamorphism, and enables the construction of pressure-temperature-deformation (*P-T-D*) paths. At Skallevikshalsen, Lützow-Holm Bay, East Antarctica (Fig. 1), microstructural studies have not been previously available and structural studies were only qualitative. In order to constrain the *P-T-D* evolution of high-temperature and ultrahigh-temperature metamorphic rocks of Skallevikshalsen (Yoshimura *et al*., 2004), we quantitatively describe the structures observed around Lake Dairi. Microstructural studies were performed on a Grt-Sil leucogneiss, and the relative timing of aluminosilicate formation and deformational events were determined. Mineral abbreviations are after Kretz (1983).

2. Overview of the Lützow-Holm Complex

The Lützow-Holm Complex is a Cambrian orogenic belt bounded by the Late Proterozoic to Early Palaeozoic complexes, *i.e.*, Rayner Complex to the east and Yamato-Belgica Complex to the west (Shiraishi *et al.*, 1992, 1994, 1997). Metamorphic grade changes progressively from upper amphibolite facies on the Prince Olav Coast to granulite facies in Lützow-Holm Bay (Hiroi *et al.*, 1991). A maximum thermal axis occurs at the southern end of Lützow-Holm Bay, around Rundvågshetta (Motoyoshi, 1986). Peak metamorphic conditions of around 1000°C and 11 kbar, and subsequent isothermal decompression are reported from Rundvågshetta (Kawasaki *et al.*, 1993; Motoyoshi and Ishikawa, 1997; Fraser *et al.*, 2000). The Lützow-Holm Complex is considered to have experienced a 'clockwise' *P-T* path as indicated by the presence of prograde kyanite and staurolite as relict inclusions in garnet and plagioclase (Hiroi *et al.*, 1983; Motoyoshi, 1986), and by reaction textures in ultramafic rocks indicative of decompression (Hiroi *et al.*, 1986). It has been reported that rocks along the Prince Olav Coast experienced the reaction, staurolite = garnet + aluminosilicate + spinel + H_2O-fluid, within the sillimanite stability field whereas those in Lützow-Holm Bay experienced the same reaction within the kyanite stability field (Hiroi *et al.*, 1983, 1987). The age of peak regional metamorphism is estimated by SHRIMP U-Pb zircon dating to be between 521±9 and 553±6 Ma (Shiraishi *et al.*, 1992, 1994). Fraser *et al.* (2000) reported that the period between 520 and 500 Ma involved approximately 600°C of cooling and approximately 23 km of relatively rapid exhumation at Rundvågshetta.

In contrast to these petrological and geochronological aspects, the structural evolution of the Lützow-Holm Complex is not yet fully understood, as pointed out by M. Ishikawa *et al.* (1994a), although regional structural geology of the region has been described in previous studies (*e.g.* Kizaki, 1962, 1964; T. Ishikawa, 1976; Yoshida, 1977, 1978; Matsumoto *et al.*, 1982; M. Ishikawa *et al.*, 1994b). Yoshida (1978) divided folds and fractures developed throughout the Lützow-Holm Complex into four deformational stages:

D_1: Represented by recumbent and isoclinal folds, with axial traces trending approximately parallel to the coast line, and minor related thrust faults.

D_2: Represented by open to closed folds, with axial traces running nearly perpendicular to D_1 folds.

D_3: Represented by gentle folds with axial traces nearly parallel to the D_1 folds, and which fold D_1 and D_2 structures.

D_4: Represented by conjugate sets of fractures.

Folding during D_1 was named F_1 by T. Ishikawa (1976) and F_n by M. Ishikawa *et al.* (1994b). Folding during D_3 produced several km-scale structures at Skarvsnes (T. Ishikawa, 1976) and Skallen (Yoshida, 1978). Structures predating D_1 have been recognized (*e.g.*, Yoshida, 1978) but have not been studied in detail. Pre-D_1 folds have been described at Akarui Point (Ikeda and Kawakami, 2004), Rundvågshetta (M.

Ishikawa *et al*., 1994a), and the Ongul Islands (M. Ishikawa *et al*., 1994b; Kawakami and Ikeda, 2004).

