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Article

Petrographic study on the high-grade metamorphic rocks from the Highland and Kadugannawa Complexes, central Sri Lanka

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Abstract

This study focused on texture of the metamorphic rocks from the central region of Sri Lanka, representing both the Highland Complex and the Kadugannawa Complex. Petrographical investigation of some pelitic and intermediate to basic granulites from the central Highland Complex and some pelitic and mafic rocks from the Kadugannawa Complex of Sri Lanka was carried out.

Among the metapelites, garnet-absent and garnet-bearing as well as spinel-absent and spinel-bearing lithologies were studied. Garnet is completely absent from biotite gneiss, while garnet biotite sillimanite gneiss occurs with or without spinel (hercynite). Garnet contains inclusions of kyanite and sillimanite inclusions, indicating that these rocks have passed the kyanite stability field during the prograde metamorphism. However, the formation process of Zn-rich hercynitic spinel as inclusions in garnet which is free from other mineral inclusions except ilmenite is not clear.

Metamorphosed intermediate to basic rocks include amphibole- and biotite-bearing meta granitoid, charnockitic gneisses and garnet amphibole pyroxene gneiss. Hypersthene is a common mineral in charnockitic gneiss, whereas garnet is absent from some. Rare cpx was found occurring in symplectites with plagioclase in meta granitoid. In contrast garnet contains inclusions of cpx in garnet amphibole pyroxene gneiss, where opx occurs as porphyroblasts. Inclusions of cpx + plagioclase ± quartz in garnet amphibole pyroxene gneiss indicate that the rock was once equilibrated in the high pressure granulite field (> 10 kbar).

Pelitic gneisses in the Kadugannawa Complex are composed of biotite gneisses. These rocks mainly consist of quartz, K-feldspar, plagioclase and biotite. Mafic gneisses include garnet -bearing and -absent rocks. Garnet-absent rocks include hornblende gneiss and migmatitic gneiss. No zoning is observed in the Kadugannawa Complex garnets, but prograde evidence is provided by several inclusion phases in garnet.

Introduction

The island of Sri Lanka is located southeast of India, and is composed predominantly of Precambrian metamorphic rocks. These occur in four major terrains,. the Highland (HC), Wanni (WC), Vijayan (VC) and Kadugannawa Complexes (KC) (after Cooray, 1954). The rocks comprising the HC are mainly granulite facies metamorphic rocks, and those of the VC are of amphibolite facies grade. Both the WC and the KC are composed of upper amphibolite to granulite facies metamorphic rocks. Due to the variety of rock types present and the tectonic juxtaposition of amphibolite and granulite facies terrains in a relatively small area, Sri Lanka is of great interest to workers in the fields of petrology, geochronology and structural geology. In addition, the metamorphic basement of Sri Lanka is a key terrain to understand the evolution of the Gondwana supercontinent, since the island was geographically close to India, Madagascar and East Antarctica, and hence formed one of the main portions of east Gondwanaland.

This study focuses on the petrology of metamorphic rocks from central Sri Lanka, close to Kandy, representing both the HC and the KC (Fig. 1). Petrographic investigations

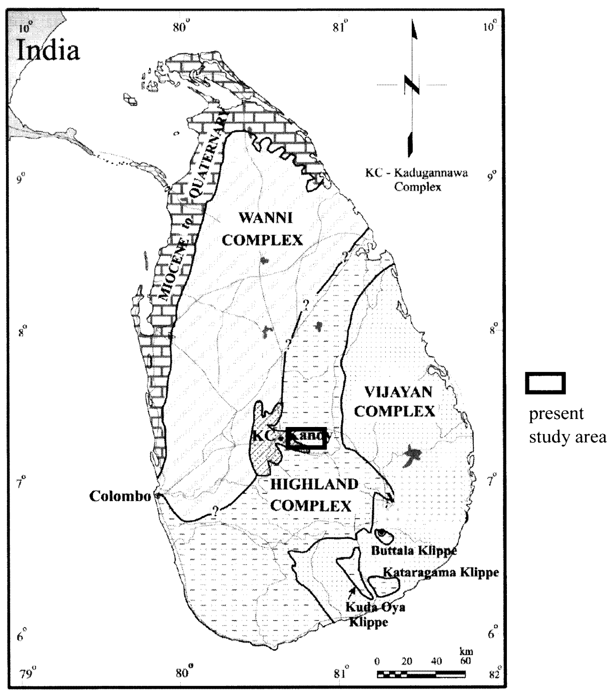

Fig. 1. Simplified geologial map of Sri Lanka showing the Proterozoic crustal units (after Cooray, 1954; figure modified from Mathavan and Fernando, 2001).

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of pelitic and intermediate to basic granulites from the central HC and pelitic and mafic rocks from the KC were carried out. Samples were collected systematically from both the HC and the KC, which show differing metamorphic grades, depending on lithology.

Outline of the Geology of Sri Lanka

Regional Geology

The Highland Complex (HC: 2-3 Ga Nd model age province) consists of an association of interlayered, predominantly granulite facies, granitoid (charnockitic) gneisses, clastic to calcareous shallow water metasediments, and post tectonic granitoids. The gneisses are intruded by mafic dykes that are now structurally concordant with their host rocks. The Wanni Complex (WC: 1-2 Ga Nd model age province) is an upper amphibolite to granulite facies assemblage of granitic and charnockitic gneisses, migmatites, minor clastic metasediments, and late to post tectonic granites. The Vijayan Complex (VC: 1-2 Ga Nd model age province) is an upper amphibolite facies suite of granitoid gneisses, including augen-gneisses, with minor amphibolite layers, quartzites, and calc-silicate rocks. The Kadugannawa Complex (KC: ~890-1006 Ma U-Pb zircon age) is an upper amphibolite to granulite facies calcalkaline suite of hornblende and biotite-hornblende orthogneisses of gabbroic, dioritic and trondhjemitic composition, along with interlayered granodioritic to granitic gneisses, charnockites and minor shallow water metasediments (Kroner et al., 2003). This complex also contains the metamorphosed and migmatized equivalents of a mafic to ultramafic complex named the Kandy Layered Intrusion (Voll and Kleinschrodt, 1991). The entire assemblage is folded into large doubly plunging synforms and antiforms.

Most of the layering in the meta-igneous and meta-sedimentary rooks of the HC, the WC, and the KC is of metamorphic and tectonic origin, and original intrusive relationships are no longer preserved (Kroner et al., 2003). The HC/VC contact is a low-angle thrust, with the HC thrust eastwards over the VC (Vithanage, 1985; Kroner, 1986; Keinschrodt, 1994, 1996; Tani and Yoshida, 1996). Several HC klippen are preserved in the VC terrain of SE Sri Lanka. The boundary between the KC and the HC is also a thrust, with the KC thrust over the HC (Kehelpannala, 1991, 1997; Kriegsman, 1993, 1994). In contrast, the boundary between the predominantly intermediate to mafic rocks of the KC and the WC is not well defined, due to lack of a clear structural break between these two units. In terms of their structural and metamorphic evolution, the KC and the WC display similar features, suggesting that they are part of the same crustal unit, with the KC representing a deeper crustal level than the WC (Kehelpannala, 1997). The boundary between the WC and the HC is also poorly defined, as again there is no clear structural break between them. However, the isotopically defined (Nd mean crustal residence ages) model age boundary appears incompatible with the structural trends in the SW part of the island (Kroner et al., 2003).

Structural Geology

Vithanage (1959) and Cooray (1954, 1961) considered the large scale folds to be evidence for a major deformation which affected the basements rocks of Sri Lanka. The first detailed structural geology study was that of Berger and Jayasinghe (1976), who recognized three major deformational events (D 1–D 3) in the Highland Complex. They interpreted that D 1 and D 2 formed the major L-S fabrics, and the large scale folds were formed by D 3. Sandiford et al. (1988) identified three different phases of folding, whereas Yoshida et al. (1990) recognized four main deformational events. The latter study also identified micro-structural features such as oriented inclusion trails in garnet porphyroblasts from metapelites, and interpreted these as predating the compositional layering.

Metamorphism

Petrologic research on Sri Lankan metamorphic rocks has concentrated on metabasaltic–gabbroic to intermediate rocks (Sandiford et al., 1988; Schumarcher et al., 1990; Schumarcher and Faulhabar, 1994), acidic charnockites (Prame, 1991 a) and metamorphosed pelitic rocks (Prame, 1991 b; Hiroi et al., 1994; Raase and Schenk, 1994). These studies have established a P/T zonation across the Sri Lankan granulite terrain. Pressures and temperatures decrease from 9-10 kbar and 830℃ in the east and southeast to 5-6 kbar 700℃ in the northwest (Faulhaber and Raith, 1991; Schumarcher and Faulhaber, 1994). The P-T path for pelitic rocks, based on the sequence kyanite (inclusions in garnet) followed by sillimanite, and followed by andalusite, is clockwise (Hiroi et al., 1990; Raase and Schenk, 1994). In contrast, reaction textures involving pyroxenes, plagioclase, garnet and quartz in some metamorphosed igneous rocks (Schumarcher et al., 1990; Prame, 1991 a) and high temperatures (>900℃) from pyroxene exsolution (Shenk et al., 1988) have been cited by these workers as an indication of isobaric cooling, which is apparently not documented in the pelitic rocks and occurred before uplift.

Osanai (1989) first reported saphirine-bearing granulites from the HC of Sri Lanka. Other UHT assemblages have been studied subsequently by Kriegsman (1991), Kreigsman and Schumarcher (1999), Osanai et al. (2000, 2003), Sajeev et al. (2003), Sajeev and Osanai (2002, 2003, and 2004a). They reconfirmed the UHT metamorphism, above 1050℃ and 11-12 kbar. Sajeev and Osanai (2002, 2004a) presented evidence for isobaric cooling from 1150℃ and 12 kbar, which was followed by a multi-stage evolution. These P/T conditions are in contrast with other granulites in the surrounding area, which preserve a maximum of 850-900℃ and 9-10 kbar, and were metamorphosed during the Pan African tectonothermal event. Sajeev and Osanai (2004b) also reported the occurrence of osumillite from Sri Lanka, and its implications for UHT metamorphism. However, due to a lack of geochronological data, they could not distinguish whether it was a product of the Pan African metamorphism or a relict of an older metamorphic event.

