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GEOLOGY OF ULTRAHIGH-TEMPERATURE METAMORPHIC ROCKS FROM TONAGH ISLAND IN THE NAPIER COMPLEX, EAST ANTARCTICA

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Abstract: The summer party of the 39th Japanese Antarctic Research Expedition (1997–1998) carried out geological field work on Tonagh Island, located at the southern-end of Amundsen Bay, northern Enderby Land, which belongs to the central Napier Complex and shows part of the highest-grade metamorphic region in the Napier Complex. The island is underlain by various kinds of ultrahigh-temperature (UHT) metamorphic rocks and subordinate amounts of two types of unmetamorphosed intrusive rocks (alkali-dolerite and granitic pegmatite). UHT-metamorphic rocks are subdivided into five lithologic units (Units I to V) owing to their lithologies and geological structures from north to south, bounded by thrust-shear zones, accompanied with remarkable anhydrous mylonite and later pseudotachylite-cataclasite. The distinctive metamorphosed mafic dikes with tholeiitic composition are also found along the shear zone, characteristically at the boundary between Units II and III. The unmetamorphosed alkali-dolerite dikes, which are designated Amundsen dikes, cut across not only the sequence of metamorphic rocks but also the unit boundary shear zone and metamorphosed mafic dike.

A geological perspective of the metamorphic rocks from Tonagh Island is generally classified into eight types on the regional map scale such as 1) orthopyroxene-bearing quartzofeldspathic gneiss, 2) garnet-bearing quartzofeldspathic gneiss, 3) two pyroxene-bearing mafic granulite, 4) garnet-orthopyroxene gneiss and granulite, 5) magnetite-quartz gneiss, 6) metamorphosed ultramafic rocks, 7) layered gneiss 1 (composed mainly of mafic gneiss and orthopyroxene-bearing quartzofeldspathic gneiss), 8) layered gneiss 2 (composed mainly of mafic gneiss and garnet-bearing quartzofeldspathic gneiss) with subordinate meta-impure quartzite, aluminous granulite, and calc-silicate granulite.

The orthopyroxene-bearing quartzofeldspathic charnockitic gneiss and garnet-bearing quartzofeldspathic gneiss are the main constituents of Tonagh Island. Unit I has a peculiarity of predominance of layered gneisses showing thin alternation (centimeters to several meters in thickness) of orthopyroxene- and garnet-bearing quartzofeldspathic gneisses, two-pyroxene mafic granulite, garnet-orthopyroxene gneiss and granulite, sapphirine-bearing aluminous gneiss, garnet-sillimanite gneiss, leucocratic quartzofeldspathic gneiss, magnetite-quartz gneiss, meta-quartzite and metamorphosed ultramafic rocks (pyroxenite and lherzolite). Units II and III are characterized by widespread distributions of two pyroxene-bearing mafic granulite (gneiss) and garnet-orthopyroxene gneiss at the upper structural level, although layered gneisses dominate at the lower structural level. In field appearance Unit II and Unit III have nearly the same lithology and may be considered repetition due to thrusting. The magnetite-quartz gneiss occurs only in Units I, II and III characteristically. Unit IV is underlain by garnet- and orthopyroxene-bearing quartzofeldspathic gneisses and layered gneisses, which look very close to the lower structural level of Units II and III. On the other hand, constituents of Unit V are mainly orthopyroxene- and garnet-bearing quartzofeldspathic gneisses with subordinate layered gneiss 1 and traces of aluminous, mafic and ultramafic granulites. Therefore the most effective tectonic boundary may be the shear zone among Units IV and V. In this paper the regional geology of Tonagh Island is described in detail, with a brief description of modes of occurrence and petrographic features of UHT metamorphic rocks and unmetamorphosed intrusive rocks.

key words: Archaean, Napier Complex, Tonagh Island, regional geology, UHT metamorphic rocks

1. Introduction

Archaen to early Proterozoic regional ultrahigh-temperature (UHT) metamorphic rocks are widely exposed in the Napier Complex, northern Enderby Land, East Antarctica (SHERATON *et al.*, 1987). The dominant rock types of the Napier Complex are pyroxene- and garnet-bearing quartzofeldspathic gneisses of igneous origin (tonalitic orthogneiss); subordinate constituents are considered to be ultramafic, mafic, pelitic, and siliceous granulites. Some of these gneisses and granulites have been characterized by UHT-type mineral assemblages of spinel+quartz and garnet+sapphirine+quartz, with or without orthopyroxene and osumilite, and orthopyroxene+sillimanite+quartz (*e.g.* DALLWITZ, 1968; SHERATON *et al.*, 1980; ELLIS, 1980; GREW, 1980; HARLEY, 1985, 1998; SANDIFORD, 1985; MOTOYOSHI and MATSUEDA, 1984; MOTOYOSHI and HENSEN, 1989; MOTOYOSHI *et al.*, 1990). High-fluorine biotite is also present as the primary phase (OSANAI *et al.*, 1995; MOTOYOSHI, 1998). The *P-T* conditions of these granulites are up to 800–1000 MPa and 1000–1100°C, found by HARLEY and HENSEN (1990) and HARLEY (1998). The age of these rocks had been determined by ion microprobe U-Pb analyses, and Sm-Nd and Rb-Sr whole rock isochron methods. The results indicate that the tonalitic precursor of the orthogneiss had intruded into the crust at *c.* 3950–3800 Ma (WILLIAMS *et al.*, 1984; BLACK *et al.*, 1986a; OWADA *et al.*, 1994; HARLEY and BLACK, 1997) and then the main metamorphism in the complex occurred at *c.* 2800 Ma (HARLEY and BLACK, 1997) or *c.* 2500 Ma (*e.g.* GREW and MANTON, 1979; DEPAOLO *et al.*, 1982; BLACK *et al.*, 1986b; OWADA *et al.*, 1994; TAINOSHO *et al.*, 1994; SHIRAISHI *et al.*, 1997; ASAMI *et al.*, 1998). The metamorphic evolution (after the peak metamorphic event) of UHT metamorphic rocks from throughout the Napier Complex has been considered to have started from at least 1000 MPa and 1000°C followed by near-isobaric cooling and later deformation under lower-grade granulite facies conditions.

The geological outline for the whole region of the Napier Complex was reported by SHERATON *et al.* (1987). After this, detailed geological investigations including geological mapping has only been done a few times (*e.g.* HARLEY, 1987; MAKIMOTO *et al.*, 1989). In 1996, the Japanese Antarctic Research Expedition (JARE) established a new earth scientific project "SEAL" (Structure and Evolution of east Antarctic Lithosphere). This project includes two types of geological research program: regional geological investigation throughout the Napier Complex and local but detailed geological investigation in a specific area. During the first austral summer season (1996–1997), a JARE-38 party carried out a detailed geological survey at Mt. Riiser-Larsen in the northern coast range along Amundsen Bay (ISHIZUKA *et al.*, 1997, 1998). Then in the second season we (JARE-39) did a careful geological survey on Tonagh Island in the Amundsen Bay region (Fig. 1) from January 24, 1998 to February 22, 1998 (OSANAI *et al.*, in prep).

In this paper we will describe the regional geology of Tonagh Island in detail with a brief description of modes of occurrences of UHT metamorphic rocks and unmetamorphosed intrusive rocks. Other detailed investigations for each geological topic from Tonagh Island are also reported by different papers in this volume as follows: structural geology (TOYOSHIMA *et al.*, 1999), metamorphism of aluminous granulites (HOKADA *et al.*, 1999), metamorphism of mafic granulites (TSUNOGAE *et al.*, 1999), and geochemistry and isotope geology of mafic granulites (OWADA *et al.*, 1999).

2. Geological Outline

Tonagh Island is located at the southern end of Amundsen Bay between the Tula Mountains and the Scott Mountains, northern Enderby Land, which belongs to the central Napier Complex (Fig. 1). The island is part of the highest-grade metamorphic region in the Napier Complex (GREW, 1982; HARLEY and HENSEN, 1990). Tonagh Island actually

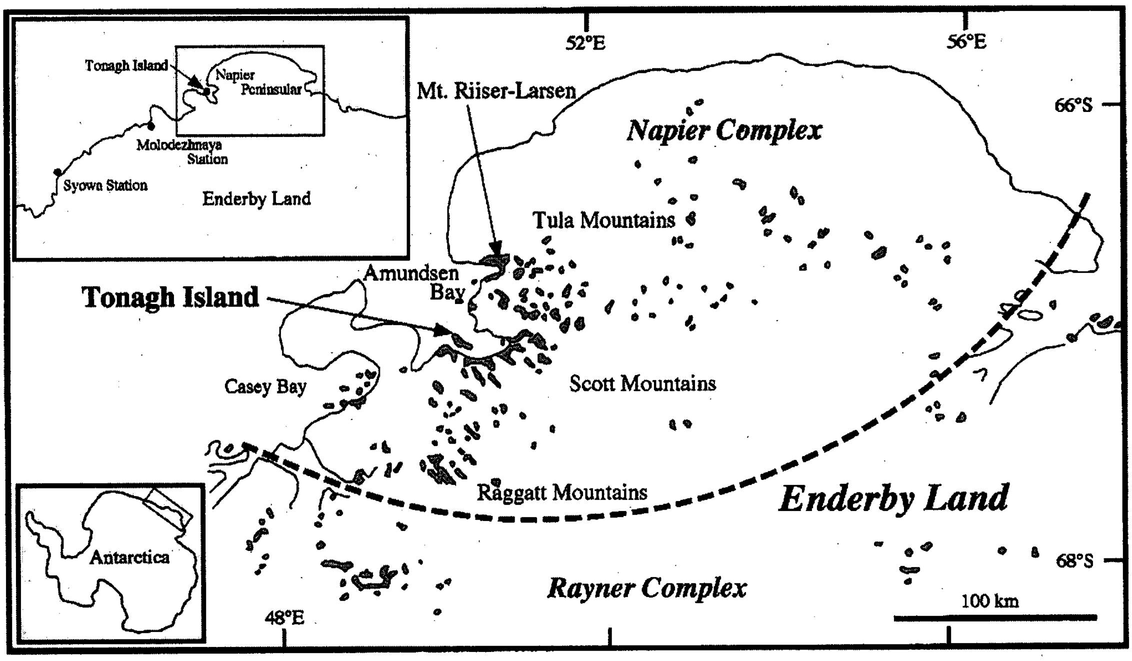

Fig. 1. Location of Tonagh Island in Enderby Land, East Antarctica. The boundary between the Napier and Rayner Complexes is after SHERATON *et al. (1987).*

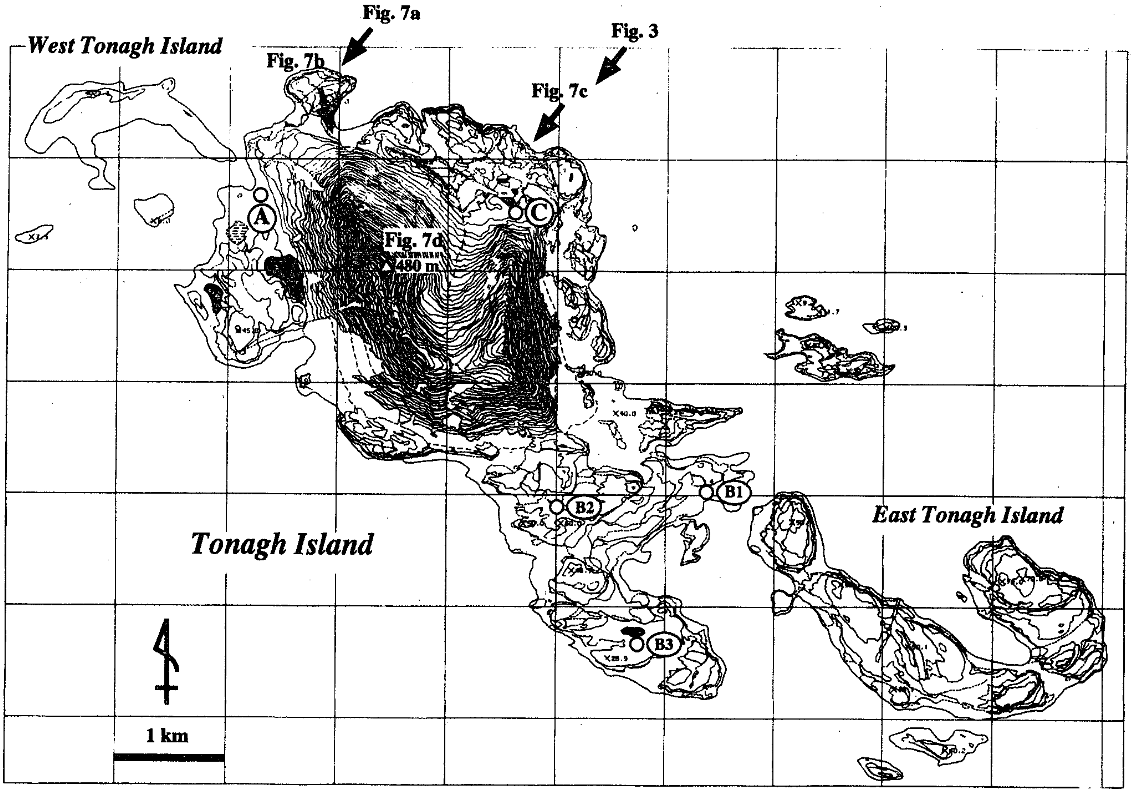

Fig. 2. Topographic map of Tonagh Island (©K. Moriwaki, NIPR). A and C represent base-camp and advanced-camp, respectively. B1 to B3 show the landing points by helicopter for geological survey in the southern part of Tonagh Island. Arrows with figure numbers indicate the view-directions of each figure.

