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Granulites from Cape Hinode in the amphibolite-facies eastern part of Prince Olav Coast, East Antarctica: New evidence for allochthonous block in the Lützow-Holm Complex

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Abstract: High-grade metamorphic rocks occurring along the Prince Harald, Sôya, and Prince Olav Coasts make up the Latest Proterozoic–Early Paleozoic Lützow-Holm Complex, which is the youngest orogenic belt in the East Antarctic Shield. A systematic increase in metamorphic grade from east to west, ranging from upper amphibolite facies on the eastern Prince Olav Coast to upper granulite facies at the head of Lützow-Holm Bay, has been well-established in the complex. However, granulites are newly found to occur as blocks sitting within meta-tonalites at Cape Hinode located on the amphibolite-facies eastern Prince Olav Coast. In addition, it is newly revealed that kyanite occurs rather commonly in meta-tonalites which contain hornblende with or without clinopyroxene. The modes of occurrence in the field, petrographical features, and major element bulk rock compositions of the granulites and related rocks are given in some detail in this study. These, along with the previously presented geochronological, geochemical and petrographical data, would indicate that the rocks in the Cape Hinode area as a whole make up a Mesoproterozoic allochthonous block in the Latest Proterozoic–Early Paleozoic Lützow-Holm Complex.

key words: Cape Hinode, Late Proterozoic, Early Paleozoic, granulites, allochthonous block

1. Introduction

The main orogenic activities in the region along the Prince Harald, Sôya, and Prince Olav Coasts (the Lützow-Holm Complex) took place during the Latest Proterozoic to Early Paleozoic times (the last stage of Pan-African orogeny) (Shiraishi *et al.*, 1994, 2003). However, older rocks of Mesoproterozoic ages around 1000 Ma have also been identified within this orogen. Such older rocks were first documented by Shiraishi

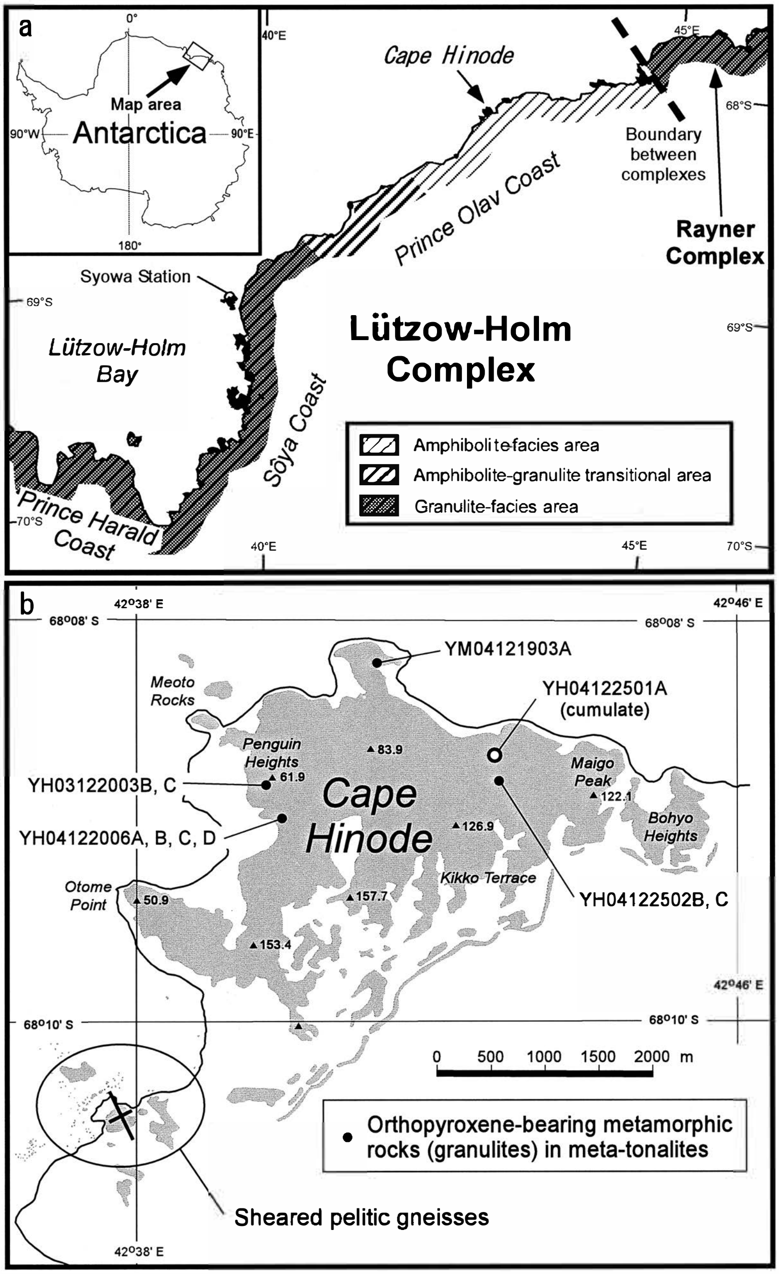

Fig. 1. Maps of the Lützow-Holm Complex (a) and Cape Hinode area (b). A systematic increase in metamorphic grade from east to west, ranging from upper amphibolite facies on the eastern Prince Olav Coast to upper granulite facies at the head of Lützow-Holm Bay, is shown in (a). Note that Cape Hinode is located in the amphibolite-facies area. Sample localities of granulites and related rocks and the occurrence of sheared pelitic gneisses in the Cape Hinode area are shown in (b). Strike and dip of shear planes in pelitic gneisses are also shown in (b).

et al. (1994) at Cape Hinode on the eastern part of the Prince Olav Coast (Fig. 1). They are metamorphosed plutonic rocks of trondhjemite-tonalite composition (hereafter, meta-tonalites), and are not known to occur in other parts of the Lützow-Holm Complex. Motoyoshi *et al*. (2004, 2005) additionally reported similar monazite EMP ages for pelitic gneisses from the same bedrock exposure. The pelitic gneisses characteristically contain retrograde kyanite replacing pre-exiting sillimanite to varying degrees (Hiroi *et al*., 1983a; Motoyoshi *et al*., 2004, 2005). Such occurrences of Al_2SiO_5 minerals are also distinctly different from other parts of the Lützow-Holm Complex where retrograde andalusite replacing pre-exiting sillimanite is occasionally found (*e.g.* Hiroi *et al*., 1983a).

Previous work in the Lützow-Holm Complex has documented a systematic increase in metamorphic grade from east to west, ranging from upper amphibolite facies on the eastern Prince Olav Coast to upper granulite facies at the head of Lützow-Holm Bay, then decreasing further west (*i.e.* Hiroi *et al*., 1983b, 1987, 1991; Shiraishi *et al*., 1984) (Fig. 1). During a detailed field study in December of 2004 (JARE-46), we found orthopyroxene-bearing metamorphic rocks (granulites) at Cape Hinode in the "amphibolite-facies" eastern part of the Prince Olav Coast. This paper describes modes of field occurrence, petrography and bulk rock compositions of the newly discovered granulites and related rocks in order to show that the metamorphic grade of the area is different from that of surrounding areas. This paper also reports the relatively common occurrence of kyanite in hornblende-bearing meta-tonalites for the first time. These data, along with previously reported geochronological data and others, would show that the rocks in the Cape Hinode area as a whole make up a Mesoproterozoic allochthonous block in the Latest Proterozoic–Early Paleozoic Lützow-Holm Complex. *P-T-t* paths and tectonic significance based on detailed mineralogy of the granulites, country meta-tonalites, and associated rocks will be presented elsewhere. Mineral abbreviations are after Kretz (1983).