Schenk et al. (1988) reported temperatures above 900℃ for the mafic granulites based on orthopyroxene exsolution in clinopyroxene, which they interpreted as evidence for isobaric cooling from higher temperatures. Sajeev and Osanai (2004a) argued that the UHT granulites of the HC probably evolved along an anticlockwise path.

Petrography

Textures of metamorphic rocks

Highland Complex

(1) Pelitic granulites

Two types of pelitic granulites were identified depending on the presence or absence of garnet (Table 1). These are garnet biotite sillimanite gneiss and biotite gneiss. In biotite gneiss, garnet is completely absent. The pelitic granulites have gneissose foliation defined by preferred orientation of biotite and sillimanite, with alternation of layers composed of quartz and feldspar.

Garnet commonly occurs as subhedral to anhedral porphyroblasts up to 8 mm in diameter, and contain inclusions of biotite, sillimanite, ilmenite, quartz and rarely hercynitic spinel and kyanite. In some pelitic granulites, garnet porphyroblasts are replaced by sillimanite and/or biotite, or symplectite of biotite and quartz at the rim (Fig. 2). Biotite and quartz inclusions are mainly found in cores, whereas sillimanite occurs in the mantle.

Both kyanite and sillimanite occur in the spinel-bearing garnet biotite sillimanite gneisses. Rare kyanite occurs only as inclusions in garnet (Fig. 3). Sillimanite mainly occurs as very fine needles, as inclusions in garnet (Fig. 3). Matrix sillimanite is usually prismatic and medium-grained, and shows typical transverse fractures. In addition, fibrolite occurs associated with hercynite symplectites. Aggregates of sillimanite collectively form the shape of a relict anhedral porphyroblast interpreted to be pseudomophic sillimanite after kyanite (Figs. 3c and d). These occur in garnet porphyroblasts.

Hercynitic spinel occurs as rare inclusions in garnet porphyroblasts, defining a lineation (Fig. 2a) in garnet biotite sillimanite gneiss. Development of hercynitic spinel symplectites associated with fibrolite at garnet rims and along fractures was also observed (Figs. 3c and e) in the same sample.

Biotite in the matrix forms a preferred orientation, and is also found as random grain overgrowths replacing garnet rims (Fig. 3f). Plagioclase grains show well developed polysynthetic twinning in many samples. In spinel-absent garnet biotite sillimanite gneiss, exsolution lamellae of K-feldspar occur in plagioclase host, forming antiperthite texture, together with fine quartz intergrown in the host (Fig. 2c). Quartz commonly occurs both as inclusions in garnet and in the matrix with plagioclase and K-feldspar. Ilmenite and rutile occur both as inclusions in garnet as well as in the matrix with other accessory phases such as zircon and monazite.

(2) Mafic granulites

These rocks are generally coarse grained and poorly foliated. The mafic granulite studied here is a garnet hornblende pyroxene granulite consisting mainly of garnet, cpx, opx, pargasitic amphibole, plagioclase, quartz, and titanite (Table 1).

Garnet occurs as subhedral or anhedral porphyroblasts up

Table 1. Mineral assemblages of the metamorphic rocks from the HC and the KC.

	Sample no.	grt	qtz	plg	Kfls	sill	ky	bt	amp	opx	cpx	mus	spl	ttn	grp	ilm	rtl	mt	zrc	mnz
Highland Complex																				
pelitic granulites																				
gt bt sill gneiss	8,8-1	+	+	+	+	+		+								+	+	+	±	
	14A,14A3	+	+	+	+	+	+	+					+			+	+		±	+
bt gneiss	10,16		+	+	+			+								+	+	+	+	
	19,29		+	+	+			+								+	+		+	
basic granulites																				
gt hb py. gneiss	14B, 14B1	+	+	+						+	+			+		+	±	+		
	14B2	+	+	+				+	+	+						+	+	±		
intermediate granulites																				
charnockitic gneiss	9		+	+	+			+	+	+						+	+	+		
	12A, 11,17	+	+	+	+			+		+						+	+	+	±	±
metagranitoid	6,6C	+	+	+	+			+	+		±			+	+	+	+		±	±
Kadugannawa Complex																				
pelitic gneiss																				
gt bt gneiss	50	+	+	+	+			+								+		+	±	
biotite gneiss	15		+	+	+			+				±				+			±	±
mafic gneiss																				
hb gneiss	2,2B,51,13			+	+			+	+							+		+		
bt gneiss	51	+	+	+	+			+	±									+		
migmatitic gneiss	1,3		+	+	+			+	+							+		+	±	±

+: present in major amount, ±: present in minor amounts

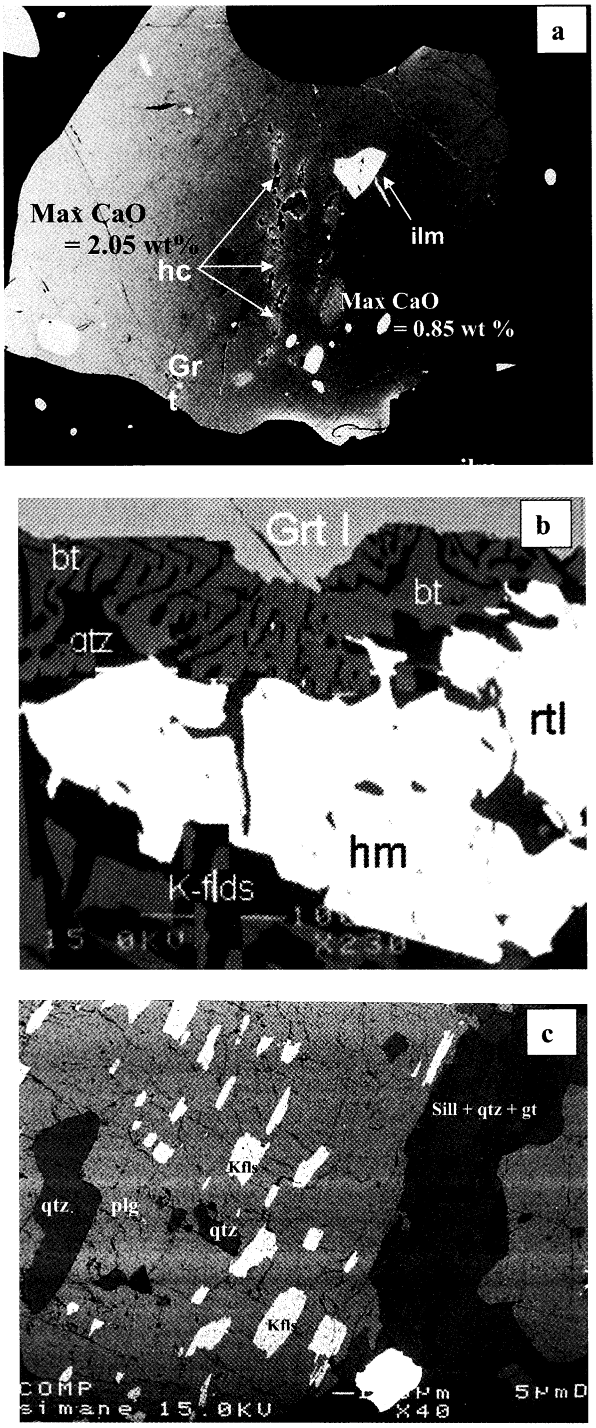

Fig. 2. Back-scattered electron image (BSE). (a) Chemical heterogeneity in garnets with hercynite + ilmenite inclusions. (b) Biotite + quartz symplectites after garnet, garnet biotite sillimanite gneiss, HC. (c) Antiperthite texture, garnet biotite sillimanite gneiss, HC.

to 15 mm in diameter. Garnet porphyroblasts contain numerous inclusions of plagioclase, quartz, titanite, ilmenite and hematite defining poikiloblastic texture. Some samples also contain rare cpx –plagioclase symplectites (Fig. 3g) within the outer cores of the garnet porphyroblasts. These cpx symplectite-bearing garnet porphyroblasts show evidence for rotation during deformation, as indicated by sigmoidal inclusion trails of quartz and plagioclase. Garnet porphyroblasts are partially replaced by secondary biotite and ilmenite at their margins.

Both orthopyroxenes and clinopyroxenes occur in these rocks. Orthopyroxene occurs as porphyroblasts up to 5 mm in size and as both fine grained and coarse grained symplectites with plagioclase (Figs. 3i, j and k). Coarse grained opx symplectites are also replaced by pargasitic amphibole (Fig. 3l). Opx porphyroblasts contain biotite, plagioclase and opaque mineral inclusions, and are later replaced by secondary biotite and ilmenite (Fig. 3h). Clinopyroxene was found in the symplectite included in the garnet porphyroblasts as well as rare inclusions in garnet (Fig. 3m). Cpx is totally absent from the matrix. Both cpx and opx are free of exsolution lamellae.

Amphibole grains texturally postdate the garnet porphyroblasts, as evident even at hand specimen scale, by the foliation defined by amphibole wrapping around the garnet. These amphiboles are pargasite.

Plagioclase occurs as porphyroblasts, inclusions in garnet, and in symplectites with opx after garnet. Plagioclases in the matrix are mostly untwinned but rarely show lamellar twinning and oscillatory zoning. These grains contain fine exsolution blebs of K-feldspar (Fig. 3n).

Due to strong retrogression, chlorite, quartz, and hematite assemblages are found between garnet porphyroblasts. Opaque phases include magnetite and ilmenite.

(3) Intermediate granulites

Intermediate granulites include charnockitic gneiss, hornblende and biotite bearing metagranitoid. Charnockitic gneiss usually has a characteristic ‘greasy’ lustre or appearance in hand specimen, exhibiting weak gneissic foliation. In contrast, metagranitoid shows a preferred orientation of minerals including hornblende, biotite and ribbon quartz. This rock type also shows a strong lineation defined by graphite. Many quartz grains are highly stretched and show subgrain boundaries.

