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THE SIGNIFICANCE OF EUHEDRAL CALCIC PLAGIOCLASE INCLUSIONS IN GARNET FROM THE LÜTZOW-HOLM COMPLEX, EAST ANTARCTICA: A TEXTURAL INDICATOR OF PARTIAL MELTING IN PELITIC GNEISSES

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Abstract: Calcic, faceted plagioclase inclusions occur commonly within garnet porphyroblasts in upper amphibolite to granulite facies pelitic rocks of the Early Paleozoic Lützow-Holm Complex, East Antarctica, as is also the case in high grade pelitic metamorphics worldwide. That euhedral plagioclase crystals are only preserved as inclusions in garnet and not in the matrix of these rocks is due to the rigid nature of garnet protecting inclusions from later deformation and recrystallization. The occurrence may have resulted from a partial melting reaction as follows-

Biotite + sillimanite + sodic plagioclase + K-feldspar + quartz $\pm$ H_2O
= granitic melt + garnet + more calcic plagioclase + ilmenite (or rutile).

Thus euhedral plagioclase is a potential indicator of partial melting during high temperature metamorphism.

1. Introduction

The tendency of certain minerals to preferentially assume an idiomorphic (or euhedral) shape (*e.g.*, garnet, staurolite, rutile, titanite, pyrite) whereas others assume a xenomorphic (or andedral) outline (*e.g.*, feldspar, quartz) is a well known feature of metamorphism (*e.g.*, SPRY, 1969, p. 148, Table 6). In contrast the development of a sequential fabric in igneous rocks enables any mineral, including plagioclase, to develop a euhedral shape as long as it is a liquidus or near liquidus phase and thus grows freely from a melt. It is in this context we comment on plagioclase in metamorphic rocks. It is characteristically xenomorphic except when preserved as calcic inclusions in garnet. In these cases it may display a strikingly euhedral outline. Matrix plagioclase is xenomorphic in these rocks.

Garnet is a mineral rigid enough to preserve mineral inclusions and/or inner textures during later deformation (*e.g.*, CHOPIN, 1984). Plagioclase is known to preserve growth zoning well due to limited intracrystalline diffusion of Al and Si in the tetrahedra of the network structure (*e.g.*, YUND, 1983). In addition, both garnet and plagioclase are common in medium to high grade metamorphic rocks over broad ranges of pressure, temperature and bulk chemical composition. Thus these minerals are highly useful in deciphering *P-T-t* paths and partial melting histories of metamorphic rocks (*e.g.*, SPEAR and SELVERSTONE, 1983).

This paper aims to document the common occurrence of calcic, euhedral plagioclase inclusions within garnet porphyroblasts in upper amphibolite to granulite facies pelitic rocks from the Lützow-Holm Complex, East Antarctica, Sri Lanka and Japan, and to propose this feature as a good criterion of partial melting during high temperature metamorphism.

2. Geological Settings

The East Antarctic Shield consists of many geotectonic units ranging in age from Archean to Paleozoic. Rocks exposed along the Prince Olav Coast and around Lützow-Holm Bay belong to the Early Paleozoic Lützow-Holm Complex. This complex is characterized by the westward progressive metamorphism from the upper amphibolite facies to the granulite facies (Fig. 1) and a well-documented clockwise *P-T-t* path of these rocks (HIROI *et al.*, 1983a, b, 1986, 1987, 1991; MOTOYOSHI *et al.*, 1985, 1989; SHIRAISHI *et al.*, 1987). Structural analysis has revealed several episodes of deformation throughout the complex during regional metamorphism (*e.g.*, YOSHIDA, 1978; ISHIKAWA and MOTOYOSHI, 1994; ISHIKAWA *et al.*, 1994). Recent U-Pb ion-microprobe (SHRIMP) zircon dating