3. General geology of Skallevikshalsen

Skallevikshalsen lies on the eastern coast of Lützow-Holm Bay, about 30 km northeast of Rundvågshetta (Fig. 1). Skallevikshalsen is underlain by layers of metamorphic rocks including Opx-Hbl gneiss (brown gneiss), Grt-bearing leucogneiss (Grt-Sil leucogneiss and Grt-Bt felsic gneiss), marble, skarn and metabasite including Grt-2Px basic granulite (Yoshida *et al*., 1976). Opx-Hbl gneiss is the most common lithology. Skarn occurs at lithological boundaries between marble and felsic rocks. These gneisses are intruded by a number of granitic pegmatites (Yoshida *et al*., 1976). All the lithologies except the granitic pegmatites are strongly deformed. The Grt-2Px basic granulite is commonly boudinaged, with leucosome filling the interboudin partitions. Marble commonly includes blocks of adjacent lithologies. Reaction zones have formed between the blocks and marble that consist of biotite, spinel, corundum and other minerals. Foliation in such blocks is discordant with that of surrounding marble. Recently, Yoshimura *et al*. (2004) estimated the peak metamorphic conditions of Skallevikshalsen to be 850–950°C and 9.0–11.0 kbar based on various geothermobarometers. Kawakami and Motoyoshi (2004) reported direct contact of spinel with quartz included in the core of garnet in Grt-Sil leucogneiss, and argued that the Spl+Qtz assemblage was probably stable around peak metamorphism. They also estimated pressure to be 6.5–8.0 kbar at 900°C by applying the GASP geobarometers to the pairs of the rim garnet and matrix plagioclase (Table 1).

4. Macroscopic to mesoscopic structures

A synform with axial trace trending ENE in the west of Lake Dairi is the major geologic structure responsible for the distribution pattern of lithologies at Skallevikshalsen (Yoshida *et al*., 1976). Three types of folds are recognized in this region, based on fold interference patterns. In this paper, we call them F_{m-1}, F_m and F_{m+1} in temporal order of formation. The dominant structures are tight F_m folds that control the orientation of gneissic layers (S_{m-1}) (Fig. 2a). F_m folds are tight to open with axes plunging gently either ENE or WSW, and with a near-vertical axial plane (Fig. 1). An axial planar foliation S_m, defined by the alignment of biotite and hornblende, is formed at the hinges of F_m folds (Fig. 2b). Figure 1 shows the orientation of the structural data projected on the lower hemisphere of the Schmidt's nets from four areas: north (area A), west (area B), southwest (area C), and further southwest (area D) of Lake Dairi. Orientation of structural data is similar in all four areas. Poles to the compositional layering foliation (S_{m-1}) define a great circle with a pole similar to F_m fold axes, showing that F_m controls the orientation of gneissic layers. Metre-scale F_m folds are commonly observed in area A.

F_{m-1} are observed around area C where the development of F_m is weaker than in area A. F_{m-1} folds are isoclinal with axial planes parallel to the compositional layering of the metamorphic rocks (Fig. 2c). They are often observed as rootless folds. Axial