Garnet occurs as subhedral to anhedral porphyroblasts up to 5 mm in size, but is absent from some charnockitic gneisses (Table 1). These garnets contain quartz and plagioclase inclusions. Many garnets are replaced by biotite. Some garnets show breakdown textures forming fine opx grains and reaction rims of plagioclase. In contrast, garnet porphyroblasts in metagranitoid are free from inclusions and occur in anhedral grains up to 3-5 mm in size. Some garnets are completely broken down to form cpx-bearing symplectites, associated with amphibole, biotite and opaques (Fig. 3o).

Hypersthene is a common mineral in charnockitic gneiss, in which it occurs as anhedral porphyroblasts. Rare cpx was found occurring in symplectites with plagioclase in metagranitoid, where opx is absent. Opx occurs as porphyroblasts and is also associated with plagioclase rims

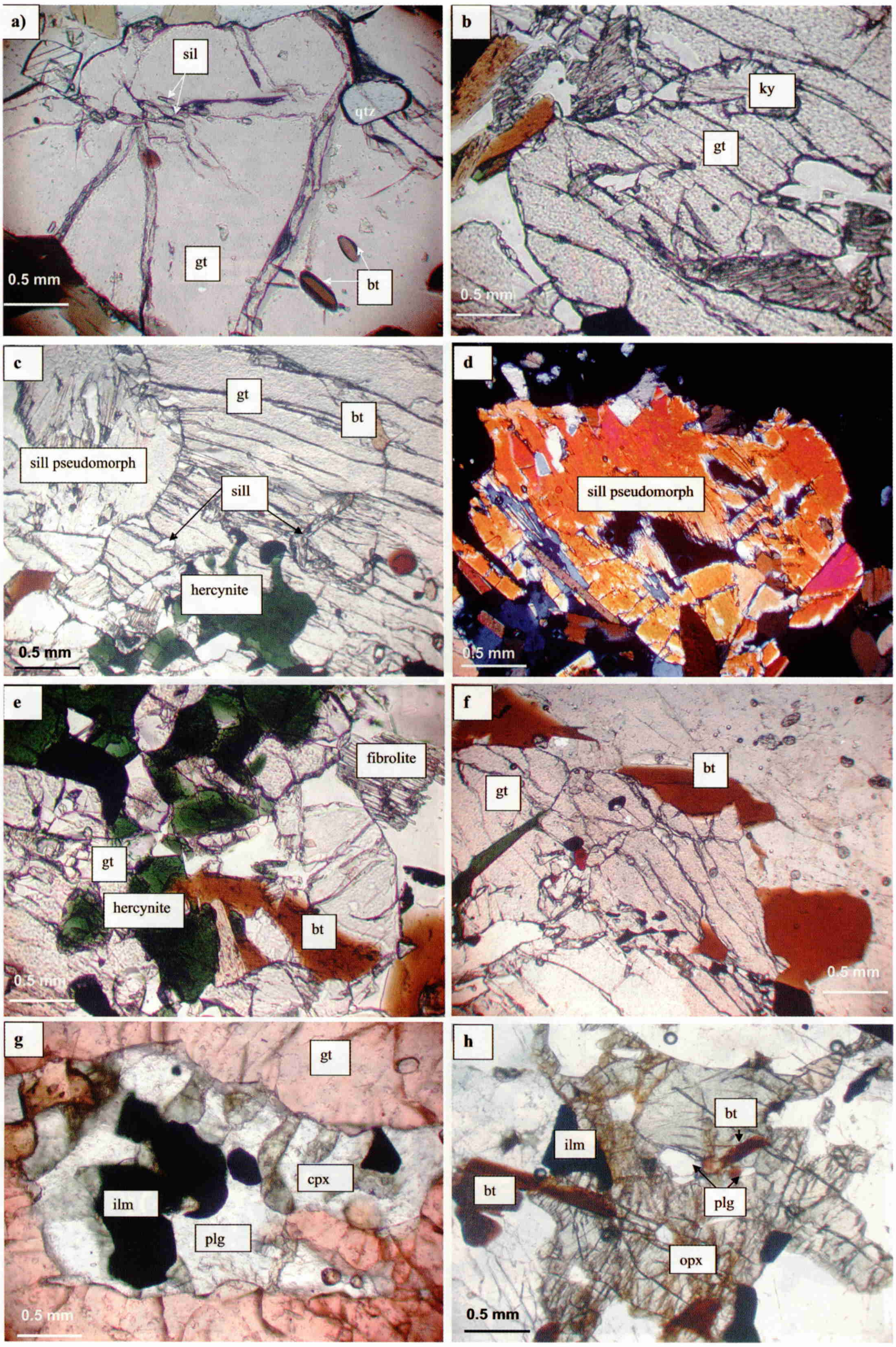

Fig. 3. (Part 1): Photomicrographs of the metamorphic rocks. (a) Occurrence of fine biotite, quartz and sillimanite needles as inclusions in garnet (sample 8), HC. (b) Occurrence of rare kyanite inclusions and sillimanite pseudomorph after kyanite close to rim of garnet (sample 14A), HC. (c) Inclusions of biotite, sillimanite and sillimanite pseudomorph after kyanite from garnet core to rim and hercynitic spinel after garnet (sample 14A). (d) Cross nicol view of the sillimanite pseudomorph shown in Fig. 3 c. (e) Growth of hercynite symplectites and fibrolite associated with garnet fractures and rims (sample 14A), HC. (f) Replacement / overgrowth of garnet rims by biotite (sample 14 A), HC. (g) Relict symplectite of cpx and plagioclase within garnet porphyroblast, mafic granulite (Sample 14B), HC. (h) Opx porphyroblasts contain plagioclase and biotite inclusions. Also, opx is replaced by biotite and ilmenite (Sample 14B), HC.

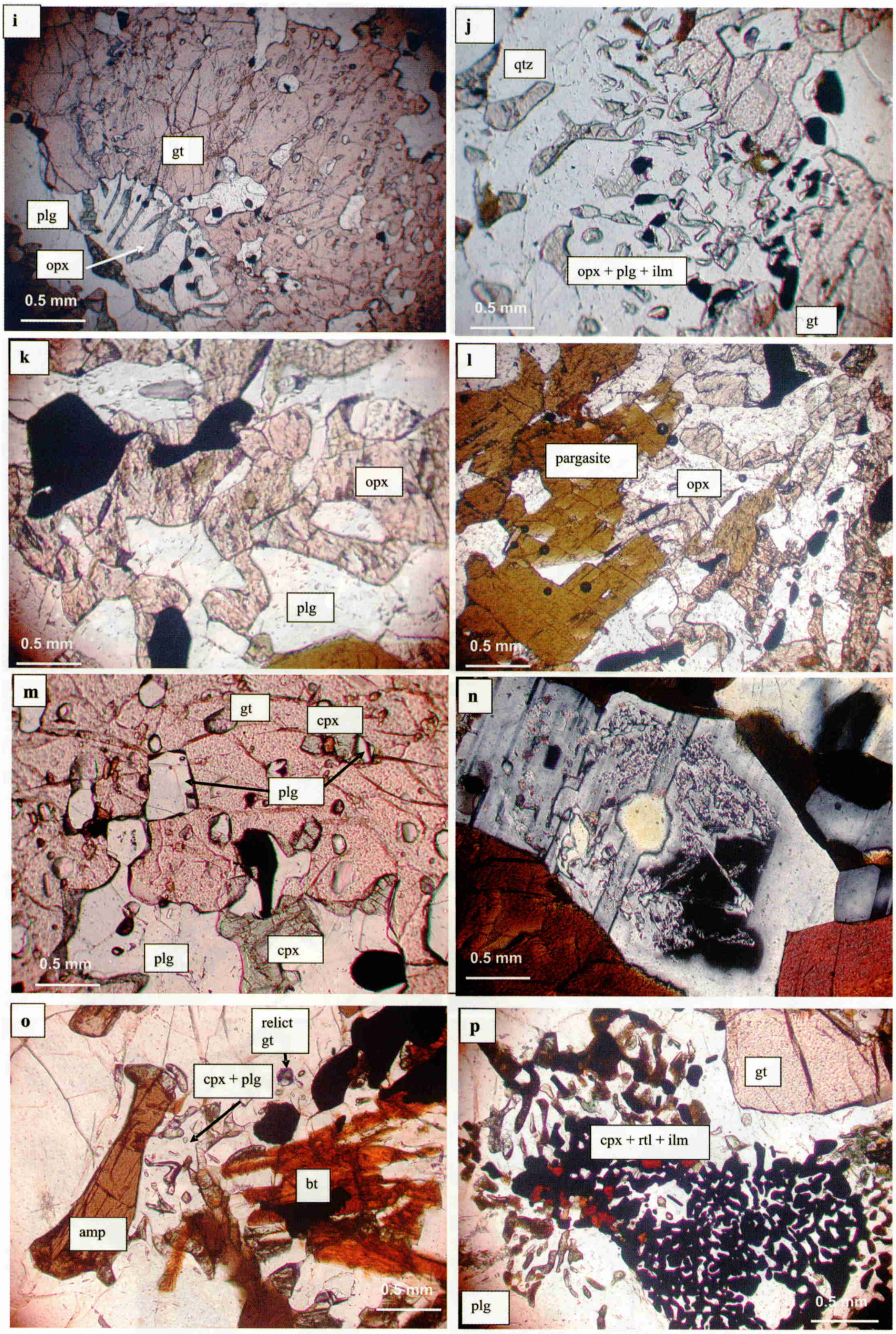

Fig. 3. (Part 2): (i) Opx symplectites with plagioclase at garnet rims (Sample 14B), HC. (j) Fine grained opx + plg + ilm symplectites with plagioclase after garnet (Sample 14B), HC. (k) Coarse grained opx symplectites with plagioclase (Sample 14B), HC. (l) Coarse grained opx symplectite is replaced by pargasite (Sample 14B), HC. (m) Cpx + plagioclase inclusions in garnet (Sample 14B), HC. (n) Plagioclase crystal with quartz inclusions showing lamellar twinning and oscillatory zoning with exsolution blebs of K-feldspar (Sample 14B) HC. (o) Formation of cpx + plagioclase symplectites (Sample 12A), HC. (p) Occurrence of cpx + rtl + ilm symplectite after garnet (Sample 6C), HC.

after garnet in charnockitic gneiss.

