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Structural evolution of the Ongul Islands, Lützow-Holm Complex, East Antarctica

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Abstract: We describe outcrop-scale folds at ten localities in the Ongul Islands, including five localities where interference patterns of two stages of folding are observed, along with structural data summarized in stereogram. F_{m-1} are recognized as isoclinal to rootless folds with fold axes trending NNW-SSE. S_{m-1} is defined by orthopyroxene, hornblende and biotite aligned parallel to the compositional layering and as axial planar foliation in F_{m-1} folds, and is folded by tight F_m. F_m have axial traces that trend NNW-SSE and subvertical axial planes dipping ENE and striking NNW-SSE. Axial planar foliation S_m is defined by biotite and hornblende in the hinges of F_m. F_{m-1} axes typically trend parallel to F_m axes and can be discriminated only in areas showing interference patterns. F_{m+1} are gentle to open with axes trending approximately N-S. Boudinage formed before D_m and interboudin partitions are filled with orthopyroxene-bearing leucosome. Judging from minerals constituting D_{m-1} and D_m structures, D_{m-1} occurred under granulite-facies conditions and at least part of D_m probably under amphibolite-facies conditions.

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

1. Introduction

The Lützow-Holm Complex is a Cambrian orogenic belt bounded by Late Proterozoic to Early Palaeozoic complexes, *i.e.* the Rayner Complex to the east and Yamato-Belgica Complex to the west (Shiraishi *et al*., 1992, 1994, 1997). Petrological aspects of the complex are well studied, mainly by Japanese geologists, and are briefly summarized by Kawakami and Ikeda (2004). In contrast, the detailed structural evolution of the Lützow-Holm Complex has not yet been fully understood, as pointed out by M. Ishikawa *et al*. (1994a) and Motoyoshi and Ishikawa (1997), although individual parts of the complex have been structurally described in previous studies (*e.g.* Kizaki, 1962, 1964; T. Ishikawa, 1976; Yoshida, 1977, 1978; Matsumoto *et al*., 1979, 1982; M. Ishikawa *et al*., 1994a, b; Motoyoshi and Ishikawa, 1997).

Yoshida (1978) divided folds and fractures developed throughout the Lützow-

Holm Complex into four groups according to the timing of formation, referred to as D_1, D_2, D_3 and D_4. D_1 was responsible for the formation of recumbent and isoclinal folds with axial traces trending approximately parallel to the coastline of the continent. Some thrusts were developed in relation with the folding. D_2 is represented by open to close folds, with axial traces nearly perpendicular to D_1 folds. D_3 corresponds to gentle folds trending NE-SW to N-S. Conjugate sets of fractures were formed during D_4. D_3 folds occur as several-km scale structures in Skarvsnes (T. Ishikawa, 1976) and Skallen (Yoshida, 1978). The D_1 folds have been named F_1 by T. Ishikawa (1976) and F_n by M. Ishikawa *et al.* (1994b).

Structures predating D_1 (pre-D_1 or pre-F_n folds) have been recognized (*e.g.*, Yoshida, 1978), but not described in detail. The importance of pre-D_1 structures has been recently emphasized by Kawakami and Motoyoshi (2004), who described foliation contemporaneous with pre-D_1 structures that is locally associated with aligned minerals included in the rims of garnet grains which contain spinel+quartz in the cores. This may indicate that a pre-D_1 event was chronologically closer to the peak metamorphism than the other stages of deformation. Pre-D_1 folds recognized in the field could, therefore, link outcrop-scale and microscopic-scale structures and reveal a relationship between deformation and mineral formation during or immediately after peak metamorphism. We researched several localities that covered a wide range of metamorphic grades, including Skallevikshalsen (Kawakami and Ikeda, 2004), Akarui Point (Ikeda and Kawakami, 2004) and the Ongul Islands (this study). This study shows that pre-D_1 folds are well preserved and common in both East and West Ongul Islands, and describes the mode of occurrence.

