ALUMINUM SILICATES IN THE PRINCE OLAV AND SÔYA COASTS, EAST ANTARCTICA

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Abstract: This paper presents the regional distribution and textural features of aluminum silicates (kyanite, sillimanite, and andalusite) in the Prince Olav and Sôya Coasts, East Antarctica. The data make it clear that the regional metamorphism in the region, probably Late Proterozoic in age, was of the medium-pressure type and that the regional metamorphic rocks locally underwent the retrograde alteration, including local development of andalusite, during the Early Paleozoic thermal event contemporaneous with the emplacement of granite and pegmatite.

1. Introduction

Aluminum silicates (kyanite, sillimanite and andalusite) are the diagnostic minerals to define the facies series of metamorphic rocks (MIYASHIRO, 1961). Until quite recently*, only sillimanite had been reported by Japanese geologists in the amphibolite- and granulite-facies rocks from the Prince Olav and Sôya Coasts (68–69.5°S, 39–45°E) (YOSHIDA *et al.*, 1976; YANAI and ISHIKAWA, 1978; YOSHIDA, 1978, 1979a, 1979b; KANISAWA *et al.*, 1979; NAKAI *et al.*, 1980; KANISAWA and YANAI, 1982), while kyanite and sillimanite have been reported by Russian geologists in the amphibolite-facies rocks in the eastern part of the Prince Olav Coast (RAVICH and KAMENEV, 1975). Thus, it has not been well-defined whether the high-grade metamorphic rocks in the present region belong to the medium-pressure series or to the lower-pressure one (*cf.* SUWA, 1968; KAMENEV, 1980, 1982). Moreover, the thermal effect of the widespread granite and pegmatite on the high-grade metamorphic rocks has not been well known.

This paper presents the regional distribution and textural features of the three polymorphs of aluminum silicate in the Prince Olav and Sôya Coasts. These data would provide an important clue not only to establish the facies series of the regional metamorphic rocks in the region but also to reveal the metamorphic history of the present portion of the East Antarctic shield.

* HIROI *et al.* (1983) and KIZAKI *et al.* (1983) reported kyanite in the sillimanite-bearing rocks from Sinnan Rocks and Niban Rock in the Prince Olav Coast, respectively.

2. General Geology

The regional geology of the Indian Ocean sector of East Antarctica was reviewed by GREW (1982). The rocks exposed in the Prince Olav and Sôya Coasts were once termed the Lützow-Holm Bay system (TATSUMI and KIZAKI, 1969). Later they were divided into two distinct geologic units, which are, from east to west, the Okuiwa group (Insel complex) and the Ongul group (RAVICH and KAMENEV, 1975; RAVICH and GURIKUROV, 1978; YOSHIDA, 1978, 1979a, 1979b; GURIKUROV, 1982). To the east of the Okuiwa group occurs the polymetamorphic Rayner complex (Fig. 1) (TRAIL and MCLEOD, 1969; KAMENEV, 1972; RAVICH and KAMENEV, 1975; RAVICH and GURIKUROV, 1978; GREW, 1978, 1981, 1982; GURIKUROV, 1982). The Okuiwa group (Insel complex) is composed of amphibolite-facies rocks, while the Ongul group consists of hornblende-granulite-facies rocks (RAVICH and KAMENEV, 1975; YOSHIDA, 1978, 1979a, 1979b; KAMENEV, 1980, 1982). YOSHIDA (1978, 1979a, b) considered that the Okuiwa group is younger than the Ongul group on the basis of the deformational and metamorphic characteristics. However, the recent geologic studies of the Prince Olav Coast (Okuiwa group) have revealed that the lithologic and deformational features in the coast are common to those of the Sôya Coast (Ongul group) (HIROI *et al.*, 1983). Moreover, HIROI *et al.* (1982) showed that the metamorphic grade increases gradually from east to west up to the lower granulite facies in the Prince Olav Coast. Therefore, the geologic units of the Prince Olav and Sôya Coasts will be collectively described as the Lützow-Holm Bay system below.

The Lützow-Holm Bay system consists largely of well-layered gneisses and partly of migmatitic rocks. Among the well-layered gneisses pelitic and intermediate rocks are abundant. The pelitic rocks are biotite gneiss, garnet-biotite gneiss, and various kinds of sillimanite-biotite gneiss. The intermediate rocks comprise biotite-hornblende gneiss and charnockitic gneiss. The latter gneiss is characteristic of the Sôya Coast. Metamorphosed basic to ultrabasic rocks occur as thin layers up to tens of meters thick and as blocks included in the charnockitic gneiss. They are amphibolites, pyroxenites and peridotites. Quartzites, calc-silicate rocks and marbles with or without skarn occur as thin layers and pods in the well-layered gneisses. Two major stages of folding have been discriminated throughout the present region; the earlier isoclinal folds with axial planes trending N-S and the later close to open folds with axial planes of the E-W trend (ISHIKAWA, 1976; YOSHIDA, 1978; MATSUMOTO *et al.*, 1979, 1982; HIROI *et al.*, 1983).

Most of the radiometric ages for the metamorphic rocks in the present region are based on K-Ar and Rb-Sr methods on whole rocks or mineral separates (YANAI and UEDA, 1974; YOSHIDA *et al.*, 1982). They show almost the same age of about 500 Ma, which suggests a heating event coeval with the granite and pegmatite activity (YANAI and UEDA, 1974; GREW, 1982). Such a thermal event of 500 Ma ago has been known over a large portion of East Antarctic shield (GREW, 1982). YOSHIDA (1978, 1979a) and YOSHIDA *et al.* (1982) supposed one or two stages of regional (?) metamorphism between 600 Ma and 400 Ma, but we here assume that such Early Paleozoic event was a thermal one which has slightly affected the pre-existing high-grade rocks. A few

Rb-Sr mineral or whole rock isochron ages from the present region are 1100 to 1200 Ma (MAEGOYA *et al.*, 1968; SHIRAHATA, personal communication), which appear to date the main regional metamorphism in the present region. GREW (1978) reported a similar Rb-Sr whole rock isochron age (987 Ma) on charnockitic gneiss of the Rayner complex and discussed the significance of the 1000 Ma metamorphic event in western Enderby Land. YOSHIDA *et al.* (1982) supposed 1900 Ma metamorphic event prior to the 1100 to 1200 Ma regional metamorphism on the basis of poor radiometric and petrographical evidence. Their petrographical data may be interpreted in a different way, and we at present assume that the main Late Proterozoic regional metamorphism was followed by the Early Paleozoic thermal event mentioned above.

Granite and pegmatite are widespread in the present region; especially in the western part of the Prince Olav Coast they are most extensively developed. They occur as sub-concordant sheets and discordant masses (mostly dikes) in the metamorphic rocks. The radiometric ages of the granite and pegmatite are about 500 Ma (YANAI and UEDA, 1974).

