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REVIEWS

Revisiting Ultrahigh Temperature Granulites of Sri Lanka: New Prograde and Retrograde Mineral Textures from the Highland Complex

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Abstract | In order to investigate probable multiple metamorphic events including Ultrahigh Temperature (UHT) metamorphism experienced by Sri Lankan metamorphic rocks, we undertook extensive sampling of granulites covering the whole Highland Complex (HC) for comprehensive studies on petrology, geochemistry and geochronology. The studied UHT metamorphic rocks are sapphirine, spinel and sillimanite bearing garnet-orthopyroxene gneiss, sapphirine and spinel bearing garnet-orthopyroxene-sillimanite gneiss, sapphirine and spinel bearing garnet-sillimanite gneiss, spinel bearing garnetiferrous quartzo-feldspathic gneiss, corundum and spinel bearing garnet-sillimanite-graphite gneiss and spinel bearing garnet-sillimanite-cordierite-graphite gneiss. UHT minerals and mineral assemblages occurring in these rocks are sapphirine, orthopyroxene+sillimanite+quartz, spinel + quartz and garnet+orthopyroxene+cordierite. The presence of orthopyroxene+sillimanite+quartz, spinel + quartz assemblages could indicated the metamorphic temperatures >900°C. The occurrence of kyanite inside the garnet, and sillimanite as an abundant mineral in the matrix indicate the clockwise *P-T* trajectory. Occurrence of orthopyroxene + sillimanite + quartz, imply the peak metamorphic history at UHT conditions under relatively higher pressures. Decompression histories are inferred mainly by cordierite+orthopyroxene symplectites around garnet. Above mineral textures demonstrate clear evidence for UHT metamorphism of the studied rocks. Further studies on thermobarometry, geochemistry and geochronology are underway to elaborate spatial and temporal evolution of the UHT pelitic granulites of the Highland Complex, Sri Lanka.

1 Introduction

Metamorphism in the deep crust at temperatures in excess of 900°C and pressures at a range of 7–13 kbar generates rocks with specific mineralogical characteristics termed as Ultrahigh Temperature (UHT) granulites (Harley, 1998, 2004). The UHT metamorphism and related processes provide important windows to understand processes in the deep crust as well as crust-mantle interactions. Generally, UHT metamorphism is well exemplified in pelitic lithologies from restricted localities in the world such as Napier Complex, Lützow Holm Complex (East Antarctica), Epupa Complex (Namibia), Betroka Belt (Madagascar), Lewsian Complex (Scotland), Southern Limpopo belt (South Africa), Quantum Massif (Vietnam), Kerala Khondalite belt, Madurai Block (India) and Highland Complex in

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Sri Lanka (Kelsey, 2008). However, considering the fact that the metamorphism is a solid state closed system process, the tectonics of regional UHT metamorphism still remains problematic with the question as to how realistically geological processes could explain attaining such extreme crustal temperatures (well above the dry solidus of granulites) in the absence of complete melting of the rocks of pelitic bulk compositions. Few tectonic models have been put forward to explain crustal metamorphism in excess of ~1000°C, which is usually followed by rapid decompression such as magmatic over-accretion, lithospheric removal after crustal thickening, channelized extrusion of deep crustal rocks after inhomogeneous extension, high heat flow in a back arc basin and ultra-hot collisional orogeny locally superheated by basaltic underplating (e.g. Harley, 2004; Kelsey, 2008; Tsunogae and Santosh, 2010; Sajeev et al. 2010). However, validity of these tectonic models is still under debate and should be applied with caution as geochemical constraints (e.g. elemental mobility, inter- and intra-crystalline diffusion etc.) at such high temperatures are not yet well understood experimentally.