2. Regional settings

The Lützow-Holm Complex is one of the high-grade metamorphic terranes constituting the East Antarctic Shield, and occurs along the Prince Harald, Sôya, and Prince Olav Coasts (Fig. 1a). Metamorphic basement rocks are exposed in numerous ice-free areas along the coasts, separated by glaciers and the continental ice-sheet. To the east of an inferred tectonic boundary lie the Rayner and Napier Complexes of Enderby Land, whereas to the southwest, across several hundred kilometers of continental ice, lies the Yamato-Belgica Complex.

Cape Hinode is located on the eastern Prince Olav Coast at around 68°09′S, 42°40′E (Fig. 1a). About 20 km^2 of rocks is exposed (Fig. 1b). The lithology over most of the area is dominated by relatively homogeneous, medium-grained, dark gray to purple meta-tonalites, the mesoscopic features of which are similar to those of anorthosites. These rocks show only a weak foliation that is folded around a large-scale, tight antiform, trending north-west. Probable igneous layering and lamination are newly observed in the rocks, as will be shown later. They are extensively intruded by pink pegmatites, which sometimes show graphic intergrowths of quartz and K-feldspar and contain blue beryl crystals, as reported by Yanai and Ishikawa (1978). Local mylonitization is observed not only in meta-tonalites but also in pegmatites.

To the southwest of Cape Hinode, separated from the meta-tonalites by a few hundred meters of intervening ice sheet, are several small outcrops of pelitic and psammitic gneisses. These consist of sillimanite-garnet-biotite gneiss and garnet-biotite gneiss with minor clinopyroxene amphibolite and garnet-bearing pegmatites, and are sheared to varying degrees. The sillimanite-garnet-biotite gneiss commonly contains

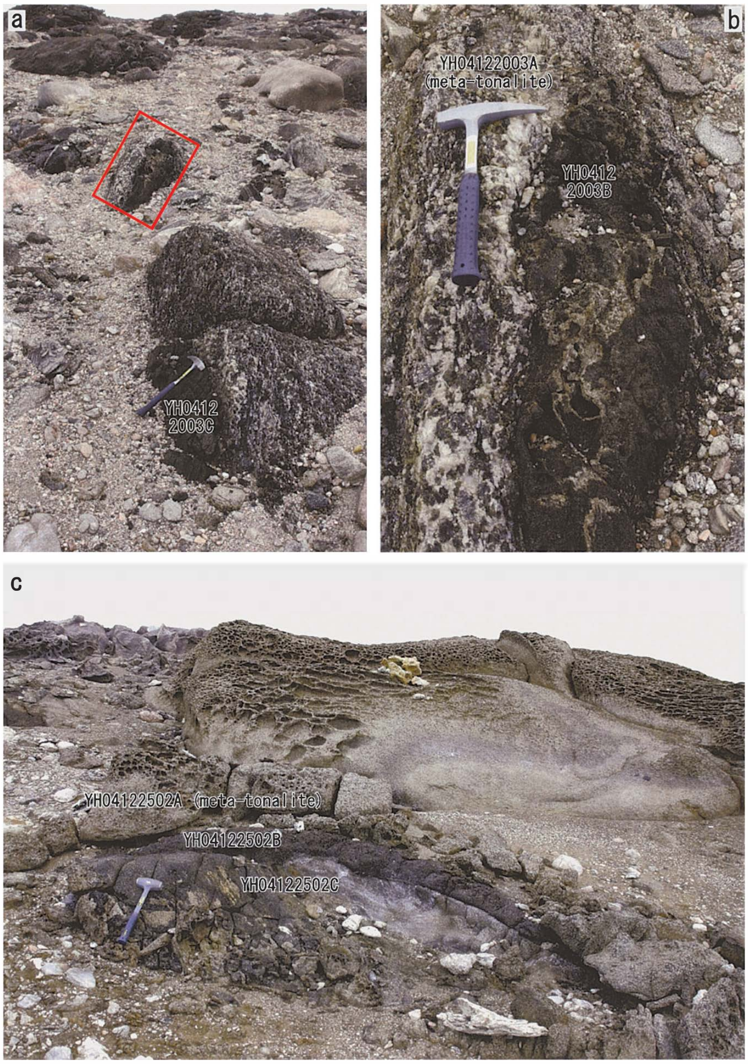

Fig. 2. Field photographs showing type-I mode of occurrence of granulites. Granulites occur in isolated bodies sitting within surrounding meta-tonalites. (b) is an enlarged photograph of the area in the rectangle in (a). Sample YH04122003A is kyanite-hornblende-bearing pegmatitic meta-tonalite next to granulite sample YH04122003B.

retrograde kyanite, which replaces pre-existing sillimanite as reported by Hiroi *et al.* (1983a) and Motoyoshi *et al.* (2004, 2005) and in this paper (see below). The relationship between these metasedimentary rocks and meta-tonalites is not clear, because the contact is obscured by ice.

3. Mode of occurrence of granulites and related rocks in the field

Orthopyroxene-bearing metamorphic rocks (granulites) occur sporadically in small bodies up to a few m thick in monotonous meta-tonalites. Orthopyroxene-free, garnet- and/or clinopyroxene-bearing basic-intermediate rocks and calc-silicate rocks are other types of blocks sporadically found in meta-tonalites. On the other hand, it is noteworthy that pelitic-psammitic rocks occurring in nearby outcrops have not been found as enclaves or blocks in meta-tonalites.

The modes of occurrence of granulites in the field are roughly divided into two types: type I as isolated lenses (Fig. 2) and type II as thin layers intercalated in well-layered bodies (Fig. 3).

The newly observed igneous layering and lamination of host meta-tonalites are defined by varying proportions of biotite and plagioclase, especially in cumulates (Fig. 4). Overturned angular unconformity is suggested in some cases (Fig. 4a).

4. Petrography of granulites and related rocks

Yanai and Ishikawa (1978) first gave the general petrography of the rocks occurr-

Fig. 3. Field photographs showing type-II mode of occurrence of granulites. Granulites occur as thin layers making up well-layered bodies enclosed in meta-tonalites. (b) is an enlarged photograph of the area in the rectangle in (a).