3. General Petrology

Most of the rocks of the Lützow-Holm Bay system show mineralogical characteristics of the upper amphibolite to lower granulite facies. In rocks of basic, intermediate, and pelitic compositions, calcium-poor amphiboles (anthophyllite, gedrite and cummingtonite) occur in the eastern part of the Prince Olav Coast (RAVICH and KAMENEV,

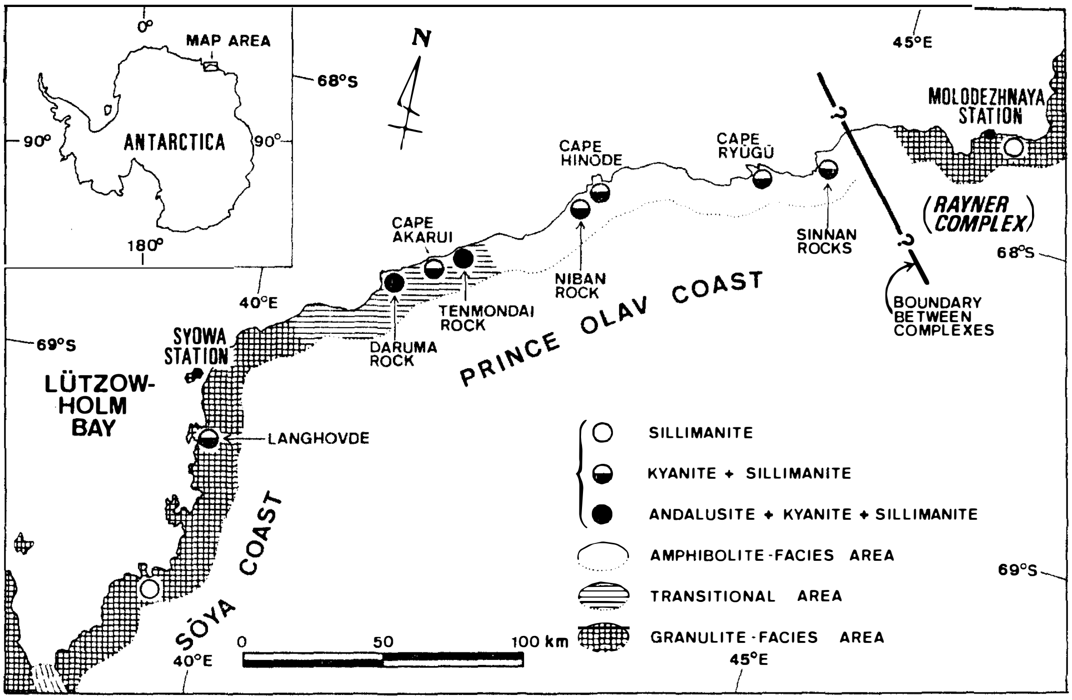

Fig. 1. Map of Prince Olav and Sôya Coasts, showing metamorphic facies of basement rocks and distribution of polymorphs of aluminum silicate. Sources of the southern part of the Sôya Coast and of the Rayner complex around Molodezhnaya Station are YOSHIDA *(1978) and* GREW *(1981), respectively.*

1975; HIROI *et al.*, 1982, 1983), while orthopyroxene sporadically occurs in the western part of the Prince Olav Coast (HIROI *et al.*, 1982; SUZUKI, personal communication). Orthopyroxene becomes much more common in occurrence in the Sôya Coast (BANNO *et al.*, 1964; KIZAKI, 1964; SUWA, 1968; YOSHIDA, 1978, 1979b; YOSHIDA *et al.*, 1982; SUZUKI, 1982). Chemical composition of hornblende in metabasites changes gradually from tremolite-tschermakite to pargasite from east to west in the Prince Olav Coast. Thus, gradual changes in mineralogy of metamorphic rocks are recognized from east to west over a distance of 300 km in the present region, and are interpreted as the results of gradual increase in metamorphic grade from east to west during a single regional metamorphic event (HIROI *et al.*, 1982). In Fig. 1 the present region is divided into three areas of different metamorphic facies.

In sillimanite-biotite gneiss the sillimanite + K-feldspar association is common throughout the present region (HIROI *et al.*, 1982). Even the corundum + sillimanite + muscovite + K-feldspar association is found in a silica-deficient rock from Sinnan Rocks situated in the easternmost part of the present region (HIROI *et al.*, 1982, 1983). These facts suggest that the muscovite + quartz association was not stable at the peak of the regional metamorphism throughout the present region, though muscovite commonly occurs in a small amount together with chlorite as a secondary mineral.

Staurolite has been reported in the eastern part of the Prince Olav Coast (RAVICH and KAMENEV, 1975; YOSHIKURA, 1979; NAKAI *et al.*, 1980; HIROI *et al.*, 1982, 1983). It is always surrounded by plagioclase and garnet, and is not in direct contact with quartz. On the other hand, the spinel + garnet + aluminum silicate (sillimanite and/or kyanite) association has been found in the central to western part of the Prince Olav Coast and also in the Sôya Coast (HIROI *et al.*, 1982; this paper). At Cape Hinode of the Prince Olav Coast, the staurolite + spinel + sillimanite association is found, being totally included in garnet (Fig. 4c) (HIROI *et al.*, 1982), and the following local dehydration of staurolite itself is inferred, in good agreement with the regional thermal structure mentioned above (HIROI *et al.*, 1982);

$$\text{staurolite} = \text{spinel} + \text{garnet} + \text{aluminum silicate} + H_2O. \qquad (1)$$

The retrograde alteration of the high-grade regional metamorphic rocks by the 500 Ma granite and pegmatite is found in several different manners. For example, yellow-brown charnockitic gneiss is bleached and altered to "hornblende gneiss" along the pegmatite (KIZAKI, 1964). Small amounts of muscovite and chlorite commonly occur in most of the high-grade rocks. Marginal chemical zoning in garnet and plagioclase and heterogeneous biotite compositions in the high-grade rocks are, at least partly, the results of the retrograde alteration (HIROI *et al.*, 1982). On the other hand, progressive recrystallization by the 500 Ma granite and pegmatite is observed in the slightly metamorphosed dike rocks of basic composition in and near the mylonite zones in the Prince Olav Coast (HIROI *et al.*, 1982). The degree of recrystallization of the dike rocks is closely related to the distance from the granite and pegmatite masses.

4. Regional Distribution of Aluminum Silicates

The regional distribution of the three polymorphs of aluminum silicate in the

Prince Olav and Sôya Coasts is shown in Fig. 1. It is obvious in the figure that kyanite and sillimanite occur ubiquitously in the present region and that andalusite occurs locally at two bedrock exposures in the western part of the Prince Olav Coast, Tenmondai and Daruma Rocks.

5. Microscopic Textures of Aluminum Silicates

Figures 2 to 9 show the representative microscopic textures of the polymorphs of aluminum silicate in ten specimens from eight bedrock exposures in the Prince Olav and Sôya Coasts. Constituent minerals of the specimens and the mineral abbreviations used in this paper are listed in Table 1. It must be emphasized here that two or three aluminum silicates usually occur in the same specimen.

