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Fluorine-rich calcic amphiboles in ultrahigh-temperature mafic granulite from Tonagh Island in the Napier Complex, East Antarctica: Preliminary report

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Abstract: Fluorine-rich calcic amphiboles occur in ultrahigh-temperature mafic granulite from Tonagh Island in the Napier Complex, East Antarctica. The amphiboles are subdivided into two types: high-grade brownish to pale brownish amphibole and retrograde greenish amphibole. The brownish amphibole is pargasitic occurring as a subhedral grain in two-pyroxene mafic granulite. It contains up to 2.2 wt% fluorine, which corresponds to an F/(F+Cl+OH) ratio of 0.54 (sample B98020801). In sample B98020802B, brownish amphibole is rimmed by an orthopyroxene-plagioclase-quartz corona, probably formed by a devolatilization reaction. It has a lower fluorine content of 0.21-0.52 wt% (F/(F+Cl+OH)=0.04-0.13). Pale brownish amphibole is a minor phase in metapyroxenite. It has the highest fluorine content (2.6 wt%, F/(F+Cl+OH)=0.60, sample B98012802F). Greenish amphibole is present as fine-grained aggregates with quartz, rimming ortho- and clinopyroxenes. Fluorine is almost absent in this amphibole.

Holloway and Ford (1975) experimentally determined that pargasite with a F/(F+Cl+OH) ratio of 0.48 is stable up to 1100°C at 5 kbar, and that F/(F+Cl+OH) increases with increasing temperature. The fluorine-rich calcic amphiboles in mafic granulites are therefore stable under UHT metamorphic conditions. The formation of an orthopyroxene-plagioclase-quartz corona in sample B98020802B can therefore be explained by breakdown of the amphibole due to its low-fluorine content. The origin of the fluorine is not known, but it is probably derived from basic magma at the stage of protolith formation.

key words: fluorine-rich amphibole, mafic granulite, Tonagh Island, Archean Napier Complex, East Antarctica

1. Introduction

The Napier Complex of Enderby Land, East Antarctica, is an example of a late-Archean high-grade terrane which has undergone granulite-facies metamorphism at a temperature higher than 1100°C (*e g* Ellis, 1980, Harley, 1985, Sheraton *et al* , 1987, Hokada *et al* , 1999) The Amundsen Bay area, located in the western part of the Napier Complex, is known as the highest grade region of the complex where sapphirine-quartz and osumilite-bearing mineral assemblages are common (Sheraton *et al* , 1987, Harley and Hensen, 1990) The presence of an orthopyroxene-sillimanite-garnet-quartz assemblage in pelitic gneiss (Sheraton *et al* , 1987) and inverted pigeonite in meta-ironstone and mafic to intermediate granulites (Sandiford and Powell, 1986, Harley, 1987) provide additional evidence of ultrahigh-temperature (UHT) metamorphism

In spite of the UHT metamorphic conditions of the Napier Complex, biotite is present as a common hydrous mineral in many lithologies including aluminous, quartzofeldspathic, mafic, and ultramafic granulites (*e g* Harley, 1985, Sheraton *et al* , 1987) Although most of the biotite is retrograde in origin, some biotite is regarded as a product of UHT metamorphism Such high-grade biotites are characterized by their high fluorine contents up to 8 wt% (Motoyoshi, 1998) Experimental studies of fluorine-bearing biotite indicate that the stability field of biotite expands to higher temperature with increasing fluorine content in biotite (*e.g* Peterson *et al* , 1991, Hensen and Osanai, 1994)

Calcic amphibole is also known as a common hydrous mineral in UHT mafic and ultramafic granulites of the Napier Complex (Ellis and Green, 1985, Sheraton *et al* , 1987) Although most amphiboles are probably of retrograde origin, some formed during or prior to peak UHT metamorphism (Tsunogae *et al* , 1999, Owada *et al* , 1999) However, the fluorine contents of calcic amphiboles of the Napier Complex have not been reported before Although fluorine-rich amphiboles have been identified elsewhere in hydrothermal veins (Damman, 1989) and contact metamorphic aureoles (Droll, 1983), those in high-grade rocks have not been discussed in detail In this study we identified fluorine-rich calcic amphibole in mafic granulite from Tonagh Island This is the first report of high-fluorine amphibole from the Napier Complex

2. Geology of Tonagh Island

Detailed regional geological and structural characteristics of Tonagh Island are given in Osanai *et al* (1999) Generally the island is composed of layered gneisses of various rock chemistry Orthopyroxene-bearing quartzofeldspathic gneiss is the most abundant lithology in the area It is commonly interlayered with mafic granulite, garnet-bearing felsic gneiss, and magnetite-quartz gneiss Ultramafic granulite is present as thin layers or lenses in quartzofeldspathic and mafic granulites Peak metamorphic conditions of Tonagh Island were determined by Hokada *et al* (1999) as T> 1100°C using ternary-feldspar equilibrium

