

Carbonic fluid inclusions in ultrahigh-temperature metamorphic rocks from Tonagh Island in the Archean Napier Complex, East Antarctica: A preliminary report

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Abstract: We report here the occurrence of high density CO₂-rich fluid inclusions in ultrahigh-temperature metamorphic rocks from Tonagh Island of the Archean Napier Complex, East Antarctica. A study on the different lithological units from Tonagh Island (garnet gneiss, sapphirine granulite, garnet-orthopyroxene gneiss, and magnetite-quartz gneiss) shows the common presence of carbonic fluid inclusions entrapped within various minerals. The melting temperatures of fluids in the first three rock types lie in the range of –56.3 to –57.2°C, close to the triple point for pure CO₂ (–56.6°C). Fluid inclusions in magnetite-quartz gneiss show slight depression in their melting temperatures (–56.7~–57.8°C) suggesting traces of additional fluid species such as CH₄ and/or N₂ in the dominantly CO₂-rich fluid. Homogenization of pure CO₂ inclusions in the garnet gneiss, sapphirine granulite, and garnet-orthopyroxene gneiss occurs into the liquid phase at temperatures in the range of –34.9~+4.2°C. This translates into high CO₂ densities in the range of 0.9–1.1 g·cm^{–3}. The estimated CO₂ isochore intersects the counterclockwise P-T trajectory of Tonagh Island at around 6–9 kbar at 1100°C, which corresponds to the peak metamorphic conditions of Tonagh Island derived from mineral phase equilibria. We therefore infer that CO₂ was the dominant fluid species present during the ultrahigh-temperature metamorphism in Tonagh Island. The stability of anhydrous minerals such as orthopyroxene in the study area might have been effected by the lowering of H₂O-activity due to the presence of CO₂ at peak metamorphic conditions (>1100°C).

key words: carbonic fluid inclusion, ultrahigh-temperature granulite, Tonagh Island, Archean Napier Complex, East Antarctica

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1. Introduction

The Napier Complex of Enderby Land, East Antarctica, is a late-Archean high-grade terrane which has undergone granulite-facies metamorphism at temperatures higher than 1000°C (*e.g.* Ellis, 1980; Harley, 1985; Sheraton *et al.*, 1987; Hokada *et al.*, 1999a; Yoshimura *et al.*, 2000). The Amundsen Bay area, located in the western part of the Napier Complex, is the highest grade region of the Complex from where sapphirine-quartz and osumilite-bearing mineral assemblages have been reported (Dallwitz, 1968; Ellis, 1980; Ellis *et al.*, 1980; Grew, 1980, 1982; Motoyoshi and Matsueda, 1984; Sheraton *et al.*, 1987; Motoyoshi and Hensen, 1989; Harley and Hensen, 1990; Hokada, 1999; Osanai *et al.*, 2000). The presence of orthopyroxene-sillimanite-garnet-quartz assemblage in pelitic gneiss (Sheraton *et al.*, 1987; Ishizuka *et al.*, 1998; Osanai *et al.*, 1999a; Hokada *et al.*, 1999b) and inverted pigeonite in meta-ironstone and mafic to intermediate granulites (Sandiford and Powell, 1986; Harley, 1987) in this area provide additional evidence for ultrahigh-temperature (UHT) metamorphism (Harley, 1998).

Stabilization of dry granulite assemblages, typically the index mineral orthopyroxene, requires the H₂O-activity to be low during granulite-facies metamorphism, since most of the crustal components such as pelitic, psammitic, and granitic rocks will be subjected to hydrous melting at high H₂O-activities during high-grade metamorphism. Several models have been proposed in the past to explain the generation of anhydrous conditions in the continental deep crust. These models include: (1) partial melting and removal of a granitic magma leaving an anhydrous granulite residue; (2) vapor-absent metamorphism of lithologies pre-baked by igneous intrusions; (3) dehydration melting and melt segregation producing dry assemblages; and (4) influx of CO₂ from external sources and dilution of pore fluid resulting in the stabilization of anhydrous minerals (*e.g.* Newton *et al.*, 1980; Newton, 1992; Lamb and Valley, 1984; Waters and Whales, 1984; Santosh, 1992; Santosh *et al.*, 1991). Structurally controlled release of fluid pressure has also been proposed as a mechanism to trigger dehydration (Miyano *et al.*, 1990).

Examination of the presence or absence of metamorphic fluid and its composition associated with granulite-facies metamorphism therefore gives us valuable information on the evolution process of the lower crust. Several reports in the past have attempted to postulate the metamorphic fluid composition of high-grade rocks in the Napier Complex. Grew (1980) suggested low H₂O-activity for the Napier Complex from the experimental deduction of Newton (1972) of nearly anhydrous conditions required for the formation of sapphirine+quartz assemblage and its reaction to form sillimanite+orthopyroxene assemblage. Sheraton *et al.* (1987) obtained $P_{\text{H}_2\text{O}} < 0.5$ for the peak metamorphism of calcic mesoperthite (Or₃₂Ab₅₀An₁₈) in quartzo-feldspathic gneiss from Spot Height 945. Their estimate is based on Morse's (1968) experimental data on alkali feldspar solvus. Grew (1982) also presented a fluid composition of $P_{\text{H}_2\text{O}} \ll P_{\text{Total}}$, based on the presence of osumilite. All these studies unequivocally suggest that low H₂O-activities prevailed during the ultrahigh-temperature metamorphism. However, no direct evidence has been presented as yet for the fluids involved in the high-grade metamorphism of the Napier Complex.