The generalized mode of occurrence of each polymorph of aluminum silicate is described in the following sections.

5.1. Sillimanite

Sillimanite is the most abundant and common phase among the aluminum silicates. It is easily distinguished in the field and under the microscope. Sillimanite usually occurs as fibers, needles and long prisms in the matrix, being in contact with most of the constituent minerals (Figs. 2a, 2b, 3a, 3b, 3c, 4a, 4b, 4c, 5a, 5b, 6a, 7a, 9a, 9b). It also occurs as inclusions in garnet, plagioclase, and andalusite (Figs. 4c, 6c, 8a, 9b).

In specimen 74010307 from Cape Hinode of the Prince Olav Coast, sillimanite associated with staurolite and spinel is found to be totally included in garnet, as mentioned above (Fig. 4c).

5.2. Kyanite

Kyanite is found in most of the sillimanite-bearing rocks, but it is much less abundant than sillimanite. Hence, kyanite tends to be overlooked in the rocks. It usually occurs as subhedral to anhedral inclusions in plagioclase and garnet (Figs. 2c, 3a, 5c, 6b, 7a, 7b, 7c, 8b, 9c); as an exception, it occurs in the matrix like the case of sillimanite in specimen 74010307 from Cape Hinode (Fig. 4b).

In rocks from the eastern part of the Prince Olav Coast, kyanite is occasionally intergrown with staurolite, both of which are included in plagioclase (Fig. 2c). On the other hand, in rocks from the western part of the Prince Olav Coast and from the Sôya Coast, kyanite is sometimes associated with spinel and garnet (Figs. 6b, 9c). The latter fact is the evidence suggesting the reaction (1), as mentioned above.

5.3. Andalusite

Andalusite has been found only in two specimens from the western part of the Prince Olav Coast. In the specimens, its occurrence is very rare compared with kyanite and sillimanite; for example, only one grain of andalusite has been found through careful examinations of 20 thin sections of specimen 80D35 from Daruma Rock (Fig. 8c).

Andalusite occasionally includes sillimanite and is often accompanied by muscovite nearby (Fig. 8c).

6. Discussion

The regional distribution of the three polymorphs of aluminum silicate shown in

Table 1. Constituent minerals of rocks described and mineral abbreviations.

Locality	Specimen No.	Figure No.	Minerals present													
			qz	pl	Ksp	mus	bi	gar	crd	sp	st	sil	ky	and	cor	op
Sinnan Rocks	81021110	2a		+	+	+	+					+			+	+
	81021401B	2b, 2c	+	+		R***	+	+	+		+	+	+			+
Cape Ryûgû	706A*	3a, 3b, 3c	+	+	+	R	+					+	+			+
Cape Hinode	74010304**	4a	+	+	+		+	+				+				+
	74010307	4b, 4c	+	+	+	R	+	+		+	+	+	+			+
Niban Rock	801301	5a, 5b, 5c	+	+	+		+	+				+	+			+
Tenmondai Rock	81012409	6a, 6b, 6c	+	+	+	R	+	+		+		+	+	+		+
Cape Akarui	75020605	7a, 7b, 7c	+	+	+	R	+	+				+	+			+
Daruma Rock	80D35	8a, 8b, 8c	+	+	+	R	+	+		+		+	+	+		+
Langhovde	68051908	9a, 9b, 9c	+	+	A****		+	+		+		+	+			+

Mineral abbreviations

and— andalusite
bi — biotite
cor — corundum
crd — cordierite
gar — garnet
Ksp—K-feldspar
ky —kyanite
mus—muscovite
op —opaque minerals
(rutile, ilmenite, magnetite)
pl—plagioclase
qz—quartz
sil—sillimanite
sp—spinel
st—staurolite

706A* : see NAKAI *et al.* (1980).
74010304** : see KANISAWA and YANAI (1982).
R*** : retrogressive.
A**** : present only in antiperthite.

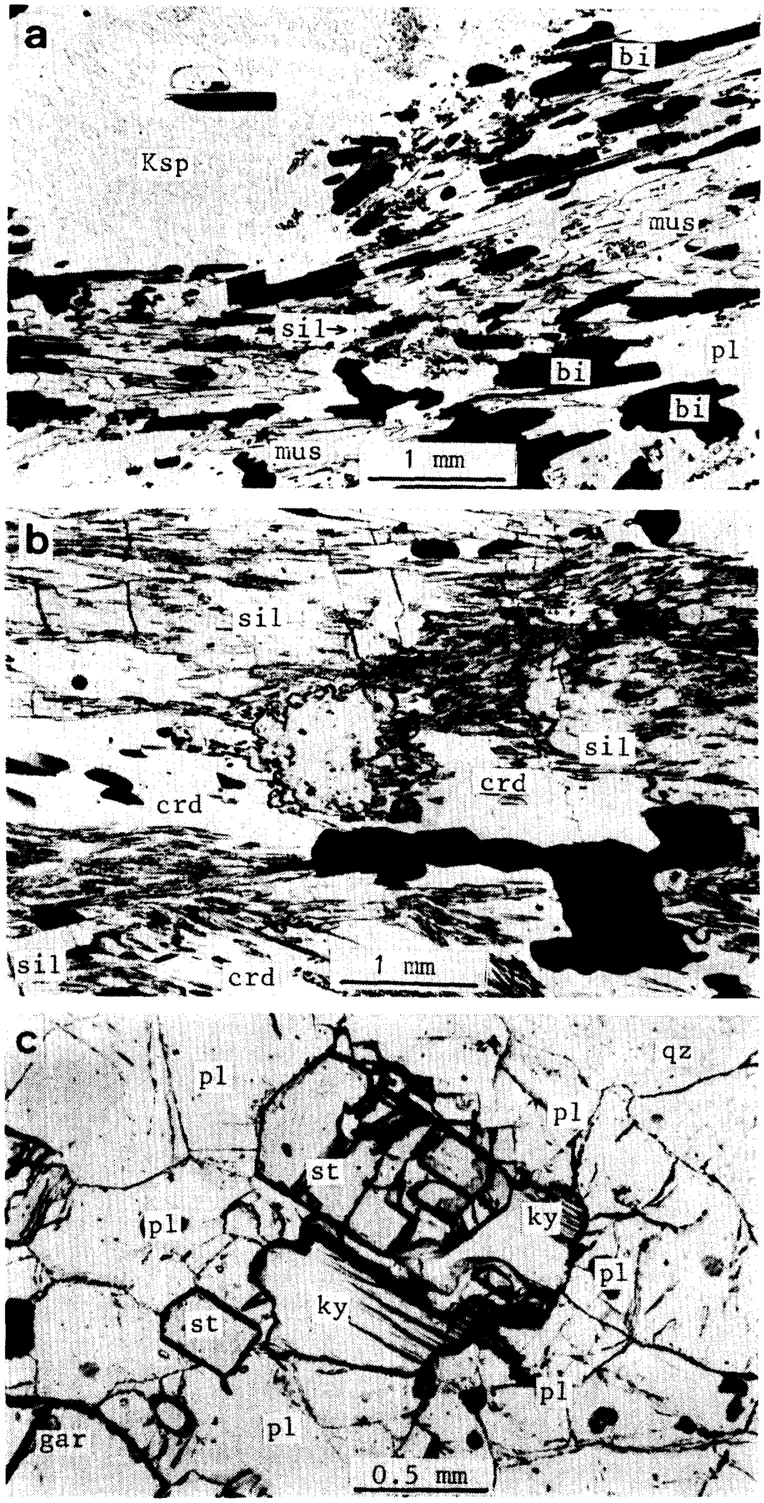

Fig. 2a. Sillimanite in a corundum-sillimanite-muscovite-biotite gneiss (Sp. 81021110). Sillimanite occurs in a small amount, being in contact with K-feldspar and plagioclase. One nicol.

