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PETROLOGICAL STUDY OF CALC–SILICATE GRANULITES IN THE SOUTHERN HIGHLAND COMPLEX OF SRI LANKA

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ABSTRACT

Present study of mineral assemblages and reaction textures of calc-silicate rocks in the southern Highland Complex of Sri Lanka around Galle area and Middeniya - Embilipitiya area has placed important constraints on the P-T-t path and fluid evolution. The studied samples can be divided into three main groups based on the mineralogy. Group I - wollastonite-bearing but grossularite-absent assemblages, Group II - grossularite-bearing but wollastonite-absent assemblages, Group III - both wollastonite and grossularite-absent assemblages. Formation of different assemblages is possibly the result of the chemistry of protoliths, P-T at the peak metamorphic conditions and graphite precipitation. The Group I lithologies preserve critical reaction textures including calcite + quartz and calcite + diopside after wollastonite, calcite + quartz + plagioclase after scapolite, and scapolite + quartz after K-feldspar that are important in re-constructing the P-T-t evolution of the terrain. Diopside rims around quartz have been observed in the Group II assemblage and replacement of diopside by amphibole has been observed in the Group III assemblage. In addition, myrmekitic intergrowth of plagioclase + quartz between calcite + K-feldspar has been observed throughout the study area. Critical retrograde reaction textures including calcite + quartz and calcite + diopside after wollastonite, and breakdown of scapolite suggest isobaric cooling following peak metamorphism during which internal fluid buffering probably prevailed. But in the studied Group I samples, grossularite + quartz was not stabilized under retrograde conditions, perhaps due to low lithostatic pressure that prevailed. Further, limited occurrence of scapolite + quartz symplectites around K-feldspar, diopside rims around quartz in Group I/II suggest carbonic fluid influx at the final stage of retrogression. On the other hand, replacement of diopside by amphibole in group III suggests hydrous fluid influx during retrogression. Thus, fluid infiltration apparently occurred locally in different assemblages. Presence of grossularite absent Group I assemblage, reaction textures and textural evidence for late fluid infiltration into the calc-silicate rocks in the study area provides further evidence to correlate the Highland Complex of Sri Lanka with the Kerala Khondalite Belt (KKB) of Southern India.

Key words: *Calc-silicate rocks, Southern Sri Lanka, Reaction textures, Isobaric cooling, Fluid infiltration, Kerala Khondalite Belt (KKB)*

INTRODUCTION

Determination of P-T-t evolution of calc-silicate lithologies of a granulite terrain is important to construct models for the origin and evolution of the continental crust. In the last few decades, calc-silicate granulites in all Gondwana fragments have received special attention due to high temperature, pressure mineral assemblages and parageneses, and reaction textures that are well preserved in those rocks (Sivaprakash, 1981; Harley and Buick, 1992; Dasgupta, 1993; Harley et al., 1994; Shaw and Arima, 1996; Satish-Kumar and Santosh, 1998; Mathavan and Fernando, 2001). These rocks are of sedimentary origin, derived from dolomitic limestone, siliceous limestone or marls and show mineral assemblages containing minerals like wollastonite, scapolite and glossularite (Bucher and Grapes, 2010). They occur as boudins, lenses or blocks and are interbanded with metapelites (Warren et al., 1987; Dasgupta, 1993; Harley et al., 1994; Satish-Kumar et al., 1996; Shaw and Arima, 1996; Mathavan and Fernando, 2001).

With the aid of new thermodynamic data on the phase equilibria of granulite-facies calc-silicate assemblages, recent studies have focused on the evaluation of pressure-temperature fluid histories of granulite-facies calc-silicates

(Satish-Kumar, 1999; Mathavan and Fernando, 2001; Dasgupta and Pal, 2005; Prame and Prema, 2014). P-T fluid evolution and interpretation of mineral assemblages and reaction textures of the calc-silicate rocks have been carried-out by constructing new reaction grids for the system K_2O-CaO-MgO-Al_2O_3-SiO_2-CO_2-H_2O (KCMASCH) (Holland and Powell, 1990, 1998; Harley and Buick, 1992; Shaw and Arima, 1996; Mathavan and Fernando, 2001; Dasgupta and Pal, 2005).

Several important detailed studies on calc-silicate granulites from India, Australia, Antarctica and Sri Lanka dealing with reaction textures, mineral assemblages, fluid evolution and P/T estimates have been published (Warren et al., 1987; Motoyoshi et al., 1991; Harley et al., 1994; Fitzsimons and Harley, 1994; Satish-Kumar and Santosh, 1998; Mathavan and Fernando, 2001). However, wollastonite + scapolite bearing assemblages lacking grossularite have been rarely used to determine the P-T-t evolution of a granulite terrain (Satish-Kumar and Santosh, 1998).

In Sri Lanka, only a few petrological studies have been carried-out on calc-silicate rocks. Several wollastonite-bearing assemblages have been reported by Hapuarachchi (1968) from the former Southwest Group, and grossularite + wollastonite bearing assemblages have been described by Mathavan and Fernando (2001) from Maligawila in the Buttala klippe, and from around Balangoda by Wickramasinghe and Perera (2014). There are several marble and calc-silicate bands extending in the N-S and NW-SE directions especially in the Galle area and Middeniya-Embilipitiya area in South-South East of Sri Lanka, close to the Highland-Vijayan Boundary. The present study is an attempt to focus on the mineral assemblages, reaction textures and P-T-t evolution of calc-silicate granulites in the latter areas in Southern Sri Lanka.