2. Geological outline of Ongul Islands

Granulite facies metamorphic rocks are widely distributed throughout the Ongul Islands (Hiroi *et al.*, 1983, 1991; M. Ishikawa *et al.*, 1994b). Dominant rock types are pyroxene gneiss, hornblende gneiss, garnet-biotite gneiss and augen gneiss with subordinate amounts of hornblende-biotite gneissose granite, garnet-orthopyroxene amphibolite, metabasite and pegmatite. Minor calc-silicate rock and marble also occur (Fig. 1, M. Ishikawa *et al.*, 1994b).

Kizaki (1962) recognized isoclinal folds with subhorizontal fold axes trending NNW-SSE as the most dominant and penetrative structures on East Ongul Island. Matsumoto *et al.* (1982) showed that the F_1 folds of Yoshida (1978) were re-orientated by close to open folds, regarded as D_2 folds, with wavelengths up to 2 km and axial traces running ESE-WNW in the Ongul Islands and adjacent areas. Matsumoto *et al.* (1982) did not recognize D_3 folds in the Ongul Islands. M. Ishikawa *et al.* (1994b) described four stages of folding (pre-F_n, F_n and two stages of post-F_n folds) in the Ongul Islands. F_n are isoclinal with fold axes parallel to a mineral lineation (L_n) defined by hornblende or orthopyroxene. The axial planar foliation of F_n, defined by biotite, strikes NNW-SSE. F_n partially deform pre-F_n folds (F_{n-1}), which are either isoclinal, recumbent or overturned. Fold axes of F_{n-1} are subparallel to those of F_n. Post-F_n folds are gentle to open. One set has subhorizontal fold axes plunging NNE or SSW and subvertical axial planes striking NNE-SSW. Another set has subhorizontal fold axes trending E-W