consists of three islands: East Tonagh Island (3×2 km), Tonagh (main) Island (hereafter Tonagh Island: 5×6 km), and West Tonagh Island (2×1 km) (Fig. 2). Detailed studies of metamorphism for meta-iron stone and pyroxene granulites from East Tonagh Island have been carried out by Harley (1987). West Tonagh Island is completely covered by moraine deposit. Therefore, we carried out the geological survey on Tonagh Island. Tonagh Island is geomorphologically divided into three major parts, nearly flat terrace in the southern, northeastern and western areas, plateau peninsular in the northern area, and steep mountain ridges extending NW-SE in the central area (Fig. 2). The central mountain ridge shows a steep slope or cliff along the western, southern and eastern sides, while the northern slope is gentle down to the northeastern terrace and covered by thick moraine or debris deposit (Fig. 3). The highest peak of Tonagh Island (67°05′51″S, 50°17′19″E) is *c.* 480 m above sea level.

A generalized geological map of Tonagh Island is shown in Fig. 4. The investigated area is underlain by various kinds of metamorphic rocks and subordinate amounts of two types of unmetamorphosed intrusive rocks (dolerite and granitic pegmatite). Metamorphic rocks are subdivided into five lithologic units (Units I to V) owing to their lithologies and structures from north to south. The boundaries of each unit are NE-SW to E-W trending steeply north dipped or near vertical thrusts or shear zones accompanying with remarkable anhydrous mylonite and later pseudotachylite-cataclasite (Figs. 3 and

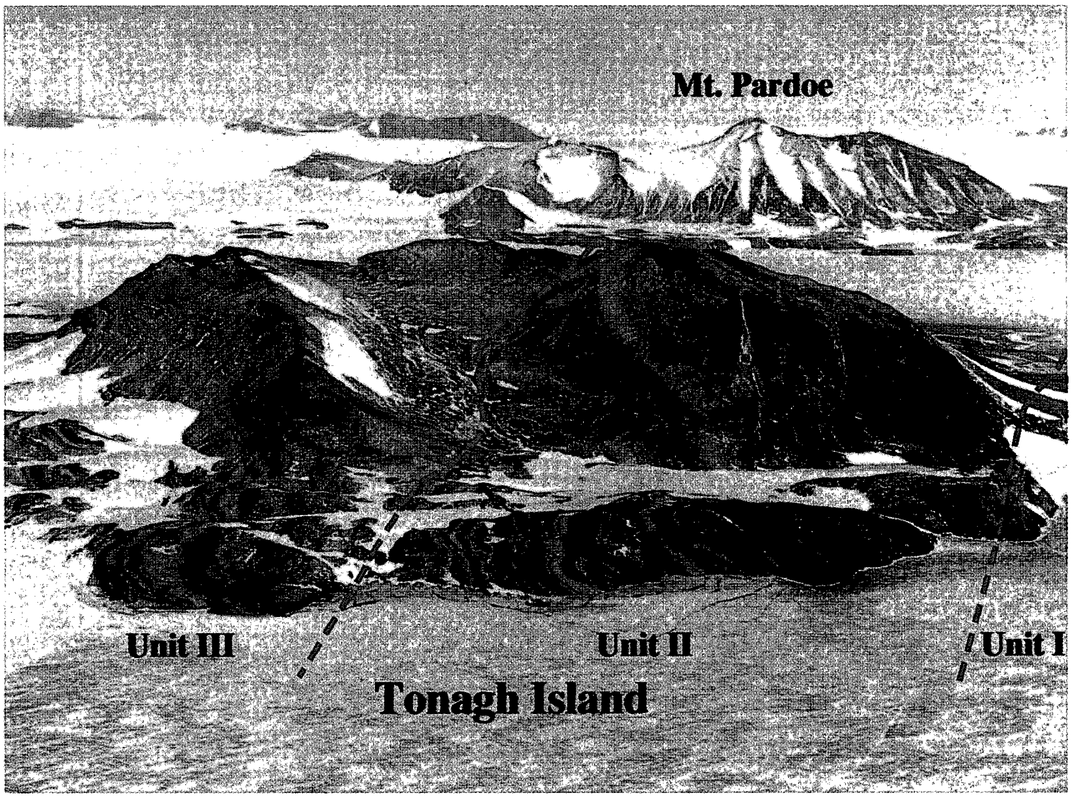

Fig. 3. Northern part of Tonagh Island in Amundsen Bay: viewed from helicopter.

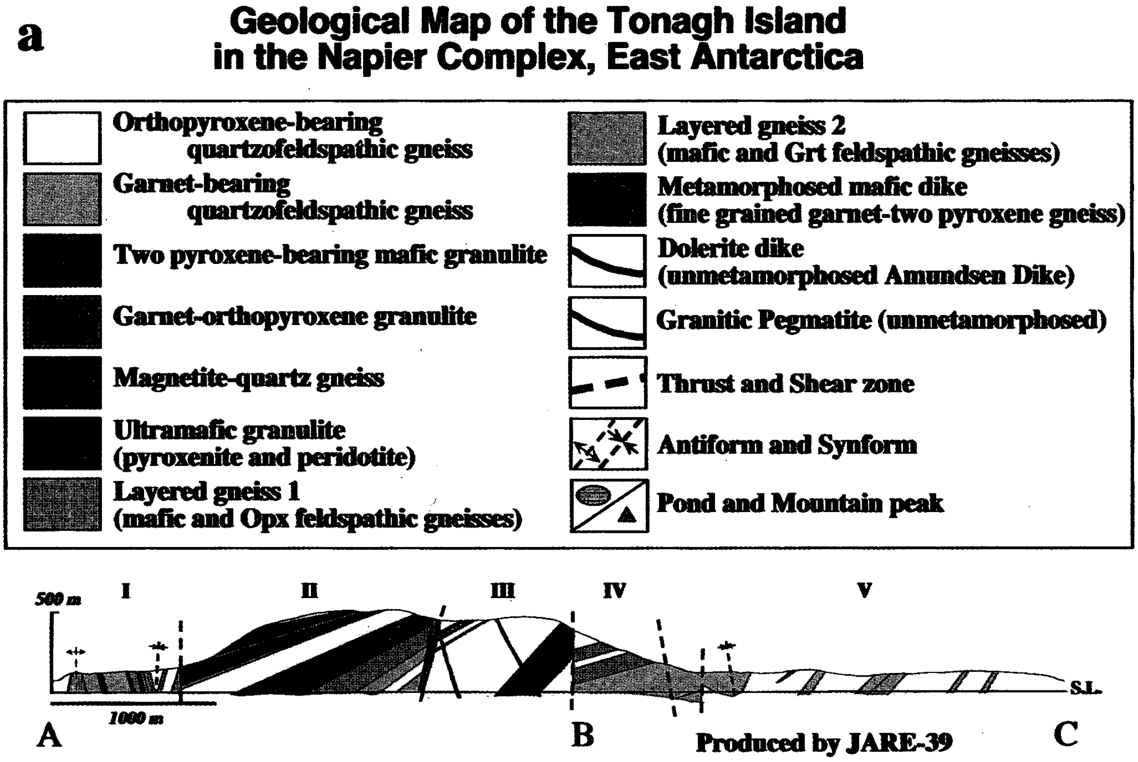

Fig. 4a. Generalized geological map of Tonagh Island. Legend and geologic cross section along the line A-B-C in the geological map.

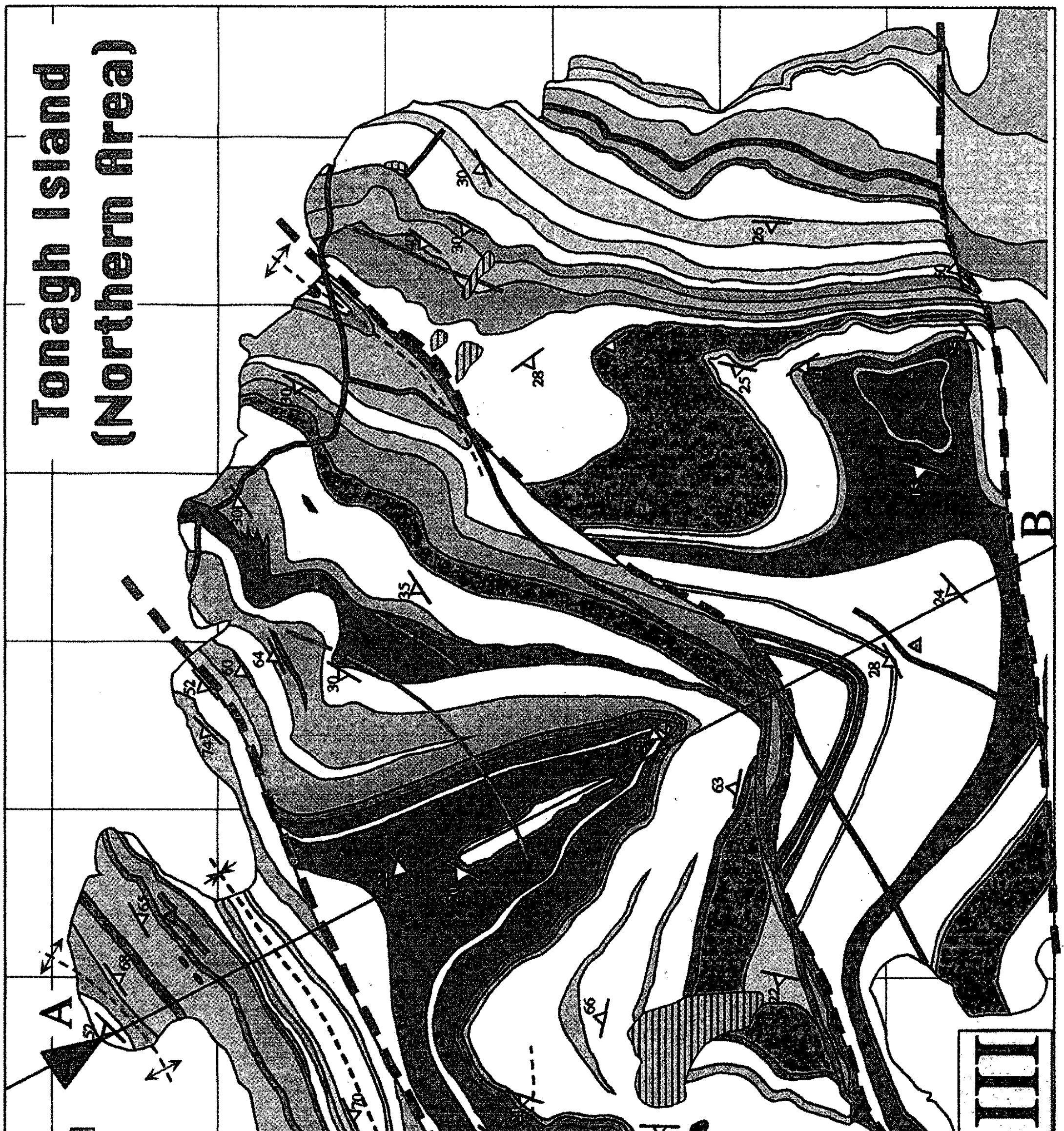

Fig. 4b. Generalized geological map of Tonagh Island. The northern part.