GEOLOGICAL SETTING AND STUDY AREA

REGIONAL GEOLOGY

Nine-tenths of the Sri Lankan geological basement consists of Precambrian metamorphic rocks and the remainder is represented by Mesozoic (Jurassic), Tertiary (Miocene) and Quaternary sedimentary formations and a few occurrences of intrusive igneous rocks. The high-grade Precambrian basement of Sri Lanka is divided in to three major units namely the Highland Complex (HC), the Wanni Complex (WC) and the Vijayan Complex (VC) (Fig. 1) (Kröner et al., 1991; Cooray, 1994). The Highland Complex consists of supracrustal rocks of meta-igneous and meta-sedimentary origin which have been metamorphosed to the upper amphibolite- and granulite-facies (Cooray, 1994). Supracrustal rocks of the Highland Complex consist of shallow water sediments and subordinate amount of a bimodal volcanic suite (Pohl and Emmermann, 1991) that had been emplaced 2 Ga or earlier (Milisenda et al., 1988, 1994; Kröner, 1991). Granulite-facies metamorphism in the Highland Complex has been dated at ~610-550 Ma (Kröner and Williams, 1993), and thermo-barometric estimates suggest metamorphic temperatures around 850-900°C and pressures of 5-6 kbars in the West of HC, and 8-10 kbars in the East of the HC (Raase and Schenk, 1994; Raith et al., 1991; Hiroi et al., 1994). The amphibolite-facies Vijayan Complex lies in Eastern and Southeastern parts of the island and regional metamorphism in the area has been dated at ~591-456 Ma (Kröner, 1991; Hölzl et al., 1994). Within the VC, there are three outliers of granulite-facies HC rocks at Kataragama, Buttala, and Kuda Oya which have been interpreted as klippen with a thrust fault at the base (Silva et al., 1981; Vitanage, 1985). It has been suggested that the HC and WC together were overthrusted on to the VC after the peak of metamorphism (Silva et al., 1981; Vitanage, 1985; Kröner et al., 1991). The Wanni Complex which lies to the West and Northwest of the Highland Complex mainly consists of granulite- to upper amphibolite-facies rocks.

STUDY AREA

The study area belongs to the Southern part of the Highland Complex (Fig. 1). The area is underlain by granulite-facies metamorphic rocks. The main rock types in the study area are garnet sillimanite biotite gneisses, charnockitic gneisses, quartzofeldspathic gneisses, marble and calc gneisses (Cooray, 1994). Marble and calc-silicate rocks occur as discontinuous layers. Faulhaber and Raith (1991) carried-out a geothermobarometric study of high grade gneisses in this area and showed that western part of the southern Sri Lanka represents a shallow crustal level while the eastern part is indicating a palaeo depth. Structural and metamorphic features suggest a substantial

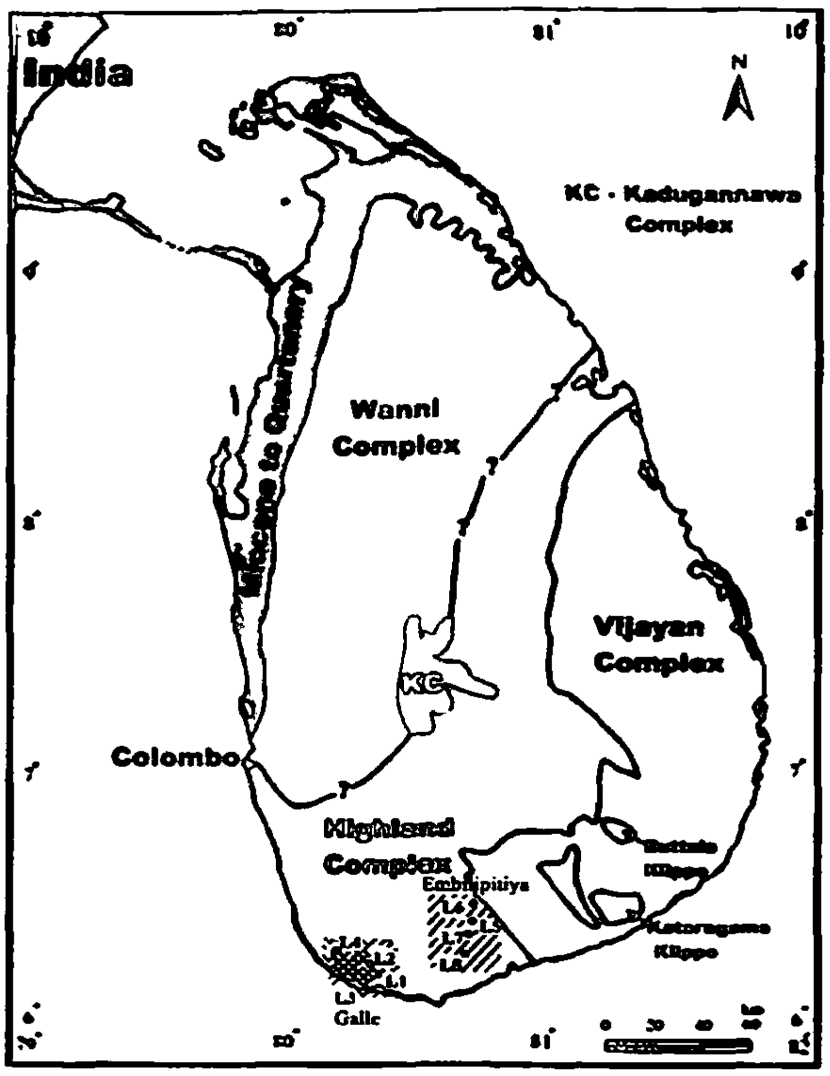

Fig. 1 Lithotectonic subdivision of the Precambrian of Sri Lanka (after Cooray, 1994), Showing Location numbers of the sampling sites. Where, area shaded represents Galle area and area shaded represents Middeniya-Embilipitiya area

section through the lower continental crust (Raith et al., 1991).

The samples of this study were collected around Galle in the SSW and Middeniya-Embilipitiya in the SSE of the island (Fig. 1). Generally, rocks in the Galle area strike Northwest and dip Southwest while rocks in the Middeniya-Embilipitiya area strike Northwest and either dip vertically or towards Southwest. Morphologically the study area belongs to the lowlands (Vitanage, 1970).

FIELD RELATIONS

Petrography of samples collected from eight locations has been studied. The sample numbers, their locations and their coordinates are given in Table 1. L1 and L3 are located close to the sea. Only samples from locations L3, L4, and L6 have been collected from large outcrops. L1 to L4 (Table 1) are situated around Galle in the SSW of the Highland Complex. In Koggala (L1) and Pilana (L2) calc-silicates occur in small-scale (2 - 4 m^2) outcrops. They are moderately weathered and show similar mineral assemblages. In the Galle Fort (L3) and around Boossa (L4) there are relatively large outcrops (20 - 60 m^2). These localities are important mineralogically and petrologically and are described here in detail.

Within the Galle Fort (Table 1) there are several calc-silicate outcrops of varying size (10 – 60 m^2) which show diverse mineralogical, textural and structural features. Most of the outcrops show moderate weathering. Grain size of the minerals varies from a few mm to more than 10 cm. Major minerals observed in those are quartz (20%), plagioclase feldspar (20%), potassium feldspar (15%), wollastonite (10%), scapolite (10%). Feldspar grains are very coarse, sometimes more than 10 cm long and occur as massive monomineralic areas or patches in several outcrops. Wollastonite and scapolite are either commonly associated with thin layers of mafic minerals and form the foliation of some outcrops (Fig. 2 A) or occur as massive relatively large aggregates (patches) of medium size grains (1-5 mm). Important structural features observed in this location are well-developed foliations, boudinage structures. Those are the result of progressive ductile deformation which occurred in the Highland Complex (Berger and Jayasinghe, 1976; Kehelpannala, 2003). Boudins of different scale occur in the area and all of them show felsic mineral composition.