Typical minerals and mineral assemblages that occur in UHT metamorphic rocks are sapphirine+quartz, orthopyroxene+sillimanite+ quartz, osumillite+garnet and spinel+quartz in pelitic rocks. UHT metamorphism has been derived from other mineral assemblages as well, such as corundum + quartz (Shaw and Arima, 1996; Osanai et al., 2006), high alumina orthopyroxene (Harley and Motoyoshi, 2000), orthopyroxene + corundum (Ouzegane and Boumaza, 1996; Kelly and Harley, 2004), inverted pigeonite (Sandiford and Powell, 1986; Tsunogae et al., 2002), garnet + corundum (Osanai et al., 2006; Shimpo et al., 2006) and high-fluorine biotite and pargasite (Tsunogae et al., 2003, Sajeev et al., 2009). Evidence for UHT metamorphism is mostly preserved in Mg-Al-rich pelitic granulites (e.g., Harley et al., 1990; Sajeev and Osanai 2004a, 2004b; Sajeev et al. 2004, 2006), and rarely in mafic-ultramafic granulites (e.g. Harley 1989, Sajeev et al., 2007, 2009). However, in mafic granulites, the UHT metamorphism can be appreciated only if the pelitic granulites that are in immediate contact with the mafic rocks also preserve evidence for UHT metamorphism, owing to the fact that there is a possibility of misinterpreting igneous textures in mafic rocks as UHT metamorphic textures (Harley, 1998). So far in Sri Lanka, limited petrological and geochronological studies have revealed evidence for occurrence of the UHT metamorphic textures from both pelitic and mafic rocks in few localities of the Highland Complex. Therefore, it is vitally important to further extend petrological, geochemical and geochronological investigations of the UHT rocks in the Highland Complex to provide insights into the Earth's deep crustal processes beneath the Sri Lankan basement. In this paper we present newly discovered mineral textures found from Sri Lankan granulites in the first stage of our on-going UHT research on the granulites of the Highland Complex of Sri Lanka.

2 Geology and Geochronology of the Sri Lankan Basement

The metamorphic basement of Sri Lanka has been considered as a key terrain to understand the evolution of the Gondwana Supercontinent since the island of Sri Lanka was geographically located close to India, Madagascar and East Antarctica as the main portions of the east Gondwanaland. Based on Nd-model ages (Milisenda et al., 1988, 1994) the Proterozoic basement of Sri Lanka has been subdivided into four litho-tectonic units (Kröner, 1991; Cooray, 1994): the Highland Complex (HC), the Wanni Complex (WC), the Vijayan Complex (VC) and the Kadugannawa Complex (KC) (Fig. 1).

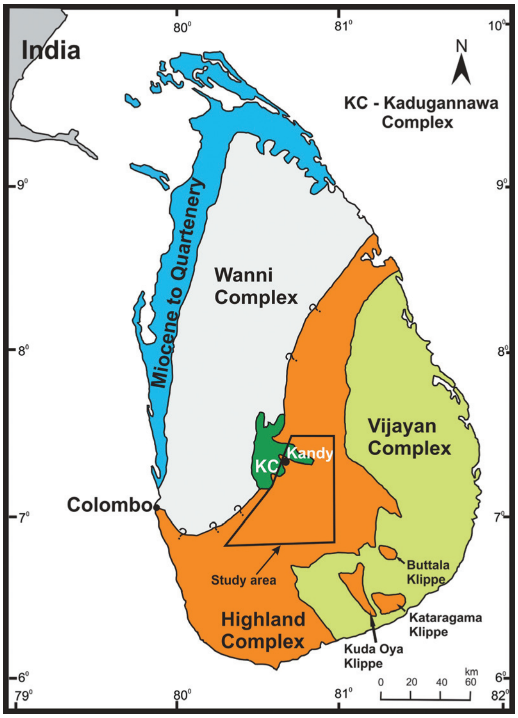

Figure 1: Proterozoic litho-tectonic units of Sri Lanka, showing the sampling area.

The U-Pb zircon/monazite and Nd-model age of the basement rocks of the HC yield 2000–3400 Ma and metamorphic age of ~550 Ma (Hö1zl et al., 1994; Milisenda et al., 1988, 1994; Malaviarachchi and Takasu, 2011a), and is composed of granulitic meta-quartzites, marbles, calcsilicates and metapelitic gneisses, intimately associated with charnockites (e.g. Perera, 1983, 1984; Cooray, 1994; Mathavan and Fernando, 2001; Malaviarachchi and Takasu, 2011b). Deposition of sediments of the HC took place from 3200 Ma to 1900–2000 Ma (Hö1zl et al., 1994 and Kröner et al., 1994). Most of the granitoid plutons, currently exposed as orthogneisses, have intrusion ages of 1800–1900 Ma and 670 Ma. Hence, the HC represents a 2000–3000 Ma old crust. Between 610 and 550 Ma, the HC was metamorphosed under regional granulite facies conditions during assembly of the Gondwana Super Continent (Kröner et al., 1994; Hö1zl et al., 1991, 1994). In the HC, metamorphic pressures and temperature decrease from 8–9 kbar and 800–900°C in the east and southeast to 4.5–6 kbar and 650–750°C in the southwest (Faulhaber and Raith, 1991, Schumacher and Faulhaber, 1994, Raase and Schenk, 1994; Kriegsman, 1996: Kriegsman and Schumacher, 1999; Braun and Kriegsman, 2003; Malaviarachchi and Takasu, 2011b). Evidences of UHT metamorphism have been reported only from few localities in the central Highland Complex (e.g. Osanai, 1989; Kriegsman, 1991; Kriegsman and Schumacher, 1999; Osanai et al., 2000, 2006; Bolder-Schrijver, 2003; Sajeev and Osanai, 2003, 2004a; Sajeev et al., 2007 and 2010) and rarely in the southwestern part (Sajeev and Osanai, 2004b) from pelitic, mafic and quartzo-feldspathic granulites. Estimated UHT conditions range between 925 and 1150°C at *P* of 9 and 12.5 kbar (Kriegsman and Schumacher, 1999; Osanai et al., 2006; Sajeev and Osanai, 2004a, 2004b; Sajeev et al., 2007 and 2010).