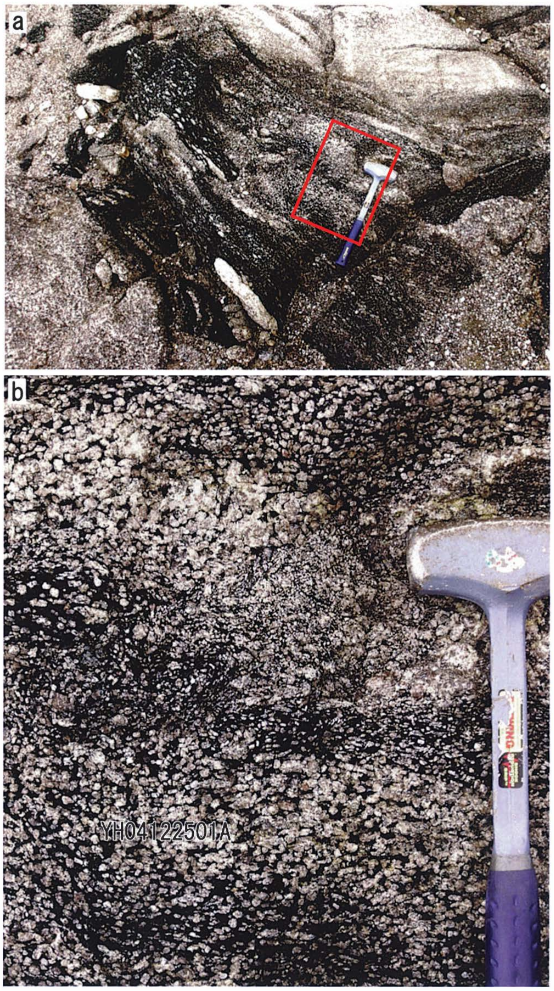

Fig. 4. Field photographs showing newly observed igneous layering and lamination of meta-tonalites. (b) is an enlarged photograph of the area in the rectangle in (a). Overturned angular unconformity is seen in (a). See Fig. 11a and b for photomicrographs of plagioclase-biotite-rich cumulate (sample YH04122501A) in (b).

ing in the Cape Hinode area in the explanation text attached to the geological map of the area. Hiroi *et al.* (1983a) presented the modes of occurrence of Al_2SiO_5 minerals together with staurolite and others in pelitic gneisses collected by K. Yanai from the Cape Hinode area. Shiraishi *et al.* (1995) and Ikeda *et al.* (1997) reported mineral assemblages and bulk rock chemical characteristics of meta-tonalites from Cape Hinode, respectively. Fraser and McDougall (1995) described pegmatite and amphibolitic gneiss samples, for which they presented K/Ar and $^{40}Ar/^{39}Ar$ mineral ages. Motoyoshi *et al.* (2004, 2005) described pelitic gneisses and garnet-monazite-rich pegmatite, for which they dated monazite EMP ages. However, orthopyroxene-bearing metamorphic rocks (granulites) have not been known to occur up to the present. In addition, kyanite is newly found to occur rather commonly in meta-tonalites.

The mineral assemblages of ten granulite and related rock samples collected mostly by Y. Hiroi are summarized in Table 1. In many cases orthopyroxene is readily visible

Table 1. Constituent minerals of granulites and related rocks from Cape Hinode.

Sample number	YM0412 1903A	YH0412 2003B	YH0412 2003C	YH0412 2006A	YH0412 2006B	YH0412 2006C	YH0412 2006D	YH0412 2501A	YH0412 2502B	YH0412 2502C
Rock type	Hornblende-rich granulite	Intermediate granulite	Basic granulite	Basic granulite	Hornblende-rich granulite	Basic granulite	Basic granulite	Pl-Bt cumulate	Intermediate granulite	Hornblende-rich granulite
Opx	○	◎	◎	◎	○	◎	◎	○[*1]	◎	○
Cpx	○	–	–	○	+	+	○	–	–	○
Hbl	◎	○	◎	○	◎	○	◎	–	◎	◎
Bt	+	+	+	+	+	+	+	◎	◎	–
Pl	○	○	○	+	○	○	○	◎	–	○
Qtz	–	○	–	+	+	–	+	+	○	○
Ap	+	+	+	+	+	+	+	+	○	+
Mnz	+	+	+	+	+	+	+	+	+	+
Zrn	+	+	+	+	+	+	+	+	○	+
Opaque minerals	+	+	+	+	+	+	+	+	+	+
Others								Spn, Cal, Aln	Cum	

◎ = abundantly present (> 20 vol%); ○ = present; + = trace amount only; – = absent

[*1] Completely altered to pinite

as reddish brown crystals associated with light green clinopyroxene, green hornblende, black biotite, and gray plagioclase. In thin section, it is noteworthy that more than half of the granulites contain quartz, indicating that they are saturated in SiO_2. Neither olivine nor garnet has been found in the granulites, and the observed mineral assemblages are relatively simple, including orthopyroxene, clinopyroxene, hornblende, biotite, plagioclase, and/or quartz. The mode of occurrence of orthopyroxene in thin section, however, is different from sample to sample, and therefore petrographical features of the samples will be given below in some detail.

4.1. Granulites

YM04121903A: This sample is from a type-I small isolated basic inclusion in meta-tonalites. Coarse-grained, homogeneous brownish green hornblende is a major constituent of this rock, and other minerals occur in minor amounts, usually as small interstitial grains (Fig. 5a, b). However, orthopyroxene and clinopyroxene show another mode of occurrence: as irregular shaped inclusions in hornblende. The included grains of orthopyroxene and clinopyroxene have common elongation directions and the same optical orientations, respectively, suggesting that they are relics of originally intergrown crystals (Fig. 5c, d). A similar intimate relationship between orthopyroxene and clinopyroxene is observed in sample YH04122502C, as shown later.

YH04122003B: This is a massive and coarse-grained rock and occurs as a type-I thin layer sitting within kyanite-bearing coarse-grained pegmatitic meta-tonalite (sample YH04122003A) (Fig. 2a, b). It is cut by a network of tonalitic veins (Fig. 2b). This rock is rather rich in anhedral orthopyroxene which is conspicuous even to the naked eye (Fig. 6a, b). Other major constituent minerals are anhedral, greenish brown, poikilitic hornblende, plagioclase, and quartz with minor brown biotite, mon-

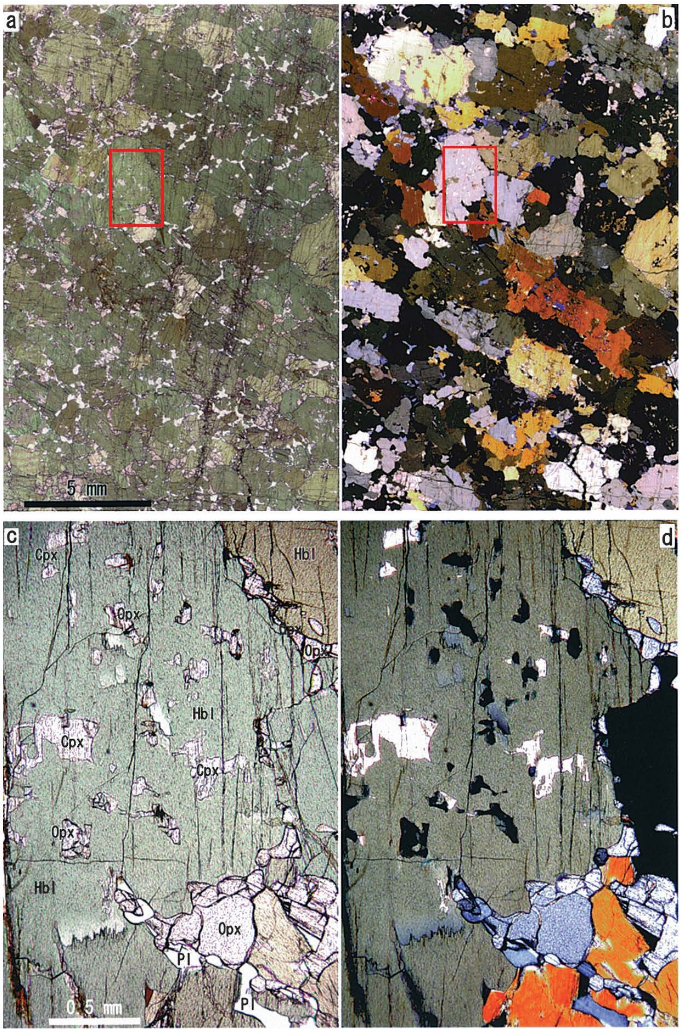

Fig. 5. Photomicrographs of hornblende-rich basic granulite sample YM04121903A collected by Y. Motoyoshi. (a) and (c); Plane polarized light. (b) and (d); Crossed nicols. (c) and (d) are enlarged photographs of the areas in the rectangles in (a) and (b), respectively. Hornblende is a major phase of this rock, and other minerals usually occur as small interstitial grains. However, orthopyroxene and clinopyroxene also occur as irregular shaped grains included in hornblende (c, d). Note that included grains of orthopyroxene and clinopyroxene have elongation directions in common to each other and the same optical orientations, respectively.