In Boossa (Table 1), located West of Galle Fort, a calc-silicate outcrop of approximately 30 m^2 in area is exposed at the lower part of a small hill (Fig. 1). This rock is characterized by presence of coarse-grained (>5 mm) minerals associated with medium size (1-5 mm) mineral grains. Major minerals observed in the samples are feldspar (25%), diopside (20%), scapolite (20%) and wollastonite (20%). The dominant mineral in the outcrop is feldspar. At some places, very coarse-grained, idioblastic feldspar associated with medium size grains of scapolite + wollastonite could be observed. Some feldspar is about 8 cm (Fig. 2 B). In addition, well-developed hornblende and pyroxene porphyroblasts (>2 cm) were observed. Some part of the outcrop consists of mafic minerals such as diopside, sphene and hornblende which occur as patches between felsic minerals (Fig. 2 C). Wollastonite is another major constituent of the outcrop and is distributed either as individual grains (Fig. 2 B) or clusters of grains with scapolite. Individual grains of wollastonite are

Table 1 Summary of coordinates of studied sample locations

Location No	Location	Sample No	Co-ordination
Around Galle			
L1	Koggala	S1 – S10	80^0 20' 45" E/ 5^0 59' N (150100/88150)
L2	Pilana	S11 – S13	80^0 17' E/ 6^0 02' 60" N (146750/93400)
L3	Galle fort	S14 – S30	80^0 12' 70" E/ 6^0 01' 50" N (138350/98300)
L4	Boossa	S31 – S52	80^0 09' 35" E/ 6^0 05' 10" N (134150/97250)
Around Middeniya-Embilipitiya			
L5	Tambalepelassa	S53 – S60	80^0 50' 20" E/ 6^0 16' N (208000/119000)
L6	Embilipitiya	S61 – S83	80^0 52' E/ 6^0 19' N (208500/122900)
L7	Katuwana	S84 – S92	80^0 34' E/ 6^0 16' N (195800/116200)
L8	Gonadeniya	S93 –S101	80^0 47' E/ 6^0 13' N (203000/113000)

very coarse-grained porphyroblasts, some are 8-10 cm in length and show well-developed three sets of cleavage. Clusters of wollastonite grains (with scapolite) are fine to medium in size and are associated with different mineralogical constituents. At some places they occur around coarse-grained feldspar as rings and in other places they are associated with mafic minerals.

Locations L5 to L8 (Table 1) are situated around Middeniya-Embilipitiya area in the SSE of the Highland Complex and L5 and L6 are the only large outcrops visited in this area. L7 and L8 are small (2 – 8 m^2) outcrops. In Katuwana (Table 1) located South of Embilipitiya mafic minerals dominate in a calc–silicate outcrop. Major minerals observed are diopside (25%), feldspar (15%), scapolite (15%), hornblende (10%), and calcite (10%). In addition, sphene occurs in minor quantities. Around Gonadeniya (Table 1) there are several impure marble and calc-silicate outcrops. But most of them show moderate weathering.

In Tambalepelessa (Table 1) situated close to the Hingura wewa (Fig. 1), there are several small calc-silicate outcrops (5 -15 m^2) exposed, and some of those are associated with impure marble outcrops.

In this area calc-silicate and marble outcrops are surrounded by charnockitic outcrops. Major minerals observed in the calc-silicate outcrops are calcite (35%), scapolite (25%) and diopside (25%) and minor amounts of garnet (5%) also can be seen. Calc-silicate rocks are well-foliated and are characterized by calcite-rich light coloured layers inter-banded with diopside-rich mafic layers (Fig. 2 D).

In Embilipitiya (Table 1) a calc-silicate outcrop is associated with pegmatitic veins at Chandrika wewa (Fig. 1). The pegmatitic veins consist of coarse-grained quartz, phlogopite and biotite. Rock exposures cover an area of about 200 m^2 and most outcrops are moderately to highly weathered. They are also highly jointed and fractured and the outcrop is separated into nearly horizontally distributed fragments (each with 0.2-0.3 m thickness) in some places. Major minerals observed in the calc-silicate outcrop are tremolite (25%), epidote (30%) and spinel (30%). Tremolite occurs as idioblastic, coarse grains within a xenoblastic, fine to medium-grained area. Some tremolite crystals are more than 1 m long and are mostly fractured while others occur as either thin crystals, radiating from a central point (Fig. 2 E) or as randomly oriented grains pointing in different directions (Fig. 2 F). Epidote shows orange to yellowish appearance in the outcrop and occurs as massive, fine to medium-grained (<0.5 mm) aggregates occupying the spaces (matrix) between tremolite. Spinel grains (<0.5 mm) in the area are purple coloured and are also associated with epidote in the matrix.

PETROGRAPHY

METHODS OF STUDY

Representative samples were collected from selected calc-silicate outcrops and important field relations were recorded. Extra-large thin-sections (1×2 inch) were prepared from important samples and were examined under the polarizing microscope in petrological lab at University of Peradeniya.

MINERAL ASSEMBLAGES IN CALC-SILICATE ROCKS OF THE STUDY AREA

Mineral assemblages of the studied calc-silicate rocks show wide variation within a given locality and among different sample localities.