Fig. 2b. Sillimanite in a staurolite-kyanite-bearing sillimanite-cordierite-garnet-biotite gneiss (Sp. 81021401B). Sillimanite is intergrown with cordierite. One nicol.

Fig. 2c. Kyanite in a staurolite-kyanite-bearing sillimanite-cordierite-garnet-biotite gneiss (Sp. 81021401B). Note that kyanite intergrown with staurolite is totally included in plagioclase. One nicol.

Fig. 2. Photomicrographs showing textures of sillimanite and kyanite in rocks from Sinnan Rocks.

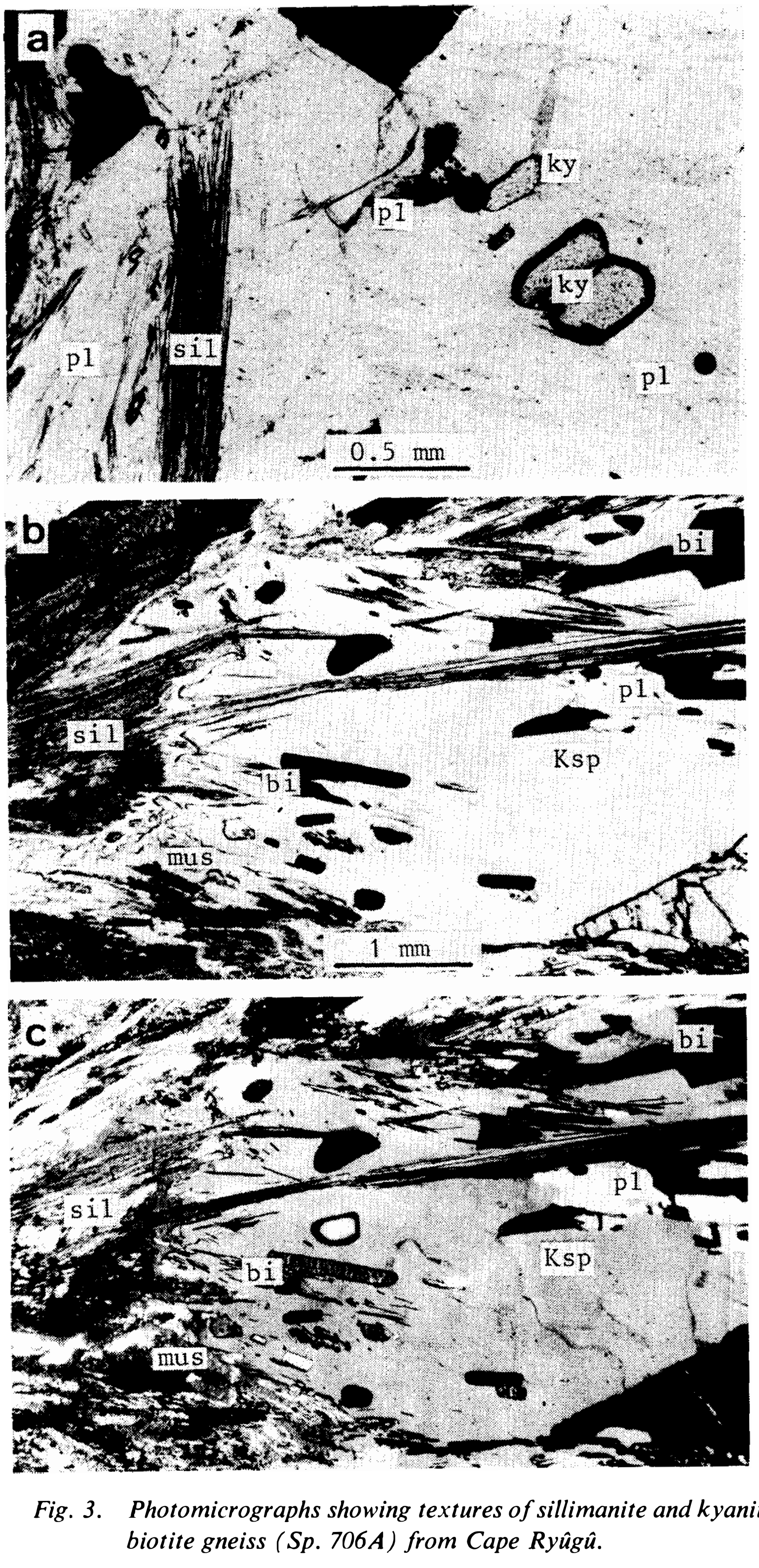

Fig. 3a. Sillimanite and kyanite included in plagioclase. One nicol.

Fig. 3b. Sillimanite associated with biotite, K-feldspar and plagioclase. Secondary muscovite is developed between sillimanite and K-feldspar. One nicol.

Fig. 3c. Ditto. Crossed nicols.

Fig. 3. Photomicrographs showing textures of sillimanite and kyanite in a kyanite-bearing sillimanite-biotite gneiss (Sp. 706A) from Cape Ryûgû.