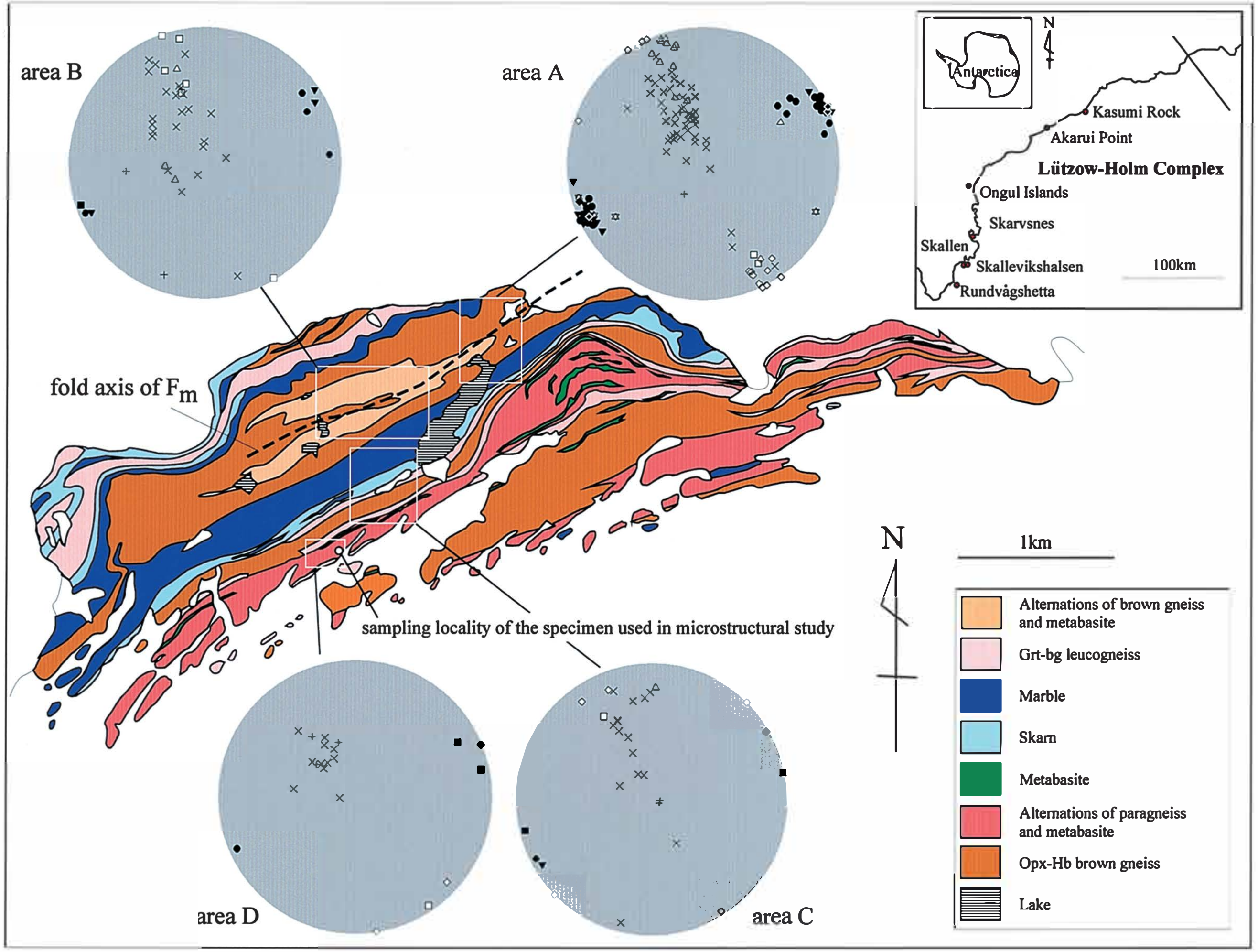

area B
area A
Antarctica
N
Kasumi Rock
Akarui Point
Lützow-Holm Complex
Ongul Islands
Skarvsnes
Skallen
Skallevikshalsen
Rundvågshetta
100km
fold axis of F_m
sampling locality of the specimen used in microstructural study
N
1km
Alternations of brown gneiss and metabasite
Grt-bg leucogneiss
Marble
Skarn
Metabasite
Alternations of paragneiss and metabasite
Opx-Hb brown gneiss
Lake
area D
area C

Fig. 1.

Fig. 1. Geological map of the Skallevikshalsen region, modified after Yoshida et al. (1976). Structural data for four areas are shown on equal area, lower hemisphere projections. ◆; F_{m-1} fold axis, ●; F_m fold axis, ■; stretching lineation on S_{m-1}, ▼; crenulation lineation (F_m), ×; pole to compositional layering foliation S_{m-1}, +; pole to F_{m-1} axial plane, △; pole to F_m axial plane, □; pole to axial planar foliation S_m, ☆; pole to intrusive plane of pegmatite, ◇; pole to F_m crenulation cleavage. Sample locality of Grt-Sil leucogneiss is also shown (TK2003011801-04).

Table 1. Summary of P-T-D relationship obtained from the field observation and microstructural study of the Grt-Sil leucogneiss from Skallevikshalsen.

	prograde stage	peak metamorphism	retrograde stage 1	retrograde stage2	retrograde stage3	retrograde stage4
P-T conditions		800-950℃, 7-10kbar (Yoshimura et al., 2004)				
metamorphic facies		granulite facies			amphibolite facies?	amphibolite facies?
deformation	no deformation?		D_{m-2}	D_{m-1}	D_m	D_{m+1}
			Sil alignment in Grt rim	rootless isoclinal fold F_{m-1}	tight fold F_m	open fold F_{m+1}
					S_m defined by Bt and Hb	
minerals & reactions (based on Kawakami and Motoyoshi, in press)	Grt core formation		Grt rim formation			
	St breakdown					
	Ky stability field →	Sil stability field	Sil inclusion in Grt rim	matrix Sil		
		Spl+Qtz formation				
		An42-45 9-11 kbar	→ (decompression)→ →GASP(900℃)→	An33-34 6.5-8 kbar		
	St+Qtz→Grt+Ky St→ Grt+Ky+Spl	Grt+Sil→Spl+Qtz	Spl+Qtz →Grt+Sil			