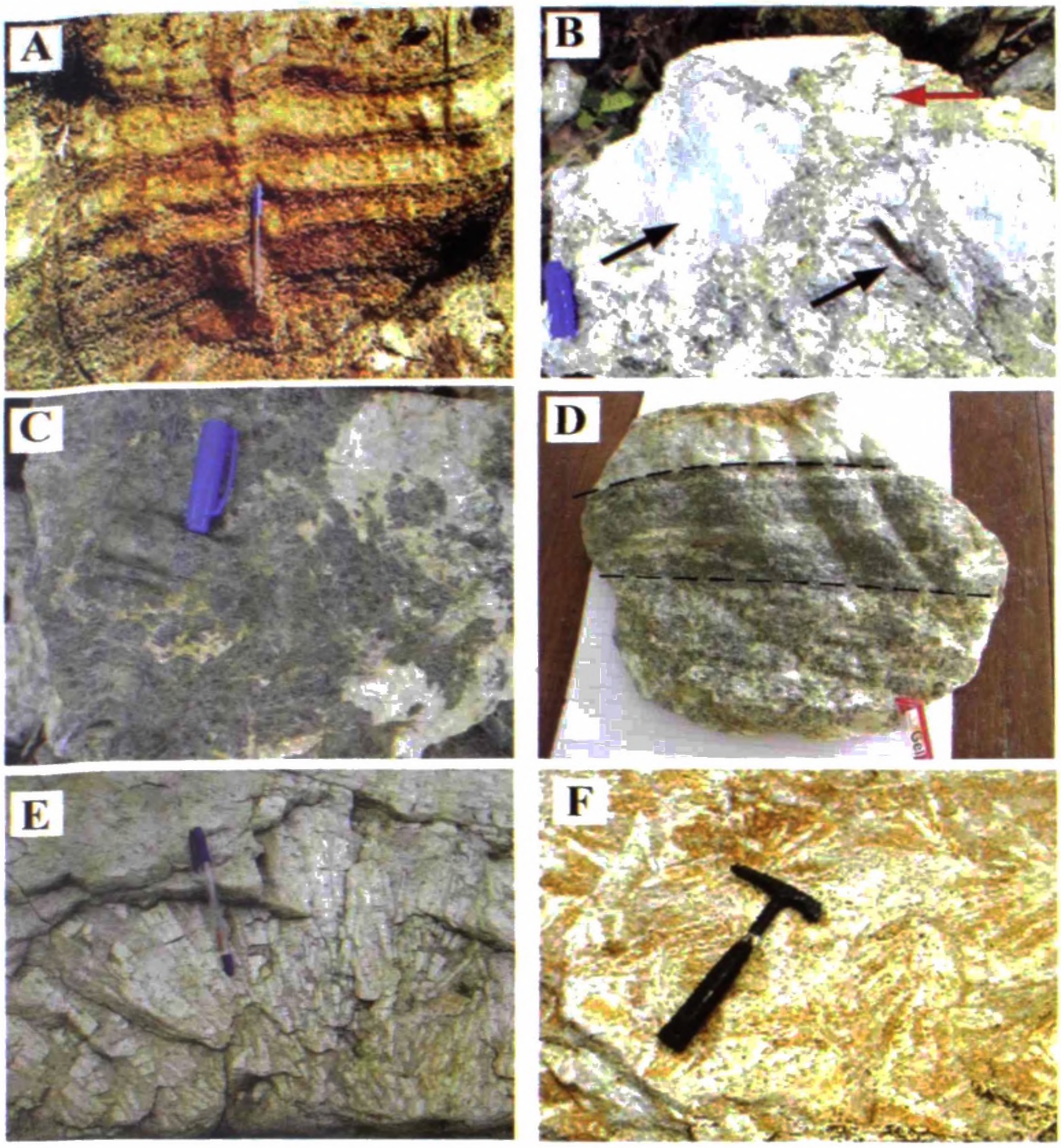

Fig. 2 Field photographs of the Study area (A) foliation defined by tightly compressed mafic bands (containing wollastonite-scapolite) with thick felsic layers at L3, (B) two porphyroblastic feldspar grains (black arrows) separated by fine-grained minerals, also a porphyroblastic wollastonite grain is (red arrow) adjacent to them at L4, (C) a mafic mineral assemblage at L3, (D) hand-specimen showing a transition of mineral assemblage and composition from impure marble to feldspar + quartz + scapolite rich area at L5 (E) Coarse-grained tremolite radiating from same point at L6. (F) Randomly oriented tremolite grains radiating in different directions at L6

Based on the presence or absence of wollastonite or grossularite, mineral assemblages can be sub-divided into three groups;

> Group I: Wollastonite-bearing but lacking grossularite (L1, L2, L3, L4),
>
> Group II: Grossularite-bearing but lacking wollastonite (L5),
>
> Group III: Both wollastonite and grossularite absent (L6, L7, L8).

Group I and Group II assemblages are restricted only to the SSW (Galle area) and SSE (Middeniya–Emblipitiya areas) of the Highland Complex, respectively. Mineralogy of Group III varies widely from place to place. Peak metamorphic mineral assemblages observed in different sample localities are based on the above grouping as summarized in Table 2. According to that sphene is a common, minor or accessory mineral in all the assemblages. Mineral abbreviations recommended by Whitney and Evans (2010) are used throughout this paper.

Table 2 Peak metamorphic mineral assemblages of calc-silicate rocks in the study area and their grouping based on occurrence of wollastonite and grossularite

Location	Group	Scp	Wo	Cpx	Afs	Pl	Grt	Spn	Cal	Qz	Tr	Spl	Ep	others
Koggala (L1)	I	+•	+	+	+	+•	-	+	+•	•	-	-	-	Gr, Amp, Ilm
Pilana (L2)	I	+	+	+	+	+	-	+	+	+	-	-	-	-
Galle Fort (L3)	I	+	+	+	+	+•	-	+	+•	+•	-	-	-	Gr, Mag
Boossa (L4)	I	+•	+	+•	+	+•	-	+	+•	+•	+•	-	-	Amp
Tambalapallassa (L5)	II	+	-	+•	+	+•	+	+	+	+•	-	-	-	Gr, Py, Mag, Ap,
Embilipitiya (L6)	III	+	-	-	-	-	-	+	+	-	+	+	+	Phl
Katuwana (L7)	III	+	-	+	+	+	-	+	+•	+•	+	-	-	Gr, Amp, Phl, Chl
Gonadeniya (L8)	III	+	-	+	+	+•	-	+	+	+•	-	-	-	Gr, Ilm, Ap

+ Mineral present, - Mineral absent, • present as a secondary or retrograde phase

Group I

Wollastonite, scapolite, K-feldspar, diopside and calcite are the major minerals (>10%) in the Group I assemblage, and Plagioclase feldspar, sphene and quartz occur as minor minerals (3-10%) with occasionally graphite, ilmenite and tremolite as accessories. The characteristic mineral of the Group I assemblage is wollastonite, and it appears in thin-section mainly as a coarse-grained porphyroblastic phase. It produces a granoblastic polygonal texture with other minerals and is primarily associated with scapolite making an aggregate (Fig. 3 A) between porphyroblastic K-feldspar. Wollastonite shows a breakdown texture in some samples at several localities. Scapolite is also a major mineral in Group I, and occurs as coarse-grained porphyroblasts or as medium-grained aggregates producing a granoblastic polygonal texture. In addition, it also occurs in overprinted assemblages and occasionally shows a break down texture. K-feldspar is usually coarse-grained and shows perthitic texture in several samples of locations L1, L3, L4.