Fluid inclusions in high-grade metamorphic rocks provide potential tools in obtaining direct information on the nature, composition, and density of fluids attending

metamorphism, which, in conjunction with mineral phase equilibria, have been widely used to infer *P-T-X* conditions and exhumation paths (e.g. Touret, 1985; Touret and Hansteen, 1988; Santosh *et al.*, 1991). Notwithstanding the debate over the timing of entrapment of carbonic inclusions during granulite facies metamorphism (e.g. Lamb *et al.*, 1987; Santosh *et al.*, 1991), CO₂-rich fluids have been demonstrated to be instrumental in effecting low H₂O-activities to stabilize the anhydrous mineral assemblages characterizing many deep continental fragments (e.g. Santosh, 1992). We therefore attempted a detailed fluid inclusion study on the ultrahigh-temperature metamorphic assemblages from Tonagh Island. Although Sheraton *et al.* (1987) made brief mention of the presence of CO₂-bearing fluid inclusions in sapphirine-bearing pelitic gneiss from Spot Height 945 in a personal communication with H. Etminan (1985), so far there has been no published report on systematic petrographic and microthermometric studies of fluid inclusions in the Napier rocks. This paper therefore is the first preliminary report which presents the petrography and microthermometric data of fluid inclusions in quartz, garnet, and orthopyroxene in various granulite facies lithologies from Tonagh Island of Amundsen Bay in the Napier Complex. The results are particularly important in the light of evaluating the nature and role of fluids involved in ultrahigh-temperature metamorphism of the Archean deep continental crust.

2. Geology of Tonagh Island

Detailed regional geological framework and structural characteristics of Tonagh Island are given in Osanai *et al.* (1999a). The area is composed dominantly of layered gneisses of varying bulk chemical composition. Orthopyroxene-bearing quartzofeldspathic gneiss is the most abundant lithology. It is commonly interlayered with mafic granulite and garnet-bearing felsic gneiss. Magnetite-quartz and garnet-orthopyroxene gneisses are minor constituents of the layered gneisses. Ultramafic granulite is present as thin layers or lenses in quartzofeldspathic and mafic granulites. Peak metamorphic conditions of Tonagh Island were determined to be >1100°C on the basis of ternary-feldspar equilibrium (Hokada *et al.*, 1999a) and phase equilibria on sapphirine granulites (Osanai *et al.*, 1999b).

Several isotopic age determinations have been reported from the high-grade 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 SHRIMP zircon U-Pb dating (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). Younger magmatism in the area is represented by a dolerite dyke (*ca.* 1200 Ma Amundsen Dyke; Sheraton *et al.*, 1987) and a lamproite dyke (466 and 476 Ma; Miyamoto *et al.*, 2000) which cut across the gneissic fabric.

The high-grade rocks from Tonagh Island are subdivided into five tectonic units (Units I to V) by high-angle and ENE-WSW to E-W trending shear zones (Osanai *et al.*, 1999a; Toyoshima *et al.*, 1999). Approximate positions of the shear zones are shown in

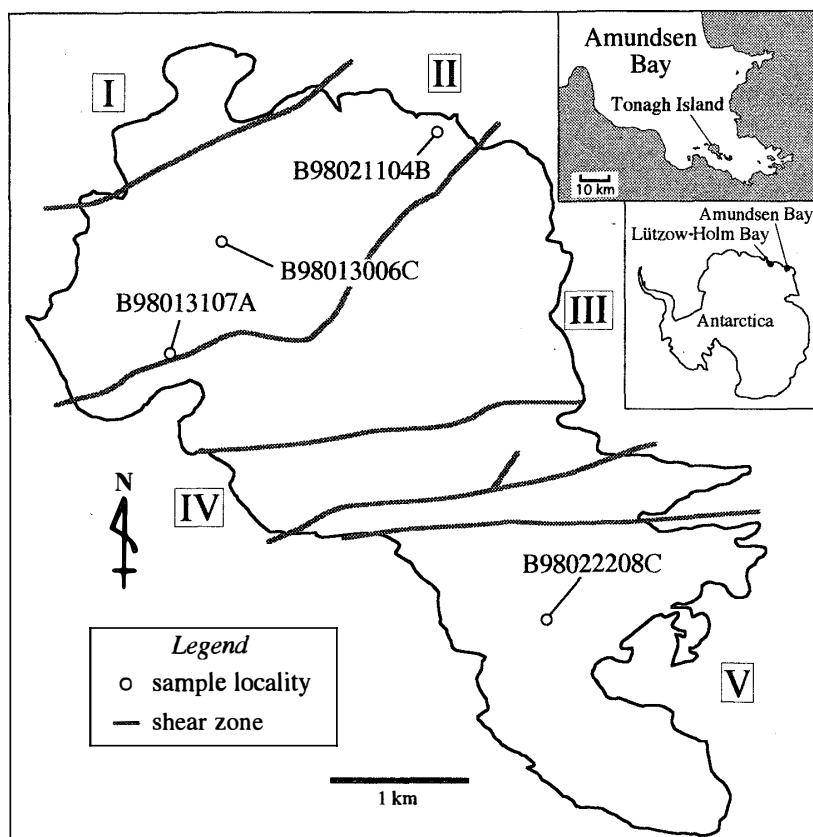


Fig. 1. Map of Tonagh Island showing localities of quartz-bearing gneisses studied in this paper. I to V denote tectonic units separated by shear zones after Osanai *et al.* (1999a) and Toyoshima *et al.* (1999).