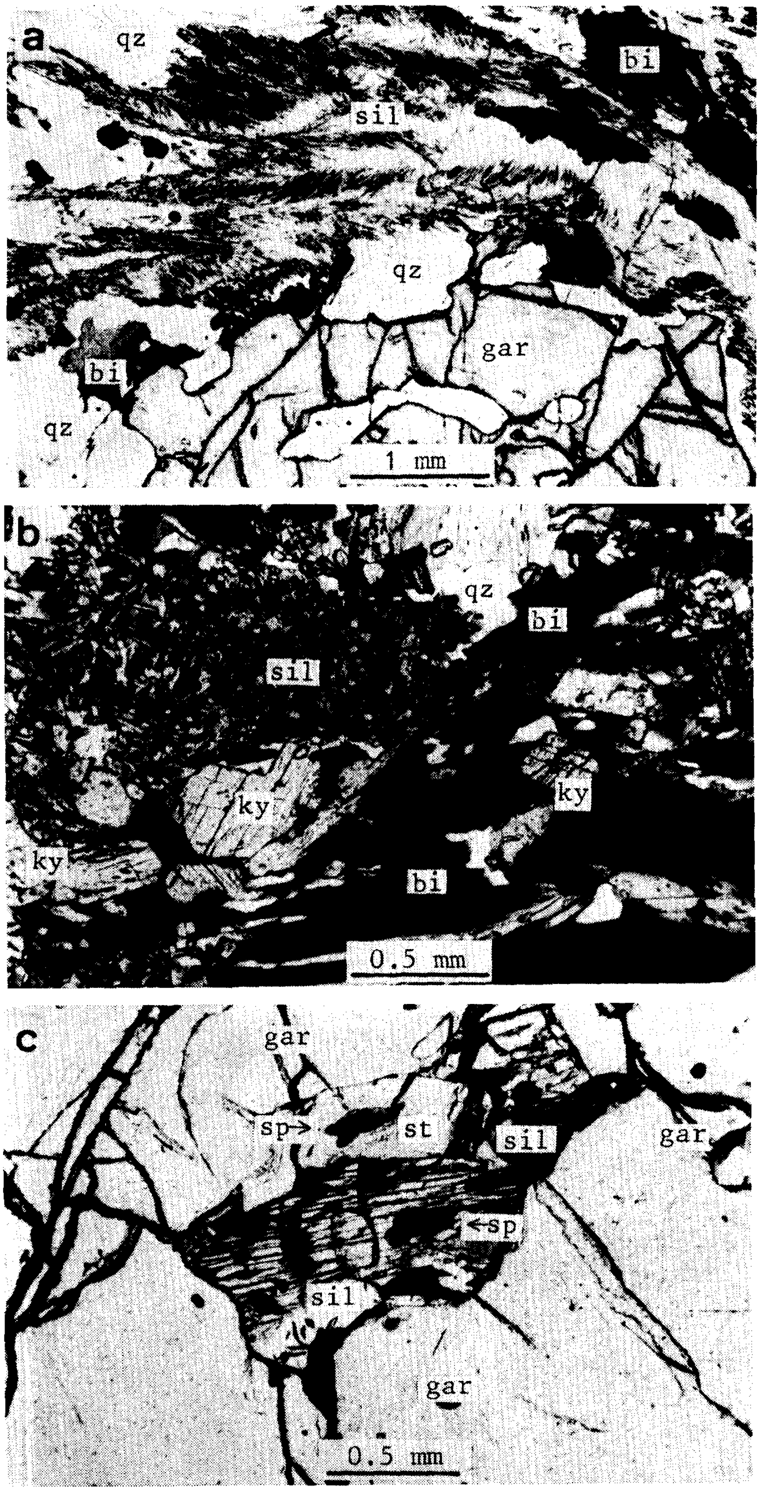

Fig. 4a. Sillimanite associated with garnet, biotite and quartz in a sillimanite-garnet-biotite gneiss (Sp. 74010304). One nicol.

Fig. 4b. Sillimanite and kyanite in a spinel-staurolite-bearing kyanite-sillimanite-garnet-biotite gneiss (Sp. 74010307). Note that both kyanite and sillimanite occur in the matrix in association with biotite and quartz. One nicol.

Fig. 4c. Sillimanite included within garnet in a spinel-staurolite-bearing kyanite-sillimanite-garnet-biotite gneiss (Sp. 74010-307). Note that spinel is intergrown with staurolite and sillimanite. One nicol.

Fig. 4. Photomicrographs showing textures of sillimanite and kyanite in rocks from Cape Hinode.

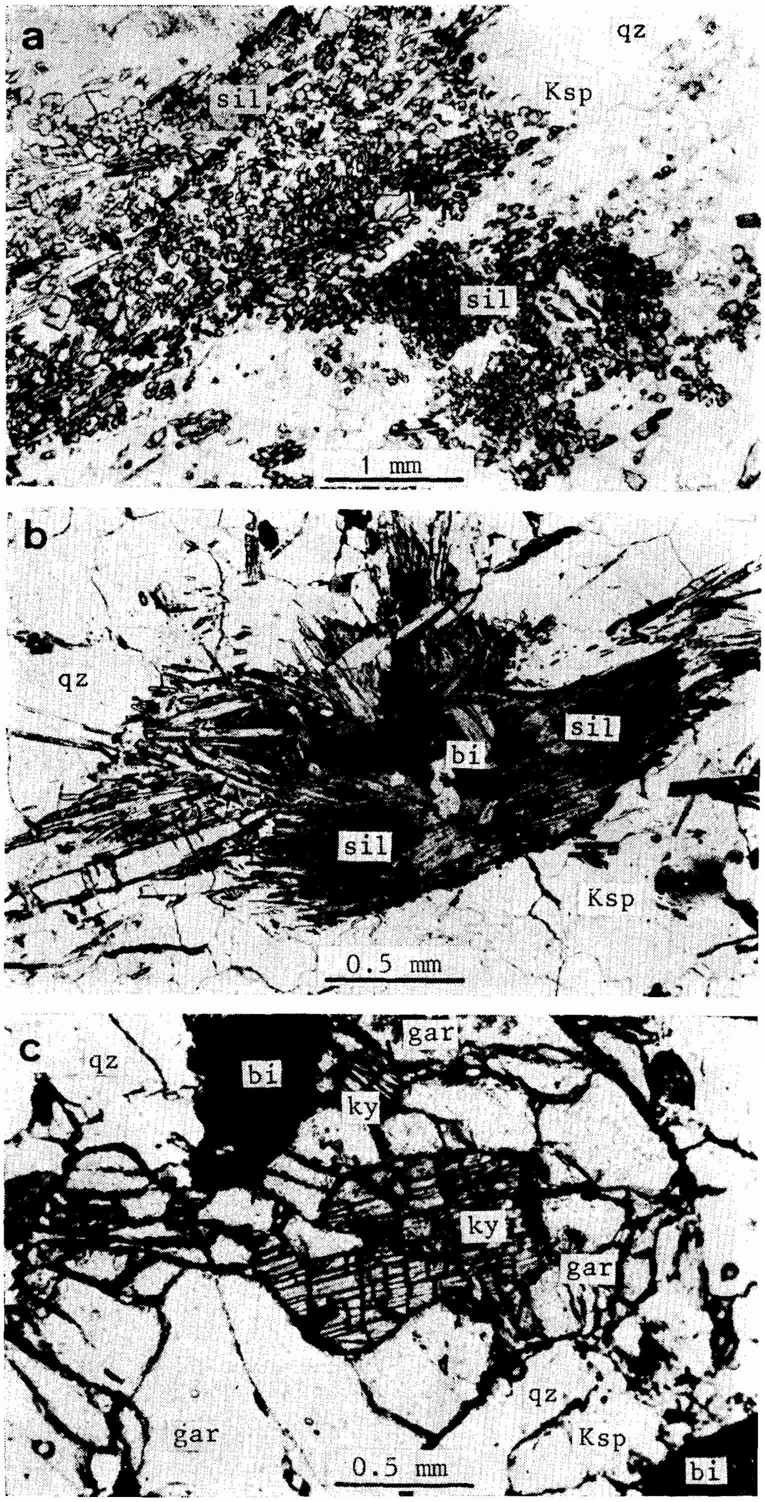

Fig. 5a. Sillimanite in the matrix, being in contact with K-feldspar and quartz. One nicol.