In both rock types, plagioclase occurs in a variety of textural settings, such as porphyroblasts, inclusions in garnet, and as coronae on garnet. Generally, plagioclase shows albite twining and contains fine quartz grains. K-feldspar and quartz occur in excess in both lithotypes.

Amphiboles occur only in metagranitoid, as porphyroblasts mainly associated with porphyroblastic titanite.

Charnockitic gneisses show retrograde alteration products of the greenschist facies such as chlorite and calcite. Symplectite of cpx + rtl + ilm after garnet was also observed in the metagranitoid (Fig. 3p).

Opaque minerals including ilmenite, magnetite and rutile occur in the charnockitic gneiss, whereas ilmenite is the only opaque phase in the metagranitoid.

Kadugannawa Complex

(1) Pelitic gneiss

Pelitic gneisses in the Kadugannawa Complex are represented by biotite gneisses. These rocks consist of quartz, K-feldspar, plagioclase, and biotite with accessory minerals including muscovite, rutile, ilmenite, and zircon (Table 1). In some samples garnet occurs and in others it does not. These rocks also show a gneissose foliation defined by quartz, feldspar, and biotite flakes.

Garnet commonly occurs as porphyroblasts up to 5 mm in diameter. These garnet porphyroblasts include biotite and quartz. In some pelitic gneisses, garnet porphyroblasts are replaced by biotite at the rim. Quartz is present both as inclusions in garnet and in the matrix with plagioclase and K-feldspar. Biotite occurs forming a preferred orientation in the matrix as well as overgrowths on garnet porphyroblasts and as inclusions in garnet. Plagioclase rarely shows polysynthetic twinning in these rocks. Rare muscovite was found in the KC rocks and ilmenite occurs in the matrix. Quartz and K-feldspar are also found in excess.

(2) Mafic gneiss

Mafic gneisses in the KC include garnet-bearing and garnet-absent rocks (Table 1). Rocks lacking garnet include hornblende gneiss and migmatitic gneiss. These are generally coarse grained and poorly foliated.

Garnet-bearing rocks consist of plagioclase, quartz, biotite, rutile and ilmenite. Garnet occurs as porphyroblasts up to 3 mm in diameter. Garnet porphyroblasts contain quartz as inclusions, and are replaced by biotite overprints at their margins. Garnet-absent mafic rocks contain hornblende, quartz, plagioclase, biotite, and ilmenite. Some garnet-absent mafic rocks lack quartz, with their dominant minerals being hornblende and plagioclase. Rare cpx is also found as porphyroblasts in some garnet-and hornblende-absent rocks. Some rare hornblende inclusions also occur in plagioclase. These rocks exhibit granoblastic polygonal texture.

Mineral Reactions

Highland Complex

(1) Pelitic gneisses

Different inclusion assemblages were observed in garnet porphyroblasts in the HC gneisses. These include garnets with biotite, quartz and sillimanite inclusions; garnets with rare kyanite inclusions; and garnets with spinel + ilmenite inclusions. Quartz mostly occurs in the cores whereas biotite and sillimanite occur in the mantles. Rare kyanite occurs in the mantles and spinel and ilmenite inclusions occur in the cores, defining an approximate linear pattern.

According to the inclusion phases of quartz, biotite and sillimanite in garnet and the K-feldspar occurring in the matrix, the following fluid-absent dehydration melting reactions can be deduced to form garnets:

biotite + sillimanite + quartz = garnet + K-feldspar + L (1)

There is no evidence preserved to infer the formation of initial sillimanite in the matrix. However, it can be formed while passing through the amphibolite–granulite boundary by the reaction:

Mg-rich chlorite = biotite + Al-silicate (2)

At higher P-T conditions, increasing anorthite in plagioclase can lead to continuous garnet formation by:

biotite + kyanite + quartz + plagioclase
= garnet + K-feldspar + L. (3)

Evidence for this reaction is that garnet bears rare inclusions of kyanite, suggesting that the rock entered the kyanite stability field with increasing pressure. The occurrence of these dehydration reactions further suggests that temperature increased during garnet growth. Production of the melt is recorded by the presence of quartz + feldspar ± garnet-bearing leucosomes observed at outcrop scale.

The formation of Zn-rich hercynitic spinel is not so clear. However, Zn-rich hercynite usually crystallizes at higher P-T ranges (Dasguptha et al. 1995). Occurrence of hercynite together with ilmenite as inclusions in some garnet may account for the retrograde action of the reactions.

garnet + aluminosilicate = spinel (hercynite) + quartz (4)

This reaction occurs at higher oxygen fugacity, and the presence of ilmenite associated with spinel probably indicates relatively higher oxygen fugacity near peak metamorphism.

Kyanite inclusion-bearing garnet breaks down to form hercynitic spinel symplectites associated with fibrolite. This spinel symplectite can be a product from reaction (4).

In many specimens, ilmenite or rutile occur associated with sillimanite and in some also as inclusions in garnet, suggesting the biotite consuming reaction:

biotite + sillimanite + quartz
= garnet + K-feldspar + ilmenite or rutile + H_2O (5)

A similar reaction was also proposed by Hiroi et al. (1994) for the HC metapelites.

Symplectite textures show much clear evidence for a retrograde P-T path. In some rocks, biotite + quartz symplectites are formed between garnet and K-feldspar in the HC pelitic gneiss, indicating the reaction:

garnet + L = biotite + plagioclase + quartz (6)

Secondary biotite overgrowths are developed on garnet porphyroblasts as well as along the cracks in garnet. Secondary biotite also occurs at grain boundaries, and in some rocks fine-grained sillimanite, biotite, and quartz are grown around garnet grains, suggesting reversal of reaction (1) during post-peak cooling.

Peak metamorphic assemblage:

Garnet + sillimanite + plagioclase + K-feldspar
+ quartz ± hercynite (in HC)

(2) Basic to intermediate granulites

Several stages of opx growth can be identified in the HC basic to intermediate gneisses, such as porphyroblastic and symplectitic opx. Inclusions of cpx in garnet porphyroblasts infer the growth of garnet postdates the cpx. However, cpx is absent from the matrix, suggesting that it is consumed while cooling, to form calcic amphiboles by the reactions:

garnet + cpx + opx + L = amp + plg + qtz (7)

cpx + opx + plg + L = amp (pargasite) (8)

Retrograde evidence is found in the form of fine grained opx and plg symplectites around garnet porphyroblasts. Breakdown of garnet is recorded by the formation of opx – plg symplectites between garnet and quartz. There are two modes of occurrence of symplectites of opx. One is fine-grained, and the other is a coarse-grained symplectite of opx with plagioclase. These textures can be explained by the following symplectite-forming reaction which occurred during decompression:

garnet + quartz = opx + plagioclase (9)

This is a reaction indicative of decompression in basic granulites (Harley, 1989). In places, fine-grained opx and plg symplectites are associated with fine grained magnetite ± ilmenite.

The coarse-grained opx symplectite is partially replaced by pargasitic amphibole, suggesting the following hydration reaction occurred during further retrogression:

cpx + plagioclase + opx + H_2O
= Ca amphibole (pargasite) (10)

Al_2O_3 content in opx varies considerably, with maximum contents in the order:

Coarse-grained opx symplectite < opx porphyroblasts
(Al_2O_3 1.19%) (Al_2O_3 2.32%)
< fine-grained opx symplectite
(Al_2O_3 3.12%)

Formation of cpx symplectite as a relic in a garnet porphyroblast and also rare cpx inclusions in the same garnet may be inferred by a reaction which occurred during initial cooling after the emplacement of the parent magmatic protolith:

opx + plg = garnet + cpx + quartz (11)

This texture is rarely preserved in some garnet porphyroblasts.

Plagioclase reaction rims over garnet porphyroblasts were observed in charnockitic gneisses. Some opx was also found associated with these plagioclase rims. This can be explained by reaction (8), which occurred during the decompression.

Secondary biotites are developed over the cracks of garnet and opx porphyroblasts, suggesting hydration reactions during the retrogression from high- temperatures. Further retrogression is identified by the growth of secondary calcite and chlorite assemblages associated with albite.

Symplectite textures are also developed extensively in the metagranitoids. Symplectite of cpx + rutile + ilmenite after garnet is the main assemblage observed. Garnet breakdown textures forming opx symplectites in the presence of amphibole and plagioclase are also found.

Kadugannawa Complex

(1) Pelitic gneisses

In contrast, only one garnet inclusion assemblage was recognized in the KC rocks, comprising biotite and quartz inclusions. According to the observations of inclusions in garnet, and the presence of K-feldspar in the matrix, the following dehydration reaction to form garnet can be inferred for the KC pelitic gneiss:

biotite + plagioclase + quartz
= garnet + K-feldspar + H_2O (12)

These dehydration reactions suggest temperature increase during garnet growth.

There is no evidence for any decompressional textures such as symplectites or reaction rims in these rocks. However, secondary biotites are overprinted on garnet porphyroblasts, partially replacing garnet in some places, suggesting reversal of reaction (12) during uplift.

(2) Mafic gneiss

The dominant minerals found were garnet, amphibole and plagioclase. Rare cpx porphyroblasts also occur in some rocks. Inclusions of biotite and plagioclase and the presence of ilmenite in the matrix suggest the reaction:

biotite + plagioclase + quartz
= cpx + garnet + K-feldspar + L (13)

Due to retrogression, chlorite + qtz assemblages are found surrounding garnets.

There is also no evidence for any decompressional textures like symplectites or reaction rims in these mafic gneisses. Retrograde evidence is mainly inferred by garnet breakdown textures, forming aggregates of biotite and opaque minerals. In addition, secondary biotite shows overprinting textures on garnet, suggesting reversal of reaction (13) during uplift.