Fig. 1. Unit I corresponds to the northwestern portion of the island. The layered gneisses vary in thickness from a few 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 quartzo-feldspathic gneisses.

3. Fluid inclusion studies

Fluid inclusions were studied in doubly polished thin wafers of representative rock samples from the different lithologic units. Preparation of doubly polished rock wafers followed the method described in Hisada *et al.* (1994). The thickness of the wafers is between 120 and 150 μm as measured by a micrometer. The nature of occurrence of inclusions, their distribution pattern, shape, size and phase categories were carefully studied and documented under a petrological microscope at varying magnifications.

In general, fluid inclusions were observed to be present in different minerals in almost all the high-grade rocks from Tonagh Island, although their size, relative abundance, and distribution pattern vary among the different rocks. In this study, we report the observations in four representative samples of quartz-bearing gneisses; garnet gneiss, sapphirine-bearing garnet gneiss, garnet-orthopyroxene gneiss, and magnetite-quartz gneiss. The sample localities are shown in Fig. 1; their mineral assemblages and

inclusion petrography are briefly summarized below.

Fluid inclusions examined in this study are subdivided into three types: primary, secondary, and pseudosecondary types as classified by Roedder (1984). Primary inclusions are generally trapped during the growth of the mineral. The inclusions therefore commonly occur along crystal-growth surfaces. Secondary inclusions are those that formed after the crystallization of a mineral. Thus, if the mineral is fractured in the presence of a fluid, it will enter the fracture and start to dissolve and recrystallize the host mineral. Pseudosecondary inclusions probably formed between the two trapping stages. If a crystal fractures during its growth, the adjacent fluid will enter the fracture and become trapped. Although such inclusions look secondary, they are trapped during the growth of the host mineral. In this study we identified all three types of inclusions. However, secondary inclusions are not discussed in this paper because they are too small to analyze.

3.1. Garnet gneiss (sample B98013107A)

Garnet gneiss is one of the major lithologic units in Tonagh Island and occurs mainly in Unit V. It is commonly interlayered with orthopyroxene-bearing felsic gneiss and mafic granulite. The analyzed sample, collected from Unit II, has a mineral assemblage of garnet, quartz, mesoperthite, and K-feldspar. Garnet in the sample shows poikiloblastic texture (up to 3.6 mm) and is free from inclusions. Matrix quartz is 0.2–0.5 mm in length; some are elongated along foliation (up to 3.8 mm). Mesoperthite (0.3–2.2 mm) is composed of about 40% plagioclase and 60% K-feldspar. K-feldspar is closely associated with mesoperthite, but its modal abundance is very low (less than 5%).

Fluid inclusions are present both in quartz and mesoperthite. Those in mesoperthite are too small (<2 microns) to analyze. Fluid inclusions in quartz have ovoidal or diamond-shaped cavities ranging in size from 3–15 microns. They form either random clusters or planar arrays which pinch out within individual grains (Fig. 2a). The planar arrays correspond to the pseudosecondary type. In the case of CO₂ inclusions, the array-bound nature need not necessarily indicate a pseudosecondary or secondary nature. Primary CO₂-rich inclusions occurring along intergrain trails are known from several high-grade terrains (*cf.* Santosh, 1992). This is due to the wetting properties of CO₂, wherein carbonic fluids propagate by microfracturing and do not form an interconnected grain boundary fluid like H₂O (Watson and Brenan, 1987).

3.2. Sapphirine-bearing garnet gneiss (sample B98021104B)

The sapphirine-bearing garnet gneiss occurs as thin (less than 1 cm) bluish bands in pinkish garnet-rich layers within leucocratic garnet gneiss. The layers are parallel to the regional foliation. The sample, collected from Unit II, has a mineral assemblage of sapphirine, quartz, sillimanite, cordierite, orthopyroxene, garnet, and K-feldspar. The coexistence of sapphirine and quartz is considered to be an indicator of ultrahigh-temperature metamorphism (Hensen and Green, 1973; Ellis *et al.*, 1980). The contact between the two minerals is defined by thin films of reaction zone composed of fine-grained garnet+sillimanite+cordierite. The texture, which has also been reported from another locality of Tonagh Island (Osanai *et al.*, 2001), suggests an isobaric cooling history following the ultrahigh-temperature metamorphic event (Hensen and Harley,