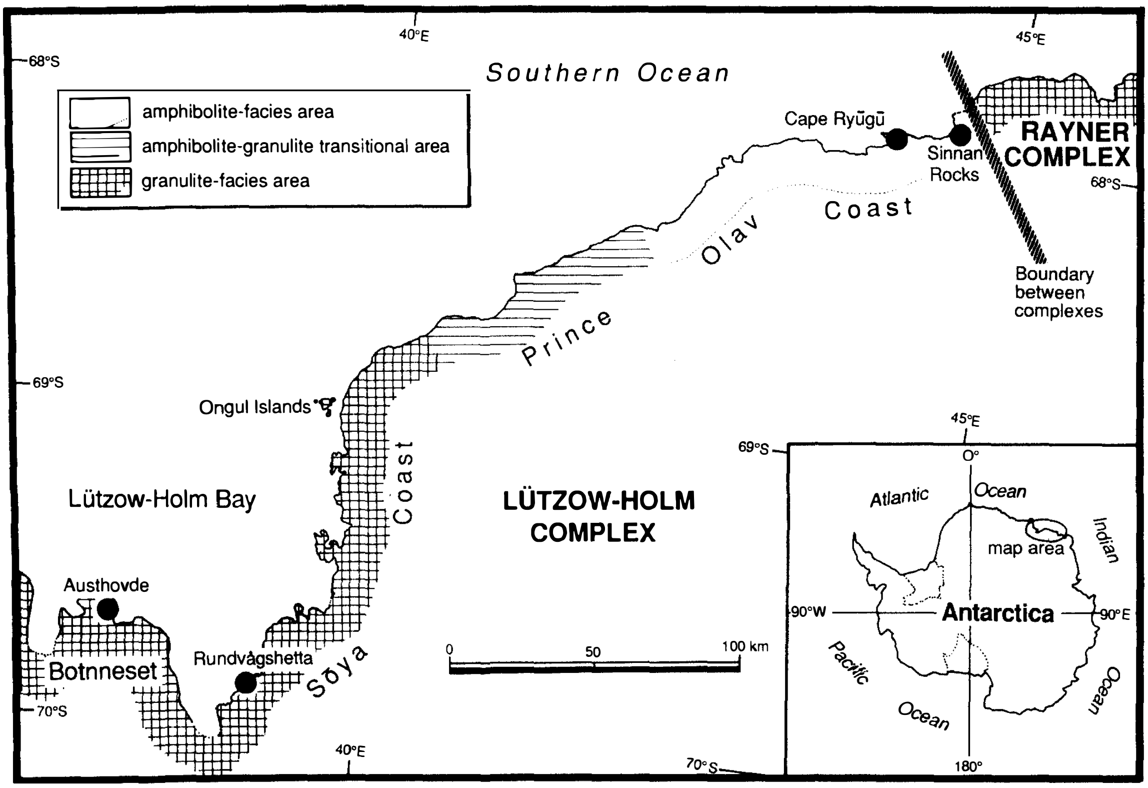

Fig. 1. Map of Prince Olav Coast and Lützow-Holm Bay area, East Antarctica, showing the boundary between complexes, metamorphic facies and sample locations.

clarified that the regional metamorphism took place 500–550 Ma (SHIRAISHI *et al.*, 1992, 1994).

3. Petrological Setting and the Mode of Occurrence of Plagioclase Inclusions in Garnet

Photomicrographs of representative garnet porphyroblasts that contain calcic, faceted plagioclase inclusions in pelitic rocks are shown in Figs. 2 to 5. These are from the eastern Prince Olav Coast at Sinnan Rocks and Cape Ryûgû which are amphibolite facies and from Rundvågshetta and Austhovde in the Lützow-Holm Bay area which are granulite facies (Fig. 1). Coexisting minerals of the photographed garnets are listed in Table 1. Representative microprobe analyses of garnet and plagioclase in the specimens from Cape Ryûgû and Rundvågshetta are given in Table 2. Some petrological notes on the bedrock exposures are given below, followed by brief descriptions of the garnets.

3.1. Sinnan Rocks

This bedrock exposure is located in the easternmost part of the Prince Olav Coast and in the lowest metamorphic grade part of the progressive metamorphic sequence of the Lützow-Holm Complex. The main rock types are pelitic-semipelitic gneisses, basic-intermediate gneisses and quartzo-feldspathic migmatites. Pelitic gneisses have such mineral assemblages as follows (HIROI *et al.*, 1983a, b, c; GREW *et al.*, 1990) (mineral abbreviations are given in Table 1 except for corundum).

1) sil+crd+bio+pla+Kfs+qtz+mag+hem.
2) sil+crd+gar+bio+pla+Kfs+qtz+mag+hem.
3) sil+gar+bio+pla+Kfs+qtz+mag+hem.
4) corundum+sil+mus+bio+pla+Kfs+mag (silica-undersaturated rock).

Relic kyanite and staurolite, though small in amount, are common inclusions in garnet and plagioclase, suggesting a clockwise prograde *P-T-t* path (HIROI *et al.*, 1983a, b, c, 1991). The upper amphibolite facies conditions are indicated by the occurrences of anthophyllite, cummingtonite, hornblende and plagioclase without orthopyroxene in *Sp. 81020910C* (see Table 1) and the mineral assemblages in other basic-intermediate rocks. HIROI *et al.* (1983b) estimated peak *P-T* conditions of 6–7 kb and around 680°C for these samples.

Garnet in both pelitic and intermediate gneisses is usually partially to extensively replaced by cordierite and/or biotite+plagioclase intergrowths (Fig. 2). Nevertheless, faceted plagioclase inclusions are found in such garnet porphyroblasts. The inclusion plagioclase is much more calcic than the matrix plagioclase in the same rock, as clearly indicated by distinctively different refractive indices.

3.2. Cape Ryûgû

This bedrock exposure is located next to Sinnan Rocks and underlain by similar rocks together with calcite marbles (NAKAI *et al.*, 1980). Relic kyanite and staurolite occur in some sillimanite-rich pelitic rocks (Fig. 3; NAKAI *et al.*, 1980; HIROI *et al.*, 1983a, b; GREW *et al.*, 1990). We have also found andalusite as a retrograde mineral, which is closely associated with chlorite after cordierite (this paper).