There are several isotopic ages from metamorphic rocks of Tonagh Island The protolith age of granulites was determined to be 3800 Ma for mafic and ultramafic granulites by the Sm-Nd isochron method (Owada *et al* , 1994) and 3230–3260 Ma for orthopyroxene-bearing quartzofeldspathic gneiss by the SHRIMP zircon U-Pb method

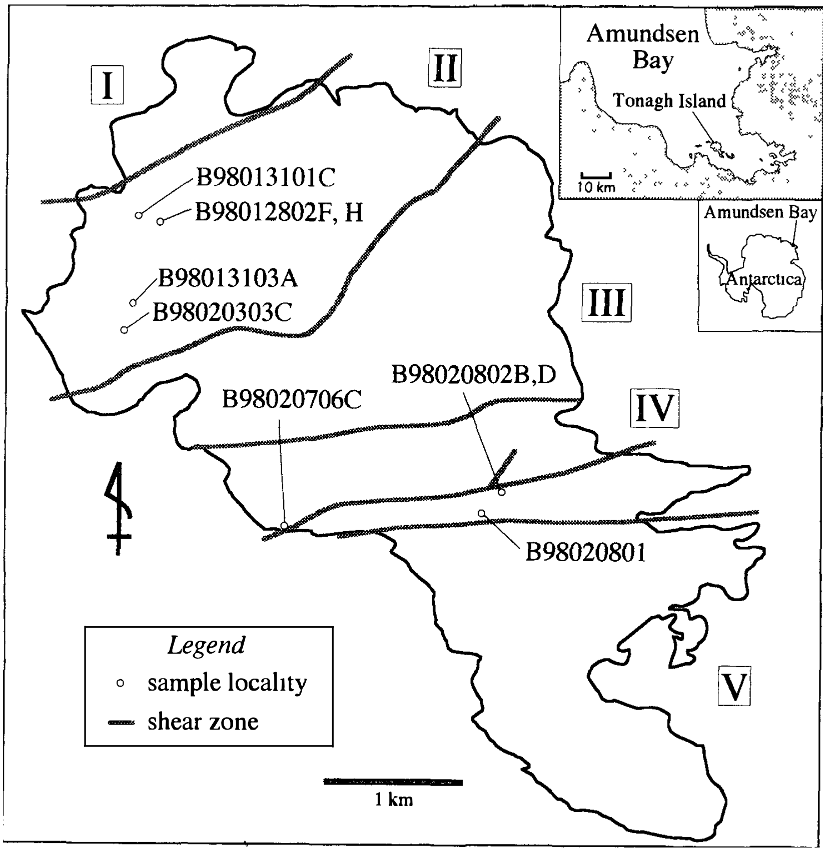

Fig 1 Location map of Tonagh Island with localities of representative samples of mafic granulite discussed in this study I to V denote crustal units separated by shear zones after Osanai et al. (1999) and Toyoshima et al (1999)

(Shiraishi *et al*, 1997) A metamorphic age of *ca.* 2500 Ma was derived from whole-rock Sm-Nd isochrons of quartzofeldspathic gneisses and ultramafic granulites by Owada *et al* (1994) and from metamorphic overgrowth of zircon around magmatic crystals by Shiraishi *et al* (1997)

The high-grade rocks from Tonagh Island are subdivided into five units (Units I to V) by high-angle and ENE-WSW to E-W trending shear zones (Osanai *et al*, 1999; Toyoshima *et al*, 1999). Approximate positions of the shear zones are shown in Fig. 1 Unit I corresponds to the northwestern portion of the island There occur layered gneisses which vary in thickness from several to several tens of centimeters Thick layers of mafic granulite (up to 100 m in thickness) are present in Units II, III, and IV. Unit V is different from the other units because of the more common occurrences of orthopyroxene- and garnet-bearing quartzofeldspathic gneisses

3. Petrography and mineral chemistry of calcic amphiboles

3.1. Analytical procedure

Chemical analyses of minerals were performed by an electron microprobe analyzer at the Research Center of Coastal Lagoon Environments, Shimane University, using an automated JEOL JXA-8800 instrument The data were obtained under conditions of 15