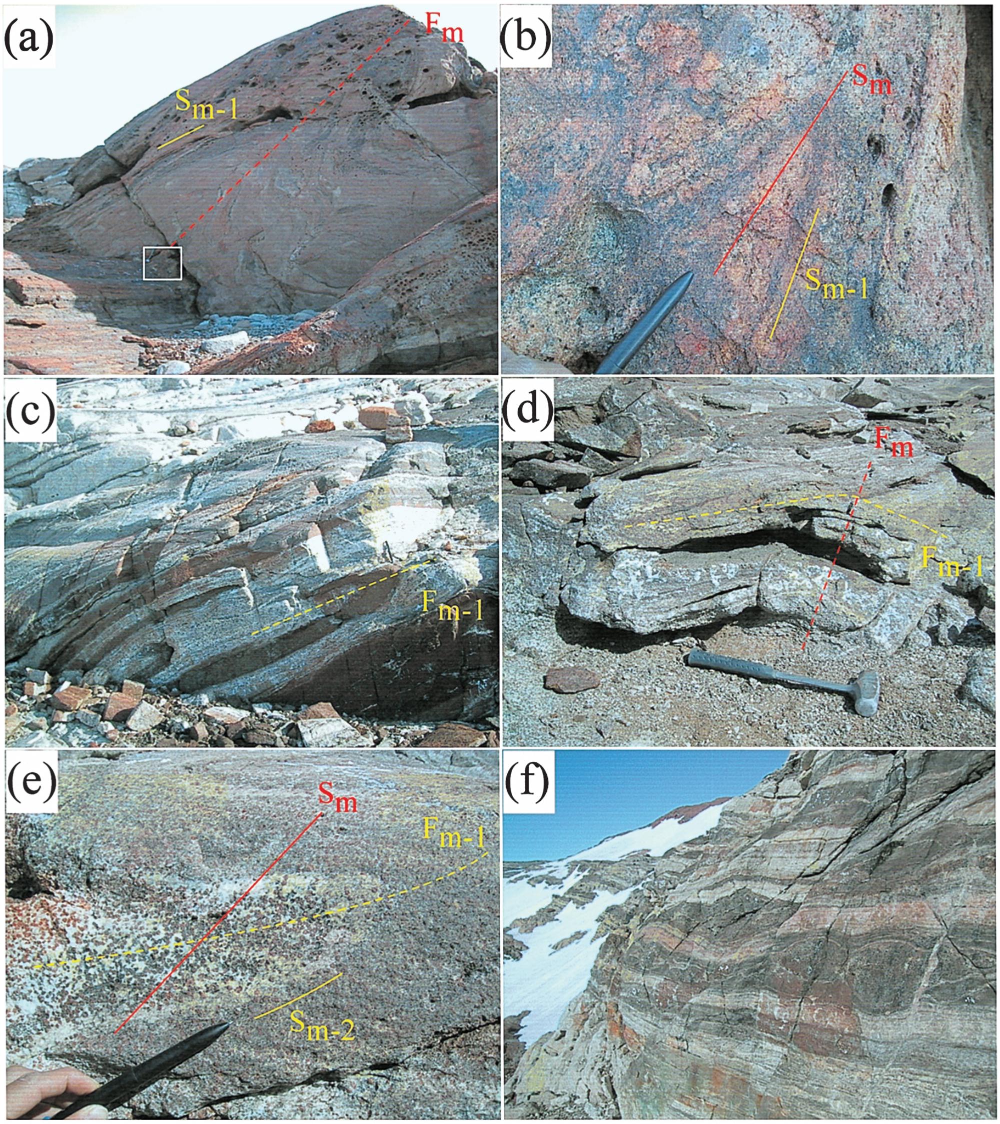


Fig. 2. *Photographs of F_{m-1} and F_m in Skallevikshalsen. (a) F_m fold, area A. (b) Enlargement of box in Fig. 2a. Axial planar S_m in the hinge of F_m, defined by aligned hornblende. (c) F_{m-1} fold, area D. (d) Interference pattern of F_{m-1} and F_m, area C. (e) F_{m-1} cut by S_m, oblique to F_{m-1} axial plane. S_m is defined by aligned biotite. Area C. (f) Boudinaged basic granulite (dark brown layers). Area D.*

planes of F_{m-1} and axial planar S_{m-1} dip gently to SSE in most cases, and are folded by F_m locally. The trends of F_{m-1} fold axes are commonly parallel to those of F_m (Fig. 1). Interference patterns between F_{m-1} and F_m are locally observed (Fig. 2d), and S_m overprint the compositional layering bent by F_{m-1} (Fig. 2e). Boudinage of competent layers is common (Fig. 2f), typically along the limbs of F_{m-1} folds, suggesting formation during D_{m-1}. Isoclinal folds with almost horizontal axial planes are observed locally in boudins of basic granulite gneiss, which may correspond to F_{m-1} or an earlier F_{m-2}.