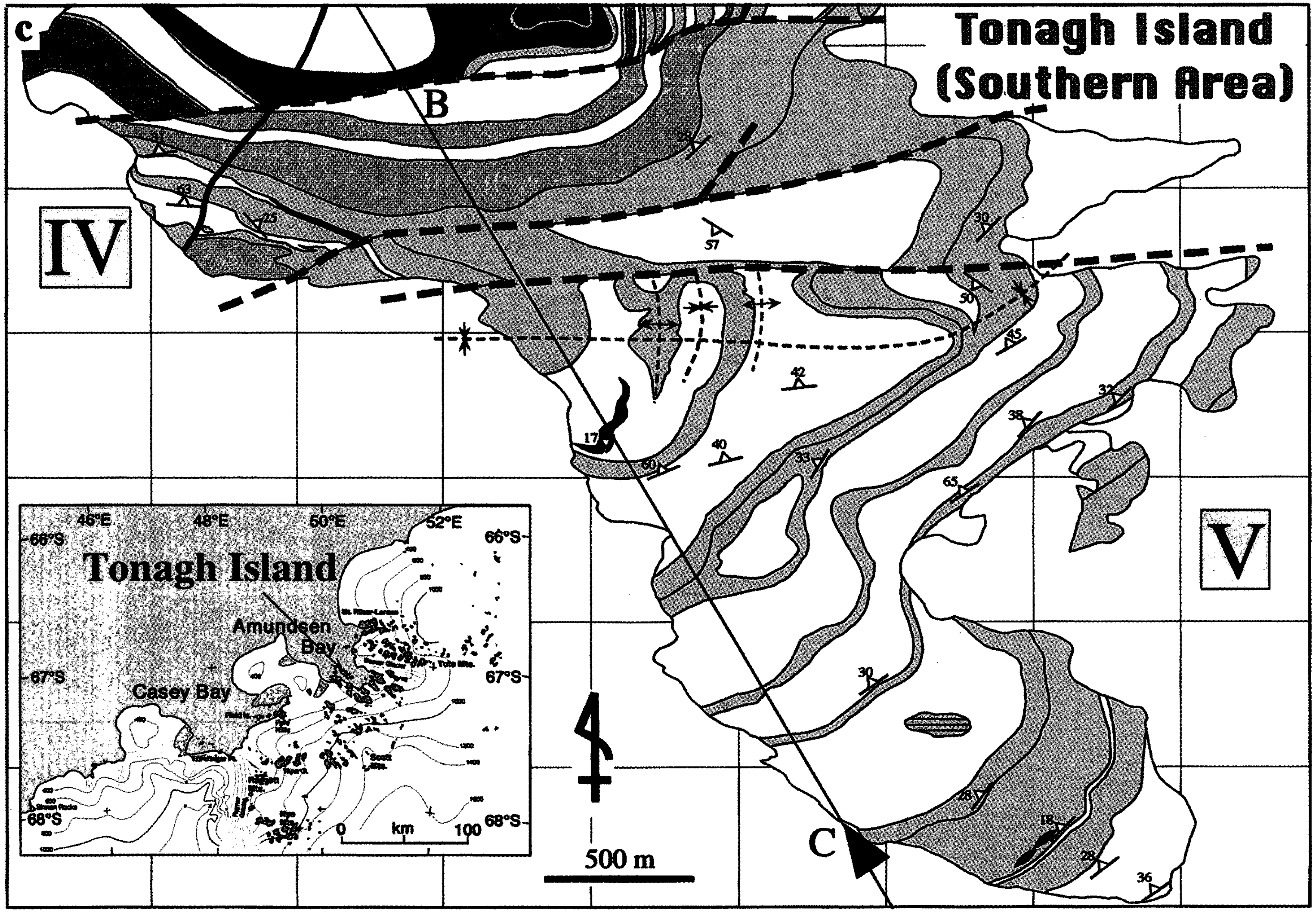

Fig. 4c. Generalized geological map of Tonagh Island. The southern part. The inset map of Fig. 4c is after K. MORIWAKI (NIPR).

4). These thrusts or shear zones cut across the island with width of several to hundreds of meters. The distinctive metamorphosed mafic dikes with tholeiitic composition are also found along the shear zone, characteristically at the boundary between Units II and III. Metamorphic foliations in each unit are different from each other. The Unit I metamorphic foliation strikes NE-SW and dips at a steep angle (50–80°) to the SE or NW, forming small-scale synforms and antiforms (Fig. 5). Those in Units II and III show nearly the same strikes (partly N-S direction only at the eastern part of Unit III) but gentler dips (15–40°) to the NW except along the sheared unit-boundaries, where metamorphic foliations bend with rather steep dips (50–60°). In Units IV and V, metamorphic foliations strike NE-SW to E-W and dip to the north with moderate angle (20–60°). There are some multi-stage-deformed synforms and antiforms especially in Unit II and Unit V, with local variation of metamorphic foliations. The preferred orientation of metamorphic minerals as well as mineral lineation is generally quite weak or invisible. The unmetamorphosed dolerite dikes, which are designated the Amundsen dike (*e.g.* SHERATON *et al.*, 1987), cut across not only the sequence of metamorphic rocks but also the unit boundary shear zone and metamorphosed mafic dike (Figs. 3 and 4).

A geological perspective of the metamorphic rocks from Tonagh Island is generally classified into eight types on the regional map scale as follows:

1) orthopyroxene-bearing quartzofeldspathic gneiss,
2) garnet-bearing quartzofeldspathic gneiss,
3) two pyroxene-bearing mafic granulite,
4) garnet-orthopyroxene gneiss and granulite,
5) magnetite-quartz gneiss,
6) metamorphosed ultramafic rocks,
7) layered gneiss 1 (composed mainly of mafic gneiss and orthopyroxene-bearing quartzofeldspathic gneiss),
8) layered gneiss 2 (composed mainly of mafic gneiss and garnet-bearing quartzofeldspathic gneiss).

As may be seen in Fig. 4 the metamorphic rock assembly as well as protolith of the metamorphic rocks of Unit I (northern area), of Units II to IV (central area) and of Unit V (southern area) are clearly different. The orthopyroxene-bearing quartzofeldspathic charnockitic gneiss and garnet-bearing quartzofeldspathic gneiss are the main constituents of Tonagh Island. The Unit I has a peculiarity of predominance of layered gneisses showing thin alternation (centimeters to several meters in thickness) of orthopyroxene- and garnet-bearing quartzofeldspathic gneisses, two pyroxene mafic granulite, garnet-orthopyroxene gneiss and granulite, sapphirine-bearing aluminous gneiss, garnet-sillimanite gneiss, leucocratic quartzofeldspathic gneiss, magnetite-quartz gneiss, meta-quartzite and metamorphosed ultramafic rocks (pyroxenite and lherzolite) (Figs. 4b, 5 and 6). Units II and III are characterized by widespread distributions of two pyroxene-bearing mafic granulite (gneiss) and garnet-orthopyroxene gneiss at the upper structural level, although layered gneisses dominate at the lower structural level. In field appearance Unit II and Unit III have nearly the same lithology, this may be considered repetition due to thrusting. The magnetite-quartz gneiss occurs only in Units I, II and III characteristically (Fig. 4b). Unit IV is underlain by garnet- and orthopyroxene-bearing quartzofeldspathic gneisses and layered gneisses, which looks very close to the lower structural level of

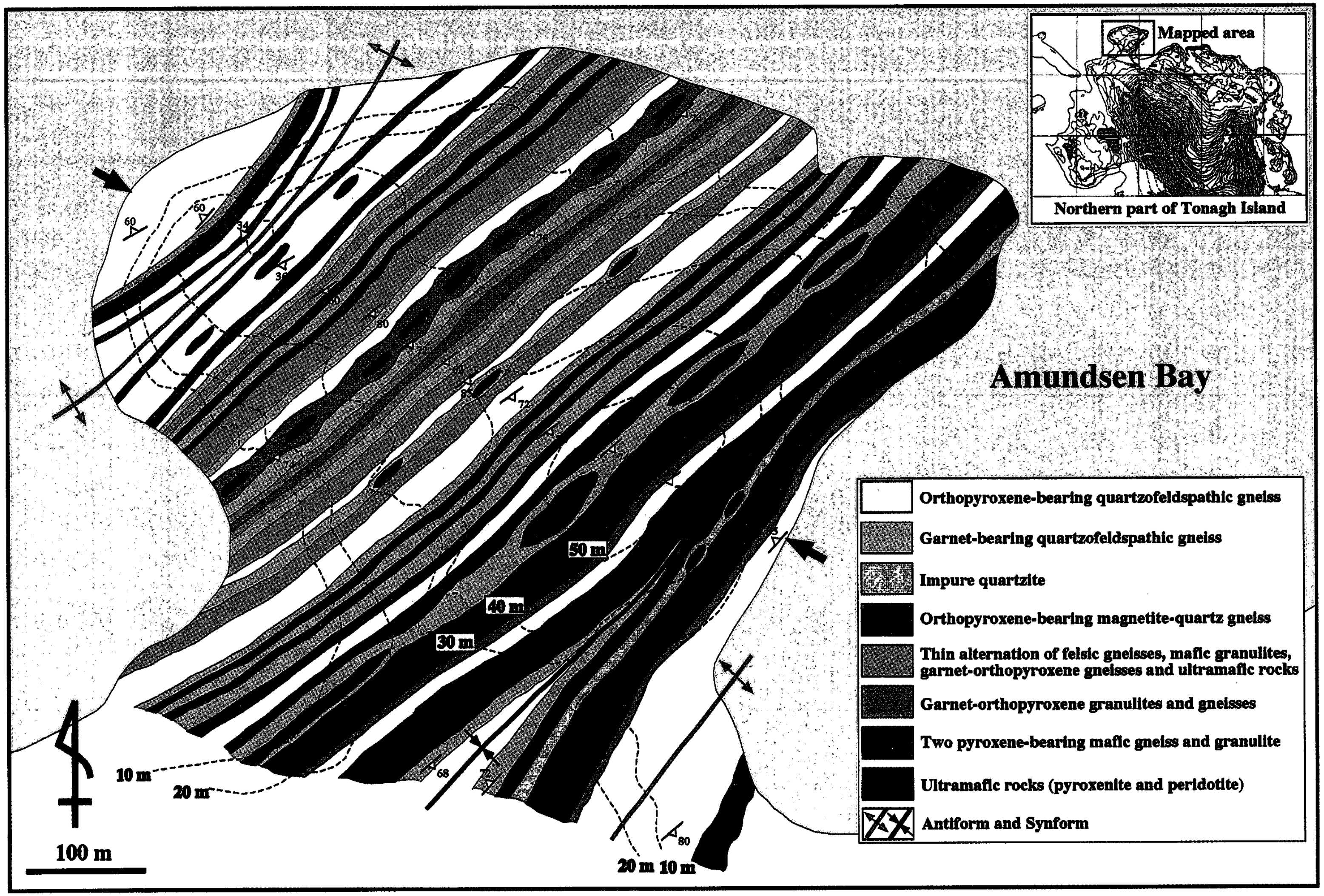

Fig. 5. Detailed geological map of the northern peninsular area. Black arrows indicate the route for continuous sampling.