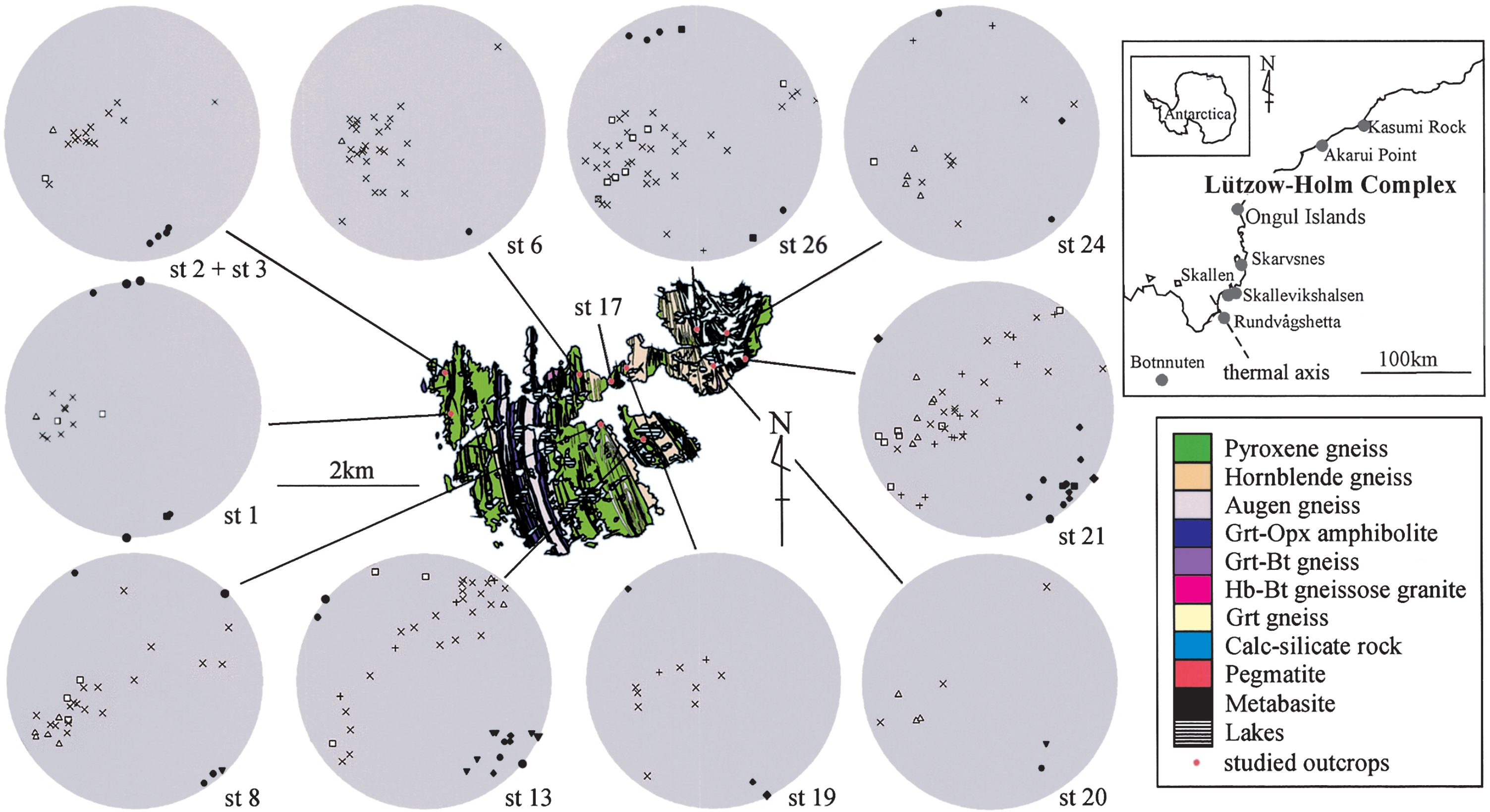

Fig. 1. Geological map of the Ongul Islands (M. Ishikawa et al., 1994b) and stereograms of structural data from ten areas. Equal area, lower hemisphere projection. ◆; *F_{m-1} axes,* ●; *F_m axes,* ■; *stretching lineation on S_{m-1},* ▼; *crenulation lineation,* ×; *poles to compositional layering and S_{m-1},* +; *poles to F_{m-1} axial planes,* △; *poles to F_m axial planes,* □; *poles to axial planar S_m.*

and subvertical axial planes striking E-W. The timing of these two folds is still not clear (M. Ishikawa *et al*. 1994b).

3. Structural descriptions

We describe here outcrop-scale folds from ten localities, numbered with prefix 'st' in Fig. 1, and plot the structural data in stereograms (Figs. 1, 2 and 3). Three stages of deformation are recognized, denoted as D_{m-1}, D_m and D_{m+1}, which can be distinguished by the superimposed relation of folds and trends of fold axes.

3.1. D_{m-1} structures

Penetrative, major foliations generally developed parallel to the compositional layering of the metamorphic rocks, which we term S_{m-1}, are mainly composed of orthopyroxene, clinopyroxene, biotite and hornblende in basic to intermediate rocks. S_{m-1} is also axial planar to F_{m-1} which are isoclinal to rootless with fold axes trending NNW-SSE. Axial planes of F_{m-1} are almost parallel to the compositional layering, and poles to F_{m-1} axial planes lie on the same great circle as poles to S_{m-1} (Fig. 1). Hinges of F_{m-1} are commonly boudinaged around the hinges of F_m (Fig. 2c, d). Axial planar S_{m-1} is locally preserved at the hinges of F_{m-1}, and consists of biotite or hornblende in most cases, depending on rock type. In st26 in Fig. 1, the long axes of the orthopyroxene crystals are aligned parallel to the axial plane of F_{m-1} (Fig. 5). Mineral lineations of hornblende, biotite and garnet aggregates are found on S_{m-1} planes. These trend NNW-SSE parallel to F_{m-1} (Fig. 1).

Boudinage is common in the Ongul Islands and timing of its formation has not been well constrained. In Fig. 2c, d, hinges of F_{m-1} are boudinaged within compositional layering S_{m-1} and folded by F_m. This indicates that boudinage structures were formed before D_m. In addition, boudinage structures are observed in two specific layers (boudinaged layers 1 and 2) in Fig. 2e, and S_{m-1} are dragged into boudin necks. Interboudin partitions are observed within the plane subparallel to the fold axes of F_{m-1}, and are filled with leucosome containing orthopyroxene and garnet (Fig. 2e, f).