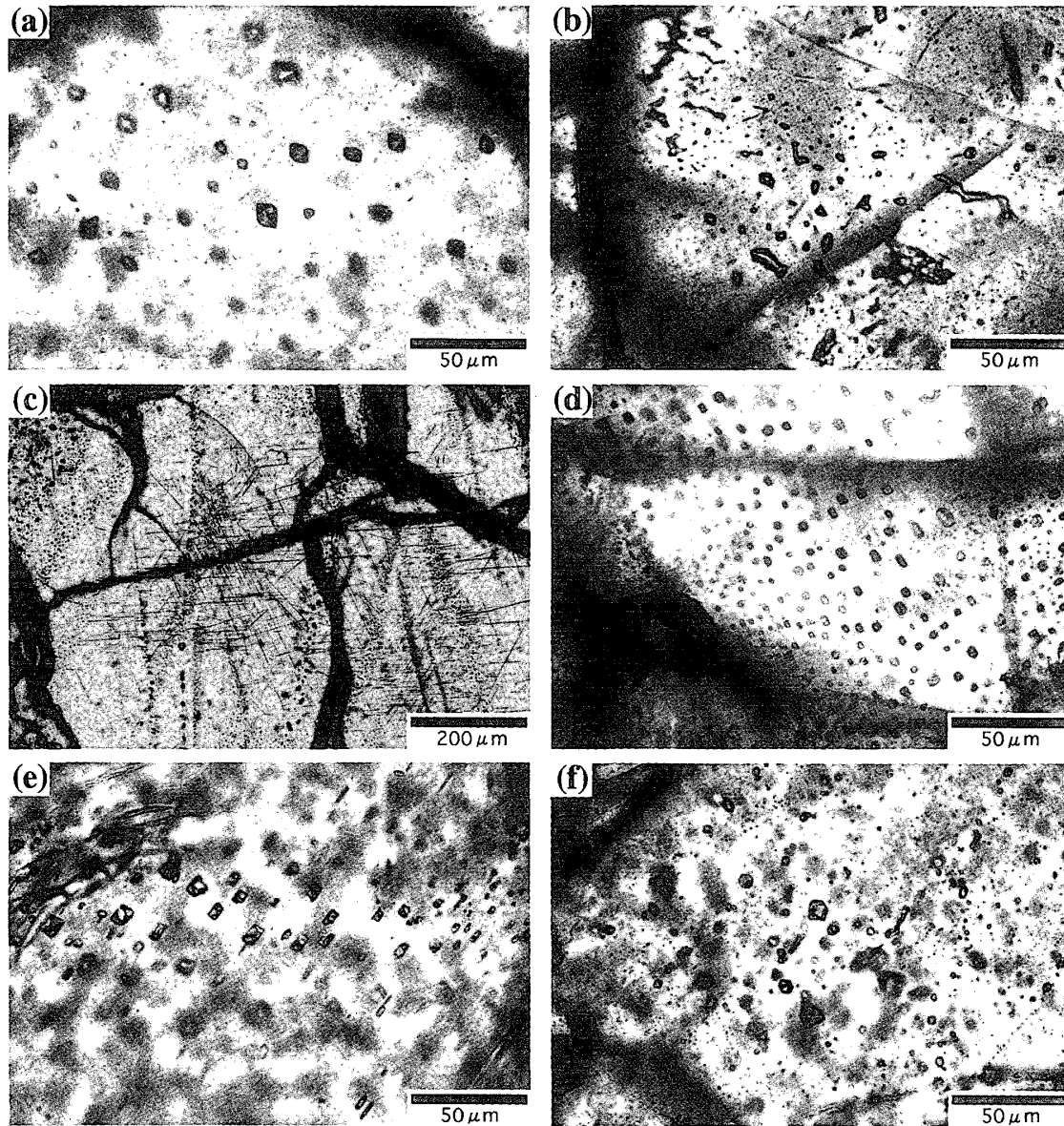


Fig. 2. Photomicrographs of fluid inclusions in Tonagh Island granulites.

(a) Scattered “primary” fluid inclusions in quartz from garnet gneiss (sample B98013107A). Note the regular “diamond” shaped negative crystal cavities. (b) CO₂ inclusions with ovoidal and elongate cavities in quartz from sapphirine-granulite (sample B98021104B). The quartz coexists with sapphirine and represents a typical ultrahigh-temperature metamorphic assemblage. (c) Trails of pseudosecondary carbonic inclusions along healed microfractures in garnet of garnet-orthopyroxene gneiss (sample B98022208C). Fibrous rutiles are also present in the garnet. (d) Garnet from garnet-orthopyroxene gneiss showing abundant CO₂ inclusions (sample B98022208C). (e) Rectangular inclusion cavities in orthopyroxene of garnet-orthopyroxene gneiss (sample B98022208C). Most of the cavities have already lost their initial fluid through cleavage traces and are now filled with secondary minerals. (f) Cluster of fluid inclusions in quartz from magnetite-quartz gneiss (sample B98013006B).

1990).

Fluid inclusions are commonly present in quartz grains. They occur as isolated clusters and have irregular shapes (Fig. 2b). The inclusion size usually ranges from 2 to 8 microns, and exceeds 20 microns occasionally. As shown Fig. 2b, an initial long tubular inclusion has apparently broken up to form two separate inclusions. The process is generally termed “necking down” (Roedder, 1984). Such inclusions may have changed their original composition and density. In this study those with necking down texture were not analyzed.