The WC yields U-Pb zircon and Nd model ages of 1000–2000 Ma (Milisenda et al., 1988, 1994; Santosh et al. 2014) and is constituted of orthogneisses and migmatitic ortho and paragneisses, which have been metamorphosed under granulite to upper amphibolite facies conditions (Kröner et al., 1991) together with some post-tectonic granites. Estimated *P-T* conditions are $P = 3.5–7.5$ kbar and $T = 600–900$°C (Schenk et al., 1991; Faulhaber and Raith, 1991). The VC rocks have U-Pb zircon and Nd-model ages of 1100–1800 Ma (Milisenda et al., 1988; 1994; Kröner et al. 2013). It mainly comprises 1000–1100 Ma old calc-alkaline granitoid gneisses, migmatitic orthogneisses and minor metasedimentary enclaves, such as meta-quartzite and calcsilicates (Kehelpannala, 1997; Kröner et al., 2013) predominantly metamorphosed under upper amphibolite-facies conditions. Rocks of the KC display U-Pb zircon ages of ~900 Ma, and are composed of hornblende- and biotite-bearing orthogneisses, gabbros, diorites, granodioritic to granitic gneisses, charnockites, enderbites and minor metasediments (Kröner et al., 2003; Willbold et al., 2004; Malaviarachchi and Takasu, 2011b). The KC has been separated from the other units (Kroner et al., 1991; Cooray, 1994). However, owing to many similarities in lithology, structures and geochronology, some authors consider the KC as a part of the WC (e.g. Kehelpannala, 1997; Kröner et al., 2013).

3 Previous Studies on the Sri Lankan UHT Metamorphism

The mostly abundant high grade metamorphic rocks are found in the HC, of which the predominant rocks represent peak metamorphic conditions up to 850–900°C and 8–10 kbar, occurred during the Pan African collision at ~550 million years ago (e.g. Milisenda et al., 1988; Kröner et al., 1991; Kröner and Williams, 1993). We refer to these granulite facies rocks as ‘ordinary granulites’ in this paper, in order to distinguish them from the granulites depicting UHT metamorphic conditions (UHT granulites). The UHT granulites are found as blocks, lenses or relics within the ordinary granulites in the HC of which sapphirine is the characteristic mineral.

Implications for UHT at several localities in the HC of Sri Lanka have been documented by several authors. Schenk et al. (1988) reported temperatures above 900°C for mafic granulites based on orthopyroxene exsolution in clinopyroxene, which they interpreted as evidence for isobaric cooling from even higher temperatures. First finding of sapphirine from Sri Lanka by Osanai (1989) in pelitic rocks led subsequent authors to stimulate research on UHT granulites of the HC. In some localities of the HC, rocks contain sapphirine bearing blocks or lenses representing UHT and high-pressure metamorphic conditions in excess of 900°C and 11–12 k bar (e.g. Osanai, 1989; Kriegsman, 1991; Kriegsman and Schumacher, 1999; Sajeev and Osanai, 2004a). They presented evidence for isobaric cooling even from 1150°C and 12 kbar after peak metamorphism at UHT granulite facies conditions, which was followed by a multi stage evolution (e.g. Sajeev and Osanai, 2004a). These *P-T* conditions are in contradiction with the other ordinary granulites in the surrounding area, which preserve a maximum of 850–900°C and 9–10 kbar and determined to be metamorphosed during the Pan African (~550 Ma) tectonothermal event. Further, Sajeev and Osanai, (2004a) concluded that the UHT granulites of the HC probably evolved along an anticlockwise path although tectonic scenarios for such evolution has not been undertaken thus far. Sajeev and Osanai (2004b) reported extremely rare UHT mineral osumillite from the south western part of the HC However, they could not interpret whether osumillite is a product of the Pan African metamorphism or a relic of an older metamorphic event due to lack of Geochronological data. These pioneering studies not only have added a value to the HC rocks of Sri Lanka, but also have a significant bearing on the thermal events and the tectonics of the Gondwana, of which Sri Lanka was the smallest but an important fragment.