azite, apatite, zircon and opaque minerals. These minerals are generally texturally in equilibrium with each other, although hornblende crystals occasionally show heterogeneity in color and hence composition (especially in the marginal part) and also in distribution of fine-grained ilmenite lamellae.

YH04122003C: This rock occurs close to sample YH04122003B, but is weakly

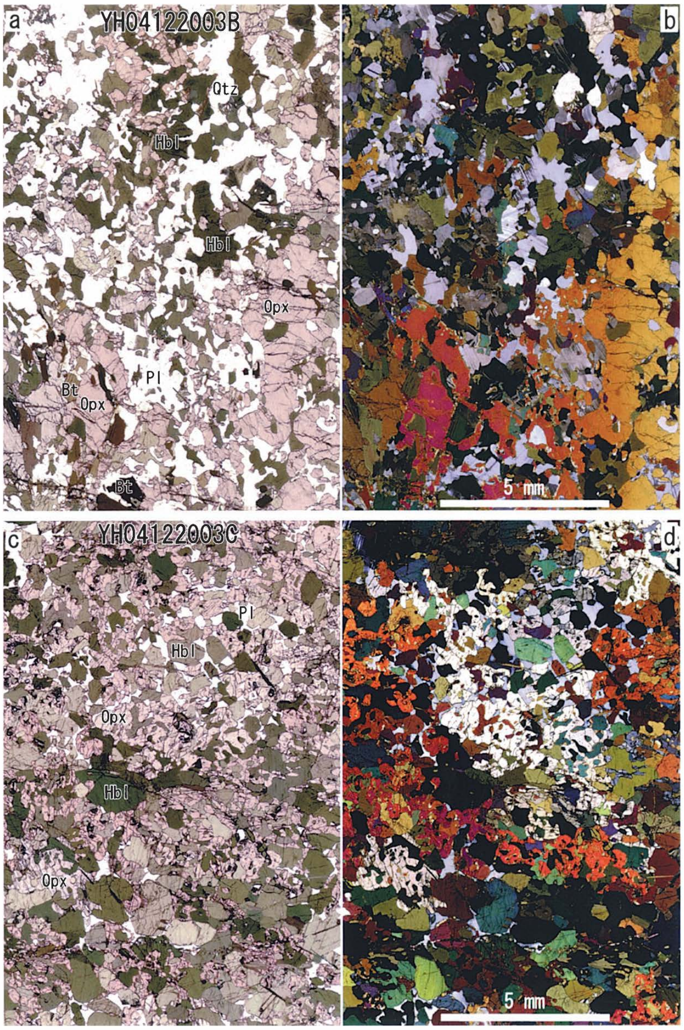

Fig. 6. Photomicrographs of intermediate granulite sample YH04122003B (a, b) and basic granulite sample YH04122003C (c, d). (a) and (c); Plane polarized light. (b) and (d); Crossed nicols. These are the most common type of granulites occurring at Cape Hinode. A relatively large amount of anhedral and poikilitic orthopyroxene is intimately associated with anhedral to subhedral brownish green hornblende and interstitial plagioclase. Biotite is locally present. Quartz is also present in sample YH04122003B.

foliated. These two samples appear to be from the same type-I thin layer now separated by meta-tonalite (Fig. 2a), and are mineralogically similar to each other. However, mafic minerals are more abundant in this rock than in sample YH04122003B, and quartz is absent in this rock. Orthopyroxene is anhedral and poikilitic, intimately interlocking with hornblende and plagioclase (Fig. 6c, d). Greenish brown hornblende commonly contains irregularly distributed ilmenite lamella.

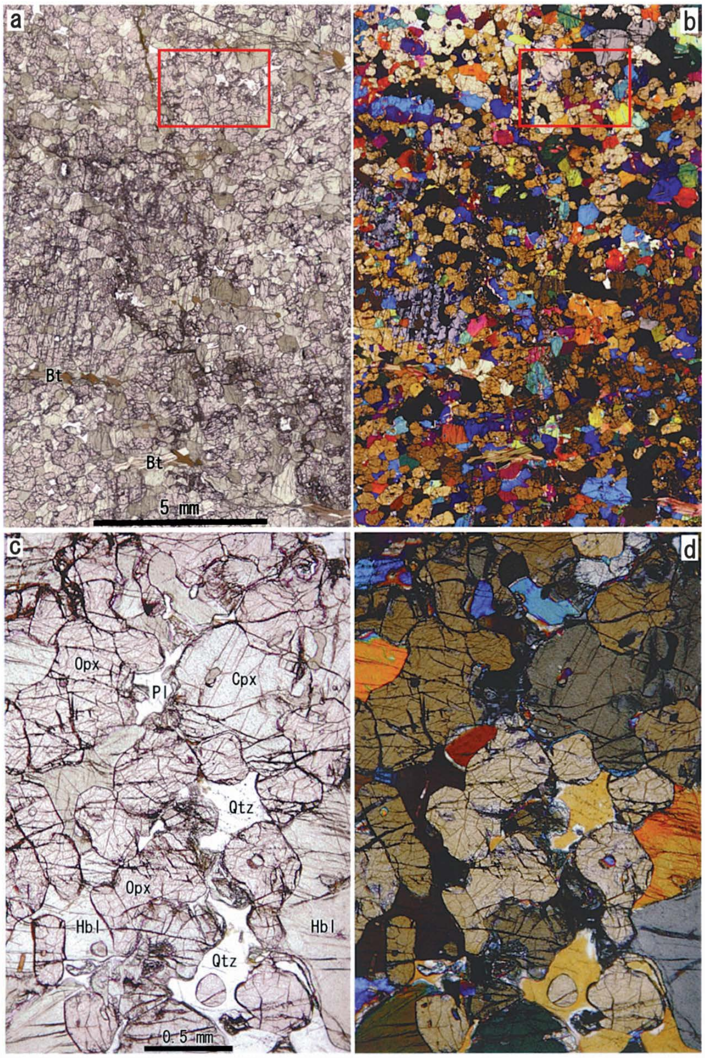

Fig. 7. Photomicrographs of basic granulite sample YH04122006A. (a) and (c); Plane polarized light. (b) and (d); Crossed nicols. (c) and (d) are enlarged photographs of the areas in the rectangles in (a) and (b), respectively. This rock is ultramafic, being extremely poor in felsic minerals, but contains small amounts of plagioclase and quartz. Biotite is locally concentrated into distinct laminae.