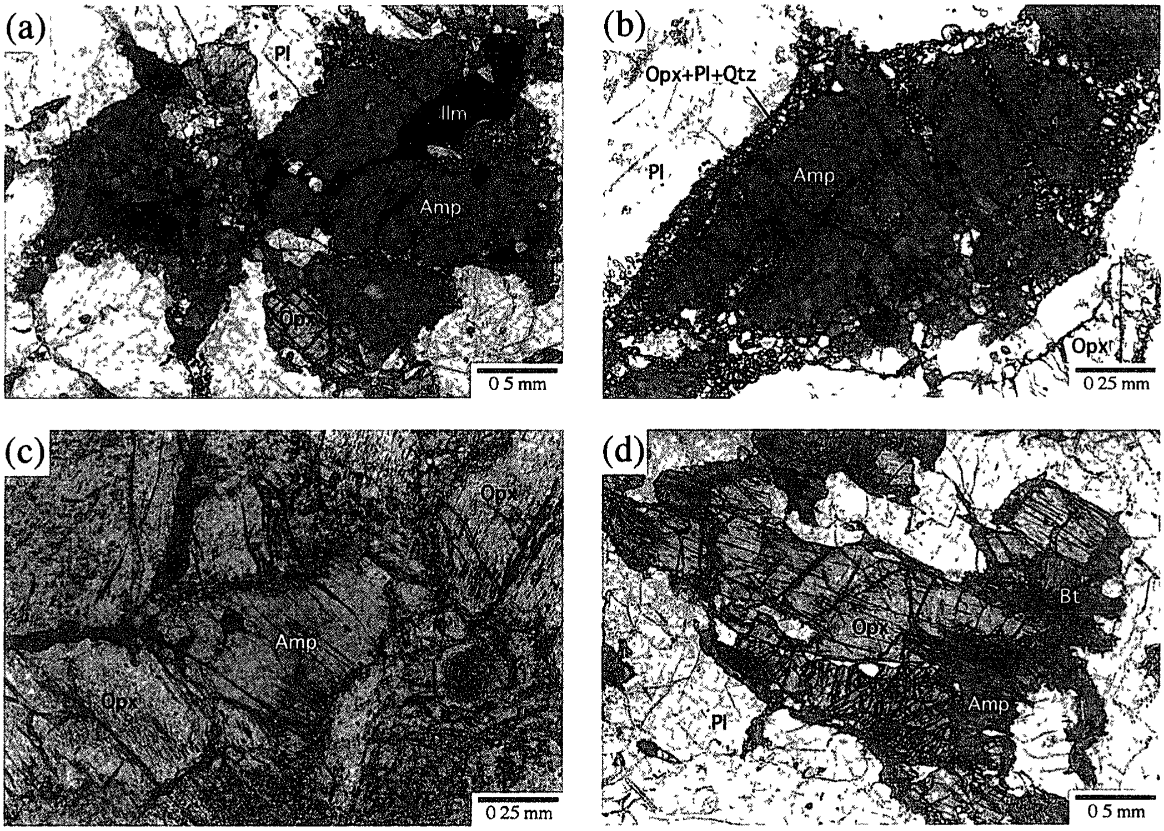

Fig 2 Photomicrographs of calcic amphibole-bearing mafic granulites and metapyroxenite All photographs are under polarized light
(a) Brownish amphibole in sample B98020801 (type 2) It coexists with orthopyroxene, clinopyroxene, plagioclase, and quartz (b) Brownish amphibole in sample B98020802B (type 2) It is rimmed by orthopyroxene-quartz-plagioclase corona which was probably formed by a devolatilization reaction (1) Ilmenite lamella is present in the amphibole (c) Pale brownish amphibole in type 6 metapyroxenite (sample B98012802F) The rock has a granoblastic texture and is composed of orthopyroxene and minor ilmenite, calcic amphibole, and clinopyroxene Amphibole is present along grain boundaries of pyroxenes (d) Greenish amphibole-quartz symplectite around orthopyroxene in type 3 mafic granulite (sample B98012802H) Biotite is also present as a hydrous phase around the pyroxene The texture is evidence of retrograde hydration by infiltration of water-bearing fluid

kV accelerating voltage and 20 nA sample current, using data processing by an Oxide-ZAF model correction program supplied by JEOL

For fluorine analysis, pure fluorite (CaF_2) was adopted as a standard sample, using the F-Kα line reflected by a TAP crystal Although the Fe-Lα line might possibly interfere with the F-Kα line, its effect was completely eliminated As discussed below, the fluorine content of green amphiboles (*ex* sample B98012802H) is therefore nearly zero even if they have high Fe content ($Fe/(Mg+Fe)>0$ 5) The count of the F-Kα line is very low (less than 120 cps) counting the time of the peak and backgrounds are set as 300 and 150 s, respectively Accuracy of the fluorine analysis was examined by ten repeated analyses of fluorite crystal The result was 48 46±0 39 wt%, which is close to the known fluorine content of pure fluorite (48 67 wt%) The error corresponds to the standard deviation of the result Ten repeated analyses of a single spot of amphibole in sample B98020801