In addition, K-feldspar shows mymerkitic texture with scapolite, wollastonite and calcite. Usually plagioclase feldspar is absent in felsic assemblages and it mainly occurs with mafic assemblages and is occasionally showing later recrystallization (S16, S18) (Fig. 3 B). Diopside in mafic assemblage in Group I commonly shows equigranular polygonal granoblastic texture and occasionally shows recrystallization (S16, S18) (Fig. 3 B). Quartz occurs as either major (L3) or minor mineral (L1, L4) in different localities and also occurs in overprinted assemblages as a retrograde break down product. Also at Boossa, it occurs as elongated stretched quartz. Different mineral assemblages within Group I show local variations, those are wollastonite + scapolite + K feldspar ± calcite ± plagioclase ± quartz, diopside + plagioclase ± K-feldspar ± sphene ± ilmenite, plagioclase + K-feldspar + quartz + diopside ± sphene ± magnetite.

Group II

Group II assemblage consists of scapolite, diopside, calcite and grossularite as major minerals, and K-feldspar, plagioclase feldspar, sphene, quartz as minor minerals with graphite and pyrite as accessories. This group is restricted only to Tambalapelessa in the study area. A notable mineral in this group is grossularite, which occurs usually as medium to fine-grains and is associated with other minerals to form equigranular polygonal granoblastic texture (Fig. 3 C). Different mineral assemblages observed in this group are, scapolite + calcite + diopside + grossularite ± plagioclase ± sphene, scapolite + calcite + diopside ± K-feldspar ± plagioclase ± quartz ± sphene (Fig. 3 D), scapolite + plagioclase + K-feldspar ± calcite ± sphene.

Group III

The Group III is characterized by presence of

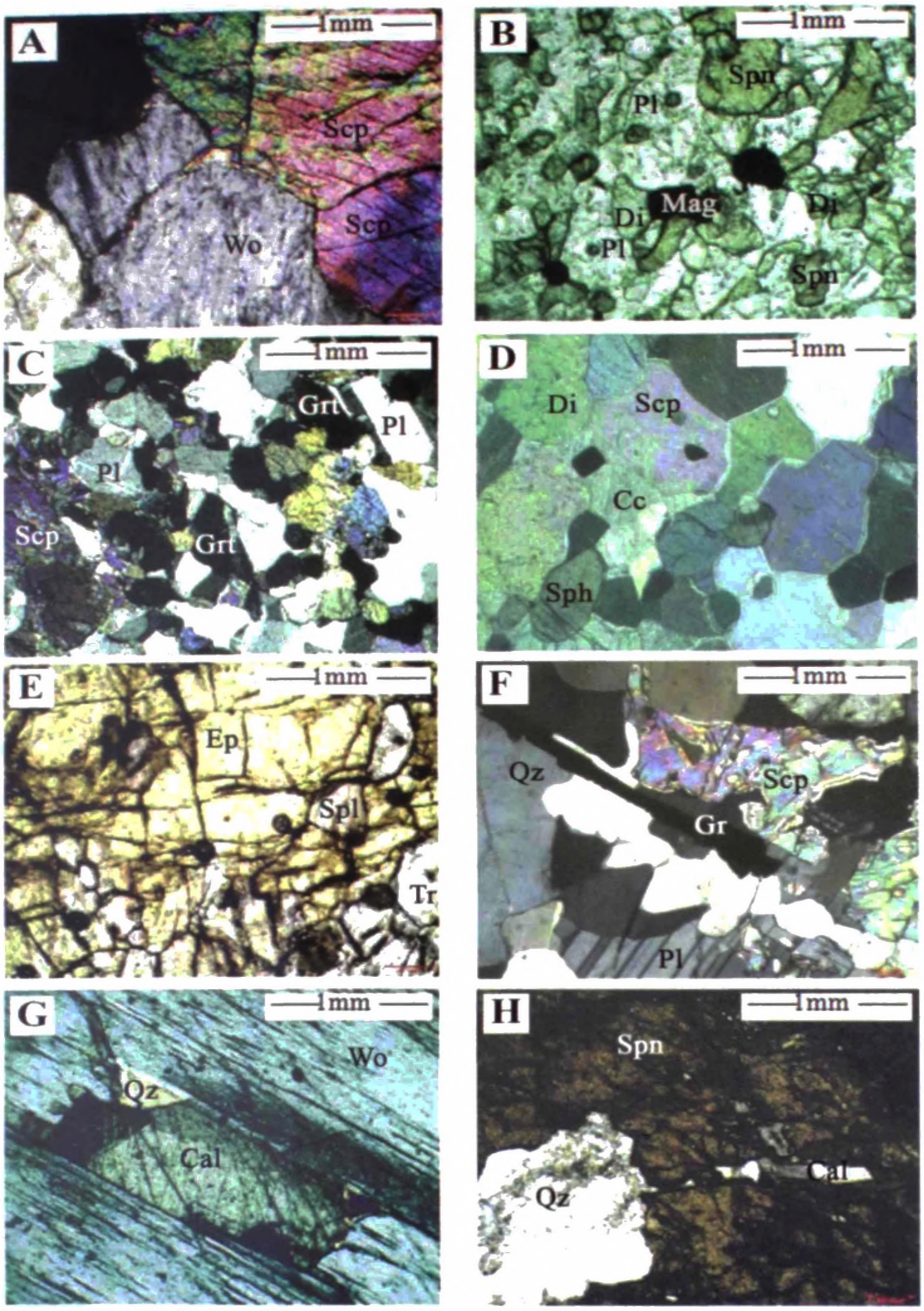

Fig. 3 Photomicrographs of thin-sections of mineral assemblages and relict textures in different groups. (A) Polygonal granoblastic texture showing by scapolite and wollastonite aggregates (XPL), (B) Recrystallized sphene + diopside + feldspar grains in coarse-grained quartz + feldspar matrix in Group I (PPL), (C) Fine to medium-grained grossularite garnet rich assemblage in Group II (XPL), (D) Polygonal granoblastic texture defined by scapolite + diopside + calcite assemblage with 120^0 grain boundary angle (XPL). (E) Coarse-grained epidote in Group III (PPL) (F) Graphite needles in Group III (XPL). (G) Calcite + Quartz inclusions within a porphyroblastic wollastonite grain (XPL), (H) Calcite and quartz inclusions within a porphyroblastic sphene grain (XPL)

different mineral assemblages which do not include wollastonite and grossularite. Embilipitiya–Chandrika wewa locality is composed entirely of different assemblages than the other locations; where coarse-grained porphyroblastic tremolite occurs in fine to medium-grained matrix of spinel + epidote (Fig. 3 E). In addition, at Katuwana, diopside, plagioclase feldspar and scapolite occur as major minerals. Replacement texture of diopside is common in samples of this location. Usually graphite needles are common in Group II/III assemblages than Group I (Fig. 3 F).