F_{m+1} folds are gentle with nearly vertical axial planes and fold axes oblique to F_m fold axes at a relatively high angle. The re-orientation of fold axes of F_m by F_{m+1} is within ten degrees, which is difficult to recognize on a Schmidt's net. The boudinage caused by the ENE-WSW stretching (D_{m-1}) can also produce regular wavy structure of the compositional layering foliation (S_{m-1}).

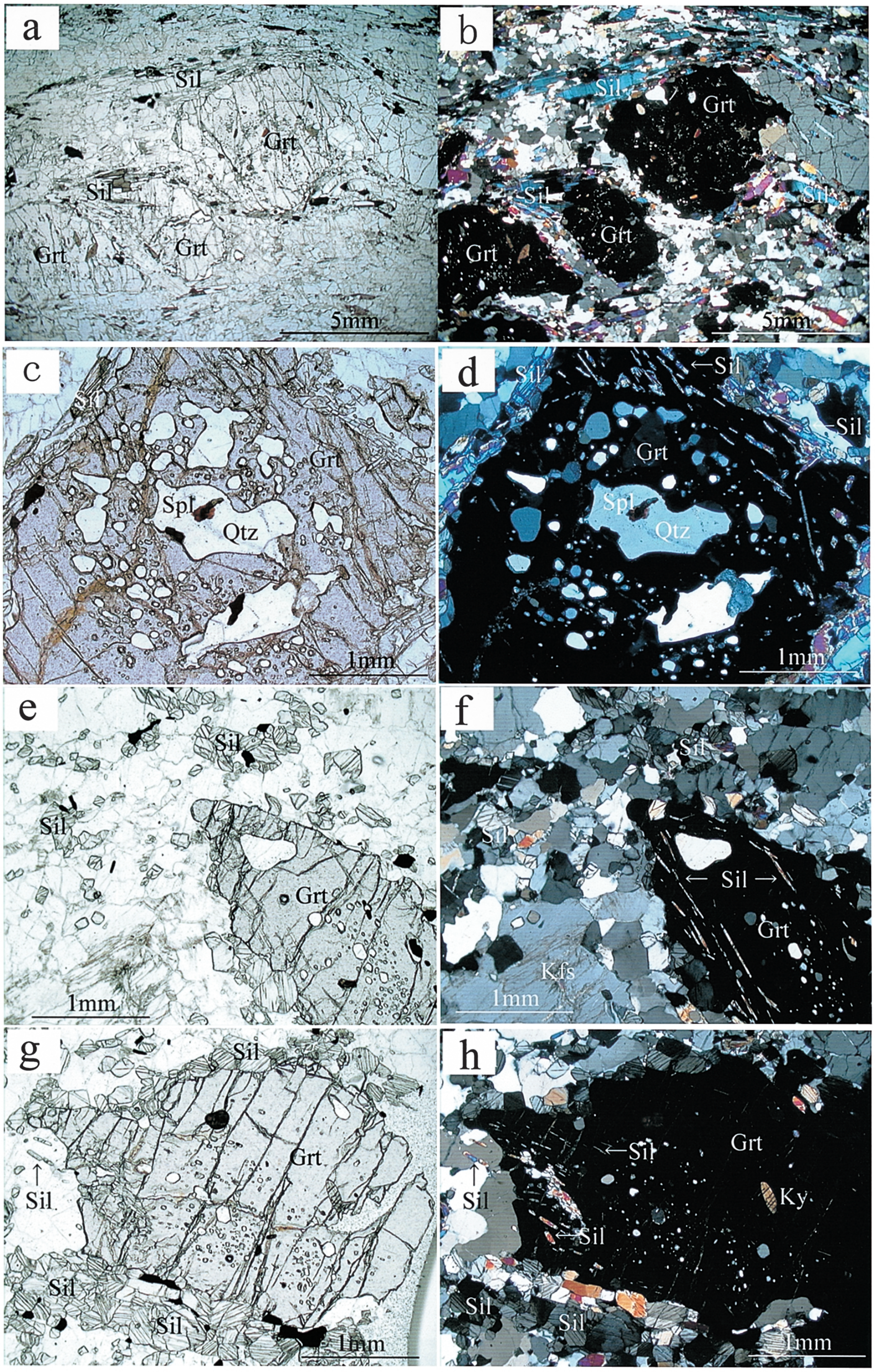
Stretching lineations in S_{m-1} planes, defined by the alignment of sillimanite, are parallel to F_{m-1} fold axes. It is clear from the field relationship that they were formed during the D_{m-1} stage, since it is observed even in localities where F_m is not strongly developed.