Table 1 Representative electron microprobe analyses of calcic amphibole in mafic granulite

	amphibole (number of oxygens = 23)									
Sample No	B98020801	B98020801	B98020802B	B98020802B	B98013101C	B98012802H	B98020706C	B98020303C	B98012802F	B98013103A
Rock type	2	2	2	2	3	3	3	4	6	6
Color	brownish				greenish				pale brownish	
	core	rim	core	rim	core	core	core	core	core	core
SiO_2	40 78	41 68	40 23	40 29	46 69	42 88	42 82	43 00	43 87	43 20
Al_2O_3	11 22	10 98	12 96	13 52	9 69	12 73	11 84	12 14	12 52	13 39
TiO_2	1 56	1 86	2 37	1 85	0 56	1 22	0 97	1 03	0 77	1 42
Cr_2O_3	0 00	0 00	0 24	0 26	0 00	0 05	0 03	0 00	0 36	0 00
FeO*	15 38	15 37	14 64	15 35	15 09	17 20	17 72	15 76	4 74	4 99
MnO	0 08	0 05	0 09	0 13	0 23	0 14	0 12	0 12	0 02	0 03
MgO	11 39	11 05	10 21	9 91	12 34	9 82	9 39	10 64	17 71	17 26
CaO	11 70	11 67	11 35	11 39	11 74	11 55	11 44	11 84	13 34	12 68
Na_2O	1 82	1 61	1 28	1 25	1 09	1 17	1 54	1 14	1 99	2 04
K_2O	2 64	2 71	3 10	3 16	0 46	1 34	1 20	1 76	1 78	2 02
F	2 05	1 93	0 47	0 40	0 00	0 01	0 03	0 12	2 58	1 73
Cl	0 26	0 26	1 44	1 45	0 01	0 00	0 10	0 23	0 02	0 01
Total	98 89	99 17	98 38	98 95	97 88	98 11	97 21	97 78	99 70	98 77
Total***	97 97	98 30	97 86	98 46	97 88	98 10	97 17	97 68	98 61	98 04
Si	6 269	6 361	6 164	6 149	6 864	6 419	6 502	6 463	6 339	6 251
Al	2 032	1 974	2 339	2 432	1 678	2 246	2 119	2 150	2 132	2 283
Ti	0 180	0 213	0 273	0 212	0 061	0 137	0 111	0 116	0 083	0 154
Cr	0 000	0 000	0 029	0 031	0 000	0 006	0 004	0 000	0 041	0 000
Fe^{2+}	1 977	1 961	1 875	1 959	1 855	2 153	2 249	1 980	0 573	0 604
Mn	0 011	0 007	0 011	0 016	0 028	0 018	0 016	0 015	0 003	0 004
Mg	2 608	2 512	2 329	2 253	2 703	2 189	2 124	2 382	3 812	3 720
Ca	1 927	1 907	1 863	1 862	1 848	1 853	1 860	1 906	2 064	1 965
Na	0 542	0 477	0 381	0 369	0 309	0 339	0 452	0 331	0 557	0 573
K	0 517	0 528	0 605	0 615	0 086	0 257	0 232	0 337	0 327	0 373
Total	16 064	15 941	15 871	15 899	15 433	15 616	15 669	15 680	15 933	15 927
F	0 997	0 930	0 228	0 195	0 000	0 005	0 012	0 058	1 180	0 789
Cl	0 034	0 033	0 187	0 187	0 002	0 000	0 027	0 030	0 004	0 001
Mg/(Fe+Mg)	0 569	0 562	0 554	0 535	0 593	0 504	0 486	0 546	0 869	0 860
F/(F+Cl+OH)**	0 499	0 465	0 114	0 097	0 000	0 003	0 006	0 029	0 590	0 395
Cl/(F+Cl+OH)**	0 017	0 017	0 094	0 094	0 001	0 000	0 014	0 015	0 002	0 001

*Total Fe as FeO, **Calculated for stoichiometry of amphibole, ***Total correlated for F and Cl showed its fluorine content to be 1.97±0.09 wt%.

For chlorine analysis, a granular aggregate of halite crystals (NaCl) was adopted as a standard sample, using the Cl-Kα line reflected by a PET crystal. There is no significant interference with the Cl-Kα line. Ten repeated analyses of a single spot of amphibole in sample B98020802B show its chlorine content to be 1.42±0.03 wt%. Analytical totals were corrected for F and Cl in the way that the wt% of oxygen corresponding to the wt% of F and Cl was subtracted from the analytical total.

Calcic amphiboles in about 20 samples of amphibole-bearing mafic granulite from Tonagh Island were analyzed. Localities of representative samples in this study are shown in Fig. 1. Compositions of calcic amphibole in the samples are listed in Table 1.

3.2. *Mineral assemblages of mafic granulite*

Mafic granulites of Tonagh Island were subdivided into five rock types (types 1 to 5) on the basis of mineral assemblages. Type 6 is a sample of ultramafic granulite (metapyroxenite). Although there are some other types of ultramafic granulite on Tonagh Island, they are not discussed in this paper because they lack amphibole. Mineral abbreviations are after Kretz (1983). Minerals in italics are secondary phases.