Garnet in pelitic gneisses is commonly partially replaced by cordierite and/or

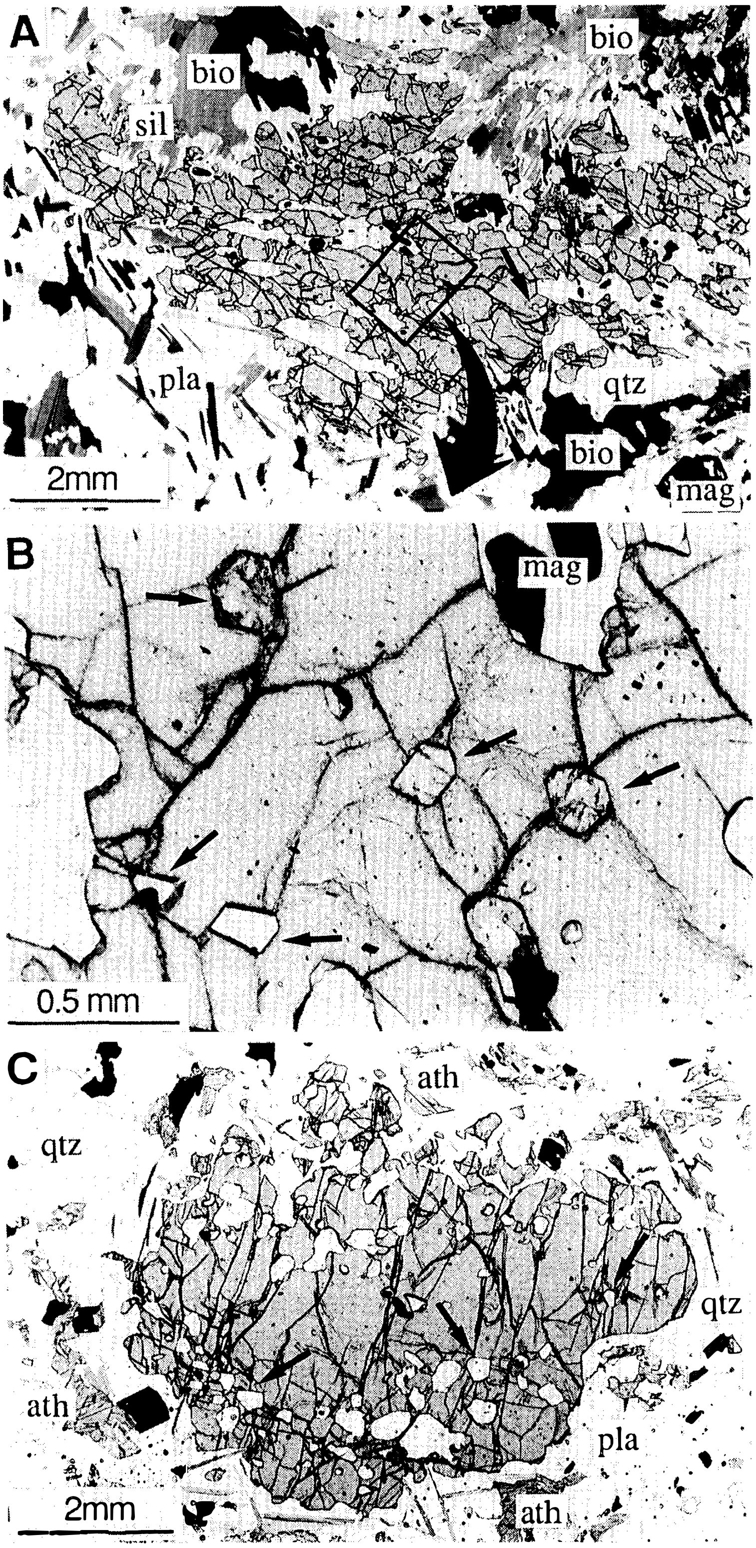

Fig. 2. Photomicrographs of garnet porphyroblasts in Sp. 81020912 (A and B) and Sp. 89020910C (C) from Sinnan Rocks. B is an enlarged photograph of the area defined by the rectangle in A. Euhedral (faceted) plagioclase inclusions (shown by arrows) remain preserved in spite of the extensive replacement of the host garnet by biotite + plagioclase intergrowths.