3.3. Garnet-orthopyroxene gneiss (sample B98022208C)

The garnet-orthopyroxene gneiss is present as a melanocratic layer several tens of cm thick in leucocratic garnet gneiss. It has a mineral assemblage of garnet, orthopyroxene, quartz, and magnetite. The foliation of the gneiss is defined by oriented quartz and orthopyroxene. Both garnet and orthopyroxene are present as porphyroblasts with grain sizes of ~10 mm and ~2.5 mm, respectively. The porphyroblasts are surrounded by fine-grained (less than 0.3 mm) aggregates of quartz, garnet, and orthopyroxene.

The coarse-grained garnet, orthopyroxene, and matrix quartz contain numerous fluid inclusions. Those in garnet occur as trails and are apparently pseudosecondary (Fig. 2c). However, several isolated clusters composed of 30 to 50 inclusions also occur in garnet (Fig. 2d). The inclusions are 2–6 microns in size and have broadly regular diamond-shaped cavities. Most of the inclusions in orthopyroxene are now empty cavities, sometimes containing opaque minerals (Fig. 2e). The fluids in these cavities appear to have leaked out, and are now filled with secondary minerals. Some inclusions carry entrapped fluids. Fluid inclusions in quartz are relatively small in size (generally less than 4 microns), have an ovoidal shape, and are generally distributed along within-grain trails.

3.4. Magnetite-quartz gneiss (sample B98013006B)

The gneiss occurs as a layer of approximately 30 cm to 2–3 m in thickness. It is occasionally present adjacent to two-pyroxene mafic granulite. The close association with metavolcanic rock and presence of banded magnetite-rich and quartz-rich layers indicate that the protolith of the gneiss corresponds to banded iron-formation. The sample is composed of fine-grained (0.05–0.3 mm) magnetite, quartz, and orthopyroxene. Coarse-grained orthopyroxene (~2.5 mm) is also present occasionally. The orthopyroxenes contain lamella of clinopyroxene as inverted pigeonite, although lamella-free orthopyroxene is also present. Garnet and K-feldspar are minor phases and are seen to coexist.

Fluid inclusions are present in aggregates of quartz and porphyroblastic orthopyroxene. Those in quartz usually occur as local clusters and show diamond-shaped negative crystal cavities (Fig. 2f). The inclusion size varies from 2 to 10 microns. On the other hand, fluid inclusions in lamella-free orthopyroxene are rectangular parallelepiped in shape and are much smaller in size (less than 4 microns). Although most fluid has already leaked along cleavage traces of orthopyroxene, some inclusions preserve the entrapped fluid.

4. Microthermometry

4.1. Analytical procedure

Microthermometric measurements were performed with the U.S.G.S. heating/freezing stage (Werre *et al.*, 1979) at the University of Tsukuba. Calibration of thermocouple was undertaken with synthetic standard materials supplied by Fluid Inc., Denver. Heating rates of the samples are 0.05°C/s for melting and 0.1°C/s for homogenization temperature analyses. We also tried to analyze at a slower heating rate such as 0.5°C/min , but there was no difference in analytical results. The precision of microthermometric results reported in this study is within $\pm 0.1^{\circ}\text{C}$ following calibrations performed at 0°C (triple point of H_2O), -56.6°C (triple point of CO_2), and the critical point of pure H_2O with density of $0.317\text{ g}\cdot\text{cm}^{-3}$ (374.1°C).

4.2. Results

The microthermometric results of fluid inclusions in quartz, garnet, and orthopyroxene from ultrahigh-temperature granulites of Tonagh Island are presented in histograms (Figs. 3 and 4). The results are summarized in Table 1.

The dominant category of inclusions in all the lithotypes is monophasic at room temperature, filled with a dense fluid phase. On supercooling, they freeze into a solid