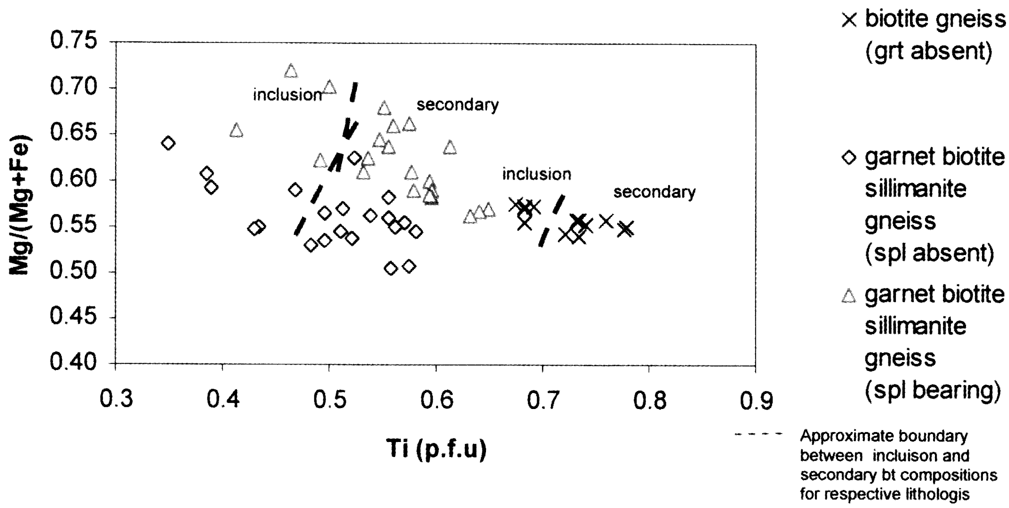

Fig. 4. Composition of biotite with textural settings. inclusion- inclusions in garnet; secondary- late biotite overprints on garnet.

Mineral Chemistry

Chemical compositions of the constituent minerals of the metamorphic rocks were examined using a JEOL JXA-8800 M electron probe microanalyzer at Shimane University. The analytical conditions used were 15 kV accelerating voltage, 25 nA probe current and 5μm probe diameter. Representative mineral analyses are given in Tables 2 to 6.

Pelitic gneiss–Highland Complex

(1) Garnet:

Different generations of garnet are present in the HC pelitic gneiss, based on inclusion patterns. These are garnets which contain biotite, sillimanite and quartz; those with rare kyanite inclusions; and those with hercynite and ilmenite inclusions. Garnets in these rocks represent almandine-rich compositions (up to X_{Alm} = 0.8), where X_{Prp} decreases slightly from core to rim. The grossular component also has a similar trend, with maximum ratio of X_{Grs} = 0.03 preserved in the porphyroblastic cores. Garnets which are rimmed by ilmenite and hematite have the highest almandine contents. X_{Prp} varies from 0.4 to 0.2, whereas X_{Grs} varies from 0.05 to 0.001.

In addition, some garnets which contain rare hercynite + ilmenite inclusions show compositional heterogeneity with respect to Ca concentration. These hercynitic spinels are rich in Zn, with maximum ZnO = 7.15 wt. %, inferring that they formed at higher temperature (Dasgupta et al., 1995).

(2) Plagioclase

Plagioclase compositions range from oligoclase to andesine. Anorthite content varies in the range from X_{an} = 0.23- 0.35. There is no significant difference in anorthite content between the plagioclase inclusions in garnet and matrix plagioclases; however garnet-absent biotite gneiss represents the minimum anorthite content.

(3) Spinel

Spinel is Fe rich, having the hercynite component calculated as Fe / (Fe + Mg) = 0.67–0.65. Inclusion spinel has higher Zn content (max. = 7.15 wt. %) than retrograde spinel, for which the maximum Zn content is 5.9 wt. %.

(4) Kyanite

Kyanite occurs as rare inclusions in garnet porphyroblasts and contains ~1 wt % of FeO.

(5) Sillimanite

Sillimanite contains 1 wt % FeO and 0.1 wt. % Cr_2O_3.

(6) Biotite

Biotites contain about 4.5–6.8 % wt. % TiO_2, and Fe/ (Fe + Mg) varies from 0.52 to 0.64. Mg ratio vs Ti (p.f.u) varies depending on the textural setting. That is, inclusion biotites in garnet and secondary biotite overprints on garnet have contrasting compositions, as shown in Fig. 4. In garnet biotite sillimanite gneiss, biotite occurs as symplectites with quartz, after garnet . These biotites have lower Mg. The secondary biotites have higher Ti contents than inclusion phases, for a single lithology. In contrast, secondary biotites have lower Mg than inclusion biotites for each lithology. Spinel-bearing lithologies have higher Mg contents in biotites, whereas garnet-absent lithologies have higher Ti contents.

(7) Opaque minerals

Rutile contains from 6.2- 8.9 wt. % FeO and up to 0.1 wt. % of Cr. Ilmenite contains up to 1.5 wt. % MgO, 0.15 wt. % MnO and 0.35 wt. % Cr_2O_3, while magnetite contains up to 0.43 wt. % Cr_2O_3.

Mafic granulites–Highland Complex

(1) Garnet

Garnets in these rocks are almandine-rich. Garnet composition is highly variable among these rocks, with the highest almandine content (X_{Alm} = 0.95) in garnets of the meta-granitoids. Almandine content decreases from the core to the rim in garnet amphibole pyroxene gneiss and inclusion-free fine grained garnets of charnockitic gneiss, but increases in porphyroblastic garnets of charnockitic

Table 2. Chemical compositions of constituent minerals in basic granulites in the HC.

Mineral	Garnet			Orthopyroxene			Cpx	Amphibole	Plagioclase			Biotite	Chlorite
Sample	14B	14B1		14	14B1	14B2	14B	14B2	14B	14B1	14B2	14B1	14B2
	core	core	rim	por	f-sym	c-sym							
SiO_2	37.50	38.07	38.29	49.59	50.74	51.13	50.51	42.89	46.41	53.88	47.90	35.01	37.10
TiO_2	0.04	0.03	0.03	0.10	0.08	0.04	0.25	1.94	0.00	0.00	0.00	5.50	2.25
Al_2O_3	20.80	20.31	20.94	1.51	2.42	0.70	1.94	11.16	33.66	28.35	33.07	14.41	9.61
FeO*	30.42	31.51	29.15	32.06	28.07	29.48	13.40	16.28	0.30	0.13	0.25	16.27	16.07
MnO	1.42	0.69	0.61	0.38	0.11	0.30	0.28	0.09	0.02	0.00	0.08	0.00	0.12
MgO	3.60	5.07	5.30	15.50	18.79	17.11	11.26	10.96	0.01	0.02	0.01	12.06	8.68
CaO	6.09	4.30	4.80	0.61	0.23	0.54	21.94	11.64	18.69	11.48	16.47	0.28	11.18
Na_2O	0.02	0.01	0.00	0.05	0.00	0.02	0.26	1.05	1.38	5.00	1.94	0.25	0.86
K_2O	0.03	0.03	0.04	0.05	0.05	0.02	0.04	1.67	0.10	0.25	0.11	9.45	1.70
Cr_2O_3	0.07	0.07	0.08	0.04	0.10	0.00	0.07	0.07	0.00	0.01	0.00	0.12	0.00
Total	99.99	100.09	99.24	99.89	100.59	99.34	99.95	97.75	100.57	99.12	99.83	93.35	87.57
O =	12	12	12	6	6	6	6	23	8	8	8	22	10
Si	2.990	3.020	3.029	1.945	1.929	1.985	1.932	6.488	2.133	2.458	2.201	5.422	2.749
Ti	0.002	0.002	0.002	0.003	0.002	0.001	0.007	0.221	0.000	0.000	0.000	0.641	0.125
Al	1.955	1.898	1.952	0.070	0.109	0.032	0.088	1.989	1.823	1.525	1.790	2.629	0.840
Fe	2.028	2.090	1.928	1.051	0.892	0.957	0.428	2.060	0.012	0.005	0.010	2.107	0.996
Mn	0.096	0.046	0.041	0.013	0.003	0.010	0.009	0.011	0.001	0.000	0.003	0.000	0.008
Mg	0.428	0.599	0.625	0.906	1.064	0.990	0.642	2.472	0.001	0.001	0.001	2.784	0.958
Ca	0.520	0.365	0.407	0.026	0.009	0.022	0.898	1.886	0.920	0.561	0.811	0.046	0.888
Na	0.004	0.002	0.000	0.004	0.000	0.002	0.019	0.308	0.123	0.443	0.173	0.075	0.123
K	0.003	0.003	0.004	0.002	0.002	0.001	0.002	0.322	0.006	0.014	0.007	1.866	0.161
Cr	0.005	0.005	0.005	0.001	0.003	0.000	0.002	0.008	0.000	0.000	0.000	0.015	0.000
Total	8.031	8.030	7.993	4.021	4.013	4.000	4.027	15.765	5.019	5.007	4.996	15.586	6.848

* Total Fe as FeO por: porphyroblast; f-sym: fine-grained symplectite; c-sym : coarse-grained symplectite

Table 3. Chemical compositions of constituent minerals in pelitic granulites in the HC.