REACTION TEXTURES

Mineral reactions and textures developed in calc-silicate rocks can be assigned to either prograde or retrograde path of the P-T-t evolution of a metamorphic terrain. Prograde textures include occasionally preserved relict minerals and mineral aggregates which result from formation of peak metamorphic assemblages of the terrain. Although most of assemblages in the study area show well-developed triple junctions between adjacent minerals indicating equilibrium conditions, some of them occasionally show overprinting of peak assemblages during retrogression. All assemblages show prograde and/or retrograde reaction textures and Group I assemblage shows more reaction textures than others.

PROGRADE REACTION TEXTURES

Prograde reaction textures are relatively rare in the study area when compared to retrograde textures.

In some samples (S38, S36), relict calcite + quartz inclusions in porphyroblastic wollastonite in a quartz deficient matrix suggest the prograde reaction (Fig. 3 G),

Calcite + quartz $\longrightarrow$ wollastonite + CO_2 **(R1)**

In sample S85, relict calcite and quartz inclusions in porphyroblastic sphene grains suggest the prograde reaction (Fig. 3 H),

calcite + quartz + ilmenite $\longrightarrow$ sphene + CO_2 **(R2)**

RETROGRADE REACTION TEXTURES

There are several reaction textures that resulted from breakdown of peak metamorphic assemblages belonging to the different groups. Those include,

Group I

In the Samples of S6, S27, S33–36, polygonal wollastonite grains are partially replaced by an intergrowth or polygonal fine-grained equigranular mosaics of calcite and quartz suggesting a vapour involving wollastonite breakdown reaction (Fig. 4 A),

wollastonite + CO_2 $\longrightarrow$ calcite + quartz **(R3)**

In addition at sample S33, fine-grained aggregate of diopside with calcite grains after wollastonite indicates a vapour absent reaction (Fig. 4 B),

2 wollastonite + dolomite $\longrightarrow$ diopside + 2 calcite **(R4)**

Also at sample S33 – S35, Fine-grained intergrowth of calcite + quartz and little plagioclase feldspar between polygonal scapolite grains indicating a scapolite break down through vapour absent reaction (Fig. 4 C),

scapolite $\longrightarrow$ plagioclase feldspar + calcite + quartz **(R5)**

At sample S6, S35, Fine-grained symplectite of scapolite + quartz between K-feldspar and Calcite + quartz (which is probably after wollastonite breakdown) indicating a metasomatic reaction (Fig. 4 D),

wollastonite + alkali feldspar + CO_2 $\longrightarrow$ scapolite + quartz + K^+ **(R6)**

These symplectites become finer towards the K-feldspar corner (Fig. 4 E), and it is the result of strong control of coronal growth by limited diffusivities of Al-Si (Harley and Santosh, 1995). Scapolite-quartz symplectites are stable only at high X_{CO_2} conditions (Harley and Santosh, 1995).

Group II

At sample S56, Fine-grained diopside rims between quartz and calcite/dolomite in a coarse -grained clinopyroxene, calcite, scapolite matrix suggesting a formation of clinopyroxene through reaction (Fig. 4 F),

dolomite + 2 quartz $\longrightarrow$ diopside + 2 CO_2 **(R7)**

Group III

At sample S95, Secondary amphibole associated with diopside and calcite, quartz in a calcite + quartz deficient matrix indicating a retrogression of diopside through a hydration reaction (Fig. 4 G),