YH04122006A: This rock forms together with others a type-II well-layered body sitting within meta-tonalites (Fig. 3a, b). This sample is ultramafic, being extremely poor in colorless minerals (Fig. 7a, b). However, this rock does contain small amounts of plagioclase and quartz as interstitial grains and as inclusions in major mafic minerals (Fig. 7c, d). Relatively fine-grained subhedral to anhedral grains of orthopyroxene are poikilitically enclosed by more coarse-grained pale green clinopyroxene and pale brownish green hornblende crystals.

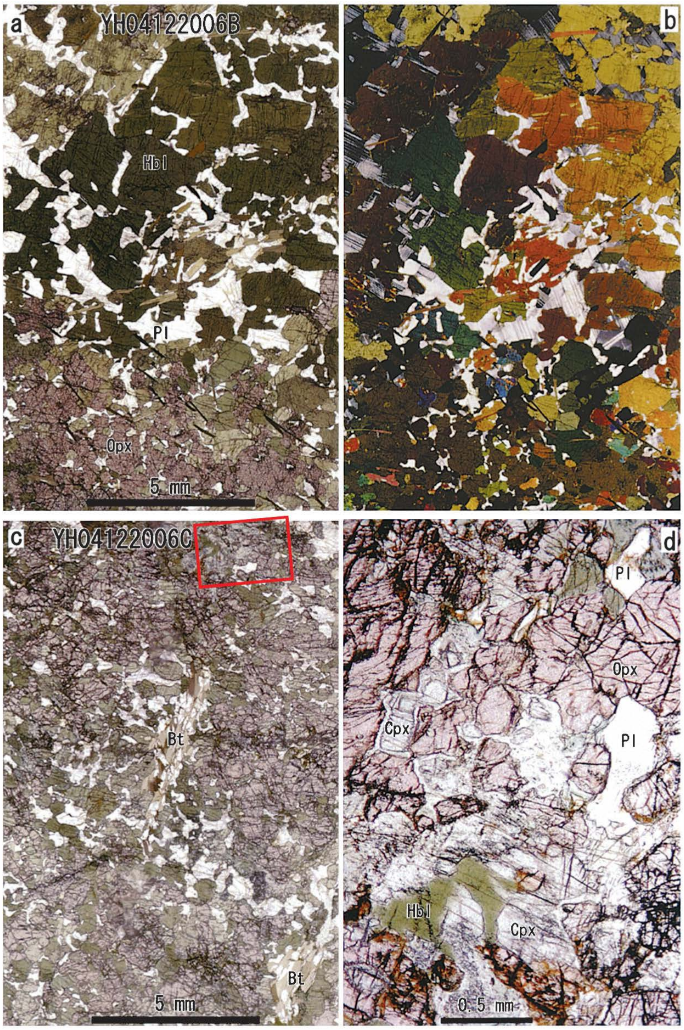

Fig. 8. Photomicrographs of basic granulite sample YH04122006B (a, b) and intermediate granulite sample YH04122006C (c, d). (a, c and d); Plane polarized light. (b); Crossed nicols. (d) is an enlarged photograph of the area in the rectangle in (c). In sample YH04122006B both hornblende and orthopyroxene are coarse grained and poikilitic. Orthopyroxene tends to be surrounded or partially replaced by hornblende in this rock. Sample YH04122006C is characterized by foliation defined by preferred orientation of orthopyroxene and hornblende and concentration of biotite into distinct laminae (c). Clinopyroxene is minor and extensively replaced by pale green hornblende (d).

YH04122006B: This is a massive, coarse-grained, heterogeneous rock, being composed mainly of hornblende and plagioclase in some parts (Figs. 8a, b). Orthopyroxene is anhedral and poikilitic. Greenish brown hornblende commonly contains irregularly distributed ilmenite lamella.

YH04122006C: This is a medium-grained and well-foliated rock. This rock forms

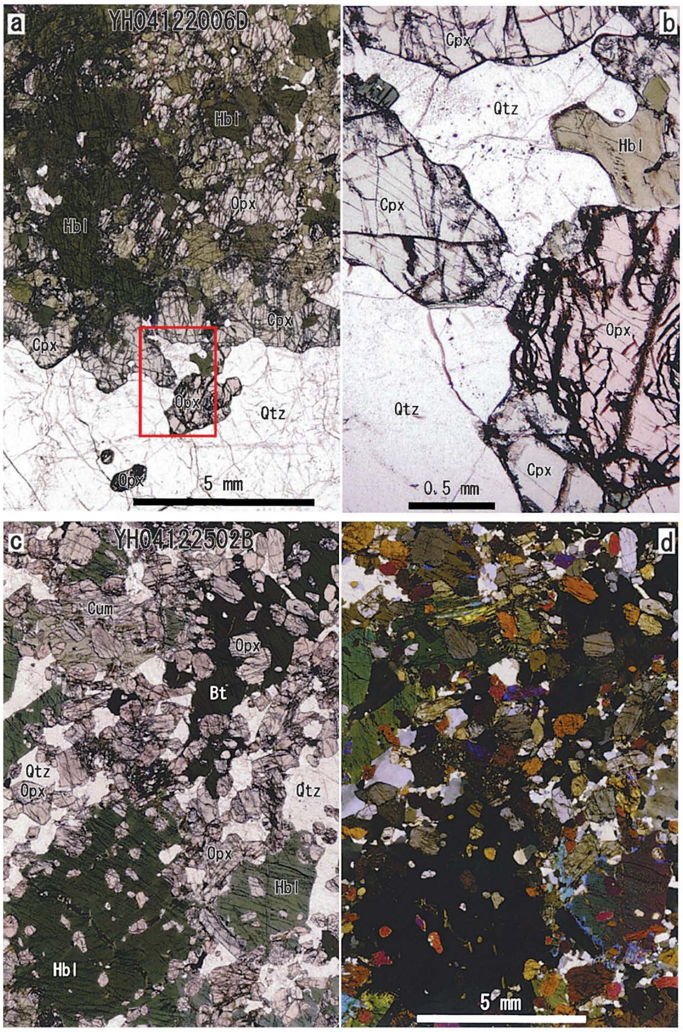

Fig. 9. Photomicrographs of basic granulite sample YH04122006D next to quartz vein (a, b) and intermediate granulite sample YH04122502B in direct contact with surrounding meta-tonalite (c, d). (a, b and c); Plane polarized light. (d); Crossed nicols. (b) is an enlarged photograph of the area in the rectangle in (a). In sample YH04122006D clinopyroxene is enriched and coarse grained in the vicinity of quartz vein (a, b). In sample YH04122502B smaller orthopyroxene grains are embedded in larger grains of biotite, hornblende and quartz (c, d). Note that the colorless mineral is quartz only, and plagioclase is absent in this rock. A small amount of cummingtonite occurs, fringing mainly hornblende and rarely orthopyroxene.

together with others a type-II well-layered block in meta-tonalites like samples YH 04122006A and YH04122006B do (Fig. 3a, b). Foliation defined by preferred orientation of orthopyroxene and hornblende and concentration of biotite into distinct laminae is characteristic (Fig. 8c). Clinopyroxene is minor and usually replaced extensively by