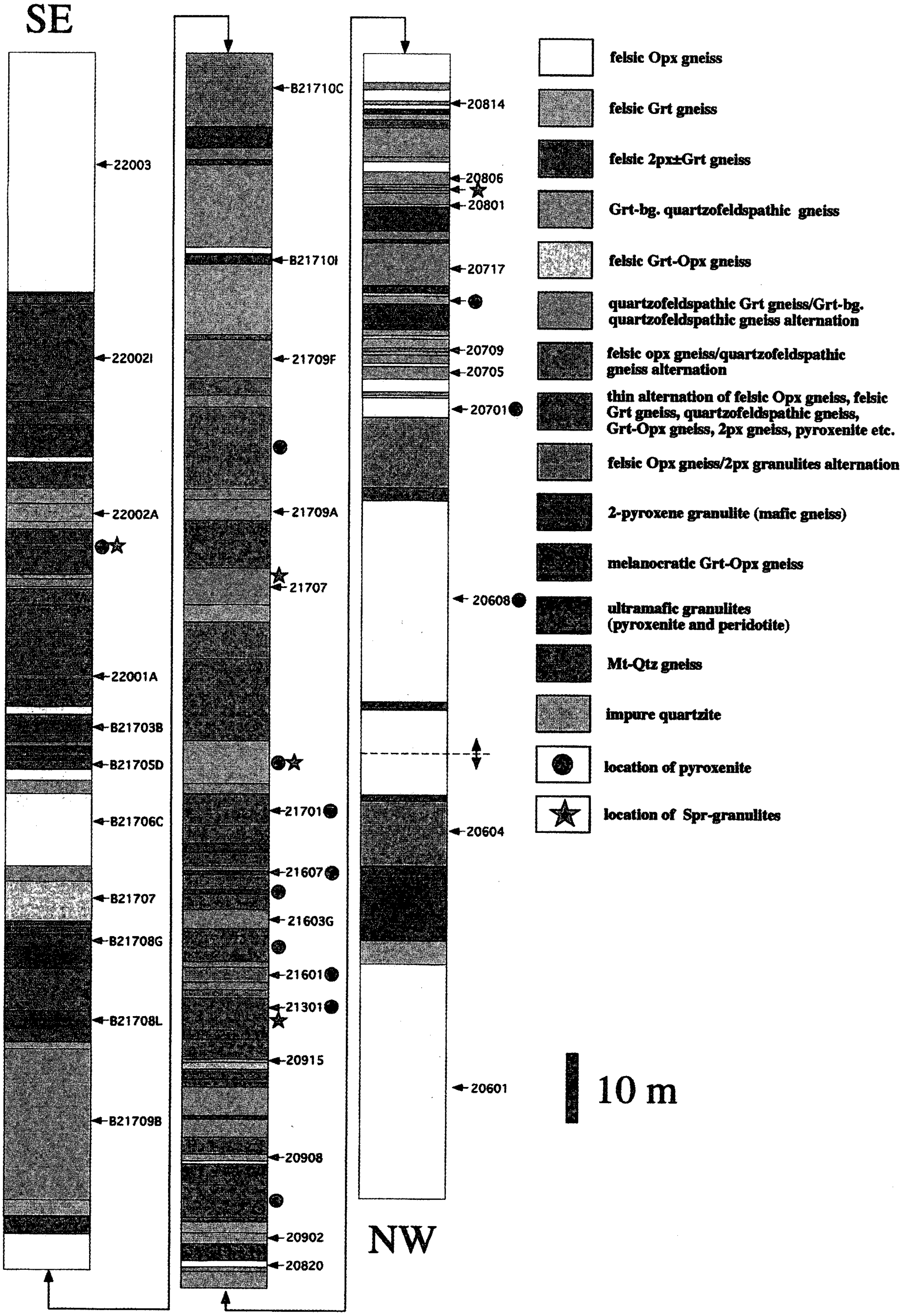

Fig. 6. Continuous horizontal column of the northern peninsula. Abbreviations for minerals are after Kretz *(1983).*

Units II and III. On the other hand, constituents of Unit V are mainly orthopyroxene- and garnet-bearing quartzofeldspathic gneisses with subordinate layered gneiss 1 and traces of aluminous, mafic and ultramafic gneisses (Fig. 4c). Therefore the most effective tectonic boundary may be the shear zone among Units IV and V (Fig. 4c). More detailed descriptions of modes of occurrence, with brief petrographical features of each metamorphic rock are given below.

3. Metamorphic Rocks

The rock classification using protoliths is difficult for high-grade metamorphic rocks, so we named the rocks using only modal variations and assemblages of metamorphic minerals. The metamorphic rocks are classified into nine rock types including the six types (1 to 6) mentioned above, but excepting two types of layered gneisses, and adding three other types as follows: 7) sapphirine-bearing aluminous gneiss, 8) metamorphosed impure quartzite and 9) calc-silicate gneiss. In this chapter we describe the modes of occurrence with brief description of petrographical features of each metamorphic rock. The first six rock types are relatively major lithologic facies, which are illustrated on the regional scale geological map of Fig. 4. The latter three types are minor and occur only as thin intercalations or blocks in layered gneisses 1 and 2 (Fig. 7).

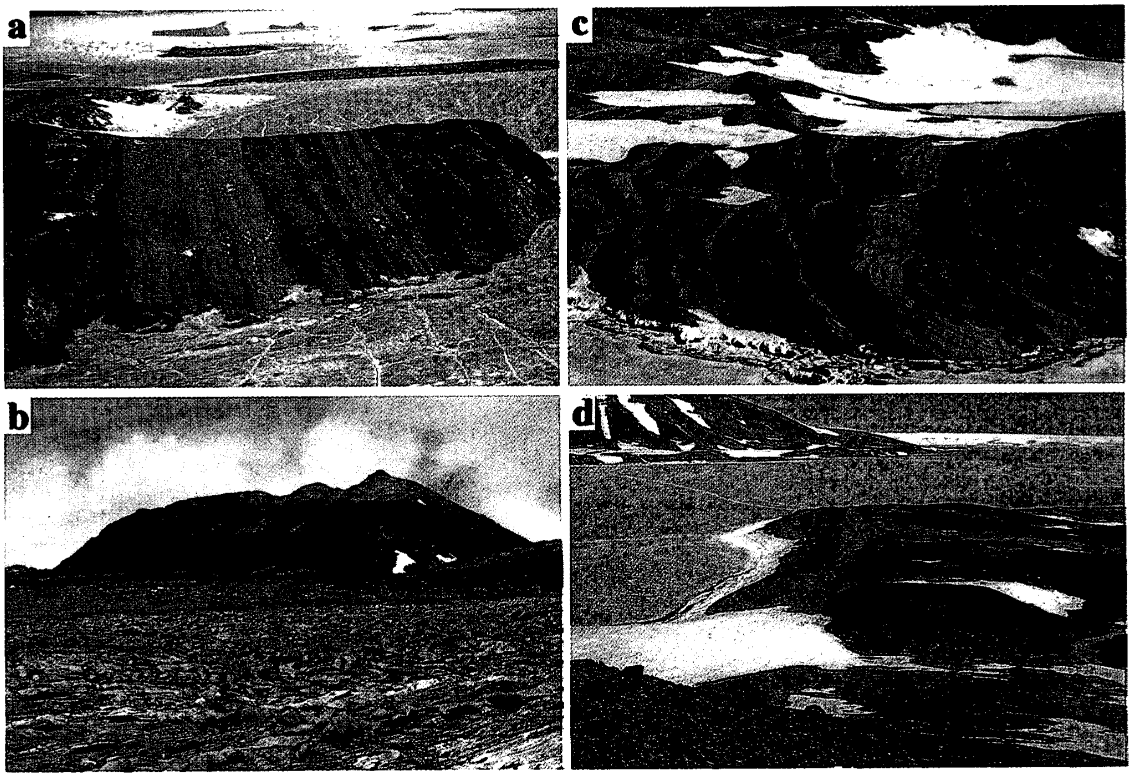

Fig. 7. The geological scenic beauty of Tonagh Island. a: Layered structure of UHT metamorphic rocks of the northern peninsular viewed from helicopter. b: The highest peak of Tonagh Island viewed from the northern peninsula. c: The layered gneiss cut obliquely by alkali-dolerite (Amundsen dike) at the northern sea shore viewed from helicopter. d: The unit boundary between Unit II and Unit III in the western part of the northern area viewed from the main ridge.

3.1. Orthopyroxene-bearing quartzofeldspathic gneiss

Orthopyroxene-bearing quartzofeldspathic gneiss (felsic Opx gneiss, which may be equivalent to the gneiss described by Ishizuka *et al.*, 1998) is widespread in the whole area of Tonagh Island as not only thick layers (up to 400 m in thickness) but also thin intercalations (centimeter to meter in scale) among the layered gneisses (Fig. 8a). The felsic Opx gneiss is commonly homogeneous, but well foliated. Compositional layering accompanying modal variations in mineral compositions in felsic Opx gneiss can also be observed. The felsic Opx gneiss is normally pale grayish brown to pale brown in color and medium in grain size. Part of the gneiss shows charnockitic pale greenish color. Very fine grained pale greenish schistose felsic Opx gneiss (mylonite–ultramylonite) without any hydrous minerals is locally developed along the small-scale shear band obliquely cutting the general foliation of felsic Opx gneiss (Fig. 8b).

The felsic Opx gneiss generally shows granoblastic texture with pleochroic orthopyroxene, K-feldspar, plagioclase and quartz as major constituents (Fig. 8c). The first three minerals usually have euhedral to subhedral crystal shape, while quartz is normally anhedral. Modal variations of K-feldspar and plagioclase are wide. Orthopyroxene is

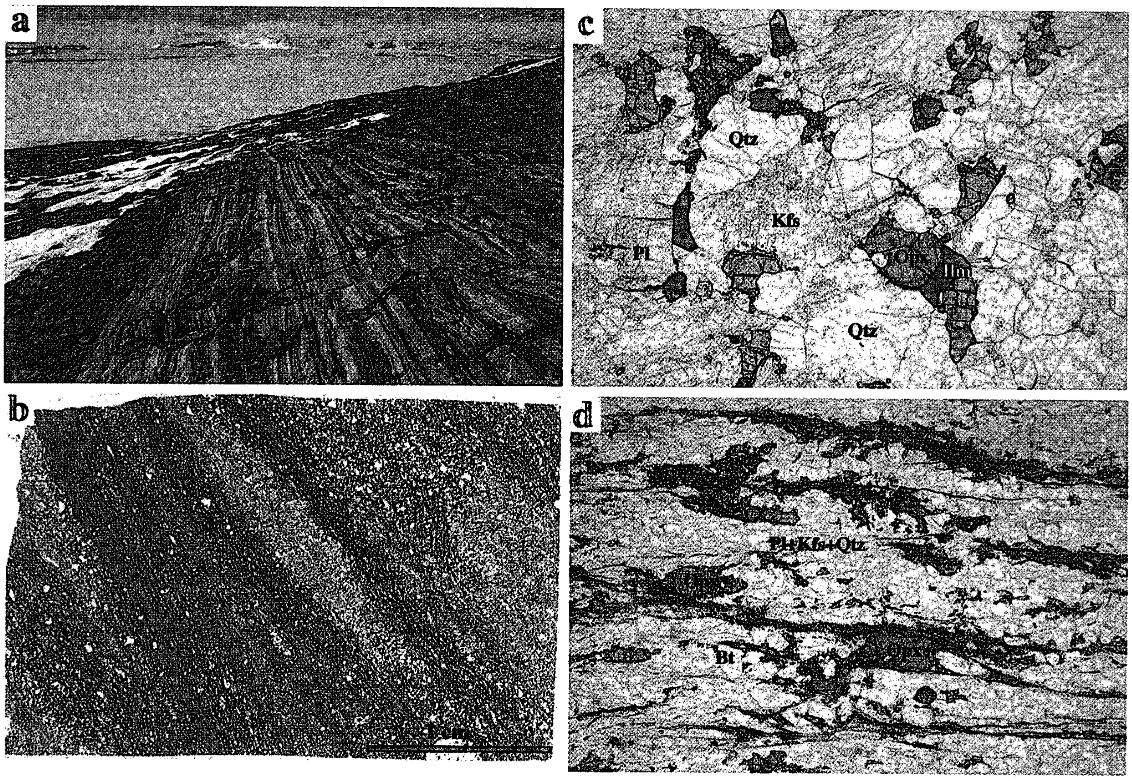

Fig. 8. Modes of occurrence and photomicrographs of orthopyroxene-bearing quartzofeldspathic (felsic Opx) gneiss. a: Thin layered-type felsic Opx gneiss. b: Photomicrograph of small-scale shear band. c: Photomicrograph of typical felsic Opx gneiss. Horizontal width of photograph hereafter is 3.6 mm for photomicrograph excepting Fig. 15c. d: Mylonitic felsic Opx gneiss. Note that secondary biotite and subgrained orthopyroxene are also observed. Opx: orthpyroxene, Pl: plagioclase, Kfs: K-feldspar, Qtz: quartz, Ilm: ilmenite, Bt: biotite.

sometimes replaced by green hornblende, biotite and biotite+quartz symplectite along cleavages and/or margins (Fig. 8d). K-feldspar is mesoperthite to perthite (mainly string- and lod-type). Garnet and clinopyroxene are rarely observed as minor constituents. In particular garnet normally includes plenty of quartz. Accessory minerals are apatite, zircon, ilmenite, magnetite and rutile. The following mineral associations are recognized in the felsic Opx gneiss:

1) orthopyroxene+biotite+mesoperthite or perthite+plagioclase+quartz,
2) orthopyroxene+mesoperthite or perthite+plagioclase+quartz,
3) orthopyroxene+garnet+mesoperthite or perthite+plagioclase+quartz,
4) orthopyroxene+clinopyroxene+K-feldspar+plagioclase+quartz,
5) orthopyroxene+clinopyroxene+K-feldspar+plagioclase.

Characteristically fine grained mylonitic felsic Opx gneiss has assemblages 2) or 3) with porphyroclastic orthopyroxene and garnet.