3.2. D_m structures

S_{m-1} is tightly folded by folds with axes trending NNW-SSE and axial planes dipping steeply ENE and striking NNW-SSE. We term these dominant and penetrative folds F_m, formed during D_m (Figs. 2a–c and 3a–c). At the hinge of F_m folds, axial planar foliation S_m is present defined by biotite and hornblende (Figs. 3a and 4a–b). Garnet is locally flattened into S_m with biotite in garnet-biotite leucogneiss on West Ongul Island (Fig. 3d–f). Orthopyroxene grains up to 1 cm in diameter are aligned along S_{m-1} at the hinge of F_m folds, and do not define S_m (Fig. 3c).

In most places, F_{m-1} and F_m have parallel axial planar foliations and NNW-SSE axial trends, so that it is not easy to discriminate F_m and F_{m-1} in the field. Interference patterns of F_{m-1} and F_m are common throughout the Ongul Islands (st13, st19, st21, st24 and st26 in Fig. 1). The clearest examples occur in the southeastern part of East Ongul Island (st21 in Fig. 1). At this locality, isoclinal folds are commonly refolded by tight folds (Fig. 2a–c).

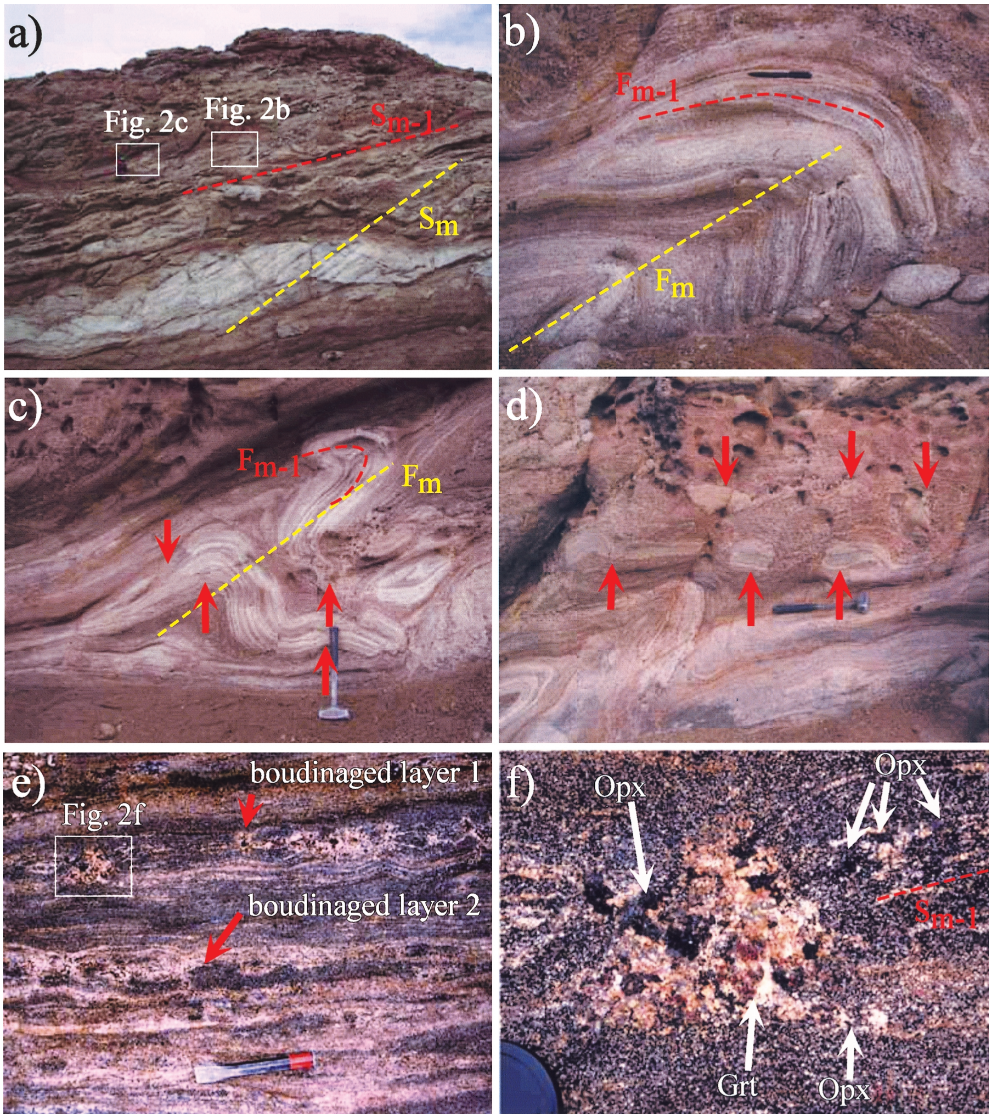

Fig. 2. *(a) Photograph of outcrop at st21 (see Fig. 1). Subhorizontal S_{m-1} is overprinted by S_m, visible in the white layer at the bottom of the photograph. F_m refold F_{m-1} in the boxed parts. View to S. (b) Enlargement of (a). F_m refolding isoclinal F_{m-1}. (c) Enlargement of (a). F_m refolding boudinaged hinges of isoclinal F_{m-1}. Boudin necks are shown by arrows. (d) Isoclinal F_{m-1} boudinaged at the hinge of F_m. Boudinaged blocks are shown by arrows. (e) Boudinaged hornblende gneiss from the western part of East Ongul Island (st17). Boudinage is developed in two specific layers (boudinaged layers 1 and 2). View to E. (f) Enlargement of (e). Interboudin partition filled with orthopyroxene- and garnet-bearing leucosome. Orthopyroxene is also aligned with S_{m-1}, as shown by arrows.*