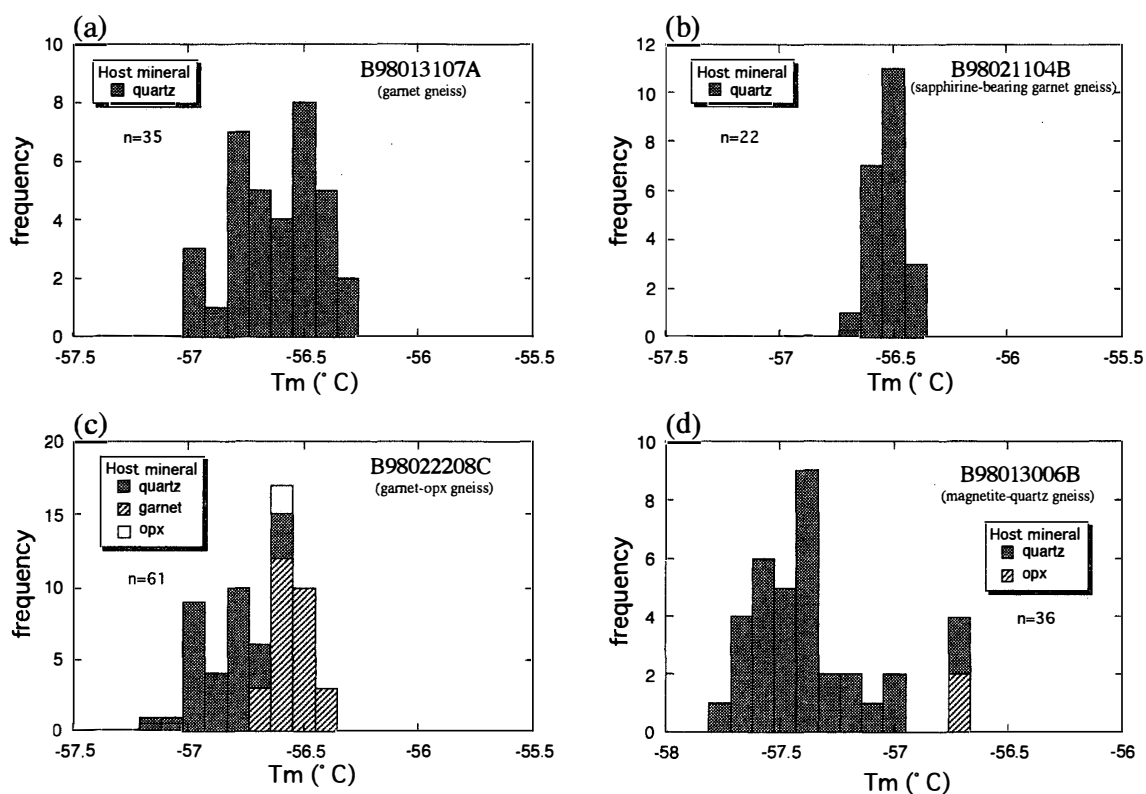


Fig. 3. Histograms showing the distribution of melting temperature (T_m) of fluid inclusions in quartz, garnet, and orthopyroxene from granulites of Tonagh Island. (a) garnet gneiss (sample B98013107A), (b) sapphirine-bearing garnet gneiss (sample B98021104B), (c) garnet-orthopyroxene gneiss (sample B98022208C), (d) magnetite-quartz gneiss (sample B98013006B).

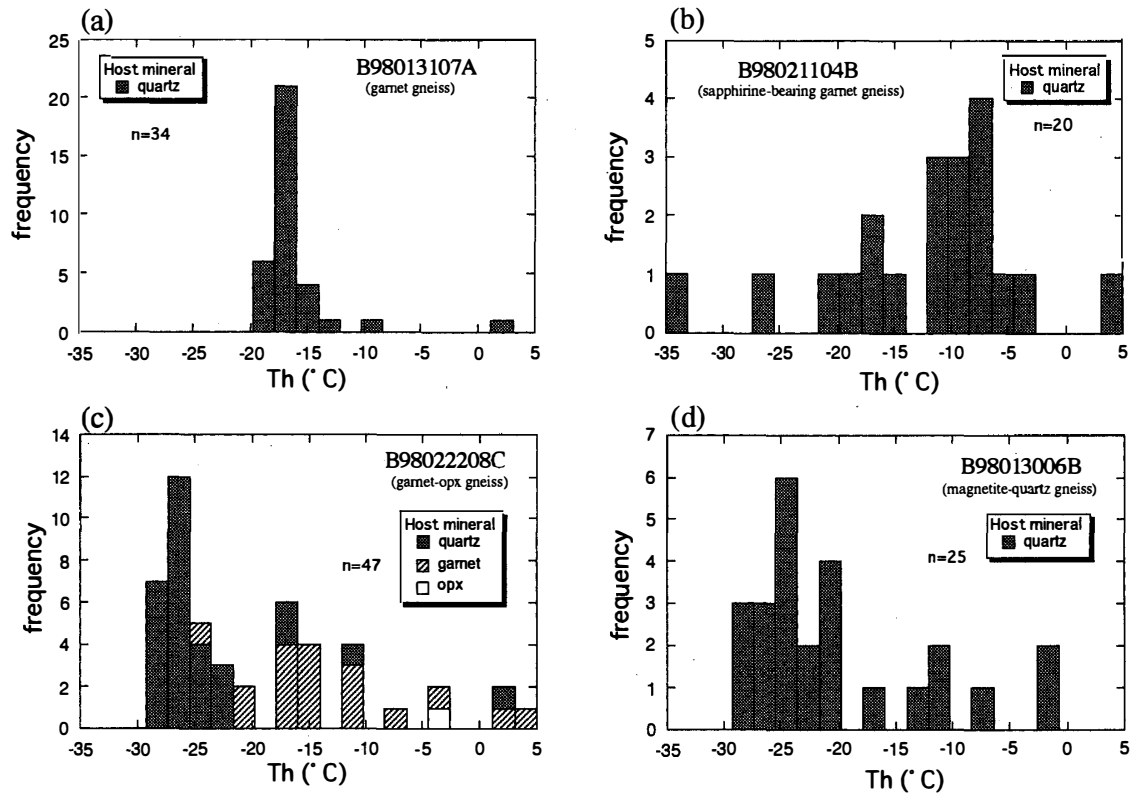


Fig. 4. Histograms showing the distribution of homogenization temperature (T_h) of fluid inclusions in quartz, garnet, and orthopyroxene from granulites of Tonagh Island. Analyzed samples are the same as Fig. 3.