3.2. Garnet-bearing quartzofeldspathic gneiss

Garnet-bearing quartzofeldspathic gneiss is also widespread on Tonagh Island, especially in the southern part (Units IV and V), several tens to hundreds of meters in thickness. In the northern part (Units I, II and III) several thin layers, ranging in thickness from a few centimeters to meters (up to 80 m), of garnet-bearing quartzofeldspathic gneiss are observed within layered gneisses as intercalations with felsic Opx gneiss, mafic granulite, magnetite-quartz gneiss and garnet-orthopyroxene gneiss, etc. (Figs. 4 and 9a). The modal variation of garnet and quartz is highly variable so that the gneiss can be divided into three types: feldspars and quartz dominant garnet-bearing type (pale brown to orange Grt-bg. quartzofeldspathic gneiss), quartz-rich and garnet-poor type (pale gray to white quartzose Grt gneiss) and garnet predominant type (pale brown to pinkish felsic Grt gneiss). These minute types are not shown on the geological map (Fig. 4), but are illustrated only in the geological column of the northern peninsula (Fig. 7).

These gneisses normally show granoblastic texture with medium to coarse grained minerals. A well foliated mylonitic part contains porphyroclastic garnet and feldspars and fine elongated quartz and biotite with asymmetrical right-lateral strike-slip sense. The constituent minerals are mainly garnet, plagioclase, K-feldspar including perthite and mesoperthite (Fig. 9b), and quartz with or without subordinate amounts of sillimanite, cordierite, spinel, sapphirine, orthopyroxene and biotite. Accessory minerals are rutile, ilmenite, zircon and apatite. The following mineral assemblages are observed in the Grt-bg. quartzofeldspathic gneiss, quartzose Grt gneiss and felsic Grt gneiss.

1) garnet+quartz+K-feldspar+plagioclase,
2) garnet+sillimanite+quartz+K-feldspar+plagioclase,
3) garnet+quartz+plagioclase,
4) garnet+sapphirine+sillimanite+cordierite+quartz,
5) garnet+sapphirine+orthopyroxene+sillimanite+quartz,
6) garnet+cordierite+sillimanite+quartz+plagioclase,
7) garnet+sapphirine+orthopyroxene+K-feldspar+plagioclase.

All these assemblages contain biotite as secondary retrograde mineral. Assemblages 1) and 2) are for Grt-bg. quartzofeldspathic gneiss, assemblages 3), 4) and 5) for quartzose Grt gneiss and those of 6) and 7) for felsic Grt gneiss. Green and brown spinels occur as

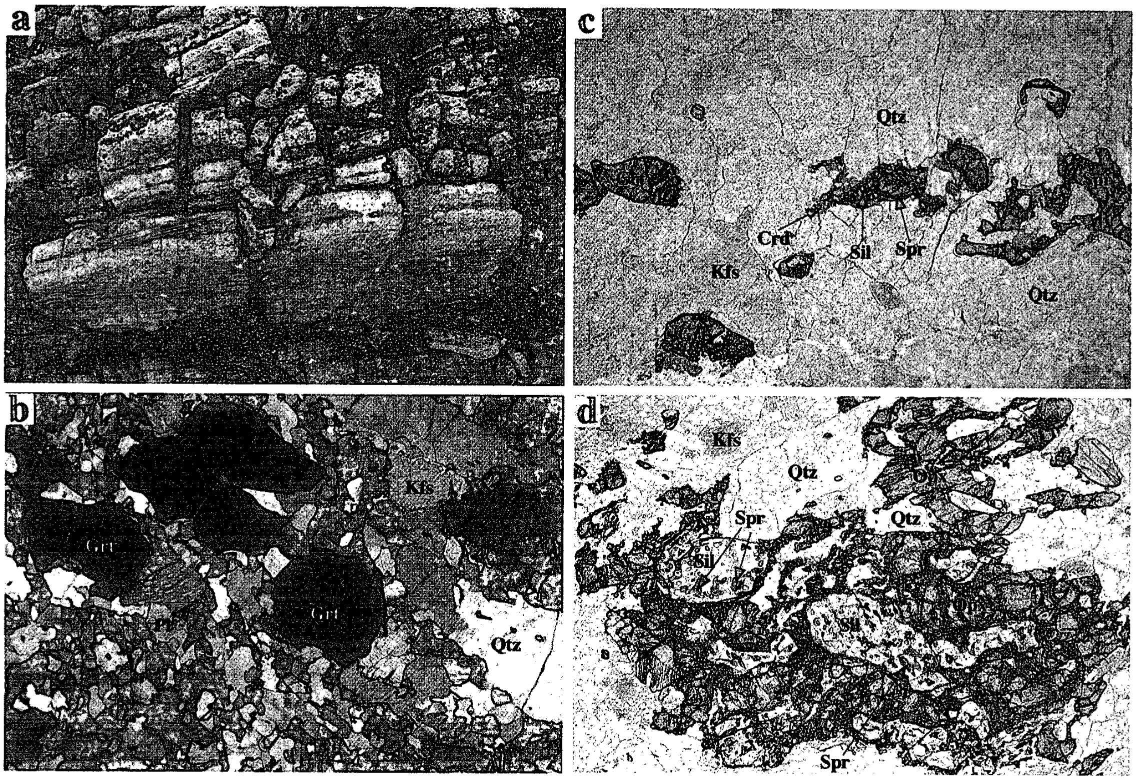

Fig. 9. Mode of occurrence and photomicrograph of garnet-bearing quartzofeldspathic (felsic Grt) gneiss. a: Close up of layered-type felsic Grt gneiss with modal variation of garnet. b: Photomicrograph of felsic Grt gneiss (crossed polar). c: Sapphirine-bearing felsic Grt gneiss. Note that sapphirine and quartz are separated by a sillimanite and pinited cordierite moat. d: Microdomain containing orthopyroxene-sillimanite-quartz assemblage in the felsic Grt gneiss. Sillimanite includes sapphirine and quartz. Grt: garnet, Spr: sapphirine, Crd: cordierite, Sil: sillimanite.

inclusions in sapphirine from assemblage 4) and in garnet from assemblage 5), respectively. In the assemblages 4) and 5), sapphirine and quartz do not show direct contact, but are armored by garnet+cordierite+sillimanite and sillimanite+orthopyroxene+quartz symplectites, respectively (Figs. 9c and 9d).

3.3. Two pyroxene-bearing mafic granulite

Orthopyroxene- and clinopyroxene-bearing mafic granulites occur usually as thick layers (up to 200 m) and also thin intercalations (ranging from several centimeters to meters) in the layered gneisses in Units I, II, III and IV. However, in Unit V, the rocks can be observed in only a few thin layers in layered gneiss 2 excepting one lenticular layer illustrated on the geological map (Fig. 4). The boundary between thin layers of two pyroxene-bearing granulite and layers in contact with them among the "layered gneiss" are sometimes oblique and gently cut the metamorphic foliation of neighboring rocks (Fig. 10a), which may indicate that the precusor of some two-pyroxene granulite was intrusive rock. Along the shear zone, especially at the boundary between Unit II and Unit III, there is a unique mafic granulite as a metamorphosed dike cutting across the foliation and layering (Figs. 4 and 10b).

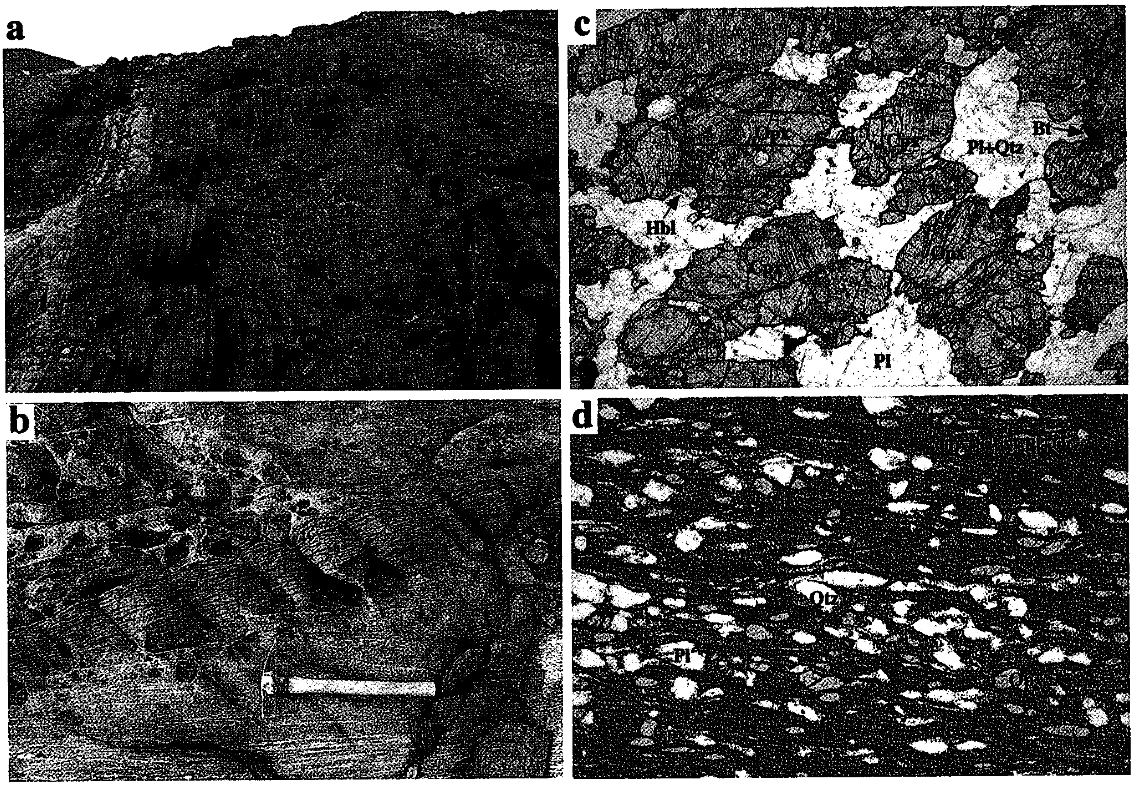

Fig. 10. Modes of occurrence and photomicrographs of two pyroxene-bearing mafic granulite. a: Thin alternation of two pyroxene-bearing mafic granulite (dark layer) and felsic Opx gneiss (light grayish layer). b: Metamorphosed mafic dike cutting the general foliation of surrounding felsic Opx gneiss along the shear zone at the boundary between Units II and III. c: Photomicrograph of typical type. Secondary hornblende and biotite are also present. d: Strongly mylonitized part along the shear zone. Cpx: clinopyroxene, Hbl: hornblende.

The layered-type two pyroxene-bearing mafic granulites are medium- to coarse-grained and granoblastic-polygonal in texture. Normally the granulite is light brownish gray (rather felsic) to light gray (rather mafic) in color. The dark gray granulitized mafic dike is fine-grained and granoblastic in texture. The briefly classified mineral assemblages of the mafic granulites are as follows:

1) orthopyroxene+clinopyroxene+plagioclase+quartz,
2) orthopyroxene+clinopyroxene+pale brown hornblende+plagioclase+quartz,
3) orthopyroxene+clinopyroxene+garnet+plagioclase+quartz,
4) orthopyroxene+clinopyroxene+hornblende+garnet+plagioclase+quartz.

Assemblages 1) to 3) including inverted-pigeonite and subcalsic clinopyroxene, occur in layered-type mafic granulite; assemblage 4) occurs in metamorphosed dikes along the sheared unit-boundary between Units II and III. Pyroxenes in this rock type characteristically include very fine needles of Fe-Ti mineral (ilmenite?). Most of these assemblages also contain secondary hornblende and biotite surrounding pyroxenes (Fig. 10c). Rarely, cummingtonite can be found accompanied by greenish hornblende. Part of the garnet may also be formed during the retrograde stage. Accessory minerals are apatite, ilmenite and magnetite in the former three-types of assemblages, but only ilmenite in assemblage

4). Mylonitic two pyroxene-bearing mafic granulite also contains very fine-grained minerals of assemblage 3) (Fig. 10d).

3.4. *Garnet-orthopyroxene gneiss and granulite*

The garnet-orthopyroxene gneiss and granulite commonly contain garnet and orthopyroxene as major phases. This type of rock occurs generally as thin intercalations ranging from several centimeters to meters in thickness among the layered gneisses, while only in Units II and III relatively thick layers (up to 150 m) also occur (Fig. 4). Here we name the gneissose and rather felsic portion "garnet-orthopyroxene gneiss", and the massive and rather meranocratic (mafic) portion "garnet-orthopyroxene granulite". Small lenticular blocks and/or pods of garnet-orthopyroxene granulite, which may be of boudinaged origin, are rarely embedded in the felsic Opx gneiss, Grt-bearing quartzofeldspathic gneiss or felsic Grt gneiss (Fig. 11a). In the layered gneisses the garnet-orthopyroxene granulite characteristically crops out at the boundary between ultramafic rock (pyroxenite and lherzolite) and felsic Grt- or Opx-gneisses coexisting with sapphirine-bearing aluminous granulites (Fig. 11b). Garnet-orthopyroxene gneiss is medium-grained pale grayish brown to pale orange, and garnet-orthopyroxene granulite is medium- to coarse-grained dark reddish gray to dark brownish gray in the outcrop.