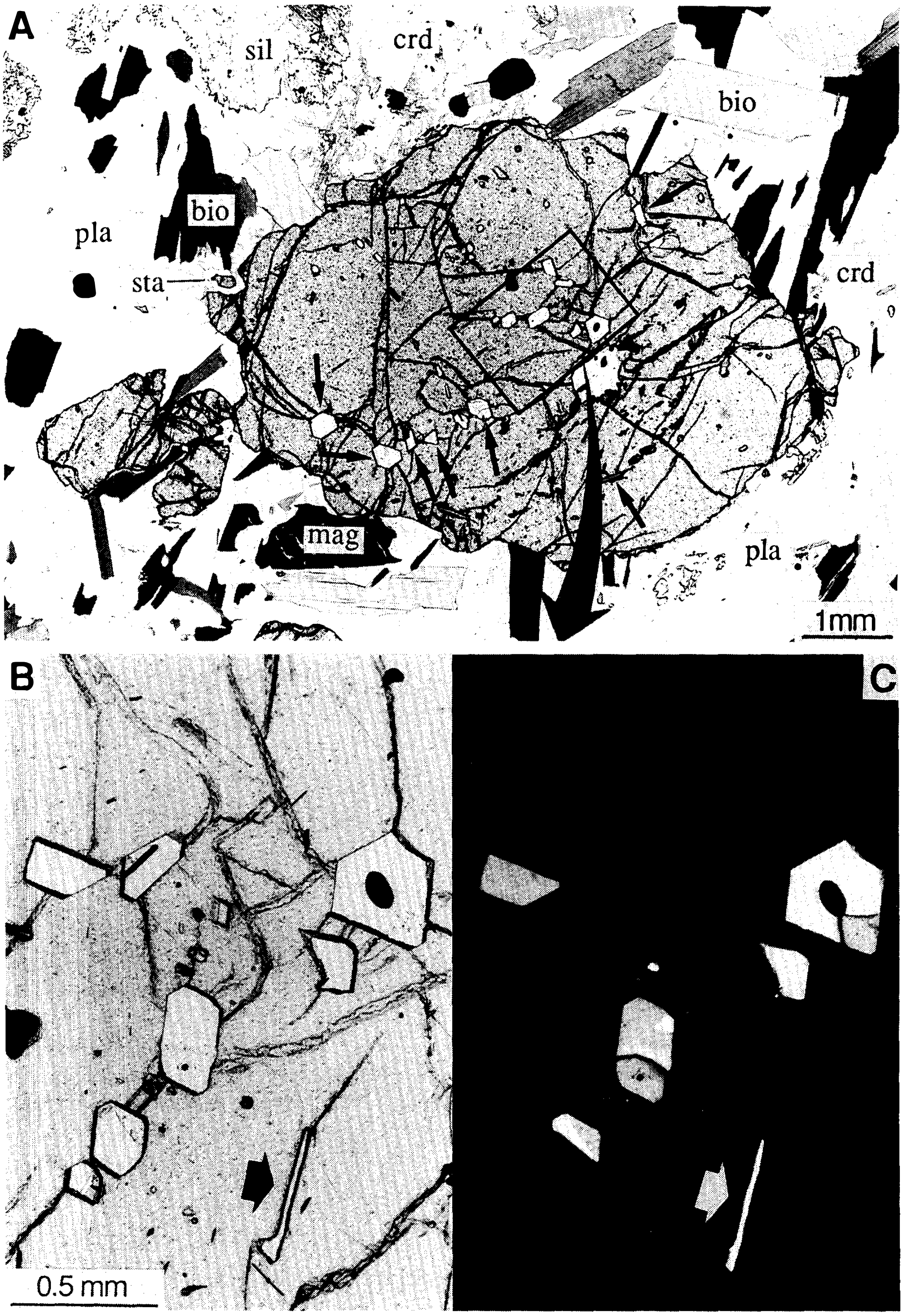

Fig. 3. Photomicrographs of garnet porphyroblast in Sp. 704A from Cape Ryûgû. B and C are enlarged photographs of the area in the quadrilateral in A. Euhedral plagioclase inclusions (shown by arrows) occur throughout the garnet, which is partially replaced by cordierite and biotite+plagioclase intergrowths. Note that most facets of plagioclase inclusions are parallel to each other, but it is not the case with the grain identified by stout arrows in B and C.