Table 1. Summary of microthermometric measurements of fluid inclusions in granulites from Tonagh Island.

Sample	Host mineral	Melting temperature			Homogenization temperature			Density (g/cm ³)	Type of inclusions ²⁾	Morphology ³⁾
		min	max	average ¹⁾	min	max	average ¹⁾			
B98013107A	Qtz	-57.0	-56.3	-56.6±0.2	-19.3	2.9	-16.0±3.7	0.98~1.02	PS	NC
B98021104B	Qtz	-56.7	-56.4	-56.5±0.1	-34.9	4.2	-12.4±8.4	0.95~1.02	PS	IR
B98022208C	Qtz	-57.2	-56.6	-56.9±0.1	-29.1	2.5	-24.1±6.3	1.01~1.07	PS	NC
	Grt	-56.7	-56.4	-56.6±0.1	-24.8	4.2	-12.9±7.4	0.99~1.02	PS	NC
	Opx	-56.6	-56.6	-56.6	-3.7	-3.7	-3.7	0.94	PS	NC
B98013006B	Qtz	-57.8	-57.0	-57.4±0.2	-28.9	-0.8	-19.9±7.8	—	P, PS	NC
	Opx	-56.7	-56.7	-56.7	—	—	—	—	PS	NC

¹⁾ error indicates standard deviation

²⁾ P: primary, PS: pseudosecondary

³⁾ NC: negative crystal, IR: irregular shape

aggregate and on slow warming, abrupt melting occurs at temperatures (T_m) close to -56.6°C , which is the triple point of pure CO_2 (Figs. 3a–c). Fluid inclusions in magnetite-quartz gneiss (sample B98013006B) show slight depression in their melting temperatures (below -56.6°C ; Fig. 3d) suggesting the probable presence of additional fluid components such as CH_4 and/or N_2 , which are known to depress the melting temperature of pure CO_2 (*cf.* Roedder, 1984). We also observed slightly varying melting temperatures for CO_2 inclusions in garnet-orthopyroxene gneiss (sample B98022208C) depending on the host mineral. As shown in Fig. 3c, the melting temperatures are higher for inclusions in orthopyroxene and garnet as compared to those in quartz, although there is a clear overlap in the range of melting temperatures. The difference may have been

derived from the different trapping stage of the carbonic fluid.

Following melting, on continued heating, the fluid trapped within the inclusions homogenizes by the gradual dissolution of the gas phase into the liquid phase. In all the cases, the CO₂ homogenizes into the liquid phase. Homogenization temperatures (Th) are compiled in Fig. 4, and fall within the range of *ca.* -35 to +4°C.

The composition of the fluid, and the temperature and phase of homogenization, allow precise estimation of the density of the fluid. For the inclusions of the present study, CO₂ densities of 1.00–1.02 g·cm⁻³ for garnet gneiss (sample B98013107A), 0.90–1.09 g·cm⁻³ for sapphirine-bearing garnet gneiss (sample B98021104B), and 0.90–1.07 g·cm⁻³ for garnet-orthopyroxene gneiss (sample B98022208C) are estimated using the homogenization temperature and experimental data of Angus *et al.* (1976). We have excluded the data from magnetite-quartz gneiss (sample B98013006B) from density estimations due to the depression in melting temperatures and probable presence of additional volatile species, which remains to be confirmed using Laser Raman spectroscopy in a future study. The composition of the fluid phase and its density value constrain it to lie along an “isochore” (line of constant volume) in *P-T* space. The underlying assumption that fluid inclusions have remained closed systems and the sizes of the cavities have remained constant since entrapment (*cf.* Roedder, 1984) allows the interpretation that density of the fluid captured within the inclusion remained unchanged from its value at the time of entrapment.

5. Discussion

This is the first report of a systematic fluid inclusion study in ultrahigh-temperature metamorphic rocks from the Napier Complex of East Antarctica. Our results indicate the ubiquitous presence of pure CO₂-rich fluids trapped within various minerals in the ultrahigh-temperature metamorphic rocks. The probable presence of traces of additional fluid phases (*e.g.* CH₄ and/or N₂) is indicated in one lithology (magnetite-quartz gneiss; sample B98013006B) from the depression of CO₂ melting temperatures. Our observation of CO₂-rich inclusions in the Napier rocks is comparable with similar reports of carbonic fluid inclusions in granulites from other crustal fragments of Gondwanaland (*e.g.* Santosh, 1986, 1992; Hansen *et al.*, 1987).

Although it is well known that CO₂-rich fluids play an important role in deep crustal and crust-mantle interface processes, the timing of entrapment of CO₂-rich inclusions in granulites has been a topic of debate (*e.g.* Lamb *et al.*, 1987; Santosh *et al.*, 1991). The occurrence of CO₂-rich fluid inclusions of syn-metamorphic nature in granulite facies rocks has been taken to indicate that carbonic fluids play a major role in lowering the H₂O-activity and stabilizing anhydrous mineral assemblages which characterize granulites (*e.g.* Newton *et al.*, 1980; Santosh, 1992). From East Antarctica, CO₂-rich fluid inclusions have been previously reported from the Lützow-Holm Bay area, where the trapped CO₂ represents traces of the syn-metamorphic fluid (Santosh and Yoshida, 1992).