The garnet-orthopyroxene granulite comprises mainly garnet, orthopyroxene and

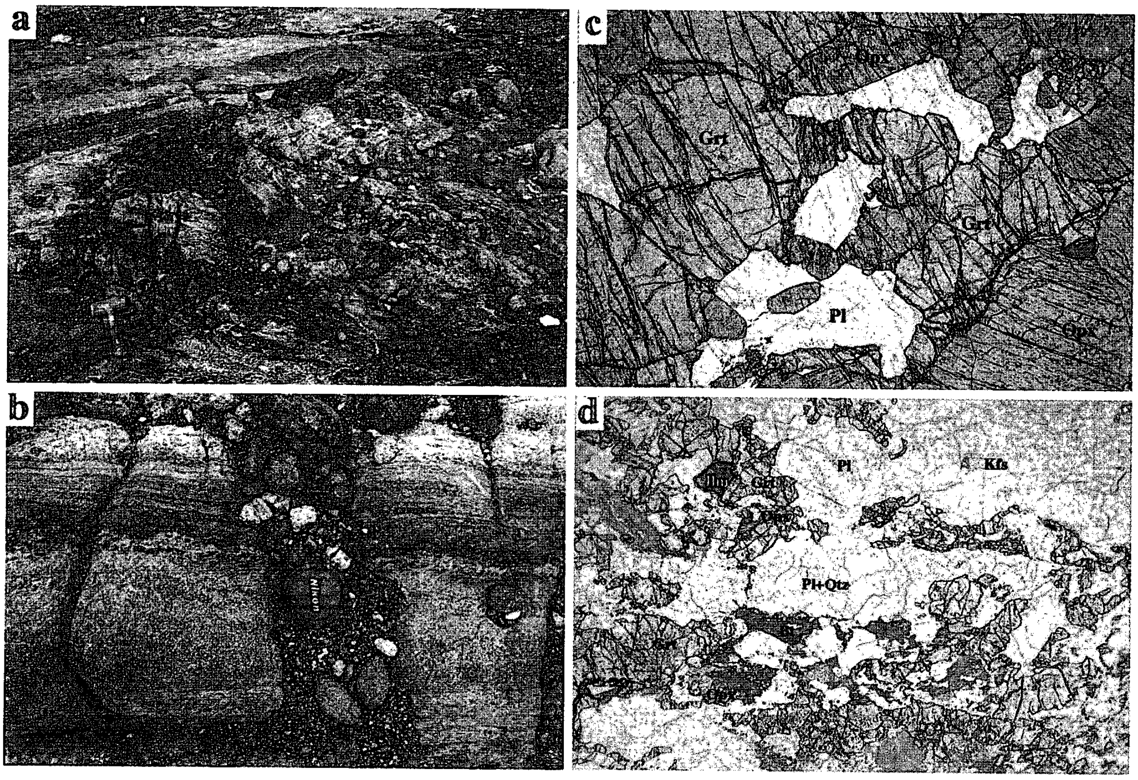

Fig. 11. Modes of occurrence and photomicrographs of garnet-orthopyroxene granulite and gneiss. a: Lenticular block of garnet-orthopyroxene granulite in the layered gneiss 2. b: Close up of garnet-orthopyroxene gneiss at the center. c: Photomicrograph of garnet-orthopyroxene granulite. Quartz and K-feldspar are also present. d: Fine-grained garnet-orthopyroxene gneiss with primary(?) biotite.

plagioclase with subordinate green spinel, sapphirine, cordierite and phlogopite (Fig. 11c). Accessories are rutile, ilmenite, magnetite, corundum and apatite. Secondary biotite and gedrite are also present. On the other hand, the garnet-orthopyroxene gneiss consisits of garnet, orthopyroxene, plagioclase, quartz and K-feldspar as the major phase, with subordinate brown spinel and clinopyroxene (Fig. 11d). Accessories are ilmenite, rutile, apatite and zircon. Secondary biotite is also present. The following assemblages are observed in the garnet-orthopyroxene gneisses (1–4) and granulites (5–7).

1) garnet+orthopyroxene+quartz,
2) garnet+orthopyroxene+plagioclase+K-feldspar+quartz,
3) garnet+orthopyroxene+spinel+plagioclase+K-feldspar+quartz,
4) garnet+orthopyroxene+clinopyroxene+plagioclase+K-feldspar+quartz,
5) garnet+orthopyroxene+plagioclase,
6) garnet+orthopyroxene+phlogopite+plagioclase,
7) garnet+orthopyroxene+sapphirine+spinel+cordierite+plagioclase.

Generally, K-feldspar shows rod- and bead-type perthite structures in the garnet-orthopyroxene gneiss. Brown spinel in the garnet-orthopyroxene gneiss occurs only as inclusions in garnet. In the sapphirine-bearing assemblage of 7), green spinel exists only as interstitial occurrences between orthopyroxene grains, where spinel and orthopyroxene direct contact is not observed by the moat of sapphirine on the spinel side and garnet on the orthopyroxene side.

3.5. Magnetite-quartz gneiss

Magnetite-quartz gneiss, which could be equivalent to the metamorphosed banded iron formation (meta-BIF) on Mt. Riiser-Larsen (Ishizuka *et al.*, 1998) and meta-ironstone in the Napier Complex including East Tonagh Island (Sheraton *et al.*, 1987; Harley, 1987), occurs as thin layers (several centimeters to meters in thickness) in Units I, II and III (Figs. 4 and 12a). The rock appears black in the magnetite-rich portion and piebald in the quartz- and feldspar-rich portion. Observed mineral assemblages are as follows:

1) magnetite+quartz,
2) magnetite+orthopyroxene+quartz,
3) magnetite+orthopyroxene+clinopyroxene+quartz,
4) magnetite+orthopyroxene+garnet+quartz+plagioclase.

The rock consists generally of fine- to medium-grained magnetite and quartz matrix with medium- to sometimes coarse-grained orthopyroxene porphyroblast (Fig. 12b). Clinopyroxene, garnet and plagioclase rarely occur with accessories of apatite and rutile.

3.6. Metamorphosed ultramafic rocks

UHT metamorphosed ultramafic rocks are distributed sporadically as thin layers (a few tens of centimeters to meters in thickness) and as boudinaged lenticular or rounded blocks (generally a few tens of meters in diameter) on Tonagh Island (Fig. 4). These rocks are commonlly massive, medium- to coarse-grained, and show three rock types of orthopyroxenite (pale green to pale brown), clinopyroxenite (black) and lherzolitic to websteritic peridorite (pale brownish green to pale brown) (Fig. 13a). At the boundary between these ultramafic rocks and felsic gneisses in the layered gneisses, metasomatic

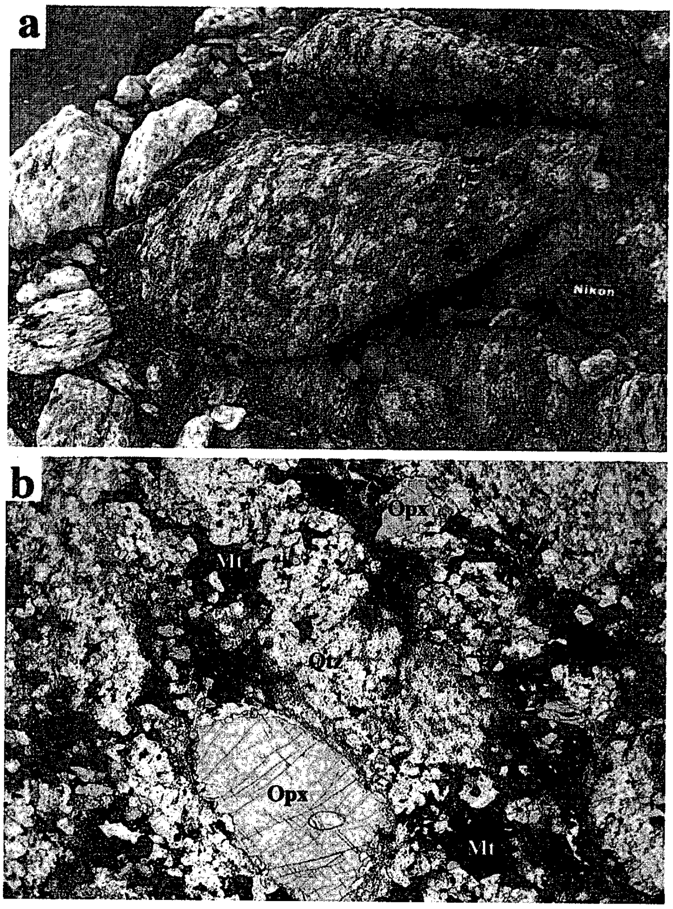

Fig. 12. Mode of occurrence and photomicrograph of orthopyroxene-bearing magnetite-quartz gneiss. a: Close up of magnetite-quartz gneiss in the layered gneiss I. b: Photomicrograph of orthopyroxene-bearing magnetite-quartz gneiss. Mt: magnetite.

(metamorphic) reaction zones (up to five meters) including garnet-orthopyroxene granulites and sapphirine-bearing aluminous gneisses have been produced (Fig. 13b). Sometimes leucocratic coase-grained garnet-bearing quartzofeldspathic rock and pale gray colored quartzose rock occur at the boudin neck of the ultramafic rocks. Strongly foliated lherzolitic peridotite block in felsic Opx gneiss is also present in Unit I, where metamorphic foliations of both ultramafic rock and surrounding felsic gneiss are clearly oblique.

Orthopyroxene and clinopyroxene are the main constituents of orthopyroxenite and clinopyroxenite, respectively (Fig. 13c). Part of the pyroxene shows an inverted pigeonitic feature. The lherzolitic peridotite contains olivine, clinopyroxene and orthopyroxene. Spinel, pale brown to colorless pargasitic hornblende, phlogopite and rarely plagioclase are also present as primary minerals (Fig. 13d). Garnet occurs only at the grain boundary between pyroxenes. Observed mineral assemblages for the ultramafic rocks are as follows:

1) orthopyroxene+spinel+garnet+phlogopite,
2) orthopyroxene+clinopyroxene+hornblende,
3) orthopyroxene+clinopyroxene+garnet,

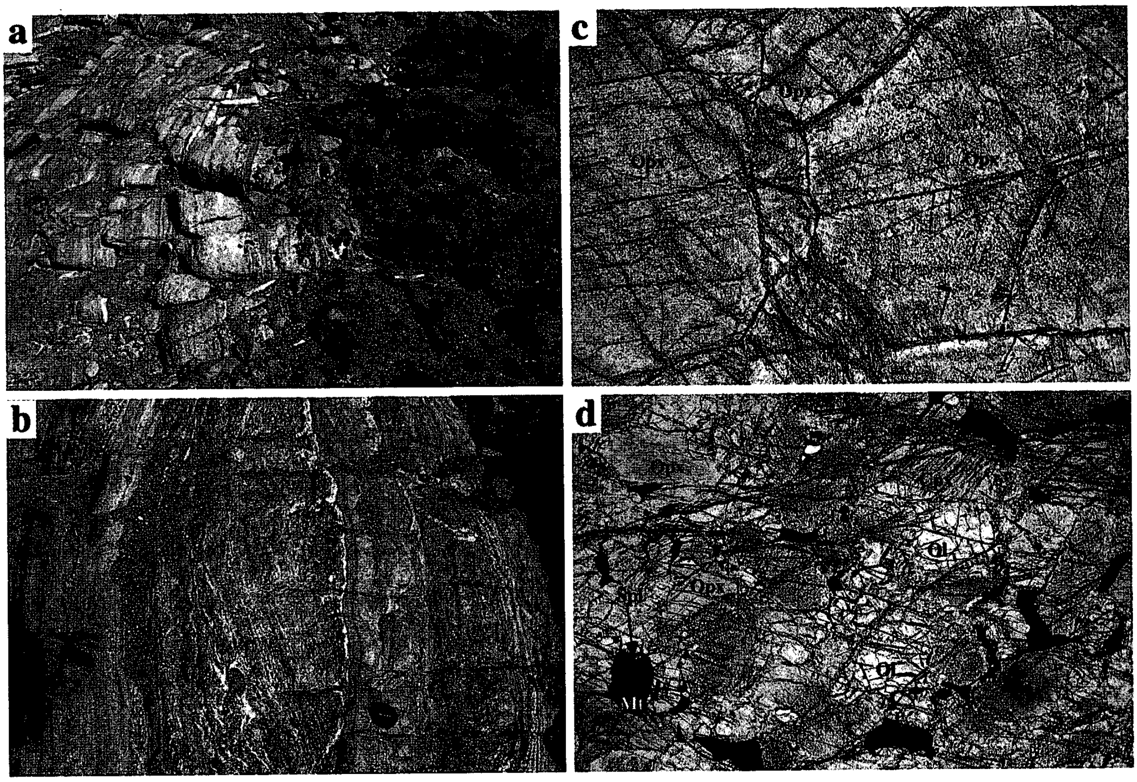

Fig. 13. Modes of occurrence and photomicrographs of metamorphosed ultramafic rocks. a: Orthopyroxenite lenticular block (right-side dark colored part) in the felsic Opx gneiss (left-side pale grayish part). Note that the sapphirine-bearing aluminous gneiss (centered pinkish part) occurs as a reaction zone. b: Pale brownish-green lherzolitic block in layered gneiss with pinkish aluminous gneiss. c: Photomicrograph of orthopyroxenite. Note very fine grains of ilmenite needles in orthopyroxene. d: Photomicrograph of metamorphosed lherzolitic ultramafic rock. Ol: olivine.