Type 1 Pl+Opx+Cpx+Qtz (±Ilm, Bt)
Type 2 Pl+Opx+Cpx+Qtz+brownish Amp (±Ilm, Bt)
Type 3 Pl+Opx+Cpx+Qtz+*greenish Amp* (±Ilm, *Bt*)
Type 4 Pl+Opx+Cpx+Qtz+*greenish Amp*+*Grt* (±Ilm, *Bt*)
Type 5 Pl+Opx+Cpx+Qtz+*Grt* (±Ilm, Bt)
Type 6 Opx+Cpx+Amp (±Ilm, Pl, Bt)

Type 1 is an anhydrous mineral assemblage and is common in all units on Tonagh Island. Type 2 contains brownish amphibole with high fluorine as discussed below. They are present in Units I and IV. Type 3 is characterized by retrograde amphibole-quartz symplectite around ortho- and clinopyroxenes. Types 4 and 5 contain retrograde garnet around ortho- and clinopyroxenes, but Type 5 contains no retrograde amphibole. Types 3 and 4 are present in Units II, III, and IV, whereas type 5 is present in Units I and V. Type 6 is a metapyroxenite and is composed of granoblastic orthopyroxene, clinopyroxene and minor amphibole.

Calcic amphiboles discussed in this study are subdivided into two types: high-grade brownish to pale brownish amphibole and retrograde greenish amphibole. Brownish to pale brownish amphibole is present in granulites of types 2 and 6, whereas greenish amphibole is present in those of types 3 and 4. High-grade amphibole is present as a subhedral mineral and its grain size is the same as those of coexisting ortho- and clinopyroxenes. Retrograde amphibole is fine-grained and is present around pyroxenes as a secondary phase.

Although some samples were collected close to shear zones, there are few hydrated samples except sample B98020706C. Infiltration of retrograde H_2O-rich fluid which formed greenish amphibole is therefore regarded as a local event and not associated with a shear zone.

3.3. *Brownish amphibole*

Brownish amphibole is coarse-grained (up to 0.4 mm in sample B98020801) and subhedral Sample B98020801 comes from a body of mafic granulite more than 5 m in thickness within orthopyroxene-bearing quartzofeldspathic gneiss It contains orthopyroxene, clinopyroxene, plagioclase, ilmenite, biotite, and apatite as well as brownish amphibole (Fig 2a). The amphibole is compositionally pargasite (Leake *et al*, 1997) and characterized by high Na+K content at the A-site, up to 1 00 (based on 23 oxygens) The Ti content of the amphibole is high, ~0 20 pfu It contains up to 2 2 wt% fluorine, which corresponds to F/(F+Cl+OH) ratio of 0 54

Sample B98020802B is from a layer of mafic granulite 50–60 cm in thickness in orthopyroxene-bearing quartzofeldspathic gneiss Although it shows a similar mineral assemblage to that of sample B98020801, brownish amphibole in this sample is rimmed by fine-grained aggregates of orthopyroxene, quartz, and plagioclase (Fig 2b) The composition of the product plagioclase (An77–79) is slightly more An-rich compared with that of matrix plagioclase (An57–61) The product fine-grained orthopyroxene has higher Al_2O_3 content (1 7 to 1 8 wt%) than the matrix (1 0 to 1 4 wt%) The texture suggests formation by a devolatilization reaction (1) of brownish amphibole

$$\mathrm{Amp+Pl\ (An57\text{–}61)=Opx+Qtz+Pl\ (An77\text{–}79)+V} \qquad (1)$$

Composition of the brownish amphibole in the sample is similar to that of sample B98020801 except for its titanium, fluorine, and chlorine contents It has the highest Ti content up to 0 28 at the core of the mineral, whereas it decreases toward the rim (Table 1) It has a lower fluorine content (0 21–0 52 wt%, F/(F+Cl+OH)=0 04–0 13) than that of sample B98020801, but has higher chlorine content of 1.2 to 1 5 wt% (Cl/(F+Cl+OH)=0 16–0 20)

Type 6 ultramafic granulite of sample B98012802F shows granoblastic texture of orthopyroxene and minor clinopyroxene and ilmenite. It contains a small amount of pale brownish amphibole along grain boundaries of pyroxenes (Fig 2c) The amphibole has a high Mg/(Fe+Mg) ratio (up to 0 88) probably due to a high-Mg bulk-rock chemistry It shows the highest fluorine content up to 2 6 wt% which corresponds to F/(F+Cl+OH) ratio of 0 60 Chlorine content in the amphibole is very low

Sample B98013103A is also a sample of type 6 It contains orthopyroxene, clinopyroxene, ilmenite, and pale brownish amphibole As shown in Fig 3, the amphibole is slightly rich in Ti and poor in Si compared with that in sample B98012802F Fluorine content of the amphibole varies from 1 8 to 2 0 wt% which corresponds to a F/(F+Cl+OH) ratio of 0 38–0 46 Chlorine content in the amphibole is also very low