The metamorphism of the Napier Complex is characterized by the presence of dry mineral assemblages, the stability of which requires anhydrous conditions. We therefore suggest that the carbonic inclusions reported in this study are evidence for the presence of a CO₂-rich ambient fluid which may have been instrumental in buffering the H₂O-

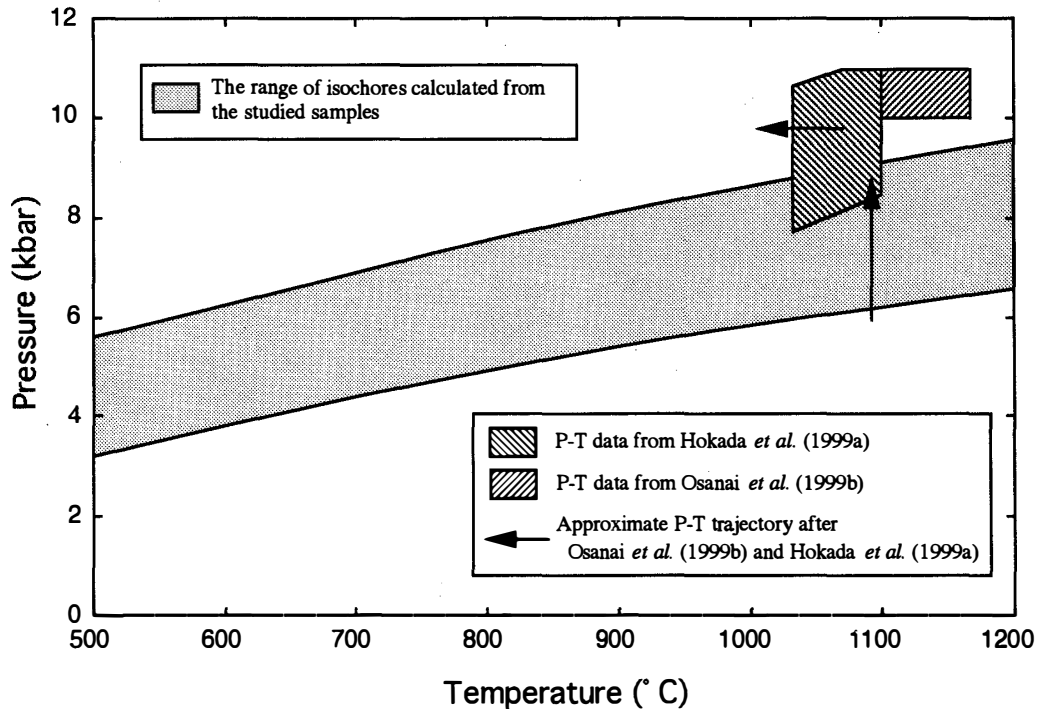


Fig. 5. The range of isochores calculated in this study. Boxes and arrays indicate P - T conditions and approximate P - T trajectory, respectively, from Tonagh Island after Osanai *et al.* (1999b) and Hokada *et al.* (1999a).

activity to low levels. The hypothesis may be supported by the density of the fluids trapped within inclusions. Isochores of the fluid inclusions, which were estimated from the density of the carbonic fluid ($0.90\text{--}1.09\text{ g}\cdot\text{cm}^{-3}$), show entrapment pressures of 4.4–6.9 kbar at 700°C, 5.4–8.1 kbar at 900°C, and 6.2–9.1 kbar at 1100°C (Fig. 5). The isochore intersects the available counterclockwise P - T trajectory of Tonagh Island at around 6–9 kbar and 1100°C which corresponds to the peak P - T condition of the area (Hokada *et al.*, 1999a; Osanai *et al.*, 1999b). The close correspondence of CO_2 isochores with the P - T estimates from mineral phase equilibria may indicate that the CO_2 -rich fluids are traces of the syn-metamorphic fluid (*cf.* Touret, 1985). However, the timing of trapping of CO_2 -rich fluid and its role in lowering H_2O -activity still remain major problems for future research.

Our study raises the interesting possibility that CO_2 -rich inclusions can be preserved in rocks which have undergone ultrahigh-temperature metamorphism followed by isobaric cooling history. Although high density CO_2 inclusions have been reported from some Archean high-pressure granulites such as those in the Nilgiri Hills, southern India (Touret and Hansteen, 1988), the preservation of high density carbonic fluids in Archean ultrahigh-temperature rocks as in the present study is of considerable significance in understanding the fluid evolution history vis-à-vis the thermal regime and exhumation in the continental lower crust. The source of fluids in Tonagh Island and their transfer mechanism remain interesting topics to be addressed in our future studies.

Acknowledgments

We express our sincere thanks to the members of JARE-39 and the crew of the icebreaker *Shirase* for giving us the opportunity for geological field investigation, and for their helpful support. We also thank Dr. K. Mizuno at the University of Tsukuba for his assistance with fluid inclusion analysis, and Dr. S. Tojo at Fukuoka University of Education for his valuable comments. Professor Y. Hiroi and an anonymous referee are acknowledged for critical reading of the manuscript. MS thanks the authorities of Kochi University for support.

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(Received February 5, 2001; Revised manuscript accepted May 16, 2001)