Mineral	Garnet								Biotite						
Sample	8		8-1		14A		14A3		8		14A		14A3		10
	core	rim	core	rim	core	rim	core	rim	inc	sec	inc	sec	inc	sec	
SiO_2	37.76	37.05	37.85	37.41	37.71	37.63	37.99	37.69	36.83	35.08	36.07	34.51	36.26	34.94	36.64
TiO_2	0.01	0.05	0.00	0.00	0.00	0.02	0.04	0.00	3.47	4.60	4.43	5.59	5.04	5.33	6.07
Al_2O_3	21.40	21.20	21.64	20.95	21.56	20.91	21.70	21.38	17.70	17.12	17.33	17.03	17.25	16.39	13.96
FeO*	31.77	35.46	30.91	32.55	30.60	33.99	31.34	32.39	15.31	17.82	14.99	16.49	12.96	13.24	17.92
MnO	0.72	1.12	0.68	0.91	0.60	0.66	0.62	0.50	0.00	0.01	0.02	0.00	0.02	0.01	0.04
MgO	7.23	4.57	7.49	6.09	7.20	5.80	7.48	7.09	13.34	11.67	13.86	11.87	14.20	13.01	12.47
CaO	1.36	1.32	1.41	1.22	1.37	0.89	1.08	0.92	0.00	0.00	0.00	0.08	0.03	0.01	0.01
Na_2O	0.02	0.04	0.00	0.01	0.01	0.01	0.00	0.06	0.12	0.12	0.13	0.10	0.19	0.07	0.04
K_2O	0.03	0.06	0.00	0.03	0.06	0.04	0.04	0.01	9.55	9.91	9.63	9.96	9.37	9.89	9.90
Cr_2O_3	0.03	0.00	0.00	0.01	0.08	0.05	0.01	0.03	0.04	0.09	0.26	0.14	0.00	0.11	0.04
Total	100.33	100.87	99.98	99.19	99.19	100.00	100.30	100.07	96.36	96.42	96.72	96.77	95.32	93.00	97.09
O =	12	12	12	12	12	12	12	12	22	22	22	22	22	22	22
Si	2.964	2.953	2.968	2.988	2.977	2.992	2.970	2.969	5.434	5.280	5.317	5.212	5.361	5.343	5.479
Ti	0.000	0.003	0.000	0.000	0.000	0.001	0.002	0.000	0.385	0.521	0.491	0.631	0.560	0.613	0.683
Al	1.980	1.991	1.999	1.971	2.007	1.960	1.999	1.985	3.078	3.036	3.012	3.032	3.006	2.954	2.461
Fe	2.085	2.364	2.026	2.174	2.020	2.261	2.049	2.134	1.889	2.243	1.848	2.082	1.602	1.693	2.241
Mn	0.048	0.075	0.045	0.062	0.040	0.044	0.041	0.033	0.000	0.001	0.003	0.000	0.003	0.001	0.005
Mg	0.847	0.543	0.875	0.725	0.848	0.687	0.872	0.832	2.935	2.618	3.046	2.672	3.129	2.967	2.781
Ca	0.114	0.113	0.119	0.104	0.116	0.076	0.090	0.078	0.000	0.000	0.000	0.013	0.004	0.002	0.002
Na	0.003	0.006	0.000	0.002	0.002	0.002	0.000	0.009	0.033	0.034	0.037	0.029	0.054	0.020	0.012
K	0.003	0.006	0.000	0.003	0.006	0.004	0.004	0.001	1.798	1.902	1.811	1.918	1.768	1.929	1.889
Cr	0.002	0.000	0.000	0.000	0.005	0.001	0.001	0.002	0.004	0.010	0.030	0.017	0.000	0.013	0.004
Total	8.046	8.054	8.032	8.029	8.021	8.028	8.028	8.043	15.556	15.645	15.595	15.606	15.487	15.535	15.557

Mineral	Hercynite			
Sample	14A		14A3	
	inc	sym	inc	sym
SiO_2	0.01	0.02	0.02	0.02
TiO_2	0.01	0.02	0.00	0.01
Al_2O_3	57.04	56.72	56.50	57.32
FeO*	27.55	25.70	28.68	27.10
MnO	0.05	0.00	0.05	0.02
MgO	8.20	8.86	7.90	8.51
CaO	0.03	0.01	0.03	0.00
Na_2O	0.17	0.12	0.20	0.14
K_2O	0.06	0.04	0.03	0.03
Cr_2O_3	0.02	0.19	0.58	0.39
ZnO	5.94	7.22	4.99	6.72
Total	99.98	98.90	98.98	100.26
O =	4	4	4	4
Si	0.001	0.002	0.002	0.002
Ti	0.001	0.001	0.000	0.001
Al	1.487	1.479	1.473	1.494
Fe	1.019	0.951	1.061	1.003
Mn	0.002	0.000	0.002	0.001
Mg	0.541	0.584	0.521	0.561
Ca	0.001	0.000	0.002	0.000
Na	0.015	0.010	0.017	0.012
K	0.003	0.002	0.002	0.002
Cr	0.000	0.003	0.010	0.007
Zn	0.194	0.236	0.163	0.219
Total	3.264	3.268	3.253	3.301

* Total Fe as FeO inc: inclusions in garnet; sec: secondary (retrograde) biotite; sym: symplectite

Table 4. Chemical compositions of constituent minerals in intermediate granulites in the HC.

Mineral	Garnet				Orthopyroxene			Biotite			Chlorite	Plagioclase			K-Feldspar		
Sample	12A		11		9	12		9	11A	17	11A	9	11A	12A	11A	12A	17
	core	rim	core	rim	por	por	sym										
SiO_2	37.14	36.84	36.83	36.71	50.25	49.07	49.00	35.61	34.83	36.65	28.82	57.85	60.30	61.117	64.56	63.90	64.27
TiO_2	0.04	0.01	0.02	0.01	0.09	0.11	0.07	5.55	4.64	5.47	0.05	0.00	0.00	0.00	0.01	0.04	0.02
Al_2O_3	20.77	20.52	19.99	20.12	1.04	1.55	1.72	14.28	12.39	13.17	12.83	26.12	23.67	23.85	18.41	18.45	18.42
FeO*	33.11	34.25	32.87	32.70	28.57	32.73	32.59	19.60	24.61	20.64	39.78	0.18	0.34	0.08	0.01	0.00	0.21
MnO	1.32	1.31	1.42	1.37	1.33	0.42	0.47	0.19	0.03	0.03	0.08	0.05	0.00	0.01	0.00	0.03	0.00
MgO	5.07	4.37	2.11	1.98	17.75	15.55	15.77	11.51	8.47	10.84	6.54	0.00	0.00	0.00	0.00	0.00	0.00
CaO	2.79	2.35	5.48	5.72	0.76	0.23	0.24	0.00	0.00	0.03	0.28	8.07	5.58	5.31	0.15	0.10	0.06
Na_2O	0.02	0.03	0.02	0.04	0.00	0.00	0.00	0.03	0.05	0.32	0.11	6.68	8.32	8.37	2.66	1.40	1.07
K_2O	0.04	0.05	0.05	0.00	0.06	0.05	0.03	9.52	9.50	9.32	0.12	0.58	0.35	0.34	12.94	14.76	15.16
Cr_2O_3	0.04	0.12	0.05	0.04	0.03	0.03	0.03	0.05	0.02	0.00	0.06	0.00	0.02	0.00	0.00	0.05	0.00
Total	100.33	99.83	98.84	98.68	99.88	99.74	99.92	96.33	94.53	96.47	88.67	99.53	98.58	99.086	98.73	98.71	99.20
O =	12	12	12	12	6	6	6	22	22	22	10	8	8	8	8	8	8
Si	2.962	2.968	3.010	3.004	1.948	1.934	1.927	5.416	5.557	5.578	2.324	2.606	2.725	2.739	2.982	2.988	2.991
Ti	0.002	0.001	0.001	0.000	0.003	0.003	0.002	0.634	0.556	0.626	0.003	0.000	0.000	0.000	0.001	0.001	0.000
Al	1.952	1.949	1.925	1.940	0.048	0.072	0.079	2.560	2.330	2.362	1.219	1.387	1.261	1.260	1.015	1.009	1.005
Fe	2.208	2.307	2.246	2.237	0.926	1.078	1.071	2.492	3.283	2.627	2.682	0.007	0.013	0.003	0.000	0.008	0.000
Mn	0.089	0.089	0.098	0.095	0.044	0.014	0.016	0.024	0.004	0.004	0.005	0.002	0.000	0.000	0.001	0.000	0.000
Mg	0.603	0.525	0.257	0.242	1.024	0.913	0.924	2.609	2.015	2.460	0.786	0.000	0.000	0.000	0.000	0.000	0.000
Ca	0.238	0.202	0.480	0.502	0.032	0.010	0.010	0.001	0.000	0.004	0.024	0.390	0.270	0.255	0.005	0.003	0.007
Na	0.002	0.005	0.003	0.006	0.000	0.000	0.000	0.008	0.016	0.095	0.017	0.584	0.729	0.727	0.127	0.096	0.239
K	0.004	0.005	0.005	0.000	0.003	0.002	0.001	1.846	1.933	1.809	0.013	0.033	0.020	0.019	0.879	0.899	0.765
Cr	0.001	0.007	0.003	0.002	0.001	0.001	0.001	0.005	0.002	0.000	0.004	0.000	0.001	0.000	0.002	0.000	0.000
Total	8.062	8.058	8.028	8.028	4.027	4.027	4.032	15.595	15.696	15.567	7.077	5.009	5.019	5.004	5.011	5.004	5.008

* Total Fe as FeO. por : porphyroblast; sym : fine grained symplectite

Table 5. Chemical compositions of constituent minerals in pelitic gneisses in the KC.

Mineral	garnet	biotite		plagioclase		K-feldspar
Sample	50	50	15	50	15	15
SiO_2	37.77	35.77	36.55	60.69	61.20	64.58
TiO_2	0.01	5.05	3.57	0.00	0.00	0.00
Al_2O_3	20.85	16.51	15.10	24.75	24.06	18.47
FeO*	32.31	16.96	20.62	0.10	0.13	0.01
MnO	1.59	0.02	0.27	0.02	0.00	0.00
MgO	5.84	12.36	10.51	0.01	0.00	0.00
CaO	1.60	0.02	0.00	6.33	6.14	0.01
Na_2O	0.01	0.11	0.10	8.14	8.18	0.90
K_2O	0.05	9.10	9.32	0.27	0.29	15.93
Cr_2O_3	0.03	0.13	0.04	0.00	0.00	0.02
Total	100.06	96.03	96.08	100.31	100.00	99.92
O =	12	22	22	8	8	8
Si	2.997	5.352	5.568	2.696	2.724	2.988
Ti	0.001	0.568	0.409	0.000	0.000	0.000
Al	1.949	2.911	2.711	1.296	1.262	1.007
Fe	2.144	2.123	2.627	0.004	0.005	0.000
Mn	0.107	0.002	0.035	0.001	0.000	0.000
Mg	0.691	2.757	2.388	0.000	0.000	0.000
Ca	0.136	0.003	0.000	0.301	0.293	0.001
Na	0.001	0.032	0.029	0.701	0.706	0.080
K	0.005	1.738	1.812	0.154	0.017	0.941
Cr	0.001	0.015	0.005	0.000	0.000	0.001
Total	8.032	15.501	15.584	5.015	5.007	5.018

* Total Fe as FeO.