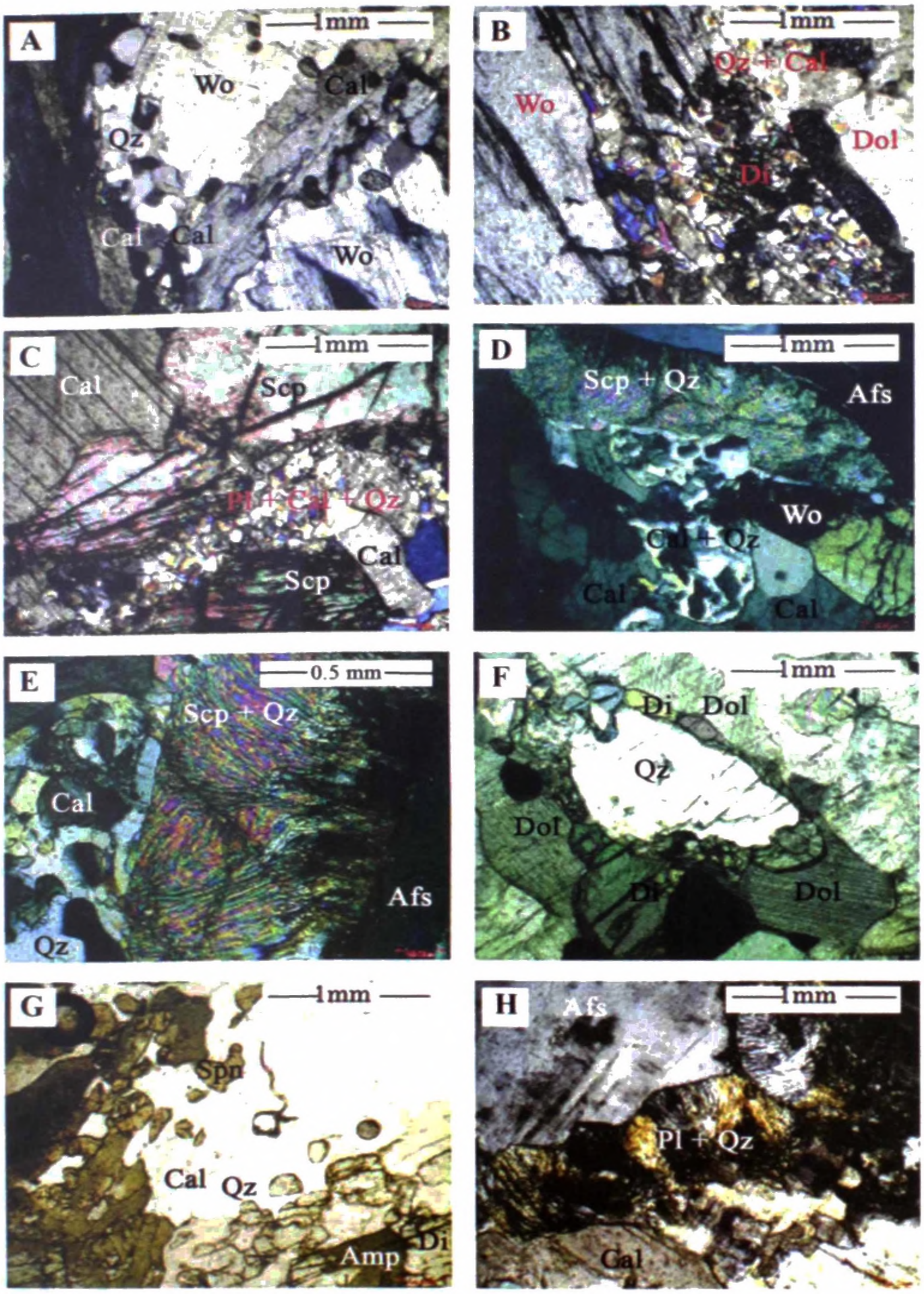

Fig. 4 Photomicrographs of thin-sections of retrograde reaction textures (A) polygonal wollastonite grains partially replaced by an intergrowth of cacite + quartz (XPL), (B) Porphyroblastic wollastonite grains partially retrogressed into fine-grained mosaics of calcite + quartz and calcite + diopside (XPL), (C) polygonal granoblastic scapolite grains partially retrogressed to fine-grained mosaics of plagioclase + calcite + quartz (XPL), (D) Pseudomorphic replacement of a wollastonite grain by calcite + quartz and scapolite + quartz symplectites after alkali feldspar (XPL), (E) Symplectite of scapolite + quartz is finer towards the alkali feldspar corner (XPL), (F) Fine-grained diopside rims around quartz and adjacent to calcite/dolomite (XPL), (G) Replacement of diopside by amphibole (PPL), (H) Intergrowth of plagioclase + quartz between alkali feldspar and calcite (XPL)

diopside + H_2O + CO_2 ⟶ Amphibole + calcite + quartz **(R8)**

In addition, mymerkitic intergrowth of plagioclase feldspar and quartz between calcite and alkali-feldspar in all Groups indicating fluid induced metasomatic retrograde reaction (Fig. 4 H),

calcite + alkali feldspar + Na^+ (fluid) ⟶ plagioclase feldspar + quartz + K^+ (fluid) **(R9)**

This mymerkitic rims around alkali-feldspar are common in everywhere in the study area and also can be seen in between alkali feldspar and scapolite or even in between alkali-feldspar grains.

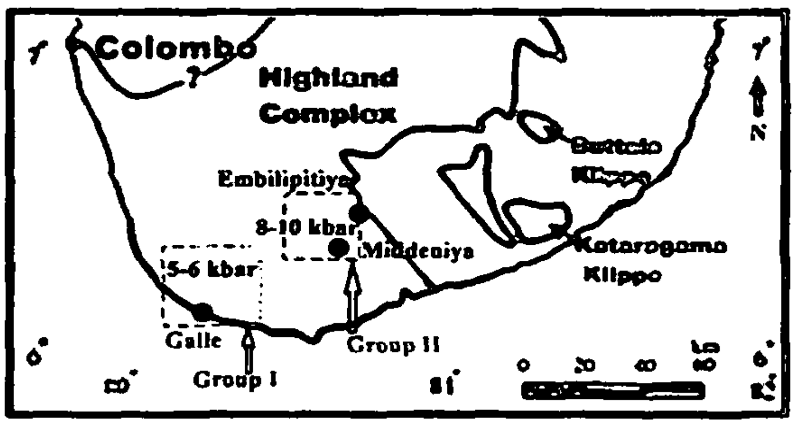

Fig. 5 Map showing distribution of Group I and Group II assemblages, according to pressure zoning mapping of Sri Lanka (after Faulharber and Raith, 1991)

DISCUSSION

According to the field and petrographic study of the calc-silicate rocks in southern Sri Lanka, three main assemblages can be identified as described in the previous section. Considering to pressure zoning mapping, Group I assemblage is restricted to the low pressure region (4-6 kbar) and Group II assemblage is restricted to the high pressure region (8-10 kbar) (Faulharber and Raith, 1991) (Fig. 5).

These assemblages can be represented in the K_2O-CaO-MgO-Al_2O_3-SiO_2-H_2O-CO_2 (KCMASHC) system and simplified form of CaO-Al_2O_3-SiO_2-H_2O-CO_2 (CASHC) system (Bucher and Grapes, 2010). Relative positions of the CASHC phases and relative compositions of the Group I and II assemblages can be represented in the SiO_2-$CaAl_2O_4$-CaO diagram (Fig. 6).

According to that the composition of the calc-silicate rocks in Group I show more SiO_2 rich composition than those of Group II. So protolith must be more siliceous in Group I than Group II.

Recorded phase relations shown that wollastonite - scapolite assemblage in Group I is stable at high to moderate X_{CO_2} conditions (Moecher and Essene, 1991; Harley and Buick, 1992). Scapolite formation through a prograde reaction (reverse reaction of R5) is required minimum temperature of about 550°C and it also depends on the activity of the phases (Hoffbauer and Spiering, 1994). According to Hoffbauer and Spiering (1994) during prograde path of metamorphism X_{CO_2} in wollastonite bearing assemblages was increased to 0.75. But near peak conditions, graphite precipitation in different localities at different level cause to stabilize the Group I and II assemblages. Present study also indicate this since presence of graphite flakes is usually higher in Group II/III assemblages (especially at location 5, 7) than the Group I assemblage.

Presence of prograde and retrograde reaction textures in the study area is important to determine the P-T-t fluid evolution of the terrain. Prograde textures provide the vital information about peak assemblage formation. Presence of calcite + quartz inclusions in a porphyroblastic wollastonite grain in quartz deficient rocks at some localities indicate the wollastonite bearing assemblages probably formed by the prograde reaction of **R1** and cause increase in X_{CO_2} of the system. Similarly sphene in the peak assemblages has formed through a prograde reaction of **R2** during prograde heating with increasing X_{CO_2} of the system (Hoffbauer and Spiering, 1994).