3.4. Greenish amphibole

This type of amphibole occurs as a secondary phase in type 4 and 5 mafic granulite Sample B98012802H is composed of plagioclase, orthopyroxene, clinopyroxene, quartz, ilmenite, biotite, and greenish amphibole The amphibole is present as fine-grained aggregates with quartz, rimming ortho- and clinopyroxenes (Fig 2d) In Fe-rich samples (*e.g* sample B98020303C), retrograde garnet also occurs with the amphibole and quartz The textures suggest retrograde infiltration of fluid and crystallization of greenish amphiboles by reactions (2) to (5)

$$\mathrm{Cpx+Pl+H_2O\rightarrow Amp+Qtz,} \qquad (2)$$

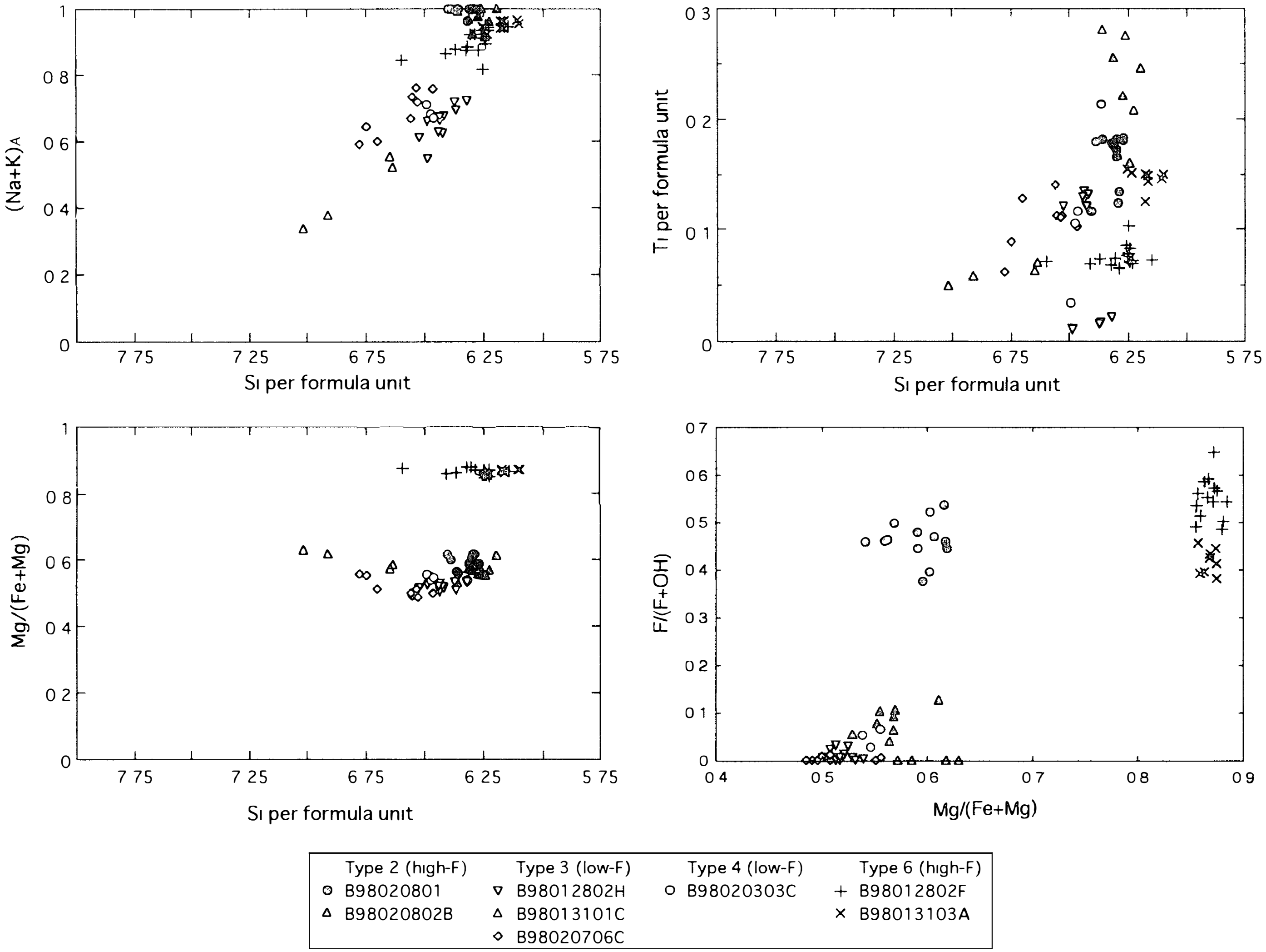

Fig 3 *Compositional diagrams showing variety in composition of calcic amphiboles in mafic granulites of Tonagh Island*