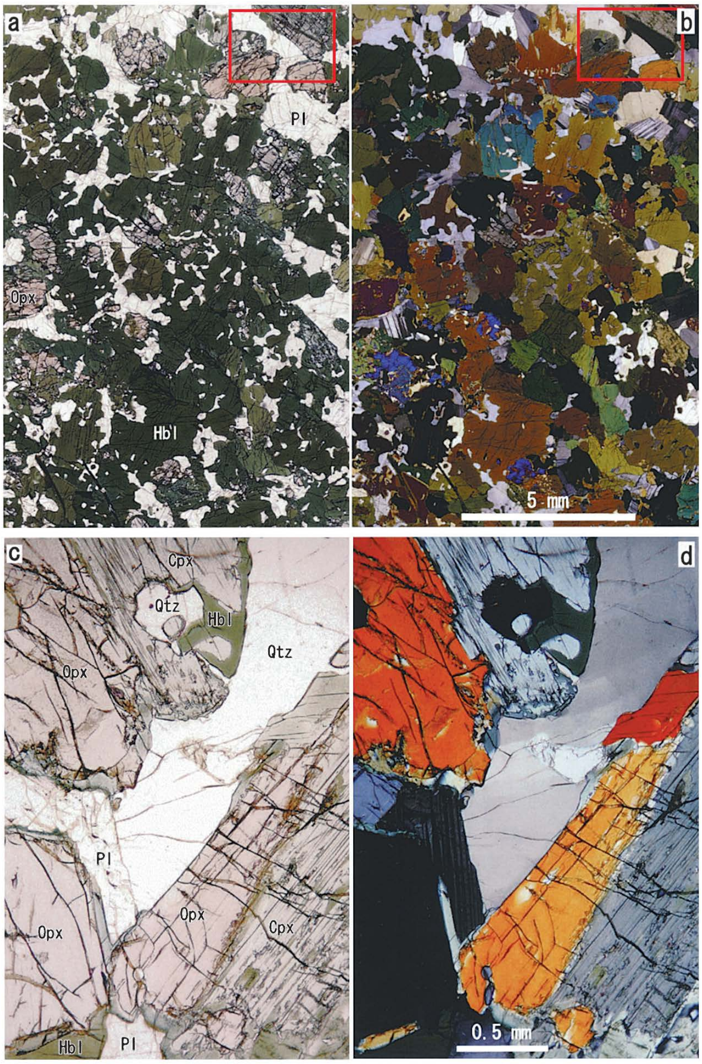

Fig. 10. Photomicrographs of hornblende-rich basic granulite sample YH04122502C. (a) and (c); Plane polarized light. (b) and (d); Crossed nicols. (c) and (d) are enlarged photographs of the areas in the rectangles in (a) and (b), respectively. Note that orthopyroxene and clinopyroxene are often intimately associated with each other and surrounded or partially replaced by brownish green to pale blue-green hornblende (c, d). Quartz is present in this rock.

pale green hornblende (Fig. 8d). Hornblende is highly heterogeneous, ranging in color from pale greenish brown to pale green.

YH04122006D: This sample is also from a type-II well-layered block enclosed by meta-tonalites and next to a concordant quartz vein (Fig. 3). Concentration of biotite, hornblende and orthopyroxene into distinct laminae is conspicuous mesoscopically. Clinopyroxene is enriched in the vicinity of the quartz vein (Fig. 9a, b). Orthopy-

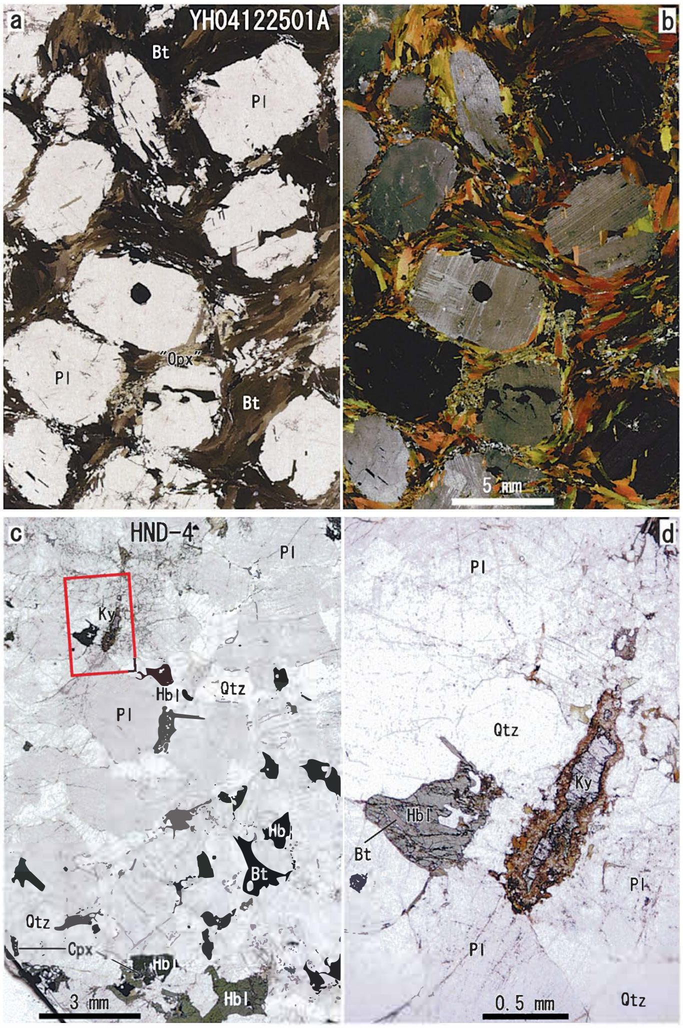

Fig. 11. Photomicrographs of plagioclase-biotite-rich cumulate sample YH04122501A (a, b) (see Fig. 4 for macroscopic features) and kyanite-clinopyroxene-hornblende-biotite-bearing meta-tonalite sample HND-4 collected by N. Ishikawa near Penguin Heights (c, d). (a, c and d); Plane polarized light. (b); Crossed nicols. (d) is an enlarged photograph of the area in the rectangle in (c). Large plagioclase crystals are scattered in the biotite-rich matrix, and a small amount of orthopyroxene is completely replaced by pinite in sample YH04122501A (a, b). Kyanite is always surrounded by pinite in the meta-tonalite (d).

roxene is occasionally extremely coarse-grained up to 30 mm long in the vicinity of the quartz vein.

YH04122502B: This is a massive, coarse-grained, homogeneous rock, occurring as a thin layer between basic granulite of sample YH04122502C and country meta-tonalites (Fig. 2c). Dark green hornblende and black biotite crystals up to 5 mm in