Fig. 5b. Sillimanite intergrown with biotite. One nicol.

Fig. 5c. Kyanite included in garnet. One nicol.

Fig. 5. Photomicrographs showing textures of sillimanite and kyanite in a kyanite-bearing sillimanite-garnet-biotite gneiss (Sp. 801301) from Niban Rock.

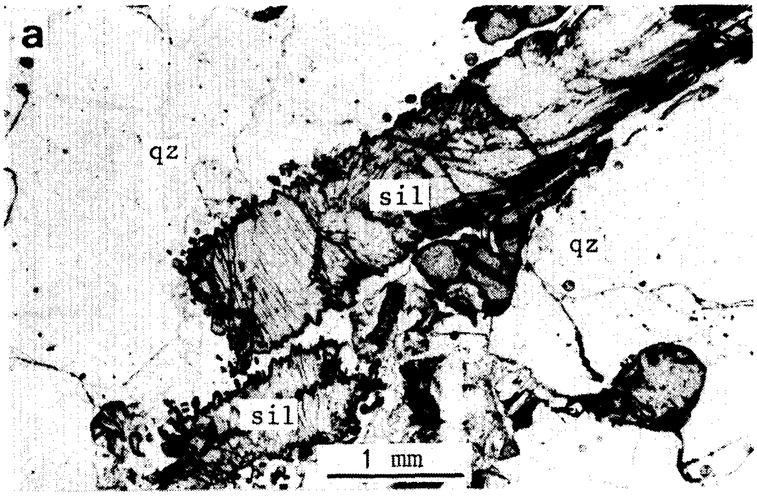

Fig. 6a. Sillimanite in the matrix. One nicol.

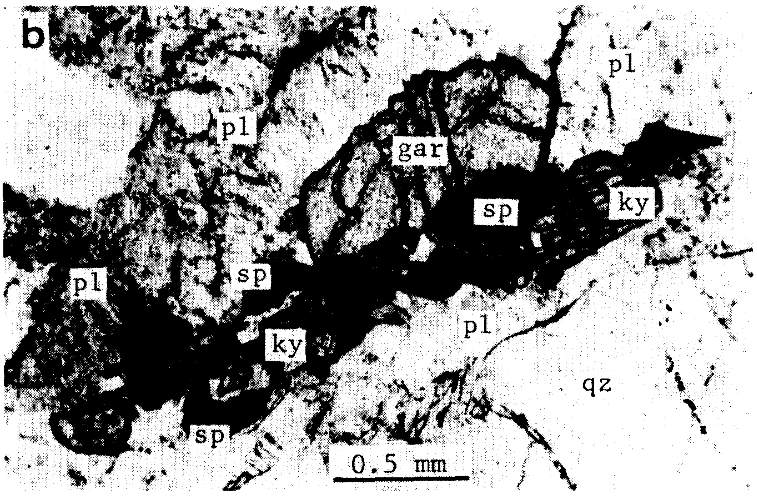

Fig. 6b. Kyanite associated with spinel and garnet. Note that all these minerals are surrounded by plagioclase and are not in direct contact with qurtz. One nicol.

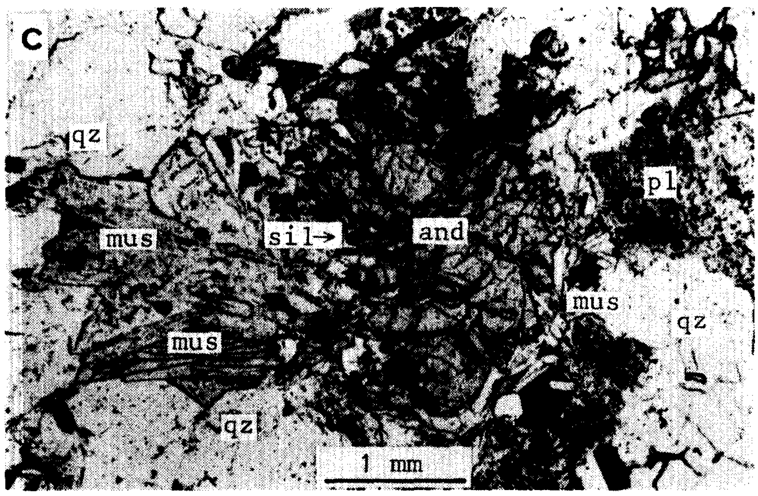

Fig. 6c. Andalusite associated with muscovite. Note that a tiny grain of sillimanite is included in andalusite. One nicol.

Fig. 6. Photomicrographs showing textures of sillimanite, kyanite, and andalusite in a spinel-andalusite-bearing kyanite-sillimanite-garnet-biotite gneiss (Sp. 81012409) from Tenmondai Rock.