5. Microscopic structures in the Grt-Sil leucogneiss

Microstructures were described in a Grt-Sil leucogneiss collected from area D (Fig. 1). The sample studied (TK2003011804) is the same as that used in the petrological study of Kawakami and Motoyoshi (2004). The sample consists of garnet, sillimanite, plagioclase, K-feldspar, quartz, and subordinate amounts of rutile, ilmenite and zircon. Myrmekite is locally observed. Biotite, chlorite and muscovite are locally present as retrograde products replacing garnet and sillimanite. Sillimanite in the matrix defines a stretching lineation trending NNE-SSW to NE-SW on S_{m-1} planes (Fig. 3a, b). Garnet grains are typically 5 mm in diameter with inclusion-rich cores and inclusion-poor rims. Inclusions in the garnet cores comprise kyanite, sillimanite, biotite, rutile, spinel, plagioclase, quartz and staurolite. Rare inclusions of spinel in direct contact with quartz are present. Aluminosilicate in the cores are typically kyanite when accompanied with spinel but sillimanite also occurs as isolated inclusions (Kawakami and Motoyoshi, 2004). Inclusions in the garnet rim are, if present, mostly sillimanite. Sillimanite grains in the rock matrix have different orientations to those in garnet rims (Fig. 3c–f). A clear example is shown in Fig. 3e, f, in which most sillimanite crystals in the matrix have *c*-axes perpendicular to the observed surface, whereas *c*-axes of the sillimanite included in the garnet rim lie subparallel to the observed surface. In a few garnet grains, however, sillimanite grains form continuous trails from matrix into garnet rims (Fig. 3g, h). Based on these observations, we consider that a discontinuous change in the orientation of the principal strain axes took place between the time of garnet rim formation and the formation of matrix minerals. Alignment of minerals included in the garnet cores is not observed.

6. Discussion

F_m and F_{m+1} folds were probably formed during the D_1 and D_2 events described by Yoshida (1978), respectively. Yoshida (1978) locates the axial trace of a fold which was formed during D_3 at the eastern margin of Skallevikshalsen; the present study, however, did not observe any folds postdating F_{m+1} in areas A–D (Fig. 1). Although folding predating D_1 has been recognized (*e.g.*, Yoshida, 1978), detailed studies on these structures have not been carried out.


a
Sil
Grt
Sil
Grt
Grt
5mm
b
Sil
Grt
Sil
Sil
Grt
Grt
5mm
c
Sil
Grt
Spl
Qtz
1mm
d
Sil
←Sil
Sil
Grt
Spl
Qtz
1mm
e
Sil
Sil
Grt
1mm
f
Sil
Sil
← Sil →
Grt
Kfs
1mm
g
Sil
↑
Sil
Grt
Sil
Sil
1mm
h
←Sil
Grt
↑
Sil
Ky
←Sil
Sil
Sil
1mm

As described above, the orientation of F_{m-1} fold axes overlaps with that of F_m, and stretching lineations in S_{m-1} planes are parallel to F_{m-1} fold axes. There are two interpretations for these observations. One is that F_m axes were originally parallel to F_{m-1} axes, and the another is that F_{m-1} axes and stretching lineations were re-oriented to the same direction as F_m during D_m stage. The F_m folds are tight to open and do not involve intense stretching parallel to F_m axes. Therefore, the first interpretation is plausible and implies that no change in the elongation direction took place between the D_{m-1} and D_m stages in Skallevikshalsen (Fig. 1). It is clear from the field relationship that the stretching lineation defined by the alignment of matrix sillimanite crystals was formed during the D_{m-1} stage. Sillimanite inclusions in garnet that orientate approximately perpendicular to the matrix sillimanite (Fig. 3e, f), are difficult to form by rigid body rotation of the garnet including matrix sillimanite during D_{m-1}, because the axis of rotation of garnet is expected to be perpendicular to the orientation of matrix sillimanite alignment within the plane of compositional layering (S_{m-1}). The alignment of sillimanite inclusions in the garnet rim, therefore, probably corresponds to a pre-D_{m-1} schistosity. We name this deformation stage D_{m-2}.

Based on the microstructural study of Grt-Sil leucogneiss from area D, constraints can be placed on the relationship between macroscopic and microscopic structures. Differences in crystal orientation between matrix sillimanite and sillimanite inclusions in garnet rims (Fig. 3e, f) suggest that a change in the orientation of the principal strain axes took place between D_{m-2} and D_{m-1}. The occasional presence of sillimanite grains in garnet rims that continued into the matrix (Fig. 3g, h) suggests that growth of the garnet rim continued into D_{m-1}.