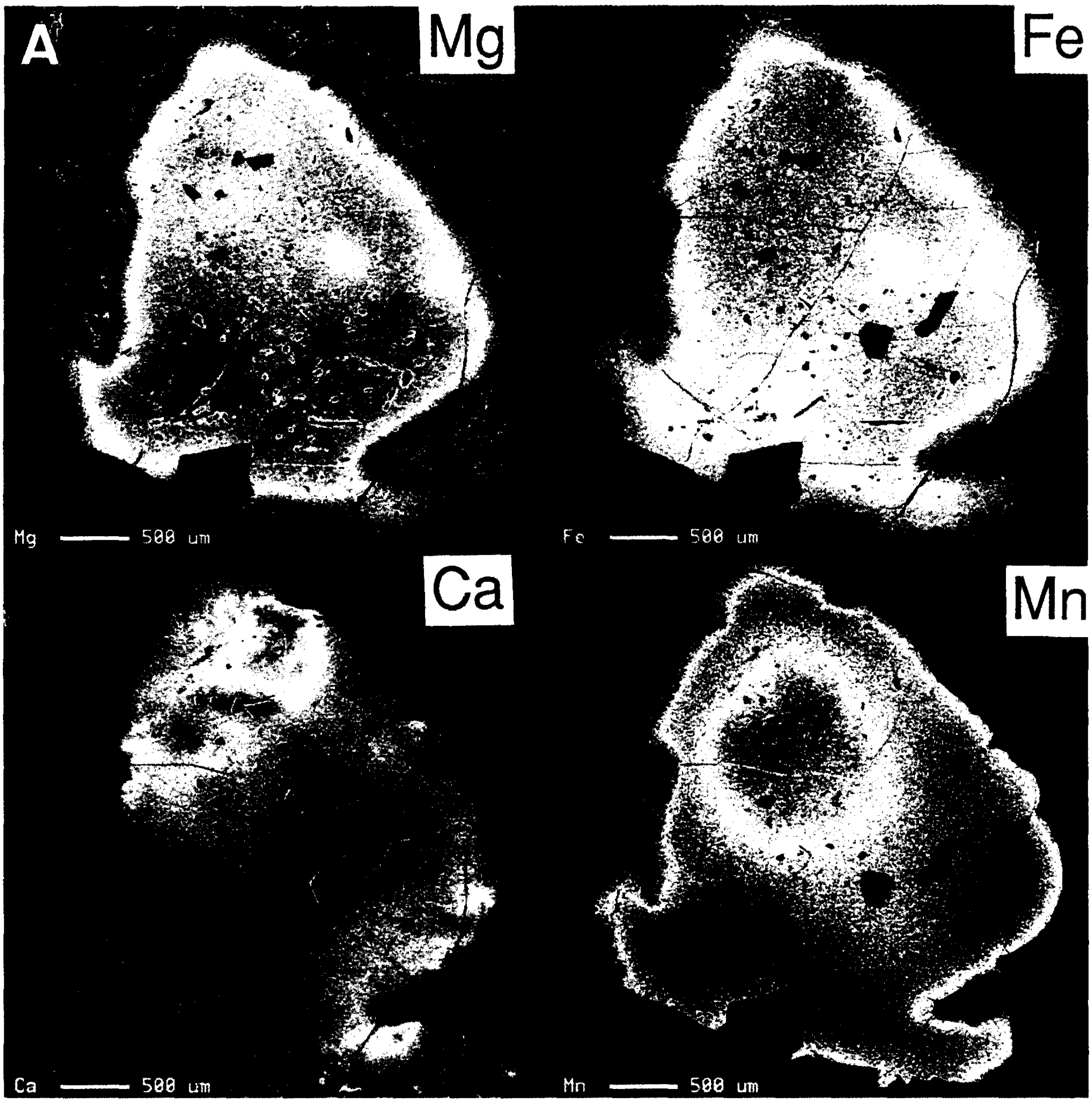

Fig. 4. Color maps of garnet porphyroblast in Sp. 704A from Cape Ryûgû for Mg, Fe, Ca and Mn. Color mapping for Ca is based on the same data, but the intensity levels set differently between A and B. Note that faceted inclusion plagioclase is much more calcic than matrix plagioclase, though variable in Ca content from grain to grain, that inclusion plagioclase is sometimes zoned normally, and that host garnet is compositionally heterogeneous.

biotite + plagioclase intergrowths. Garnet shown in Fig. 3 contains many faceted plagioclase inclusions. Most of the inclusion plagioclases have facets with similar orientations, but some do not (see Figs. 3B and 3C). In some cases, the faceted plagioclases themselves contain rounded inclusions of quartz and opaque oxides (see Figs. 3B and 3C). Figure 4 shows the result of color mapping for Fe, Mg, Ca and Mn in another garnet porphyroblast from the same rock. It is evident that inclusion plagioclase is much more calcic (up to *c.* 90 mole% An) than matrix plagioclase (*c.* 50 mole% An) (Table 2). Most of the inclusion plagioclase grains are homogeneous, but some are zoned normally. In the present case,

Fig. 4B.

host garnet is heterogeneous compositionally, and the Ca content of inclusion plagioclase varies from grain to grain. There seems to be a positive correlation between the An content of inclusion plagioclase and the Ca content of surrounding garnet. In addition, it appears that the plagioclase inclusions are usually surrounded by Ca depletion halos in the garnet.

3.3. *Rundvågshetta*

This exposure consists mainly of orthopyroxene- and/or garnet-bearing quartzo-feldspathic gneisses, basic-intermediate gneisses and pelitic-psammitic gneisses (MOTOYOSHI *et al.*, 1986). MOTOYOSHI *et al.* (1985) summarized the petrographic characteristics of pelitic rocks from the granulite facies Lützow-Holm Bay area, and showed that the