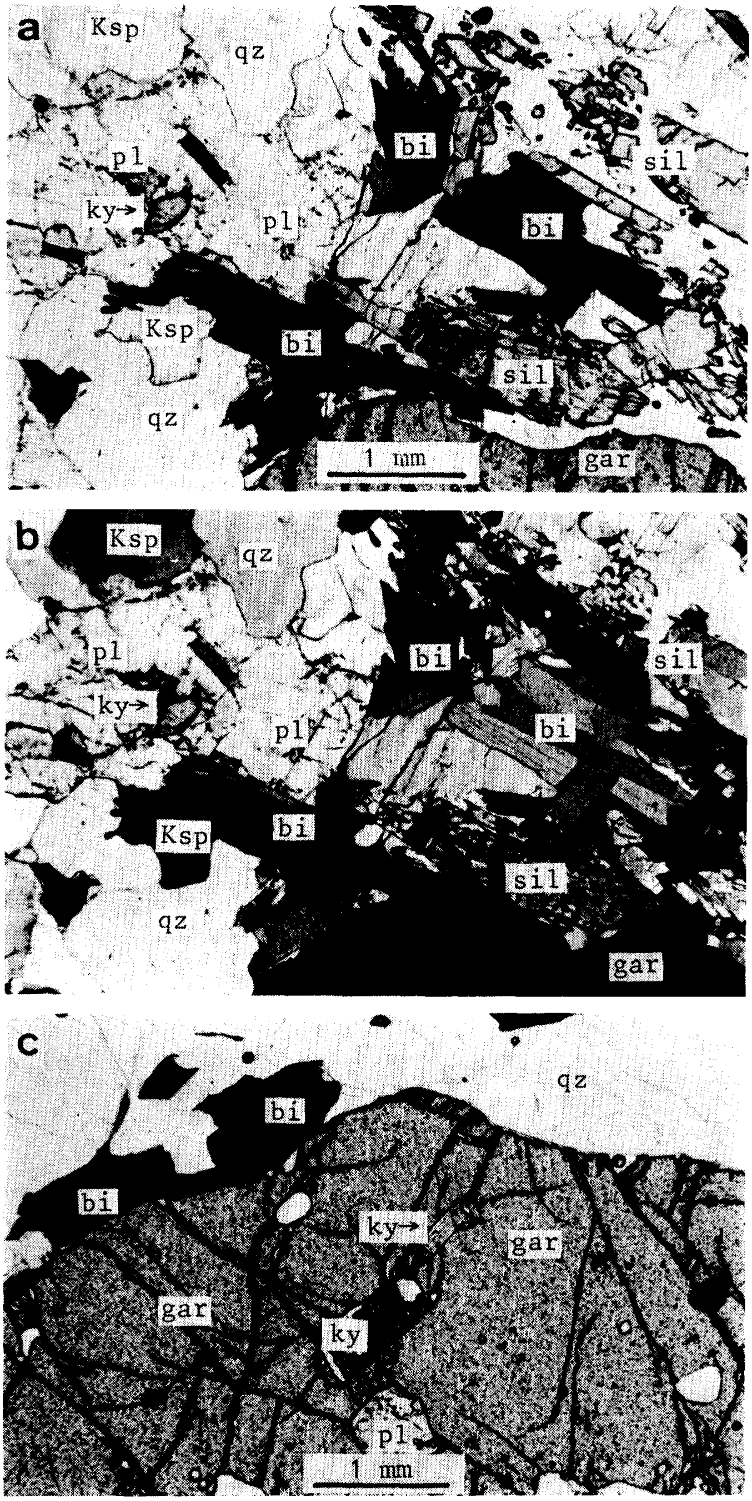

Fig. 7a. Sillimanite in the matrix and kyanite included in plagioclase. One nicol.

Fig. 7b. Ditto. Crossed nicols.

Fig. 7c. Kyanite included in garnet. One nicol.

Fig. 7. Photomicrographs showing textures of sillimanite and kyanite in a kyanite-bearing sillimanite-garnet-biotite gneiss (Sp. 75020605) from Cape Akarui.

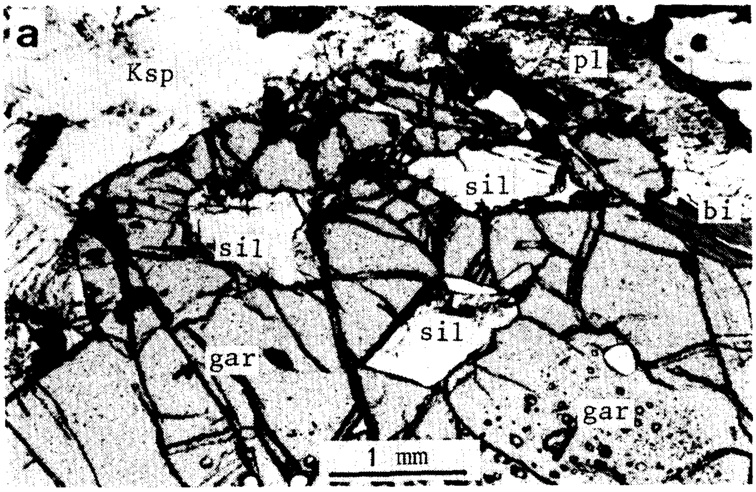

Fig. 8a. Sillimanite included in garnet. Sillimanite usually occurs as inclusions in garnet in this specimen. One nicol.

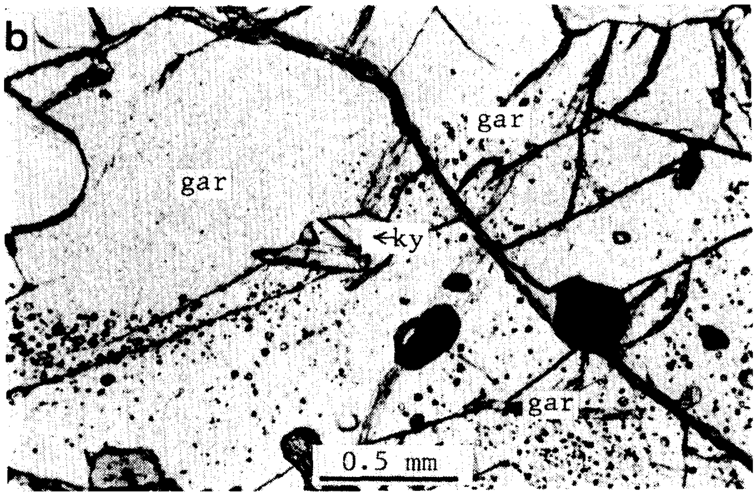

Fig. 8b. Kyanite included in garnet. One nicol.

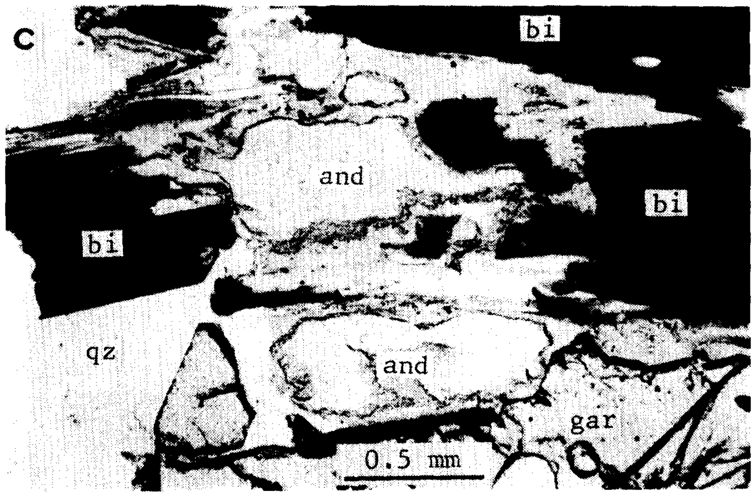

Fig. 8c. Andalusite in the matrix, being in contact with garnet, biotite, and quartz. Andalusite is partly altered to pinite. One nicol.

Fig. 8. Photomicrographs showing textures of sillimanite, kyanite, and andalusite in a spinel-andalusite-kyanite-bearing sillimanite-garnet-biotite gneiss (Sp. 80D35) from Daruma Rock.

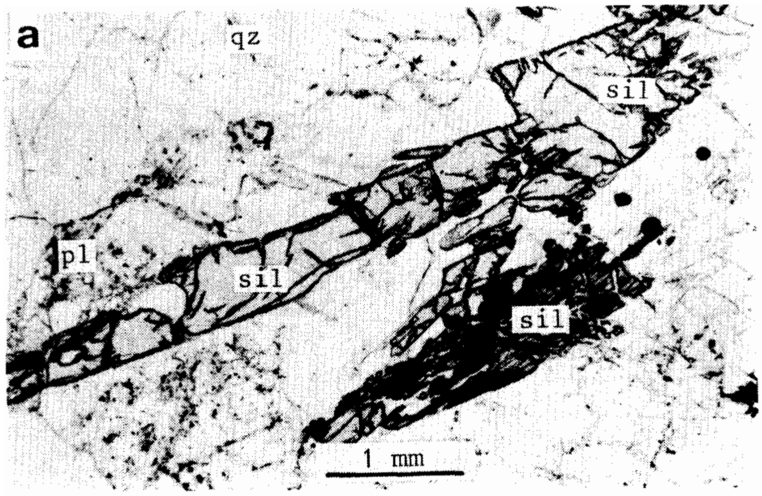

Fig. 9a. Sillimanite in the matrix. One nicol.