$$\mathrm{Opx+Pl+H_2O \rightarrow Amp+Qtz,} \qquad (3)$$

$$\mathrm{Cpx+Pl+H_2O \rightarrow Grt+Amp+Qtz,} \qquad (4)$$

$$\mathrm{Opx+Pl+H_2O \rightarrow Amp+Grt+Cpx+Qtz} \qquad (5)$$

As shown in Fig 3, greenish amphiboles are classified as pargasite or hornblende They are characterized by low-Na+K in the A-site and low Ti compared with brownish amphiboles Generally the fluorine contents of greenish amphiboles formed by reactions (2) and (3) are low (less than 0 01 wt%, samples B98013101C, B98012802H, and B98020706C) Greenish amphibole formed by reactions (4) and (5) has a slightly higher fluorine content of 0 10–0 38 wt% (sample B98020303C) This is, however, still lower than that of brownish amphiboles The F/(F+Cl+OH) ratio of the two types of greenish amphibole are <0 01 and 0 03–0 09, respectively Their chlorine contents are very low (<0 1 wt%) except for sample B98020303C (0 23–0 31 wt%)

4. Discussion

As shown in Table 1, brownish amphiboles have higher fluorine content than greenish amphiboles The low fluorine content of the latter and their occurrence as secondary phases indicate that some H_2O-bearing fluid was introduced during retrograde metamorphism Chlorine content of the amphibole is very low except for sample B98020802B in which a devolatilization reaction (1) occurred

Brownish amphiboles have a wide range in fluorine contents· 0.21 wt% (sample B98020802B) to 2 62 wt% (sample B98012802F) The cause of this variation is not known, but it is probably related to bulk rock chemistry We therefore analyzed apatite coexisting with calcic amphibole, because it is the only mineral with a higher fluorine content than amphibole As shown in Table 2, the fluorine content of apatite increases with increasing fluorine content in calcic amphibole in the same sample Owada *et al* (1999) pointed

Table 2 Representative electron microprobe analyses of apatite coexisting with calcic amphibole

	Apatite (number of oxygens = 12 5)			
Sample No	B98020801	B98020802B	B98020303C	B98020706C
Rock type	2	2	4	3
CaO	53 37	53 83	54 13	54 10
P_2O_5	41 72	41 80	42 72	42 11
F	6 90	6 01	5 97	3 78
Cl	0 05	0 74	0 12	1 01
Total	102 03	102 37	102 94	101 00
Total*	99 12	99 68	100 40	99 18
Ca	4 913	4 933	4 885	4 926
P	3 035	3 027	3 046	3 030
Total	7 948	7 960	7 931	7 956
F	1 875	1 625	1 589	1 017
Cl	0 007	0 107	0 017	0 145

*Total correlated for F and Cl

out, on the basis of euhedral crystal shape of apatite and its occurrence as inclusions in magmatic olivine in ultramafic granulite, that at least some apatites are igneous in origin Higher fluorine content in apatite and calcic amphibole in sample B98020801 than those in sample B980020706C indicates that the fluorine content is controlled by bulk rock chemistry The fluorine may therefore be derived from Archean basic magma at the stage of protolith formation This implies a variation of fluorine content in the magma However, further studies on fluorine contents in amphiboles and bulk rock are needed to fully understand the origin of fluorine

Holloway and Ford (1975) experimentally investigated the stability of a pargasite of intermediate F/(F+Cl+OH) content ($NaCa_2Mg_4Al^{VI}Si_6Al_2{}^{IV}O_{22}[(OH)_{0\,57}F_{0\,43}]_2$) Although their experiment should not be applied directly to a natural system, the results indicate that the fluorine-bearing pargasite is stable up to 1100°C at 5 kbar, and that the F/(F+Cl+OH) of amphibole increases with increasing temperature The fluorine-rich calcic amphibole discussed in this study can therefore be regarded as a stable mineral during UHT metamorphic conditions A devolatilization reaction of brownish amphibole in sample B980020802B (Fig 2b) occurred under UHT metamorphic conditions because of its lower fluorine content (F/(F+Cl+OH)<0 13) compared with the other brownish amphiboles (F/(F+Cl+OH)=0 36-0 60) Investigation of reaction textures and fluorine contents of amphibole is therefore useful to appraise the peak metamorphic temperature of UHT metamorphic complexes

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References

Damman, A H (1989) Hydrothermal orthoamphibole-bearing assemblages from the Gasborn area, West Bergslagen, central Sweden Am Mineral, **74**, 573-585

Droll, K (1983) Fluorine incorporation in amphiboles implications for the behavior of fluorine in contact metamorphosis Fortsch Mineral, **61**, 1