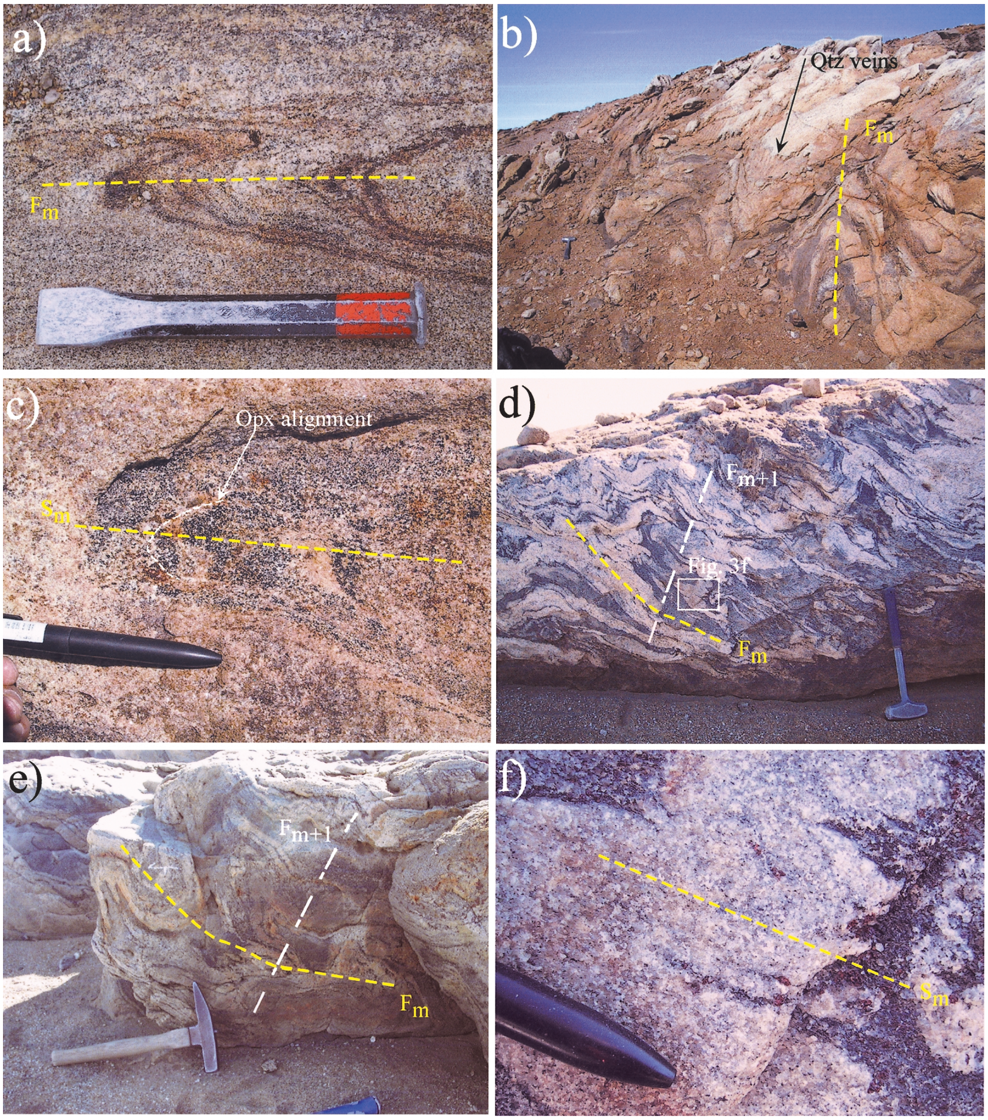

Fig. 3. (a) F_m in the western part of East Ongul Island. Axial planar foliation defined by biotite (S_m) at the hinge of the fold. (b) F_m folds in the eastern part of West Ongul Island (st8). View to SSE. Quartz veins formed parallel to axial planar S_m. (c) Enlargement of the hinge of (b). The axial planar foliation S_m mainly consists of aligned hornblende grains. Coarse orthopyroxene grains are aligned with S_{m-1}. (d)–(e) F_m refolded by gentle F_{m+1} (st1). View to N. (f) Enlargement of (d). Lens-shaped garnet grains define axial planar S_m, along with biotite grains.

Orientation of S_m and F_m is almost constant across the islands (Fig. 1). Poles to S_{m-1} planes lie on a great circle, with a pole parallel to the orientation of F_m axes. This is consistent with the field observation that S_{m-1} is folded by F_m (Figs. 2a–c and 3a–c).

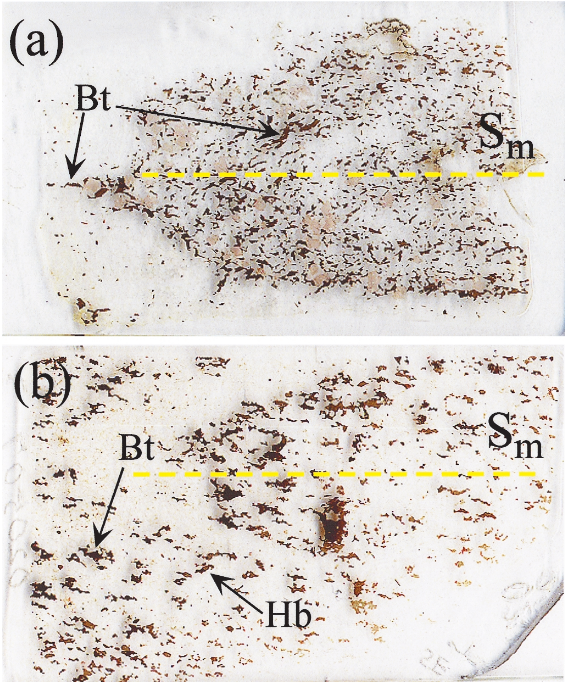

Fig. 4. Photographs of thin sections of the hinge of F_m. (a) Garnet-biotite gneiss from st1. Biotite defines the axial planar foliations S_m. (b) Hornblende gneiss from st21. Hornblende and biotite define the axial planar foliations S_m.

3.3. D_{m+1} structures

F_{m+1} are gentle to open folds with axes trending approximately N-S. Axial planes dip gently to west. Axial planar S_m are folded by F_{m+1} (Fig. 3d, e). Scattering of the plotted data of S_m poles observed in Fig. 1 is probably due to these folds. We could not recognize gentle folds with E-W fold axes, described by M. Ishikawa *et al.* (1994b), because of difficulty in distinguishing such folds from the undulation of compositional layering foliation caused by the ductile boudinage.

4. Discussion

F_{m-1}, F_m and F_{m+1} folds probably correspond to F_{n-1}, F_n and one of the post-F_n folds of M. Ishikawa *et al.* (1994b), respectively, and F_m corresponds to F_1 of T. Ishikawa (1976) and D_1 folds of Yoshida (1978). Although the axial traces of F_{m+1} were not clearly determined, they trend approximately N-S and may correspond, therefore, to D_3 folds. M. Ishikawa *et al.* (1994b) described mineral lineations defined by elongated quartz, orthopyroxene aggregates and preferred orientations of hornblende, and named them L_n. These are probably the same mineral lineations we observed on S_{m-1}. M. Ishikawa *et al.* (1994b) considered that L_n lineations formed coevally with F_n, because the trend of elongation is identical to that of F_n fold axes.