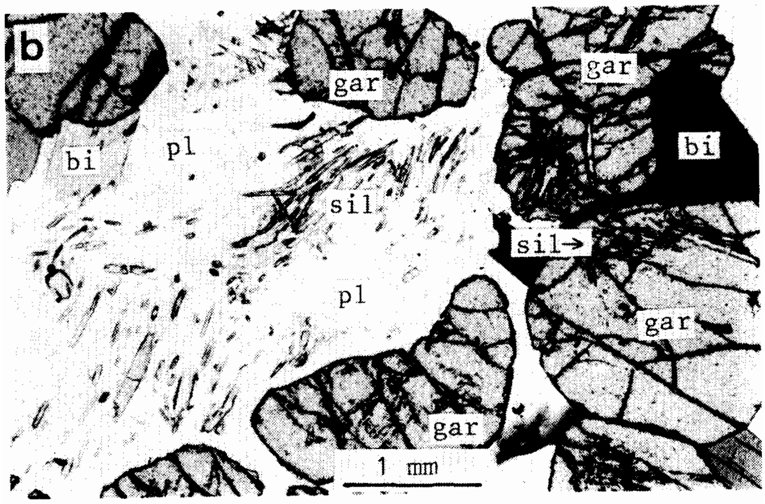

Fig. 9b. Sillimanite included in garnet and plagioclase. One nicol.

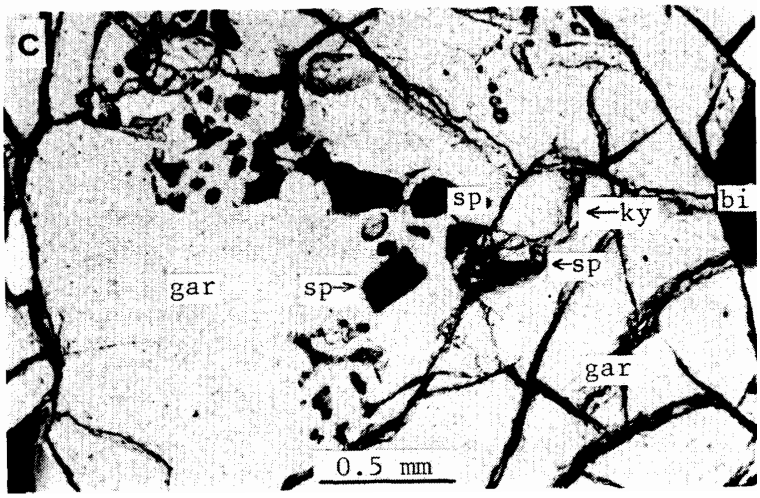

Fig. 9c. Kyanite included in garnet. Note that spinel is also included in garnet, being intergrown with kyanite and occurring near kyanite. One nicol.

Fig. 9. Photomicrographs showing textures of sillimanite and kyanite in a spinel-kyanite-bearing sillimanite-garnet-biotite gneiss (Sp. 68051908) from Langhovde.

Fig. 1 suggests that kyanite and sillimanite are the products of the regional metamorphism and andalusite, on the other hand, is a product of another local metamorphic event.

The coexistence of two or three polymorphs of aluminum silicate in a rock is not always interpreted as the evidence indicating that the rock was formed under the P-T conditions of the univariant reactions or of the triple point. Electron microprobe analyses of the aluminum silicates show that they contain only trace amounts of Fe and Mn. The textural features of the three polymorphs, in conjunction with the regional distribution of the minerals, suggest that sillimanite was the stable phase at the peak of the regional metamorphism and that kyanite was a metastable relic at that time. It is highly probable that kyanite was formed at an earlier stage of prograde recrystallization of the high-grade rocks during the same regional metamorphism. Preservation of metastable kyanite as inclusions within plagioclase and garnet in the sillimanite-zone rocks has been known in many metamorphic terranes of the kyanite-sillimanite type (*e.g.* the Unazuki schists in central Japan (HIROI, 1983)). Thus, it may be safely concluded that the regional metamorphism in the present region, probably Late Proterozoic in age, was of the medium-pressure type. This conclusion agrees with KAMENEV's (1980, 1982) interpretation for the facies series of the high-grade metamorphic rocks in the present region. It may also agrees with YOSHIDA's (1978, 1979a, 1979b) and YOSHIDA *et al.*'s (1982) interpretations for the baric type of their "dominant granulite-facies metamorphism (M_2)" of the Ongul group, but their interpretations for the metamorphic histories of the Ongul and Okuiwa groups are not necessarily compatible with the present data and conclusion.

The occurrence of kyanite associated with spinel and garnet in the Sôya Coast, in common to that in the western part of the Prince Olav Coast, provides strong evidence of the common metamorphic history of the rocks throughout the present region (Lützow-Holm Bay system). The petrologic and tectonic significance of the occurrence of kyanite, in addition to sillimanite, as a product of the staurolite dehydration (1) will be discussed elsewhere.

The rare occurrence of andalusite in the western part of the Prince Olav Coast may be safely attributed to the thermal metamorphism of the 500 Ma granite and pegmatite, because (1) andalusite occurs in rocks cut extensively by the 500 Ma granite and pegmatite, (2) the textural relation between andalusite and sillimanite suggests that andalusite was formed later than sillimanite, and (3) andalusite is usually accompanied by muscovite which must have been unstable at the peak of the regional metamorphism, at least in the quartz-bearing rocks. Calculated temperatures based on biotite and adjacent garnet-rim compositions are in agreement with the interpretation for the origin of andalusite in the present region (HIROI *et al.*, 1982). Thus, it is suggested that the present portion of East Antarctic shield was uplifted by 500 Ma ago after the Late Proterozoic regional metamorphism.

7. Summary

The regional distribution and textures of sillimanite, kyanite, and andalusite in the Prince Olav and Sôya Coasts make it clear that the regional metamorphism in the region, probably Late Proterozoic in age, was of the medium-pressure type and that the present portion of East Antarctic shield was uplifted by 500 Ma ago when granite and pegmatite were emplaced.

Acknowledgments

We would like to express our thanks to all geologists of Japanese Antarctic Research Expedition for their information about the geology. We thank Mr. S. YOSHIKURA of Kochi University and Dr. T. KANO of Yamaguchi University for providing the specimens from Cape Ryûgû. One of us (Y.H.) thanks Prof. S. BANNO of Kyoto University for his critical discussion.

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(Received March 31, 1983; Revised manuscript received June 13, 1983)