Presence of overprinted assemblages in the study area gives details on retrograde evolution of the metamorphic terrain after peak metamorphism. Break down of wollastonite via **R3** is a result of either cooling or increase of X_{CO_2} of the system and vapour absent reaction of **R4** is through cooling but independent in X_{CO_2} during retrogression. Breakdown of scapolite by **R5** is result of cooling but independent to change in P/ X_{CO_2} during retrogression. Further formation of scapolite + quartz symplectites through **R6** is either result of decompression or increase in X_{CO_2} during retrogression (Satish-Kumar and Santosh, 1998) whereas diopside rims around quartz formed via **R7** is result of either decompression or at higher X_{CO_2} level. Finally **R8, R9** are result of interaction with aqueous fluid phases.

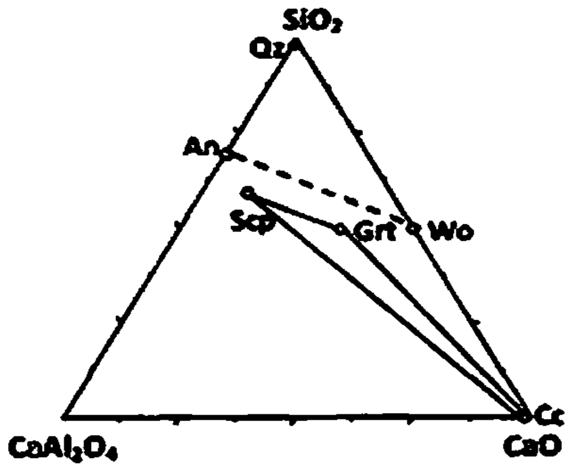

Fig. 6 CaO-SiO_2-$CaAl_2O_4$ diagram showing CASV phases of the Group I and Group II assemblages. The area showing solid lines indicate the Group II main mineral assemblage and the dash lines indicate major minerals of the Group I assemblage

According to the textural interpretation of the study area, P-T-t evolution of the terrain can be suggested. When considering the retrograde path of the terrain, reactions **R3**, **R4** and **R5** indicate a cooling dominated path after peak metamorphism but reaction **R6** and **R7** indicate a decompressional path. Such interpretation does not consider Xco_2 evolution of the system. When consider the effect of Xco_2, most of the reactions which indicates cooling independent of action of CO_2. So that during early stage of cooling probably internal fluid buffering has prevailed, as noted by previous workers (Mathavan and Fernando, 2001).Reaction R6 and R7 can also form through increment of CO_2 probably through interaction with externally derived carbonic fluid. If one considers only cooling in the system represented by wollastonite and scapolite breakdown, then the scapolite + quartz symplectites do not form (Satish-Kumar and Santosh, 1998) and instead grossularite + quartz rims form between scapolite and wollastonte or calcite as noted in many terrains including the Highland complex of Sri Lanka (Warren et al., 1987; Harley et al., 1994; Shaw and Arima, 1996; Mathavan and Fernando, 2001; Prame and Prema, 2014; Wickramasinghe and Perera, 2014). Also scapolite + quartz symplectites were formed later and at lower temperatures than the mosaics of calcite + quartz (Harley and Santosh, 1995) (Fig. 4 D and E). Consider the P-T-t path based on the previous studies on Pelitic and mafic rocks, they interpreted isobaric cooling following peak metamorphism and subsequent decompression (e.g. Perera, 1987; Schenk et al., 1991; Prame, 1991). So, authors in a view that these reactions might be occurred during that decompressional event. However, chemical analysis of rocks and construction of P-T, P-Xco_2 grids need to further confirm it. Further reactions **R8** and **R9** are result of interaction with hydrous fluids during metamorphic evolution.

According to the textural features different assemblages in the area show different post peak fluid evolution. Group I and II assemblages show probable influx of carbonic fluid during later stage of retrogression while Group III assemblage shows influx of hydrous fluid during retrogression. So, fluid evolution of the area shows local variation. No evidence has been observed to determine relative time of carbonic and hydrous fluid infiltration during present study.

Consider overall petrography, P-T-t path of present study may involve initial cooling after peak metamorphism with early stage of internal fluid buffering and subsequent locally affected final stage influx of external Xco_2 rich fluid and hydrous fluid. This explanation is merely based on the observed textural features; however a most reasonable explanation may require further petrological and geochemical analysis and construction of relevant grids for the study area.

Further the present study is more consistent with the P-T-t evolution of the Highland Complex Sri Lanka suggested by previous workers using the pelitic and mafic rocks. They also suggested that retrograde path involved initial isobaric cooling (e.g. Perera, 1987; Prame, 1991; Schenk et al., 1991; Raase and Schenk, 1994). Recent studies on geochronological (Milisenda et al., 1994; Brandon and Meen, 1995) structural (Cenki and Kriegsman, 2005) and Petrogenetic (Sreejith and Ravindra Kumar, 2013) data suggest a correlation with Southern India and the Sri Lanka. The Highland Complex of Sri Lanka and Kerala Khondalite Belt (KKB), Southern India shows similar crust formation age of 2.0-3.0 Ga (Milisenda et al., 1994; Brandon and Meen, 1995), Pan African Ultrahigh temperature metamorphism between 610-530 Ma and similar P-T-t path including initial cooling and subsequent decompression (Perera, 1987; Schenk et al., 1991; Satish-Kumar and Harley, 1998). Also Sreejith and Ravindra Kumar (2013) introduced a geochemical relation of granite-ademellite rocks of the HC with Orthogneisses of KKB. Present study shows some similarities with calc-silicate rocks in KKB with respect to

Petrography. Those similarities include presence of grossularite absent Group I assemblage without retrograde garnet formation, textures of reactions 4, 5, 6 and textural evidence for final stage of carbonic fluid influx.

CONCLUSIONS

Calc-silicate rocks in Southern Sri Lanka show three groups of mineral assemblages; Group I:- Wollastonite bearing but grossularite absent, Group II:- Grossularite bearing but wollastonite absent, Group III:- Both wollastonite and grossularite absent. Formation of different assemblages is result of a peak metamorphic pressure condition, chemistry of protolith and graphite precipitation at peak condition. The petrography of present study suggests a probable P-T-t path involving initial cooling after peak metamorphism with early stage of internal fluid buffering. In addition, Group I/II assemblages show subsequent final stage of external Xco_2 rich fluid influx while group III assemblage shows subsequent hydrous fluid influx. These fluid infiltrations have been probably occurred at local scale in the study area. Finally present study on calc-silicate rocks provides further evidences for a correlation between KKB of Southern India and the Highland Complex of Sri Lanka.

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