Table 6. Chemical compositions of constituent minerals in mafic gneisses in the KC.

Mineral	garnet	biotite			plagioclase			K-feldspar	amphibole	
Sample	50	2B	3	51	1	3	51	1	2B	3
SiO_2	36.93	36.44	35.59	35.70	59.37	57.64	57.43	63.65	43.72	43.55
TiO_2	0.00	4.83	5.14	4.08	0.00	0.00	0.00	0.03	1.69	2.08
Al_2O_3	20.35	15.29	14.09	15.32	25.28	25.46	26.56	18.56	10.25	10.57
FeO*	27.53	11.71	13.22	19.92	0.11	0.14	0.07	0.36	14.71	14.95
MnO	3.73	0.16	0.14	0.10	0.01	0.00	0.00	0.01	0.49	0.22
MgO	5.12	15.69	15.03	10.83	0.00	0.00	0.00	0.00	13.32	12.81
CaO	4.95	0.04	0.05	0.00	7.29	7.42	9.77	0.08	11.24	10.94
Na_2O	0.01	0.06	0.04	0.03	7.37	6.99	6.79	1.18	1.63	1.68
K_2O	0.01	9.60	9.14	9.79	0.55	0.45	0.36	15.72	0.83	0.83
Cr_2O_3	0.02	0.03	0.03	0.05	0.02	0.05	0.01	0.02	0.03	0.06
Total	99.55	93.85	92.47	95.82	100.00	98.15	100.99	99.61	97.91	97.69
O =	12	22	22	22	8	8	8	8	23	23
Si	2.974	5.462	5.462	5.461	2.656	2.628	2.564	2.965	6.538	6.523
Ti	0.000	0.545	0.593	0.469	0.000	0.000	0.000	0.001	0.190	0.234
Al	1.932	2.702	2.548	2.761	1.332	1.368	1.398	1.019	1.806	1.866
Fe	1.854	1.468	1.696	2.547	0.004	0.005	0.003	0.014	1.839	1.873
Mn	0.255	0.020	0.018	0.013	0.000	0.000	0.000	0.001	0.062	0.028
Mg	0.615	3.506	3.439	2.469	0.000	0.000	0.000	0.000	2.971	2.862
Ca	0.427	0.006	0.008	0.000	0.349	0.362	0.467	0.004	1.801	1.755
Na	0.001	0.016	0.013	0.010	0.639	0.617	0.588	0.106	0.472	0.487
K	0.001	1.837	1.790	1.909	0.032	0.026	0.020	0.934	0.159	0.158
Cr	0.001	0.003	0.003	0.006	0.001	0.002	0.000	0.001	0.003	0.007
Total	8.060	15.565	15.572	15.645	5.013	5.008	5.040	5.045	15.841	15.793

* Total Fe as FeO

gneiss. Metagranitoid garnets have almost constant composition. X_{Prp} of garnets from the garnet amphibole pyroxene gneiss vary from 0.27 to 0.19. In the case of charnockitic gneiss, pyrope varies from 0.14 to 0.08. In meta-granitoid, the pyrope content is almost constant.

The highest grossular content (X_{Grs}= 0.38) is found in garnet from amphibole pyroxene gneiss. Grossular content decreases from core to rim in both garnet amphibole pyroxene gneiss and charnockitic gneiss garnets. In metagranitoids, garnet rims are richer in grossular than the cores (max. X_{Grs}= 0.23).

(2) Orthopyroxene

Opx occurs as porphyroblasts, fine-grained symplectites, and coarse-grained symplectites after garnets, with X_{Mg} = 0.85–1.00. Alumina contents differ markedly in the garnet amphibole pyroxene gneiss. Opx in the symplectites after garnet has Al contents from 2.11 to 3.12 wt. %, whereas the opx in the coarse grained symplectites has Al_2O_3 contents ranging from 0.70 to 1.19 wt.%. However, porphyroblastic opx in the matrix contains 1.35 to 2.09 wt.% of Al_2O_3. Symplectitic opx in all lithologies has greater Al content than opx porphyroblasts. Opx in lithologies lacking garnet also have relatively higher X_{Mg} ratios.

(3) Clinopyroxene

Clinopyroxenes occurs as rare inclusion phases in garnet, and as internal symplectite with plagioclase in garnets of the garnet amphibole pyroxene gneiss. Rare cpx was found occurring in symplectites with plagioclase in meta-granitoids. No great compositional variations were observed among these occurrences except for variable aegirine content in cpx in meta-granitoids. However, the relict association of cpx + plg ± qtz in garnet amphibole pyroxene gneiss represents the field of the high pressure granulite assemblage (Green and Ringwood, 1967; De Waard, 1965).

(4) Plagioclase

Plagioclase occurs as porphyroblasts in the matrix, as inclusions in garnet, in symplectites with opx, and as coronas on garnet. Anorthite content is highly variable, with maximum of X_{An} = 0.90 in garnet amphibole pyroxene gneiss, and minimum of X_{An} = 0.20 in charnockitic gneiss. Anorthite contents show marked contrast in garnet amphibole pyroxene gneiss as,

matrix < symplectite < inclusions in grt

However, anorthite contents of plagioclase in metagranitoids is almost constant. In charnockitic gneisses, X_{An} is variable in the range from 0.20 to 0.63.

(5) Amphibole

Amphibole occurs in garnet amphibole pyroxene gneiss and metagranitoid rocks, and are classified using Leake et al. (1997). Accordingly, all the amphiboles have $(Ca+Na)_B$ > 1.00 and Na_B < 0.50, and hence belong to the *calcic amphibole* group. In the case of garnet amphibole pyroxene gneiss, all amphiboles have Si in the range 6.37-6.47 and Mg / (Mg + Fe^{2+}) between 0.51 and 0.59 with Al^{VI} > Fe^{3+}, falling into *pargasite.* In contrast, metagranitoid amphiboles have Si between 6.02 and 6.23 and Mg / (Mg + Fe^{2+}) of 0.10 -0.18, with Al^{VI} < Fe^{3+}, and are classified as *hastingsite.*

(6) Titanite

Titanite occurs as numerous inclusions in garnet porphyroblasts, along with plagioclase, and contains about 1.9 wt% Al_2O_3 and about 1 wt% FeO. In metagranitoids, titanite occurs mainly in the matrix, associated with amphiboles..

Pelitic gneiss–Kadugannawa Complex

(1) Garnet

One generation of garnet was recognized, and it contains no significant chemical zoning. Garnet porphyroblasts are almandine-rich, with almandine content varying from X_{Alm} = 0.79 to 0.88. Spessartine content is slightly greater than in the HC pelitic gneisses. X_{Grs} ranges up to 0.032. However, there is no significant variation in grossular content.

(2) Plagioclase

Plagioclase occurs as inclusions in garnet and as a matrix mineral, and has compositions ranging from oligoclase to andesine. Anorthite content varies in the range X_{an} = 0.11 to 0.43.

(3) Biotite

Biotites contain about 3.4–3.5 wt% TiO_2, while Fe/ (Fe + Mg) varies from 0.58 to 0.67. There is no significant difference in composition between inclusion phases and retrograde / later overprinted phases of biotite.

(4) Amphibole

Amphibole occurs only in biotite gneiss. $(Ca+Na)_B$ > 1.00 and Na_B < 0.50 indicates it belongs to the *calcic amphibole* group. Si varies between 6.02 and 6.23 and Mg / (Mg + Fe^{2+}) values fall in the range 0.66-0.72, with Al^{VI} < Fe^{3+} giving classification as *magnesiohastingsite* (Leake et al., 1997).

(5) Opaque minerals

Magnetite was the dominant opaque phase, and contains up to 6.6 wt % TiO_2.

Mafic gneiss–Kadugannawa Complex;

(1) Garnet

Garnets are almandine rich. Almandine content varies as X_{Alm} = 0.74 - 0.77. Comparatively, these garnets are richer in the spessartine component than HC garnets. Grossular content is about X_{Grs} = 0.1, and shows no significant variation. No zoning was observed.

(2) Plagioclase

All the plagioclase in these rocks is andesine . No significant variation of anorthite content was observed between inclusions in garnet and matrix plagioclase.

(3) Biotite

Biotites contain about 4.1-5.0 wt % TiO_2, and Fe/ (Fe + Mg) varies from 0.48 to 0.63. There is no significant difference in composition between inclusion phases and retrograde / later overprinted phases of biotite. However, garnet bearing mafic gneisses have slightly lower Mg / (Fe+ Mg).

(4) Amphiboles

Amphiboles occur in hornblende gneiss and migmatitic gneiss. All belong to the *calcic amphiboles* (values of $(Ca+Na)_B$ > 1.00 and Na_B < 0.50). Si varies between 6.19 and 6.47 and Mg / (Mg + Fe^{2+}) values fall in the range 0.59-0.74, with Al^{VI} < Fe^{3+} identifying *magnesiohastingsite* (Leake et al., 1997).

Discussion

Inclusion assemblages in garnet porphyroblasts in the HC pelitic granulites exhibit a prograde pressure increase from the sillimanite stability field to the kyanite stability field, nearly at the margin of the amphibolite - granulite facies boundary. This is evidenced by kyanite inclusions in garnet porphyroblasts, which infer formation of garnet in the kyanite stability field. Prismatic sillimanite needles are included in garnet porphyroblasts in the same rock which contains kyanite bearing garnets. The reaction line which constrains formation of garnet from aluminosilicates indicates that the rock reentered the sillimanite stability field, with further garnet growing at the expense of sillimanite. However, there is no direct evidence to infer any reaction for formation of kyanite, which is locally and rarely preserved in garnet porphyroblasts. It may have been formed at the expense of staurolite under relatively higher pressure, through the reaction:

(Zn rich) staurolite + qtz

= kyanite + (Zn rich) hercynite + garnet ----- (A)

However, there is no evidence for any staurolite, which may reflect its total consumption through the prograde metamorphism.