4) clinopyroxene+orthopyroxene+spinel,
5) clinopyroxene+orthopyroxene+phlogopite,
6) clinopyroxene+orthopyroxene+hornblende+phlogopite+spinel,
7) olivine+clinopyroxene+orthopyroxene+hornblende+phlogopite,
8) olivine+clinopyroxene+orthopyroxene+hornblende+spinel.

Accessories include magnetite and magnetite+corundum intergrowths.

3.7. Sapphirine-bearing aluminous granulite and gneiss

Sapphirine-bearing aluminous UHT metamorphic rocks are distinguished into two types of massive granulites and foliated gneisses. Sapphirine-bearing aluminous granulites and gneisses on Tonagh Island, especially in Units I, II and III, show various modes of occurrence as follows:

(a) thin metasomatic(?) reaction zone (up to 1 m in thickness) in the layered gneiss between ultramafic and quartzofeldspathic gneisses, coexisting with garnet-orthopyroxene and melanocratic orthopyroxene granulites (Figs. 13a and 14a). This type of rock shows medium- to coarse-grained gneissose structure with various colors, from pale pinkish to dark brownish, due to the constituent minerals.

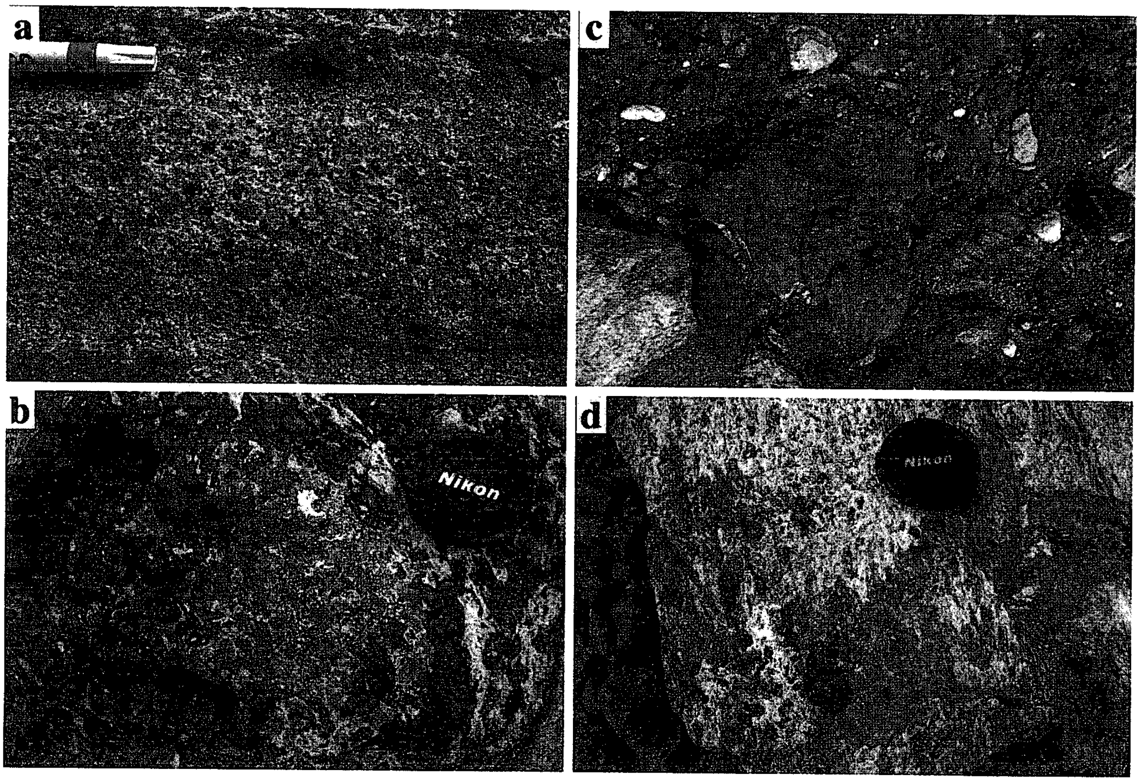

Fig. 14. Close up pictures of sapphirine-bearing aluminous granulites and gneiss. a: Sapphirine-garnet-orthopyroxene-cordierite-sillimanite granulite in the reaction zone between ultramafic and felsic gneisses. b: Sapphirine-orthopyroxene-garnet granulite block in the felsic gneiss. c: Sapphirine-spinel-corundum-phlogopite granulite in the felsic gneiss. d: Thin layer of sapphirine-garnet-orthopyroxene-sillimanite-quartz gneiss in the layered gneiss 1.

(b) dark colored lenticular or rounded blocks (several centimeters to meters in diameter) or reaction zone correlating with type (a) rocks in the layered gneisses with medium- to coarse-grained massive texture.

(c) lenticular or rounded block (several centimeters to meters in diameter) in the quartzofeldspathic gneisses, usually surrounded by granitic leucosome, as may be derived from restite remaining after partial melting of country rocks. Commonly this type of rock is coarse-grained massive granulite (Fig. 14b). Some blocks show zonal structure reflecting the modal variation of minerals. Phologopite-rich variety in the zoned block shows pale brown at the core part and reddish brown at the mantle due to the modal proportion and color of phlogopite (Fig. 14c), while the phlogopite-poor variety is light gray to pinkish gray in color; and

(d) quartzofeldspathic leucocratic fine- to medium-grained thin layers (several centimeters to a few meters) among layered gneiss alternating with mafic granulites, magnetite-quartz gneiss, and other sapphirine-free quartzofeldspathic gneisses (Fig. 14d).

Sapphirine-bearing gneiss and granulite of types (a), (b) and (c) do not contain quartz, while gneiss of type (d) characteristically coexists with quartz. Observed mineral assemblages of the sapphirine-bearing aluminous metamorphic rocks are classified into the following types:

1) sapphirine+orthopyroxene+spinel,
2) sapphirine+orthopyroxene+cordierite+spinel,
3) sapphirine+garnet+orthopyroxene+cordierite+spinel+sillimanite,
4) garnet+orthopyroxene+sapphirine,
5) garnet+orthopyroxene+spinel+sapphirine,
6) sapphirine+spinel+corundum+phlogopite,
7) sapphirine+spinel,
8) garnet+orthopyroxene+sapphirine+cordierite,
9) garnet+sillimanite+sapphirine+quartz,
10) garnet+orthopyroxene+sapphirine+sillimanite+quartz,
11) garnet+orthopyroxene+sapphirine+cordierite+sillimanite+quartz.

All these assemblages except 4) and 5) contain plagioclase and K-feldspar as major phases. Assemblages 4) and 5) contain only plagioclase. Trace and accessory minerals are rutile, zircon, ilmenite and apatite.

The first three assemblages are equivalent to type (a) including characteristically chromium-rich greenish euhedral sapphirine and chromian brownish spinel (Fig. 15a). Partly symplectite intergrowths of sapphirine+orthopyroxene and sapphirine+plagioclase are also observed. Sillimanite occurs only as inclusions in garnet. In assemblage 3), cordierite+orthopyroxene+Kfeldspar+quartz symplectite can also be observed as may be the breakdown product of osumilite (BERG and WHEELER, 1976; AUDIBERT *et al.*, 1993). Assemblages 4) and 5) correspond to type (b), where pale-bluish sapphirine occurs only as an interstitial exsolved phase from aluminous orthopyroxene (up to 11.5 wt% of Al_2O_3). This type of rock is characteristically poor in felsic minerals (Fig. 15b). Assemblages 6) to 8) and 9) to 11) are seen in type (c) and type (d) rocks, respectively. Assemblage 6) in type (c) occurs in the block with zonal structure, where high-magnesian colorless sapphirine porphyroblast includes colorless spinel and corundum surrounded by colorless phlogopite in the core (Fig. 15c). However, less-magnesian bluish sapphirine, coexisting with pale brownish phlogopite, includes green spinel and corundum at the mantle of the block. Small bluish pods of sapphirine-spinel-feldspar granulite (assemblage 7)) occur in the mantle part of this block. Detailed petrographic features of these assemblages are mentioned in HOKADA *et al.* (1999). Type (d) rocks would have formed as normal UHT subsolidus reaction products, where the following reaction textures are observed: sapphirine+garnet+quartz=orthopyroxene+sillimanite or sapphirine+quartz=orthopyroxene+sillimanite+cordierite through the isobaric cooling (IBC: *e.g.* HARLEY, 1998) (Fig. 15d).

3.8. Metamorphosed impure quartzite

Medium- to coarse-grained impure quartzite occurs as thin intercalations within layered gneisses in Units I, II, III and IV (Figs. 6, 7 and 16a). The layers with milky light gray color range from several centimeters to several meters in thickness. Commonly, mineral assemblages of impure quartzite from the Napier Complex are quite variable, as has been reported by many workers (*e.g.* MOTOYOSHI and MATSUEDA, 1987; MOTOYOSHI *et al.*, 1990; ISHIZUKA *et al.*, 1998). Nevertheless, those from Tonagh Island are relatively simple in that quartz is the most prominent component and minor or rare plagioclase, K-feldspar, orthopyroxene and garnet are also contained (Fig. 16b).

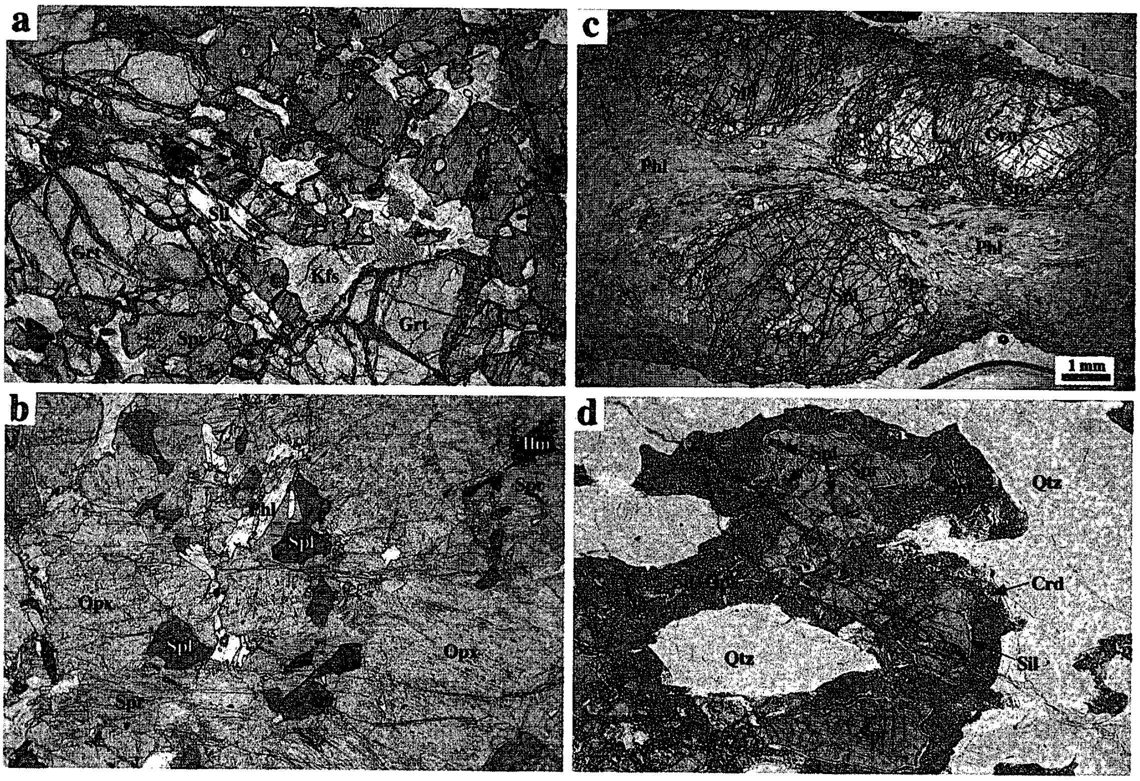

Fig. 15. Photomicrographs of sapphirine-bearing aluminous granulites. a: Chromian green sapphirine-bearing aluminous granulite. Brownish chromian spinel is also present. b: Orhopyroxene-spinel-sapphirine-phlogopite granulite of lenticular block in the felsic gneiss. Note sapphirine occurs at the boundary between orthopyroxene and spinel. c: A sapphirine-spinel-corundum spots characteristically occur in the phlogopite-rich aluminous granulite as block in the felsic gneiss. d: Sapphirine-quartz granulite as a thin layer in layered gneiss. Note that the reaction product of orthopyroxene-sillimanite-cordierite symplectite occurs between sapphirine and quartz. Spl: spinel, Phl: phlogopite, Crn: corundum.