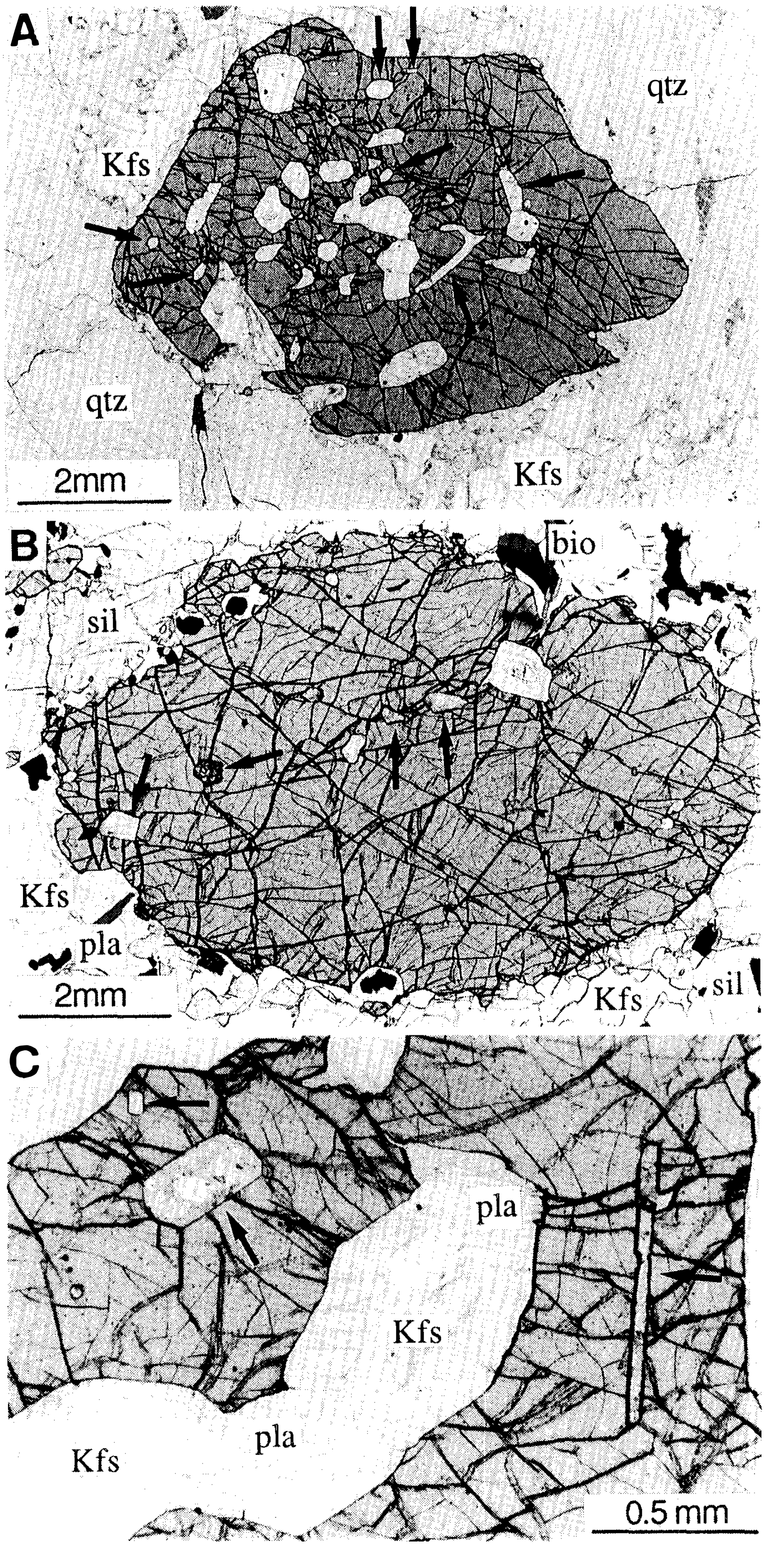

Fig. 5. Photomicrographs of garnet porphyroblasts in Sp. RH-11109J from Rundvågshetta (A) and Sp. 93012401A from Austhovde (B and C). Rundvågshetta garnet contains faceted inclusions of both plagioclase (pointed by arrows) and quartz (too fine grained to be seen). Austhovde specimen is exceptionally rich in garnet and sillimanite.

Table 1. Consitutent minerals of studied specimens..

Location	Sample No.	sil	kya	and	sta	spr	crd	gar	bio	ath	cum	hbl	pla	Kfs	qtz	mag	rut	ilm	apa
Sinnan Rocks	*81020910C*				○			○	○	○	○	○	◎		○	○		○	○
	81020912	○	○		○			○	○				◎		○	○		○	○
Cape Ryûgû	*704A*	○	○	○	○		○	○	○				◎	○	○	○		○	○
Rundvågshetta	*RH-11109J*	○	○			○		○	○				○	○	◎		○	○	○
Austhovde	*93012401A*	◎						◎	○				○	○	○	○		○	○

Mineral abbreviations

and: andalusite, apa: apatite, ath: anthophyllite, bio: biotite, crd: cordierite, cum: cummingtonite, gar: garnet, hem: hematite, hbl: hornblende, ilm: ilmenite, Kfs: K-feldsper, kya: kyanite, mag: magnetite, qtz: quartz, rut: rutile, sil: sillimanite, spr: sapphirine, sta: staurolite.

◎: abundant (>30 modal percent), ○: present.

Table 2. Representative EPMA analyses of plagioclase and garnet.

Sample No.	*704A* (Cape Ryûgû)					*RH-11109J* (Rundvågshetta)				
Mineral	pla matrix	pla inclu-1	pla inclu-2	gar halo*	gar core	pla matrix	pla inclu-1	pla inclu-2	gar halo*	gar core
SiO_2	55.67	45.02	45.33	38.91	39.18	60.73	53.77	57.29	39.90	39.59
TiO_2	0.01	0.01	0.01	0.00	0.00	0.04	0.00	0.00	0.00	0.02
Al_2O_3	28.09	34.98	34.70	21.45	21.07	24.75	28.31	25.73	23.13	22.90
Cr_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
FeO**	0.10	0.21	0.16	28.07	26.65	0.05	0.06	0.08	19.69	19.36
MnO	0.00	0.00	0.03	3.09	3.61	0.00	0.01	0.00	0.34	0.33
MgO	0.02	0.00	0.02	6.13	4.77	0.01	0.00	0.00	16.01	15.17
CaO	9.98	18.91	18.52	3.67	5.52	6.29	10.47	8.08	0.94	1.90
Na_2O	5.87	1.09	1.20	0.04	0.03	7.89	5.27	6.59	0.00	0.00
K_2O	0.02	0.02	0.02	0.00	0.00	0.40	0.45	0.70	0.00	0.00
total	99.76	100.24	99.99	101.36	100.83	100.16	98.34	98.47	100.01	99.30
O	8	8	8	12	12	8	8	8	12	12
Si	2.509	2.077	2.093	3.011	3.053	2.699	2.468	2.610	2.950	2.953
Ti	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.00	0.001
Al	1.492	1.902	1.889	1.957	1.935	1.297	1.532	1.381	2.015	2.013
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.020	0.002
Fe	0.004	0.008	0.006	1.817	1.737	0.002	0.002	0.003	1.217	1.208
Mn	0.000	0.000	0.001	0.202	0.238	0.000	0.000	0.000	0.020	0.021
Mg	0.001	0.000	0.001	0.707	0.554	0.001	0.000	0.000	1.764	1.687
Ca	0.482	0.935	0.917	0.304	0.461	0.300	0.515	0.394	0.074	0.152
Na	0.513	0.098	0.107	0.006	0.005	0.680	0.469	0.582	0.000	0.000
K	0.001	0.001	0.001	0.000	0.000	0.023	0.026	0.041	0.000	0.000
total	5.002	5.021	5.015	8.004	7.983	5.003	5.012	5.011	8.040	8.037
An or Gr%	48.4	90.4	89.5	10.0	15.4	29.9	51.0	38.7	2.4	5.0

*Calcium depletion halo around plagioclase inclusion.