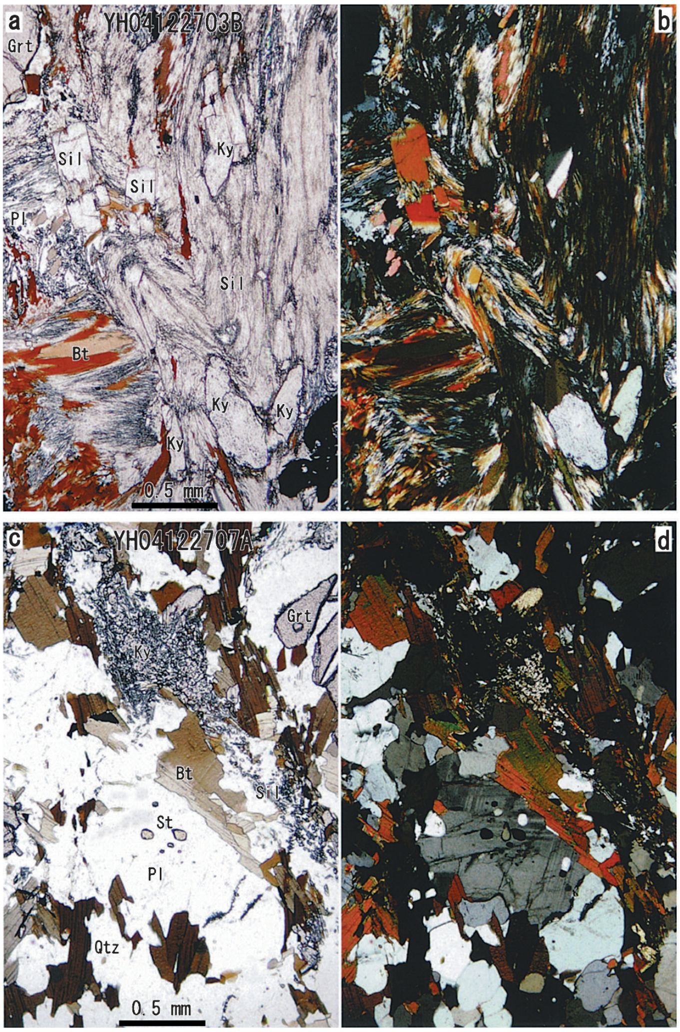

Fig. 12. Photomicrographs of sheared pelitic gneiss samples YH04122703A (a, b) and YH04122707A (c, d) from the southwestern part of the Cape Hinode area (see Fig. 1 for locality). (a) and (c); Plane polarized light. (b) and (d); Crossed nicols. In sample YH04122703B a small amount of undeformed kyanite overgrows highly deformed sillimanite (a, b). In sample YH04122707A retrograde kyanite has replaced most of the pre-existing sillimanite (c, d). Relict prograde staurolite is also seen as inclusions in plagioclase in sample YH04122707A. Note that these sillimanite-rich and kyanite-rich rocks occur side by side.

diameter are conspicuous in the brown matrix composed of orthopyroxene and quartz. In thin section, a small amount of cummingtonite is observed to occur, fringing mostly brownish green hornblende and rarely orthopyroxene. Coarse-grained biotite and hornblende crystals are commonly deformed and cracked. Hornblende commonly contains irregularly distributed ilmenite lamella. This rock is unusual in that plagioclase is absent. In addition, this rock is relatively rich in zircon. These features suggest that this rock is originated from a kind of cumulate.

YH04122502C: This sample is from a lens at least 1 m thick sitting within surrounding meta-tonalites and accompanied by massive intermediate granulite sample YH 04122502B (Fig. 2c). It is mesoscopically medium- to coarse-grained massive hornblende gneiss or hornblende gabbro, consisting largely of hornblende and plagioclase. In thin section, however, small amounts of orthopyroxene and clinopyroxene occur, being closely associated with each other and often surrounded or replaced by hornblende (Fig. 10a, b). In addition, these minerals are occasionally in direct contact with plagioclase and minor quartz (Fig. 10c, d). Hornblende is mostly poikilitic and relatively homogeneous, but locally heterogeneous in color and hence composition, especially next to replacing pyroxenes.

4.2. Other rocks

YH04122501A: This rock is a kind of cumulate composed mainly of plagioclase and biotite (Figs. 4 and 11a, b). In thin section, coarse-grained plagioclase grains are scattered in a biotite-rich matrix. Small amounts of orthopyroxene, which is completely replaced by pinite, and quartz also occur in the matrix.

HND-4: This is a typical, medium-grained, dark gray meta-tonalite consisting mainly of plagioclase and quartz with small amounts of clinopyroxene, hornblende, biotite, kyanite, K-feldspar, magnetite, ilmenite, apatite, monazite and zircon (Fig. 11c). Minor muscovite, carbonate minerals, and pinite are alteration products. Clinopyroxene is usually replaced partially to completely by hornblende, which, in turn, is replaced partially by biotite. Kyanite is anhedral, being always surrounded by pinite (Fig. 11d). K-feldspar occurs as antiperthite lamella in plagioclase.

YH04122703B: This is a sheared pelitic gneiss rich in sillimanite and garnet, occurring in the southwestern part of the Cape Hinode area (Fig. 1). Major sillimanite is deformed, and overgrown by undeformed kyanite crystals (Fig. 12a, b).

YH04122707A: This is a strongly sheared pelitic gneiss from the southwestern part of the Cape Hinode area (Fig. 1). In this rock retrograde kyanite has replaced most of the peak metamorphic sillimanite, which is now present as minor inclusions in kyanite, plagioclase, and garnet (Fig. 12c, d). Relict staurolite is occasionally found as anhedral inclusions in plagioclase and garnet. Note that retrograde kyanite-rich rocks and peak metamorphic sillimanite-rich rocks occur side by side.

5. Bulk rock compositions of granulites and related rocks

Bulk rock compositions of selected granulite and related rock samples from Cape Hinode are presented in Table 2. Silica content ranges from 48 up to 55 wt%. Their bulk rock compositions are plotted on an ACF diagram in Fig. 13, although some of them do not contain quartz and hence are not appropriate for the plotting. In comparison with N-MORB, they are poor in TiO_2, Al_2O_3, CaO, and P_2O_5 and rich in FeO, MnO, and MgO. Such chemical characteristics are indicative of enrichment in mafic minerals, especially orthopyroxene, with concomitant depletion in plagioclase, because Al_2O_3 and CaO are the major components making up plagioclase. Such a

Table 2. Bulk rock compositions of granulites and related rocks from Cape Hinode.

Sample number	YH0412 2003B	YH0412 2003C	YH0412 2006B	YH0412 2006C	YH0412 2006D	YH0412 2501A	YH0412 2502B
SiO_2	55.37	48.01	49.30	54.35	50.85	51.25	55.36
TiO_2	0.76	0.74	0.98	0.30	0.57	2.34	0.67
Al_2O_3	11.31	8.73	12.15	8.64	8.21	17.45	5.03
Fe_2O_3*1	12.38	16.46	11.93	10.15	13.35	11.26	21.14
MnO	0.28	0.36	0.24	0.26	0.29	0.08	0.76
MgO	11.16	15.59	12.84	17.71	17.59	5.32	13.15
CaO	6.44	7.28	8.69	6.90	7.58	3.11	2.15
Na_2O	2.47	1.30	2.44	1.90	1.42	3.16	0.17
K_2O	0.79	0.87	1.09	0.57	0.69	4.65	1.94
P_2O_5	0.05	0.09	n.d.	n.d.	n.d.	0.23	0.01
Total	101.01	99.43	99.66	100.77	100.53	98.85	100.38