So far, results from numerous studies established that the Pan-African metamorphic event of Sri Lanka occurred at ~550 Ma as a result of multiple collisions among crustal blocks during the amalgamation of the Gondwana Supercontinent. However, this high grade metamorphism was attained after intense phases of penetrative deformation that obliterated all original contacts between supracrustal rocks and voluminous gabbroic to granitoid intrusives, followed by a widespread and pervasive retrogression (e.g. Voll and Kleinshrodt, 1991; Kehelpannala, 1997; Kröner et al., 2003). Therefore, apparently it is very difficult to find the relics of evidence for earlier metamorphic stages. Importantly, similar UHT petrological evidence have also been reported from some other east Gondwana fragments worldwide including Antarctica, India and Madagascar, suggesting possible occurrence of an event of extreme crustal metamorphism under UHT conditions in the Gondwana Supercontinent. Importantly, it is already known that the UHT rocks of the HC can be correlated petrologically with adjacent UHT terrains such as Fore-finger point in east Antarctica (e.g. Harley et al., 1990), Lutzow Holm Complex, east Antarctica (e.g. Yoshimura et al., 2004) and the Madurei Block in southern India (Sajeev et al., 2001, 2004a). These studies, however, pointed out that any correlation of specific metamorphic events in these terrains remains incomplete due to the lack of detailed isotope geochronology from the UHT granulites. Such a UHT metamorphic event may predate the wide-spread Pan African high grade metamorphism (~550 Ma), which may have overprinted most of the previous UHT textures of the granulites of the HC and other Gondwana fragments.

A few studies on geochronology of the Sri Lankan UHT have been carried out to reconcile the timing of the UHT metamorphism. While appreciating their efforts, however, it is questionable as to how far it could represent the overall geochronological evolution of the UHT metamorphism in the HC, since the previous studies on age determinations were performed with only a very few samples. Osanai et al. (1996) reported a ~670 Ma metamorphic event for sapphirine bearing granulites by using the Sm-Nd whole rock isochron method. Also, they presented a retrograde age of ~520 Ma based on the whole rock biotite internal isochron method. Sajeev et al. (2003) reported an internal Sm-Nd isochron age for the metamorphism of ~1500 Ma based on the analysis of a garnet core, whole rock and felsic fraction. However, considering the closure temperature of garnet in the Sm-Nd system, they interpreted the estimated age as a cooling age after peak UHT metamorphism. Also, they reported an orthopyroxene reference isochron age of 550 Ma, implying that these UHT granulites have subsequently been affected by the Pan African metamorphism. Sajeev et al. (2007) reported U-Pb age of ~580 Ma from metamorphic zircons in UHT mafic granulites. Sajeev et al. (2010) used sapphirine granulites for SHRIMP to conclude that the Sri Lankan UHT granulites approached peak metamorphic conditions ~570 Ma, then cooled and decompressed nearly isothermally ~550 Ma. Hence, it still remains a necessity and significance to work on these rarely exposed UHT rocks of the HC to explore more evidence for the existence of an UHT zone, probably resulting from an early metamorphic event within the high grade terrain of Sri Lanka. Thus, an elaborative *P-T-t* geochemical study backed by extensive sampling is indispensible to systematically reconstruct the Lower Cambrian metamorphic complexity of the Sri Lankan basement.

4 Studied Samples

For better interpretation of probable multiple metamorphic events experienced by the HC of Sri Lanka, we have undertaken extensive sampling of granulites covering the whole HC in order to carry out comprehensive study of petrology, geochemistry and geochronology. More than 500 sample locations consisting of pelitic lihologies are identified to be sampled, of which more than 400 samples have already been collected and processed for detailed thin section studies and geochemistry.