Ellis, D J (1980) Osumilite-sapphirine-quartz granulites from Enderby Land, Antarctica P-T conditions of metamorphism, implications for garnet-cordierite equilibria and the evolution of the deep crust Contrib Mineral Petrol, **74**, 201-210

Ellis, D J and Green, D H (1985) Garnet-forming reactions in mafic granulites from Enderby Land, Antarctica-implications for geothermometry and geobarometry J Petrol, **26**, 633-662

Harley, S L (1985) Garnet-orthopyroxene bearing granulites from Enderby Land, Antarctica metamorphic pressure-temperature-time evolution of the Archean Napier Complex J Petrol, **26**, 819-856

Harley, S L (1987) A pyroxene-bearing meta-ironstone and other pyroxene-granulites from Tonagh Island, Enderby Land, Antarctica further evidence for very high temperature (>980°C) Archaean regional metamorphism in the Napier Complex J Metamorph Geol, **5**, 341-356

Harley, S L and Hensen, B J (1990) Archaean and Proterozoic high-grade terranes of East Antarctica (40-80°) a case study of diversity in granulite facies metamorphism High-temperature

Metamorphism and Crustal Anatexis, ed by J R Ashworth and M Brown London, Unwin Hyman, 320-370

Hensen, B J and Osanai, Y (1994) Experimental study of dehydration melting of F-bearing biotite in model pelitic compositions Mineral Mag, **58A**, 410-411

Hokada, T, Ishikawa, M, Ishizuka, H, Osanai, Y and Suzuki, S (1999) Alkali feldspar compositions of the Archean Napier Complex, East Antarctica Further evidence for 1100°C ultrahigh-temperature crustal metamorphism Abstr 8th Int Symp Antarct Earth Sci, Wellington, 144

Holloway, J G and Ford, C E (1975) Fluid absent melting of the fluorohydroxy-amphibole pargasite to 35 kilobars Earth Planet Sci Lett, **25**, 44-48

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

Leake, B E, Woolley, A R, Arps, C E S, Birch, W D, Gilbert, M C, Grice, J D, Hawthorne, F C, Kato, A, Kisch, H J, Krivovichev, V G, Linthout, K, Laird, J, Mandarino, J A, Maresch, W V, Nickel, E H, Rock, N M S, Schumacher, J C, Smith, D C, Stephenson, N C N, Ungaretti, L, Whittaker, E J W and Youzhi, G (1997) Nomenclature of amphiboles Report of the subcommittee on amphiboles of the International Mineralogical Association, commission on new minerals and mineral names Am Mineral, **82**, 1019-1037

Motoyoshi, Y (1998) Ultra-high temperature metamorphism of the Napier Complex, East Antarctica a metamorphic perspective J Geol Soc Jpn, **104**, 794-807 (in Japanese with English abstract)

Osanai, Y, Toyoshima, T, Owada, M, Tsunogae, T, Hokada, T and Crowe, W A (1999) Archean geology of Tonagh Island in the Napier Complex, Enderby Land, East Antarctica Polar Geosci, **12**, 1-28

Owada, M, Osanai, Y and Kagami, H (1994) Isotopic equilibration age of Sm-Nd whole rock system in the Napier Complex (Tonagh Island), East Antarctica Proc NIPR Symp Antarct Geosci, **7**, 122-132

Owada, M, Osanai, Y, Toyoshima, T, Tsunogae, T, Hokada, T and Crowe, W A (1999) Petrography and geochemistry for mafic and ultramafic rocks from Tonagh Island in the Napier Complex, East Antarctica A preliminary report Polar Geosci, **12**, 87-100

Peterson, J W, Chacko, T and Kuehner, S M (1991) The effects of fluorine on the vapor-absent melting of phlogopite+quartz implications for deep crustal processes Am Mineral, **76**, 470-476

Sandiford, M and Powell, R (1986) Pyroxene exsolution in granulites from Fyfe Hills, Enderby Land, Antarctica Evidence for 1000°C metamorphic temperatures in Archean continental crust Am Mineral, **71** 946-954

Sheraton, J W, Tingey, R J, Black, L P, Offe, L A and Ellis, D J (1987) Geology of an unusual Precambrian high-grade metamorphic terrane-Enderby Land and western Kemp Land, Antarctica BMR Bull, **223**, 51 p

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

Toyoshima, T, Osanai, Y, Owada, M, Tsunogae, T, Hokada, T and Crowe,W A (1999) Deformation of ultrahigh-temperature metamorphic rocks from Tonagh Island in the Napier Complex, East Antarctica Polar Geosci, **12**, 29-48

Tsunogae, T, Osanai, Y, Toyoshima, T, Owada, M, Hokada, T and Crowe, W A (1999) Metamorphic reactions and preliminary *P-T* estimates of ultrahigh-temperature mafic granulite from Tonagh Island in the Napier Complex, East Antarctica Polar Geosci, **12**, 71-86

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