**total Fe as FeO.

relatively high temperature mineral assemblage of spinel+quartz occurs at this outcrop. HIROI *et al.* (1991) therefore presumed that the thermal peak is located near here in the progressive metamorphic sequence of the Lützow-Holm Complex. This is supported by later discoveries of the occurrence of high temperature and high pressure mineral assemblage sillimanite+orthopyroxene+garnet from this outcrop (KAWASAKI *et al.*, 1993; ISHIKAWA *et al.*, 1994). MOTOYOSHI *et al.* (1989) estimated *P-T* conditions of 7–8 kb and 760–830°C here, but the newly found mineral assemblage suggests even higher *P-T* values of equilibration. Sapphirine is also reported to occur in some pelitic rocks, though it is not in direct contact with quartz (MOTOYOSHI *et al.*, 1985; KAWASAKI *et al.*, 1993; ISHIKAWA *et al.*, 1994). In spite of the high temperature metamorphic conditions, relic kyanite occurs as inclusions in garnet, suggesting a clockwise prograde *P-T-t* path (MOTOYOSHI *et al.*, 1985, 1986)

Figure 5A shows a garnet porphyroblast containing relatively coarse grained inclusions of plagioclase in *Sp. RH-11109J*, most of which are euhedral and much more calcic (up to *c.* 50 mole% An) compared to the matrix plagioclase (*c.* 30 mole% An). Fine grained, euhedral quartz inclusions are also seen in the marginal part of this garnet porphyroblast.

3.4. Austhovde

SHIRAISHI and YOSHIDA (1987) gave brief petrographic descriptions of the Botnneset area including the outcrop at Austhovde which consists of basic-intermediate gneisses, quartzo-feldspathic gneisses, quartzite, pelitic-semipelitic gneisses and dolomitic marbles. This lithological association is common in the Lützow-Holm Bay area. Ultramafic rocks occur as isolated blocks and thin layers enclosed in the gneisses (HIROI *et al.*, 1986; SHIRAISHI and YOSHIDA, 1987).

In Figs. 5B and 5C are shown garnet porphyroblasts in *Sp. 93012401A*. This specimen is exceptionally rich in garnet and sillimanite and may be a restite.

4. Discussion

4.1. Origin of faceted forms of plagioclase inclusions in garnet

The occurrence of euhedral plagioclase inclusions within garnet in both amphibolite facies and granulite facies pelitic rocks of the Lützow-Holm Complex is not uncommon, as shown above. Similar examples of Sri Lankan pelitic granulite (*Sp. H88112501A*) and the amphibolite facies Takanuki pelitic gneiss (*Sp. HZ13-B*) of the Abukuma Mountains, Japan, are shown in Fig. 6. WHITNEY (1991) also reported a similar occurrence of faceted plagioclase inclusions within garnet in the upper amphibolite facies Skagit Gneiss, Northern Cascades range of Washington.

The facets of plagioclase inclusions in garnet could either be the crystal faces of plagioclase or host garnet. In the former case the plagioclase inclusions are euhedral, whereas in the latter case the plagioclase inclusions are negative crystals. The facets of plagioclase inclusions may be plagioclase crystal faces in the Antarctic, Sri Lankan and Japanese examples, because (1) these do *not always* show common orientations coincident with certain crystal planes of host garnet with simple Miller's indices (see Figs. 3 and 6), (2) the host garnets are commonly partially replaced by biotite+plagioclase intergrowths from outside and along cracks, resulting in their anhedral grain forms, and (3) inclusion plagioclase is not always reversely zoned, in spite of the fact that it is usually surrounded by Ca depletion halos. On the other hand, WHITNEY (1991) interpreted the facets of plagioclase inclusions in garnet from the Skagit Gneiss as being the negative