Absence of the aligned inclusions in garnet cores, where prograde and peak mineral assemblages are preserved (Kawakami and Motoyoshi, 2004), suggests that the prograde stage and the metamorphic peak belonged to a period without strong deformation, predating D_{m-2} (Table 1). It is suggested that the process that caused metamorphism, especially the introduction of a heat source, did not involve strong deformation until metamorphic rocks reached peak temperatures. D_{m-2} and D_{m-1} were probably accompanied by decompression (Kawakami and Motoyoshi, 2004) and probably correspond, therefore, to the exhumation stage of the metamorphic terrane. Although microstructural studies of other rock types are required to establish the validity of the

---

Fig. 3 (opposite). Photomicrographs of Grt-Sil leucogneiss (TK2003011801-04) showing the mode of occurrence of aluminosilicate. (a) Matrix sillimanite defining S_{m-1}. Inclusion minerals in the garnet core are unaligned. The view plane is normal to S_{m-1} and parallel to the lineation of matrix sillimanite. Plane polarized light. (b) Same view under crossed polars. (c) Spl+Qtz inclusion and abundant quartz inclusions in a garnet core and aligned sillimanite inclusions in the garnet rim. The view plane is the same as in (a). Plane polarized light. (d) Same view under crossed polars. (e) Matrix sillimanite with different crystal orientations from that included in the garnet rim. The view plane is normal to S_{m-1} and lineation of matrix sillimanite. Plane polarized light. (f) Same view under crossed polars. (g) Alignment of sillimanite inclusions in the garnet rim is continuous into the matrix. Most of sillimanite crystals in the matrix have different crystal orientations. Plane polarized light. (h) Same view under crossed polars.

P-T-D evolution summarized in Table 1, we propose the existence of D_{m-2} stage and attainment of peak metamorphic conditions without strong deformation in Skallevikshalsen.

Acknowledgments

We are grateful to the crew members of the icebreaker *Shirase* and members of JARE-44 for their support on the research expedition. Y. Kawano and T. Kawasaki are thanked for their support in the field. We are thankful to Y. Osanai, K. Shiraishi, and Y. Motoyoshi for support and discussions and to M. Aoya, Y. Yoshimura and Y. Hiroi for comments and discussions. Thanks are also due to T. Hokada and D.J. Dunkley for constructive reviews. This study was financially supported by a Grant-in-Aid for the Japan Society for the Promotion of Science (JSPS) Fellows (No. 05864) to T. Kawakami and Grant in Aid for Scientific Research (C) (No. 14540451) from JSPS to T. Ikeda.

References

Fraser, G., McDougall, I., Ellis, D.J. and Williams, I.S. (2000): Timing and rate of isothermal decompression in Pan-African granulites from Rundvågshetta, East Antarctica. J. Metamorph. Geol., **18**, 441–454.

Hiroi, Y., Shiraishi, K., Yanai, K. and Kizaki, K. (1983): Aluminum silicates in the Prince Olav and Sôya Coasts, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **28**, 115–131.

Hiroi, Y., Shiraishi, K., Motoyoshi, Y., Kanisawa, S., Yanai, K. and Kizaki, K. (1986): Mode of occurrence, bulk chemical compositions, and mineral textures of ultramafic rocks in the Lützow-Holm Complex, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **43**, 62–84.

Hiroi, Y., Shiraishi, K., Motoyoshi, Y. and Katsushima, T. (1987): Progressive metamorphism of calc-silicate rocks from the Prince Olav and Sôya Coasts, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **1**, 73–97.

Hiroi, Y., Shiraishi, K. and Motoyoshi, Y. (1991): Late Proterozoic paired metamorphic complexes in East Antarctica, with special reference to the tectonic significance of ultramafic rocks. Geological Evolution of Antarctica, ed. by M.R.A. Thomson *et al*. Cambridge University Press, 83–87.

Ikeda, T. and Kawakami, T. (2004): Structural analysis of the Lützow-Holm Complex in Akarui Point, East Antarctica, and overview of the complex. Polar Geosci., **17**, 22–34.

Ishikawa, M., Motoyoshi, Y., Fraser, G.L. and Kawasaki, T. (1994a): Structural evolution of Rundvågshetta region, Lützow-Holm Bay, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **7**, 69–89.

Ishikawa, M., Shiraishi, K., Motoyoshi, Y., Tsuchiya, N., Shimura, T. and Yanai, K. (1994b): Geological map of Ongul Islands, Lützow-Holm Bay, Antarctica. Antarct. Geol. Map Ser., Sheet 36 (with explanatory text 21 p.). Tokyo, Natl Inst. Polar Res.