The selected samples are Al-Mg-rich meta-pelitic rocks, from the inner HC including specific locations of Udaperadeniya, Ampitiya, Talatuoya, Madamahanuwara, Ududumbara, Hunnasgiriya, Gampola, Nawalapitiya, Kotmale, Ramboda, Walapane, Galaha, Avissawella, Ingiriya, Bulathsinhala and Kukuleganga (Fig. 1). Out of the studied samples, several rocks mainly included at least one or more characteristic UHT minerals or assemblages composed of garnet, sapphirine, orthopyroxene, sillimanite, cordierite and spinel.

The studied rocks were categorized depending on the constituent minerals.

1. *Sapphirine, sillimanite and spinel bearing garnet-orthopyroxene gneiss (Rock A)*: Rock A occurs as a thin layered fragment (abut 20–30 cm thickness) within a massive charnockite. Major minerals in the Rock A are garnet, orthopyroxene, biotite and sillimanite. This rock is quartz saturated and most of quartz grains show stretched textures. A plenty of porphyroblastic garnet (0.3–2.5 cm in diameter) and elongated orthopyroxene (1–3.5 cm in length) can be identified within the fragment.
2. *Sapphirine and spinel bearing garnet-orthopyroxene-sillimanite gneiss (Rock B)*: Rock B is found as an interlayered with a sillimanite bearing granet-orthopyroxene gneiss (can be regarded as the host rock) that occurs as a common lithilology in the quarry. This quartz saturated rock is relatively fresh and comprises porphyroblasts of garnet (0.5–2.5 cm in diameter) surrounded by orthopyroxene-sillimanite corona and/or orthopyroxene-codrierite symplectite. Purple colour cordierite can be observed in the matrix. Porphyroblasts of garnet (0.5–3 cm in diameter) and orthopyroxene (0.5–2.5 cm in diameter) can be identified in the host rock.
3. *Sapphirine bearing Garnet-sillimanite gneiss (Rock C)*: Rocks C is well foliated and occur as thin layered fragment within a massive charnockite. Garnet occurs as porphyroblasts clearly in two sizes. The most abundant garnets are of 0.5–1 cm in diameter and the less abundant garnet porphyroblasts are 3–5 cm in diameter. Both type of garnets occasionally rimed by orthopyroxene-cordierite symplectites. There are plenty of biotite grains occurring in this rock associated with porphyroblasts of garnet.
4. *Spinel bearing garnetiferrous quartzofeldspathic gneiss (Rock D)*: Rock D is well foliated and found at a road cut with thick bedding planes (1–1.25 m) alongwith two sets of strong joint planes. Stretched quatz is indicative of strong deformation suffered by the rock. This rock alternatively interbands with a staurolite bearing garnet- sillimanite-hornbende-biotite gneiss.
5. *Corundum and spinel bearing garnet-sillimanite-graphite gneiss (Rock E)*: Rock E occurs as fresh massive exposures where quartz saturated and quartz deficient domains can be identified. This rock contains various sizes of garnet from <0.5 cm to >4 cm in diameter. Stretching quartz and recrystallized feldspars in quartz-saturated domains indicate intense deformation conditions. In some quartz absent domains, tiny corundum grains are observed. Associated to these corundum are plagioclase, orthoclase, sillimanite and spinel. This pelitic rock occurs as a layer within massive charnockite.
6. *Spinel bearing garnet-sillimanite-cordierite-graphite gneiss (Rock F)*: Rock F is exposed in an excavated embankment. This rock contains garnet porphyroblasts of sizes up to ~8 cm in diameter and some parts of the rock are enriched in cordierite appearing as zones of light purple colour. Coarse sillimanites and spinel can also be observed under naked eye. Alternative dark coloured layers, which contain orthopyroxene, biotite, plagioclase, while quartz can also be seen within rock F. At some domains, both dark coloured layers and the host rocks are folded forming isoclinal folds.

5 Mineral Textures

The following petrograhic observations are found as evidence for the UHT metamorphism suffered by the studied rocks of the HC.

5.1 *Sapphirine*

In Rock A, weakly pleochroic sapphirine is found as closely associated rare inclusions with spinel in the core and mantle areas of porphyroblastic garnet (Fig. 2a–c). Rarely co-existence of sapphirine and spinel was observed. The sapphirine is pale bluish in colour and occur in sizes ~0.1 mm, showing rounded (Figs. 2a and b) and prismatic shapes (Fig. 2c). Characteristically, the sapphirine grains in this rock have sharp grain contacts and are in textural equilibrium with host garnet. Sapphirine and spinel occur in a modal percentage of <5% in the rock.