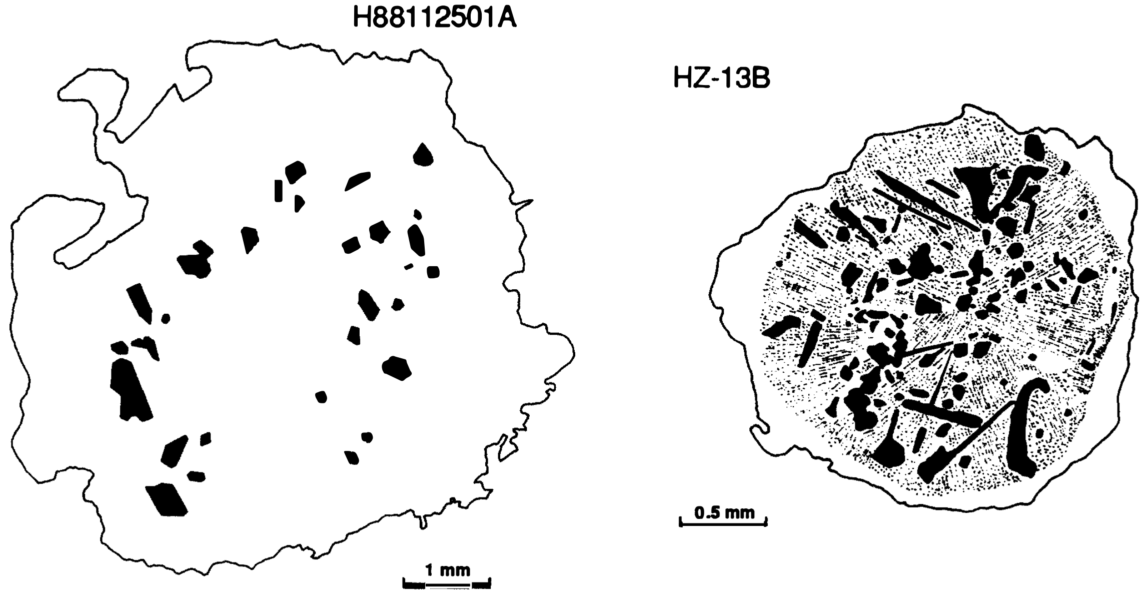

Fig. 6. Sketches of garnet porphyroblasts containing euhedral, calcic plagioclase inclusions (black) in Sri Lankan pelitic granulite (Sp. H88112501A) and amphibolite facies Takanuki pelitic gneiss from Abukuma, Japan (Sp. HZ13-B) (Hiroi, 1992, 1995 ; Hiroi and Ellis, 1994). Note these garnets have two parts, cores with the inclusions and margins free of inclusions. The core of the Abukuma garnet shows textural sector zoning displayed by alignment of fine grained inclusions.

crystal faces of the host garnet. This interpretation was based on the observation that the facets have common orientations in each garnet and are parallel to planes of rutile exsolution in the host garnet and that plagioclase inclusions in the Skagit Gneiss are always reversely zoned.

Euhedral plagioclase may be difficult to form by a solid-state growth in contact with neighboring grains. It is most probably due to unimpeded growth in an isotropic medium, presumably a melt at high temperatures (*e.g.*, Ashworth and McLellan, 1985).

4.2. Origin of calcic plagioclase inclusions in garnet in pelitic gneisses

Inclusion plagioclase is slightly to significantly more calcic than the matrix plagioclase, although An content of both inclusion and matrix plagioclases varies from rock to rock, probably depending upon the bulk chemical composition. Plagioclase inclusions are commonly surrounded by Ca-depletion halos in the host garnet, but they are not always reversely zoned in the case of Antarctic, Sri Lankan and Japanese rocks. Therefore, inclusion plagioclase may not have become calcic by getting Ca from the surrounding garnet through such a net transfer reaction as follows during decompression at high temperatures-

$$\underset{\text{grossular}}{Ca_3Al_2Si_3O_{12}} + \underset{\text{sillimanite}}{Al_2SiO_5} + \underset{\text{quartz}}{SiO_2} = \underset{\text{anorthite}}{CaAl_2Si_2O_8}.$$

We propose instead that the inclusion plagioclase formed as euhedral, calcic grains in a melt. There is a positive correlation between An content of inclusion plagioclase and Ca content of host garnet, as mentioned above. As long as we ignore an insignificant effect of minor apatite breakdown and assume no metasomatic introduction of Ca from outside, partial melting to form a granitic liquid containing abundant albite component may be the only way to make both of these Ca-bearing minerals more calcic simultaneously, as there is no other major Ca-bearing minerals to supply Ca.

4.3. *Implications of the occurrence of euhedral, calcic plagioclase inclusions in garnet in pelitic metamorphics*

The formation of euhedral, calcic plagioclase inclusions in garnet in pelitic rocks containing more sodic plagioclase in the matrix may be most satisfactorily explained by a partial melting reaction such as follows-

Bio + sil + sodic pla + Kfs + qtz $\pm$ H_2O
= granitic melt + gar + more calcic pla + ilm (or rut).

Sodic matrix plagioclase together with other minerals may have crystallized from the granitic melt. Partial melting of pelitic rocks occurs at temperatures > 650°C at pressures > 5 kb in the presence of H_2O-rich fluid, or even in the absence of H_2O-rich fluid it would begin at *c*. 750°C at pressures > 5 kb if there were such hydrous minerals as mica (*e.g*., WYLLIE, 1977; THOMPSON, 1982; GRANT, 1985; VIELZEUF and HOLLOWAY, 1988; LE BRETON and THOMPSON, 1988). The Lützow-Holm Complex rocks were metamorphosed at temperatures > 680°C and pressures > 5 kb (HIROI *et al*., 1983b, 1991; MOTOYOSHI *et al*., 1985, 1989; SHIRAISHI *et al*., 1987). The occurrence of euhedral inclusions of plagioclase containing up to *c*. 90 mole% An together with garnet and a "granodioritic partial melt" (now the matrix of the rock) in the specimen from Cape Ryûgû is consistent with the experimentally determined solidus phase relations at the estimated *P-T* conditions in Sinnan Rocks (see Fig. 2.10 of JOHANNES, 1985). It, in turn, would be a criterion indicative of partial melting of the rocks during high temperature metamorphism.

Acknowledgments

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