3.9. *Calc-silicate gneiss*

On Tonagh Island, calc-silicate gneisses are found only as boulders ranging from a few centimeters to several meters in diameter around the layered gneiss area of Unit II without any moraine deposits. Therefore, these boulders could be derived from autochthonous origin. According to SHERATON *et al.* (1987), calc-silicate gneisses are very rare in the Napier Complex, such as in the Khmara Bay area (diopside-plagioclase-scapolite±grossular), Mt. Gleadell (diopside-plagioclase-quartz), and the nunatak west of Mt. Bergin (diopside-plagioclase-grossular-scapolite-quartz). Wollastonite-bearing assemblages also were found only at McLeod Nunataks (WARREN and HENSEN, 1983), McIntyre Island (SANDIFORD and WILSON, 1986) and Mt. Pardoe (OSANAI, unpubl. data).

Medium- to coarse-grained calc-silicate gneisses from Tonagh Island are classified into three types as follows (Figs. 16c and 16d):

1) diopside+grossular+quartz+plagioclase,
2) diopside+scapolite+zoisite+plagioclase+quartz,
3) diopside+wollastonite+calcite+quartz.

Accessory minerals are ilmenite, apatite and titanite.

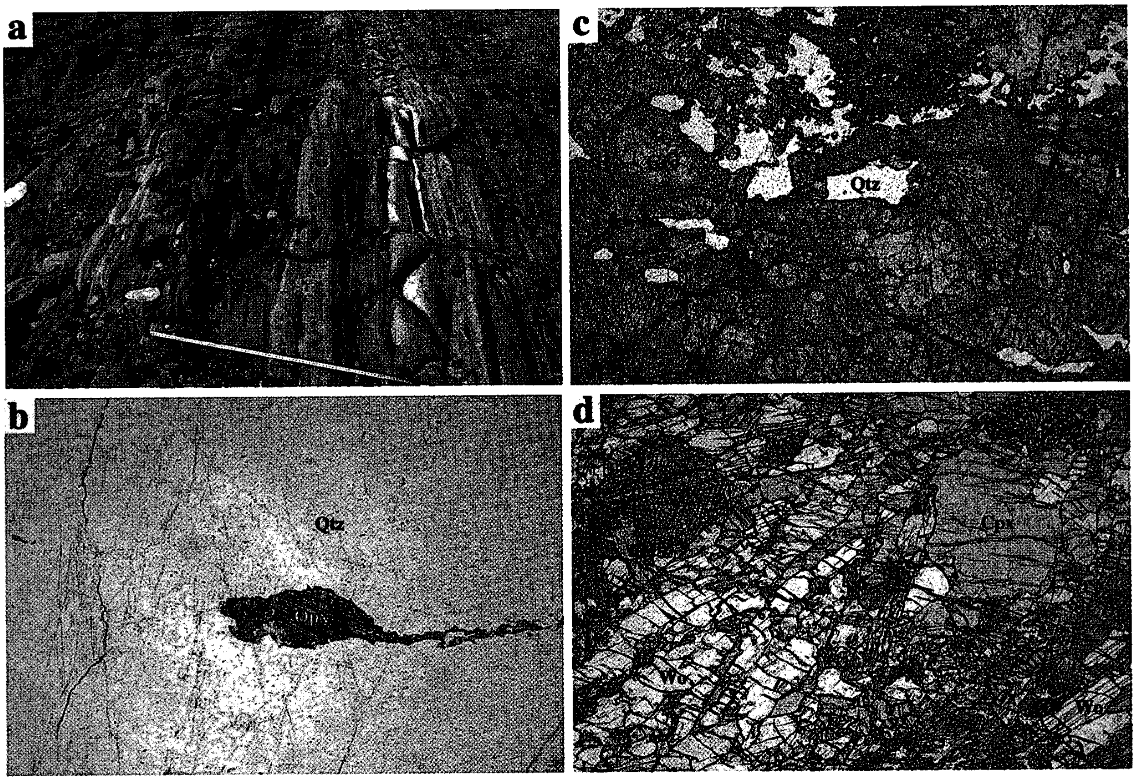

Fig. 16. Mode of occurrence of impure quartzite and photomicrographs of impure quartzite and calc-silicate gneisses. a: Thin intercalations of impure quartzite (pale grayish layers) in the layered gneiss. b: Orthopyroxene-bearing quartzite with secondary biotite. c: Photomicrograph of clinopyroxene (diopside)-grossular-quartz gneiss. d: Clinopyroxene-wollastonite-bearing calc-silicate gneiss.

4. Unmetamorphosed Intrusive Rocks

Unmetamorphosed intrusive rocks from Tonagh Island are subdivided into two types such as alkali-dolerite (so called Amundsen dike: SHERATON *et al.*, 1987) (Fig. 17) and granitic pegmatite. Mappable scale dikes are distributed in Units II, III and IV (Fig. 4), while other small scale intrusive rocks of both types as well as aplitic rock occur throughout Tonagh Island. Intrusive directions of alkali-dolerite, which cut across not only layered sequences of metamorphic rocks but also the tectonic boundary between Units II and III, are NE-SW and WNW-ESE with a conjugate system. Those of granitic pegmatite and aplitic rock strike mainly NE-SW with steep dip. The width of intrusive rocks varies from a few centimeters to several meters (up to 15 m). A chilled margin of the alkali-dolerite (several centimeters in thickness) is well developed, but thin intrusions lack a distinctive chilled margin. On the other hand, the granitic pegmatite is not having any chilled margin. The boundary between the alkali-dolerite and host metamorphic rocks shows no thermal effect, while a retrograde hydration effect with amphibole formation in the host pyroxene-bearing gneisses (several centimeters in width) appears at the boundary between granitic pegmatite and adjacent country rock. The approximate ages of the igneous activities for the alkali-dolerite and granitic pegmatite are considered to be

Fig. 17. Mode of occurrence of unmetamorphosed mafic dike (alkali-dolerite: Amundsen dike), which cuts the host metamorphic foliations in Unit II obliquely. Width of the dike is c.2 m.

c. 1200 Ma (SHERATON and BLACK, 1981) and 500–550 Ma (BLACK *et al.*, 1983), respectively.

The alkali-dolerite dike (Amundsen dike) contains phenocrysts of purplish brown clinopyroxene, biotite and plagioclase with fine-grained groundmass (green amphibole, clinopyroxene and plagioclase). The chilled margin of the rock is characteristically fine-grained and contains the same minerals except biotite. Accessory minerals are ilmenite, magnetite, apatite and sulfide minerals. The granitic pegmatite is mainly biotite-pegmatite containing plagioclase, K-feldspar, quartz and biotite, while part of the pegmatite is muscovite- and garnet-bearing pegmatite instead of biotite.

5. Short Discussion and Concluding Remarks

The geology of the ultrahigh-temperature metamorphic rocks and unmetamorphosed intrusive rocks is described above. The metamorphic rocks are subdivided into five lithologic units owing to the differences of rock assembly and their structures. The conspicuous layered structure of the metamorphic rocks in the Napier Complex, especially in the layered gneisses, is considered to indicate the sedimentary precursor in its origin (*e.g.* SHERATON *et al.*, 1987; ISHIZUKA *et al.*, 1998). However, it is also possible that non-layered or non-stratified rock complex would form remarkable layered structure through strong deformation processes (PASSCHIER *et al.*, 1990: Figs. 1.1 and 3.8). In fact, the quartz-free metamorphic rocks from the layered gneiss have massive and boudinaged structures without any mineral lineations, while most of the quartz-bearing rocks show intense deformation structure including asymmetrical pressure shadow. The layered structure including the direct contact of magnetite-quartz gneiss (metamorphosed BIF) and mafic granulite may show these rocks derived from supracrustal precursor, but it is difficult to determine whether the protolith of the UHT metamorphic rocks from Tonagh Island is of sedimentary origin or not. As shown in Fig. 4, the regional scale geology of Tonagh Island can be divided into the northern area (Units I to IV) and the southern area (Unit V). The geologic succession through the whole area shows upward structural polarity from south to north in each unit except Unit I. Mafic and ultramafic rocks are predominant in the northern area and rare in the southern area. Therefore, it is speculated that the northern and southern areas may be equivalent to lower and upper successions of the early Archean greenstone belt (*e.g.* the Barberton area: TAYLOR and MCLENNAN, 1985), respectively.

The isotopic ages for the UHT metamorphic rocks of Tonagh Island were previously reported by the Sm-Nd isochron method (OWADA *et al.*, 1994) and zircon U-Pb SHRIMP method (SHIRAISHI *et al.*, 1997) using the samples collected by JARE-31 (OSANAI *et al.*, 1990). According to them, the protolith age of the mafic and ultramafic granulites is *c.* 3800 Ma (OWADA *et al.*, 1994) and that of the orthopyroxene-bearing quartzofeldspathic gneiss is 3230–3260 Ma (SHIRAISHI *et al.*, 1997). Then, the *c.* 2500–2550 Ma peak metamorphic event with UHT conditions can be detected by seven points whole-rock isochron using quartzofeldspathic gneisses and ultramafic granulites (OWADA *et al.*, 1994) and by metamorphic overgrowth zircon (SHIRAISHI *et al.*, 1997). The first magmatic activity without any metamorphic evidences recorded in the alkali-dolerite dike (Amundsen dike) of *c.* 1200 Ma (SHERATON *et al.*, 1987). The Amundsen dike cuts both the unit-boundary shear zone and the metamorphosed tholeiitic dike along the shear zone (Fig. 4). The ages of *c.* 1800 Ma (OSANAI *et al.* unpubl. data) and 1500 Ma (OWADA *et al.* unpubl. data) are also determined using garnet-whole rock internal isochrons of Sm-Nd system, which may show the retrograde age passing through the closure temperature of garnet. Therefore, the UHT metamorphic rocks of Tonagh Island were exhumed into the upper part of the crust before *c.* 1200 Ma and after 1800–1500 Ma.

The metamorphic rocks, especially in the garnet-orthopyroxene gneisses, aluminous granulites and gneisses, and mafic granulites, indicate reliable signs of UHT metamorphism. The origin and precurser proposed for the aluminous high-grade metamorphic rocks including sapphirine-bearing granulites have been reviewed by many authors including DROOP and BUCHER-NURMINEN (1984), ARIMA and BARNETT (1984) and PATTISON and TRACY (1991) as follows:

A. Isochemical models
  1. metamorphism of unusual sedimentary bulk chemical composition,
  2. metamorphism of hydrothermal altered basalt or mafic igneous rocks,
  3. metamorphism of ultramafic rocks (troctolitic in composition).

B. Chemical change models
  4. restitic nature remaining after partial melting of pelitic rocks,
  5. high-grade (high-temperature) contact metamorphism and/or metasomatism in between felsic rock and ultramafic rock.

Silica-undersaturated sapphirine-bearing aluminous granulites of types (a), (b) and (c), described above, would have formed as restite and/or metasomatic reaction products under the ultrahigh-temparature condition. The sapphirine and quartz-bearing granulite of type (d) could have also derived from subsolidus reaction under UHT-condition with magnesian and aluminous pelitic composition. In any case, most of the metamorphic rocks from Tonagh Island show the anhydrous mineral assemblages, excepting later retrograde hydration with formation of micas and amphiboles. Why the rocks became into anhydrous? One possibility is that the rocks had experienced at least one-stage (ultra-) high-grade metamorphism with forming the anhydrous bulk chemical composition before the thermal peak (*c.* 2500 Ma). This is supported by the heat-buffer model of VIELZEUF *et al.* (1990). Detailed analyses of the geological and metamorphic evolution of the central part of the Napier Complex including Tonagh Island are still under progress.

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