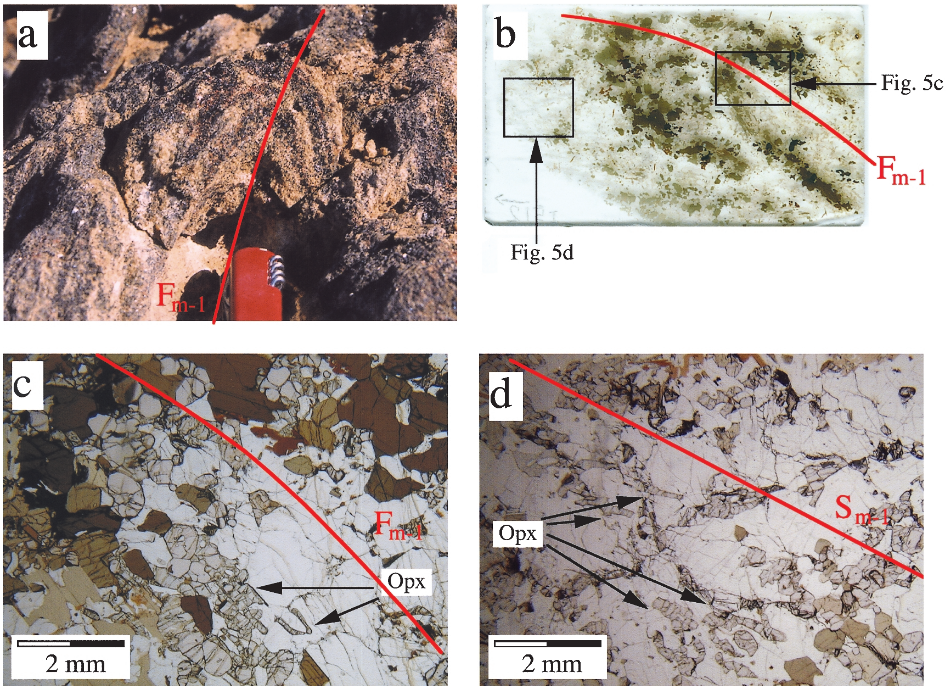

Fig. 5. (a) Photograph of an intrafolial fold (F_{m-1}) from st26. (b) Photograph of thin section (#I-512) cut perpendicular to the F_{m-1} axis. (c) and (d) Photomicrographs of the boxed area of (b), in plane-polarized light. Long axes of orthopyroxene grains are parallel to the F_{m-1} fold axis at both hinge (c) and limb (d) parts of the F_{m-1} fold.

F_{m-1} ($=F_{n-1}$), however, has the same trend of fold axis as F_m ($=F_n$), and the mineral lineations we observed are developed on S_{m-1} planes. Presence of boudinages formed before D_m suggests that strong extension took place before D_m. It is also probable that these mineral lineations were formed before D_m.

Presence of orthopyroxene aligned parallel to the axial planes of F_{m-1} (Fig. 5), orthopyroxene in the boudin necks and also in the S_{m-1} foliations (Fig. 2e, f), and orthopyroxene grains aligned along S_{m-1} planes in the hinges of F_m folds (Fig. 3c) suggest that D_{m-1} took place under granulite-facies conditions. In contrast, since biotite and hornblende, but not orthopyroxene, are commonly aligned on S_m planes at the hinge of F_m folds (Fig. 4a–b), part of D_m possibly took place under amphibolite-facies conditions. Metamorphic grades under which dominant folds were formed in the Ongul Islands correspond to those suggested by Kawakami and Ikeda (2004) for Skallevikshalsen. However, the absence of the petrological evidence that preserves the prograde metamorphic stage in the Ongul Islands, such as relic kyanite and staurolite (*e.g.* Hiroi *et al.*, 1983, 1991; Motoyoshi *et al.*, 1985) limits understanding of the prograde pressure-temperature-deformation evolution of the Ongul Islands.

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