Ishikawa, T. (1976): Superimposed folding of the Precambrian metamorphic rocks of the Lützow-Holm Bay region, East Antarctica. Mem. Natl Inst. Polar Res., Ser. C (Earth Sci.), **9**, 41 p.

Kawakami, T. and Ikeda, T. (2004): Structural evolution of the Ongul Islands, Lützow-Holm Complex, East Antarctica. Polar Geosci., **17**, 12–21.

Kawakami, T. and Motoyoshi, Y. (2004): Timing of the spinel + quartz formation in the garnet-sillimanite leucogneiss from Skallevikshalsen, Lützow-Holm Complex, East Antarctica. J. Mineral. Petrol. Sci., **99** (in press).

Kawasaki, T., Ishikawa, M. and Motoyoshi, Y. (1993): A preliminary report on cordierite-bearing assemblages from Rundvågshetta region, Lützow-Holm Bay, East Antarctica: Evidence for a decompressional *P-T* path? Proc. NIPR Symp. Antarct. Geosci., **6**, 47–56.

Kizaki, K. (1962): Structural geology and petrology of East Ongul Island, East Antarctica. Part I. Structural geology. Nankyoku Shiryô (Antarct. Rec.), **14**, 27–35.

Kizaki, K. (1964): Tectonics and petrography of the East Ongul Island, Lützow-Holm Bukt, Antarctica. JARE Sci. Rep., Ser. C (Geology), **2**, 24 p.

Kretz, R. (1983): Symbols for rock-forming minerals. Am. Mineral., **68**, 277–279.

Matsumoto, Y., Nishida, T., Yanai, K. and Kojima, H. (1982): Geology and geologic structure of the Northern Ongul Islands and surroundings, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **21**, 47–70.

Motoyoshi, Y. (1986): Prograde and progressive metamorphism of the granulite facies Lützow-Holm Bay region, East Antarctica. D. Sc. Thesis, Hokkaido University, 238 p.

Motoyoshi, Y. and Ishikawa, M. (1997): Metamorphic and structural evolution of granulites from Rundvågshetta, Lützow-Holm Bay, East Antarctica. The Antarctic Region: Geological Evolution and Processes, ed. by C.A. Ricci. Siena, Terra Antarct. Publ., 65–72.

Shiraishi, K., Hiroi, Y., Ellis, D.J., Fanning, C.M., Motoyoshi, Y. and Nakai, Y. (1992): The first report of a Cambrian orogenic belt in East Antarctica—An ion microprobe study of the Lützow-Holm Complex. Recent Progress in Antarctic Earth Science, ed. by Y. Yoshida *et al*. Tokyo, Terra Sci. Publ., 67–73.

Shiraishi, K., Ellis, D.J., Hiroi, Y., Fanning, C.M., Motoyoshi, Y. and Nakai, Y. (1994): Cambrian orogenic belt in East Antarctica and Sri Lanka: Implications for Gondwana Assembly. J. Geol., **102**, 47–65.

Shiraishi, K., Ellis, D.J., Fanning, C.M., Hiroi, Y., Kagami, H. and Motoyoshi, Y. (1997): Re-examination of the metamorphic and protolith ages of the Rayner complex, Antarctica: Evidence for the Cambrian (Pan-African) regional metamorphic event. The Antarctic Region: Geological Evolution and Processes, ed. by C.A. Ricci. Siena, Terra Antarct. Publ., 79–88.

Yoshida, M. (1977): Geology of the Skallen region, Lützow-Holmbukta, East Antarctica. Mem. Natl Inst. Polar Res., Ser. C(Earth Sci.), **11**, 38 p.

Yoshida, M. (1978): Tectonics and petrology of charnockites around Lützow-Holmbukta, East Antarctica. J. Geosci., Osaka City Univ., **21**, 65–152.

Yoshida, M., Yoshida, Y., Ando, H., Ishikawa, T. and Tatsumi, T. (1976): Geological map of Skallen, Antarctica. Antarct. Geol. Map Ser., Sheet 9 (with explanatory text 16 p.). Tokyo, Natl Inst. Polar Res.

Yoshimura, Y., Motoyoshi, Y., Miyamoto, T., Grew, E.S., Carson, C.J. and Dunkley, D.J. (2004): High-grade metamorphic rocks from Skallevikshalsen in the Lützow-Holm Complex, East Antarctica: Metamorphic conditions and possibility of partial melting. Polar Geosci., **17**, 57–87.