Alternatively, it is possible to form kyanite at moderately higher pressures through the reaction:

Mg chlorite = biotite + kyanite ------ (B)
(Spear, 1993)

However, the slope of the reaction line for (B) in P-T space is entirely temperature dependent (Spear, 1993), and hence it is almost impossible to form kyanite when an increase of pressure is suggested. Therefore, the formation of some prograde sillimanite can be suggested by reaction (B). Accordingly, of the options above, reaction (A) is preferred, since it accounts for formation of Zn rich hercynite, which is preserved as inclusion phases together with ilmenite in garnets of the same kyanite-bearing samples. Furthermore, reaction (A) is more sensitive to pressure than temperature due to the negative slope of the reaction line in P-T space, hence supporting the suggested early increase of pressure. Some previous studies have reported a few occurrences of small staurolite grains only as relict inclusions in garnet (eg. Raase and Schenk, 1994; Hiroi et al., 1994) from some other localities of the HC. However, the absence of staurolite from the samples examined here is apparently due to total consumption through prograde dehydration and hence not surviving at the peak metamorphism, and is not due to any difference in bulk chemistry.

Polymorphic change of sillimanite to kyanite can also be suggested through increasing pressure. This interpretation can be eliminated due to the lack of kyanite pseudomorphs after sillimanite. However, there is evidence for 'sillimanite pseudomorphs after kyanite, similar to those reported by Raase and Schenk (1994). These kyanite pseudomorphs consist of aggregates of nearly sub-parallel prisms of sillimanite, showing the shape of kyanite porphyroblasts, and not the typical shape of andalusite. This shows the rock entered the sillimanite stability field from the kyanite field. In addition, the sequence of inclusions (i.e. fine needle-shaped sillimanite occurs nearly in the core; relict kyanite occurs in the mantle together with kyanite pseudomorphs, and coarse prismatic sillimanite occurs at the rim or outer margin of the same garnet porphyroblast) suggests that kyanite formation took place between two sillimanite forming stages. Accordingly, it is evident that these pelitic granulites experienced an early pressure increase during the prograde path, as the rocks experienced tectonic thickening of the crust due to continental collision.

In the case of metabasic and intermediate rocks, it not clear whether the opx porphyroblasts and cpx crystallized from a primary melt at depth or during a metamorphic process. Formation of opx at the expense of cpx can be related to a metamorphic process occurring during cooling of the igneous intrusion in the deep crust. No cpx occurs in the matrix, but only a few cpx relics are preserved as inclusions in garnet and a rare symplectite inside garnet, suggesting a cpx consuming reaction must have occurred. A possible reaction to form opx and anorthite at the expense of cpx was described by Schumarcher et al. (1990):

garnet + cpx + quartz = opx + plagioclase ------------ (C)

Moreover, if fluid infiltration occurred at this stage, the garnet + cpx + opx assemblage can also become unstable under high water / fluid activity. That in turn can form amphiboles at a relatively higher temperature, by the reaction:

cpx + opx + plagioclase + L = amphibole ------------ (D)
(Ganguly et al., 2001)

Petrographic evidence for occurrence of this reaction is preserved in some parts of the rock.

The calcic amphiboles found in the metabasites are pargasite. Tsunogae et al. (2003) argued that F-rich pargasites can be formed even at very high temperatures as a result of F-bearing fluid infiltration. However, this suggestion cannot be confirmed here, as F was not determined during the analysis of the amphiboles. However, both reactions (C) and (D) can account for eliminating cpx from the rock system, provided that suitable conditions prevailed. Schumarcher et al. (1990) considered that (C) was the only reaction to remove cpx from the system. They did report the presence of pargasite in their study.

Presence of numerous inclusions of elliptical titanite and anorthite-rich plagioclase suggest that the garnet porphyroblasts are the products of slow cooling of a basic intrusion, rather than originating from a metamorphic process. No exsolution features were observed in pyroxenes, in contrast to Schumacher et al. (1990) and Schenk et al. (1990). who described coarse exsolution lamellae in metabasic and charnockite pyroxenes for which pre-exsolution temperatures were in excess of 900℃.

When all the cpx was eliminated by reactions (C) and / or (D), reaction (C) stopped with garnet + quartz assemblage in an equilibrium state. However, there is evidence that this equilibrium was broken at later stages, and new opx and plagioclase grew in the form of a symplectite between garnet and quartz. This can be due to restarting of reaction (C) and the formation of opx + plagioclase using the grossular component of the garnet, at the absence of cpx. This is evidenced by the characteristic depletion of grossular in the rim of garnet porphyroblasts. This symplectite texture is also occurs pervasively in all these rocks except metagranitoid, and is typically indicative of decompression. In metagranitoid, different symplectites are found, as described in a previous section.

The Ti contents of the amphiboles are noteworthy, and merit discussion. The effect of Ti in amphiboles coexisting with Ti-rich phases such as rutile, ilmenite and titanite has been discussed by Raase (1974) and Spear (1981), who considered that it can be used as a rough temperature indicator. According to analytical data acquired here, all HC amphiboles which co-exist with Ti-rich phases are extremely titaniferous, with values of over 0.3 p.f.u.. Hastingsite in the metagranitoid has maximum Ti content of 0.39 p.f.u, and pargasite in the metabasites has maximum Ti of 0.32 p.f.u. In contrast, magnesiohastingsite in Kadugannawa Complex mafic gneiss has a maximum Ti content of 0.21 p.f.u. According to Raase (1974) and Spear (1981), the HC amphiboles are indicative of crystallization temperatures in excess of 800℃, whereas those of the KC indicates 700–800℃ or low crystallization temperatures. This suggests that at least the high Ti amphiboles of the HC metabasites and intermediate granulites are of primary origin and have undergone metamorphism, supporting the interpretation for HC metabasite amphiboles of Schumarcher et al. (1990).

In the case of the intermediate rocks it is also probable that garnet and opx may have initially crystallized from a parent magma of granitic composition, and later fractionated during cooling to form opx-bearing charnockitic and granitic rocks which were subsequently metamorphosed to form charnockitic gneisses and metagranitoids.

Accordingly, we consider that the initial assemblages of the metabasites and intermediate rocks were derived from primary melts of basic and granitic composition respectively, which were intruded into a middle-deep crust which had already been thickened by continental collision tectonics.

In all the rocks studied, mainly amphibolite facies and later greenschist facies retrogression suggests flushing of large volumes of pervasive H_2O-rich fluid. However, the formation of calcite + chlorite assemblages in charnockitic rocks also suggest infiltration of CO_2 rich fluids at later stages.

Conclusions

Petrographic examination shows that the KC mineral assemblages represent a lower metamorphic grade than those of the HC. Evidence for prograde metamorphism is provided by several inclusion phases in garnet porphyroblasts, whereas retrograde effects are demonstrated by overprinting textures of secondary or late stage assemblages. No characteristic decompressional / retrograde textures such as symplectites, reaction rims, or coronae were observed in the samples studied.

Inclusions of fine needles of sillimanite in garnet infer the formation of garnet at the expense of sillimanite. An early pressure increase is inferred from the presence of relic kyanite inclusions in garnet. Sillimanite pseudomorphs after kyanite further indicate that the sillimanite stability field was entered after the pressure increase (i.e. formation of kyanite). Consequently, we conclude that during their evolution these granulites were equilibrated twice in the sillimanite stability field, at distinctly different P-T conditions.

In contrast, metabasic and intermediate granulites evolved through a cooling path from the peak metamorphism, after emplacement of their protolith into the lower crustal units. However, the rocks examined here contain no evidence for initial isobaric cooling after the emplacement of their igneous protoliths, as suggested by previous studies (e.g. Schumarcher et al., 1990; Schenk et al., 1991, Prame, 1991b). These studies identified growth of garnet, cpx and quartz from orthopyroxene and plagioclase and subsequent breakdown to the same assemblage, which they interpreted in terms of isobaric cooling. Preservation of relic cpx + plg ± qtz in garnet within metabasite shows that these mafic granulites were in equilibrium in the high pressure granulite field (>10 k bar; O'Brien and Rotzler, 2003). This finding has not been reported previously. Therefore, we conclude that the mafic granulites of the Highland Complex of Sri Lanka suffered high pressure granulite facies metamorphism, probably as a result of an Early Palaeozoic continental collision (Shiraishi et al., 1994).

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（要　旨）

Malaviarachchi S.・Takasu A.，スリランカ中央部 Highland コンプレックスおよび Kadugannawa コンプレックス中の変成岩の記載岩石学的研究．地球資源環境学研究報告，24，31-46

スリランカ中央部に分布する Highland コンプレックスの泥質および中性～塩基性グラニュライトおよび，Kadugannawa コンプレックス中の泥質および塩基性変成岩の記載岩石学的研究を行った．これらの変成岩の岩石組織を記載するとともに，主要構成鉱物の X 線マイクロアナライザーによる化学組成の分析を行った．

泥質変成岩はざくろ石を含むものと含まないもの，またスピネルを含むものと含まないものについて研究を行った．黒雲母片麻岩中には一般にざくろ石は含まれない．いっぽう，ざくろ石－黒雲母－珪線石片麻岩はスピネルを含む場合と含まない場合がある．ざくろ石は包有物として，藍晶石と珪線石を含み，この変成岩は藍晶石の安定領域を経由する昇温変成作用を受けたことを示す．

変成中性～塩基性岩は角閃石および黒雲母をともなう花こう岩質岩，チャーノカイト質片麻岩，ざくろ石－角閃石－輝石片麻岩であり，チャーノカイト質片麻岩には斜方輝石が普通に出現するが，それらの一部の変成岩にはざくろ石は含まれない．変成花こう岩質岩中にはまれに単斜輝石がシンプレクタイトとして斜長石とともに存在する．いっぽう，ざくろ石－角閃石－輝石片麻岩では，ざくろ石は単斜輝石＋斜長石±石英を包有し，斜方輝石は斑状変晶として存在する．このざくろ石－角閃石－輝石片麻岩は変成履歴の中で高圧のグラニュライト相を経たことを示す．