*1 Total Fe as Fe_2O_3
n.d. = not detected

Analyst: K. Seno

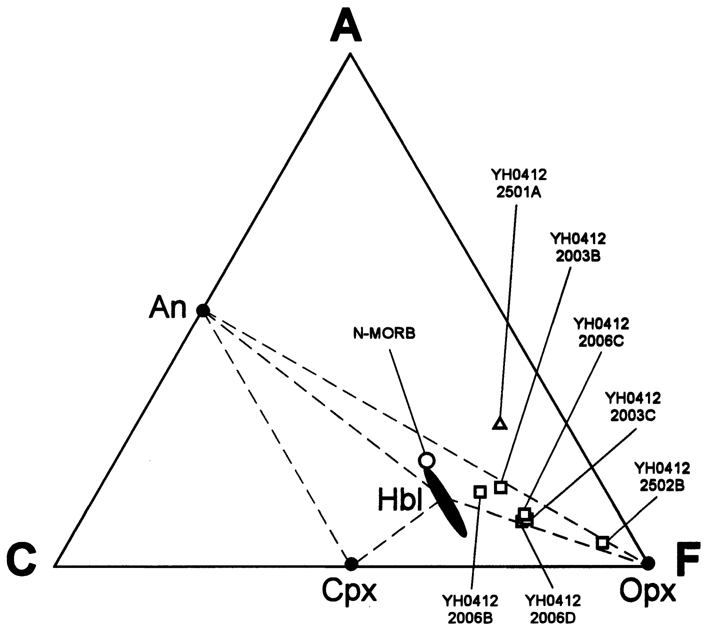

Fig. 13. ACF diagram showing observed mineral assemblages by broken tie lines and bulk rock compositions of granulites and related rocks from Cape Hinode. N-MORB composition is also plotted for comparison. Total iron is assumed to be FeO.

feature is clearly shown by the ACF plot in Fig. 13. The extreme depletion in plagioclase is actually exampled by sample YH04122502B which does not contain plagioclase (Table 1), and are extremely poor in Al_2O_3, CaO, and Na_2O (Table 2). One of the plausible mechanisms to produce such chemical characteristics of the granulites and related rocks from Cape Hinode as a whole is fractional crystallization of andesitic magmas during the formation of original rocks. In this respect, it is important that cumulates are newly found to occur in the meta-tonalite, as shown in Fig. 4. More detailed discussion will be presented elsewhere with more chemical data including trace element abundances and isotopic characteristics.

6. Discussion and conclusions

Orthopyroxene-bearing metamorphic rocks (granulites) have not been found at Cape Hinode, and therefore, metamorphic rocks at Cape Hinode have been considered to belong to the amphibolite facies, without discordance with those in the neighboring bedrock exposures along the eastern Prince Olav Coast (Hiroi *et al*., 1983b, 1987, 1991). However, granulites do occur at Cape Hinode as reported in this study, indicating that the metamorphic grade is different between Cape Hinode and other bedrock exposures to the east (*e.g*., Sinnan rocks, Cape Ryûgû, and Akebono Rock) and to the southwest (*e.g*., Niban Rock and Kasumi Rock) on the eastern Prince Olav Coast. The newly found granulites do not show mineral textures indicative of prograde metamorphism but show more or less retrograde metamorphic features such as the partial replacement of pyroxenes by hornblende with or without biotite, plagioclase, and quartz. Similar retrograde metamorphic features are observed in the country meta-tonalites. This, along with the chemical characteristics and relatively simple mineral assemblages of the granulites, suggests that the granulites are originated from cumulates, that is, products of fractional crystallization of tonalitic magmas.

Another newly revealed fact in this study is that kyanite occurs relatively commonly in hornblende-bearing meta-tonalites. Although its origin may be debatable, kyanite is important for the origin and evolution of meta-tonalites, because the coexistence of kyanite with clinopyroxene, hornblende, plagioclase, and quartz is rare and suggests a limited range of *P-T* condition (*e.g.* Lambert and Wyllie, 1974; Huang and Wyllie, 1986). Kyanite is also known to occur as a retrograde phase replacing peak metamorphic sillimanite to varying degrees in sheared pelitic gneisses in the southwestern part of the Cape Hinode area, as shown above. The occurrence of retrograde kyanite in pelitic gneisses from the Cape Hinode area contrasts with the general occurrence of prograde kyanite in pelitic gneisses in many other bedrock exposures of the Lützow-Holm Complex, regardless of the metamorphic grade (*e.g.* Hiroi *et al*., 1983a, 1991). In addition, retrograde andalusite has been found in some other bedrock exposures of the Lützow-Holm Complex (Hiroi *et al*., 1983a). All these facts are significant geological and petrological features that make rocks of the Cape Hinode area as a whole distinctly different from those of surrounding bedrock exposures.

Shiraishi *et al*. (1994, 2003) reported U/Pb zircon ages of ~550 Ma for samples from different metamorphic grades within the Lützow-Holm Complex and interpreted these zircon ages as the times of main regional metamorphism, making the Lützow-Holm Complex the youngest orogenic belt in the East Antarctic Shield. However, a meta-tonalite sample from Cape Hinode was exceptional; the youngest zircon age obtained was 1017±13 Ma. In addition, Shiraishi *et al*. (1995) reported Sm-Nd and

Rb-Sr isochron ages of around 1000 Ma for meta-tonalites from Cape Hinode, and interpreted these ages as times of igneous crystallization. Based on these ages and the distinct lithological characteristics of meta-tonalites, Shiraishi *et al.* (1994, 1995) proposed that the rocks in the Cape Hinode area constitute an exotic block within the Lützow-Holm Complex. Motoyoshi *et al.* (2004, 2005) also proposed the same idea based on similar Mesoproterozoic monazite EMP ages (935–1007 Ma) for sheared retrograde kyanite-bearing pelitic gneisses and associated garnet-monazite-rich pegmatite from the southwestern part of the Cape Hinode area. Because no data indicative of Early Paleozoic overprinting event were obtained, they concluded that regional metamorphism including retrograde kyanite formation took place around 1000 Ma ago. On the other hand, Fraser and McDougall (1995) reported K/Ar and $^{40}Ar/^{39}Ar$ mineral (biotite, muscovite, and hornblende) ages ranging from 480±5 Ma to 526±5 Ma for pegmatites and amphibolitic gneiss from the Cape Hinode area, indicating a certain Early Paleozoic thermal overprint in common with the surrounding areas of the Lützow-Holm Complex. One of the pegmatites is associated with sheared pelitic gneiss in the southwestern part of the Cape Hinode area, while the amphibolitic gneiss is from Otome Point, sitting within meta-tonalites. As they pointed out, these Early Paleozoic ages may date not the peak of regional metamorphism but cooling ages, because estimated granulite-facies peak metamorphic temperatures are much higher than the closure temperatures in the K-Ar systems. Thus, overgrowth of monazite and zircon did not take place, but only resetting of K/Ar and $^{40}Ar/^{39}Ar$ mineral ages occurred during the last stage of Pan-African orogeny at Cape Hinode.

All these data may indicate that the rocks in the Cape Hinode area as a whole make up a Mesoproterozoic allochthonous block, probably tectonically involved in the Early Paleozoic Lützow-Holm Complex during its cooling stage, as suggested by the strong deformation features observed not only in sheared pelitic gneisses but also in meta-tonalites and pegmatites. In this connection, it is important that meta-tonalites similar to those at Cape Hinode in both radiometric ages and chemical characteristics are known to occur in the southwestern part of the Sør Rondane Mountains, East Antarctica (around 72°S and between 23°E and 25°E) (Ikeda and Shiraishi, 1998). In addition, Asami *et al.* (1992) reported the occurrence of retrograde kyanite in sillimanite-grade pelitic gneisses from the central-western part of the Sør Rondane Mountains (around 72°S and between 24°E and 25°E). In any case, the timing and mechanism of emplacement of such an allochthonous block are significant points to be unraveled based on more data including *P-T-t* paths followed by the rocks.

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