Sapphirine is found in the Rock B as an aggregate at the rim of garnet porphyroblasts and in the matrix as well. Sapphirine in the matrix occur as randomly distributed porphyroblasts

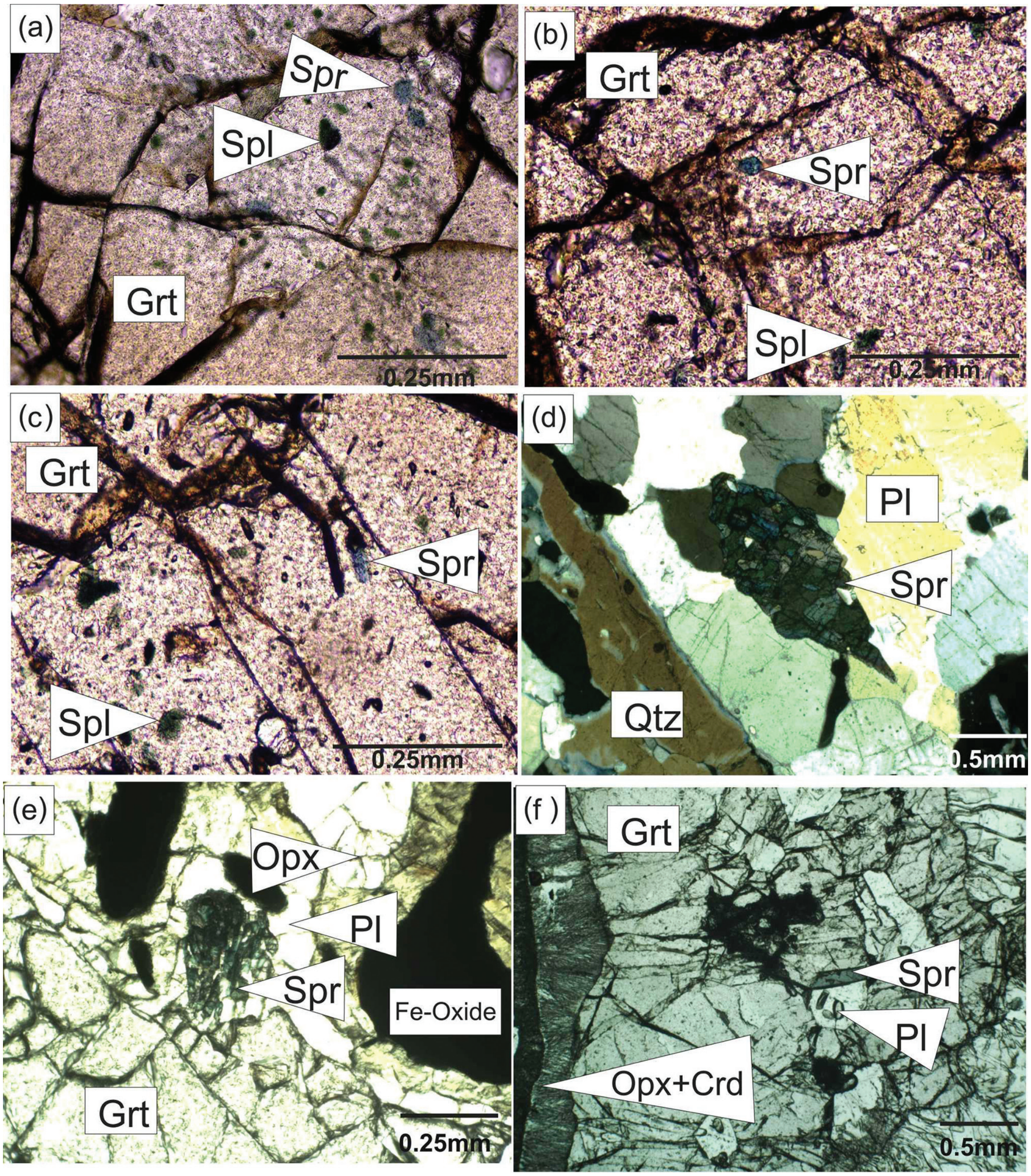

Figure 2: Different petrographic occurrences of sapphirine in the studied samples. (a–c) rounded to prismatic sapphirine in garnet in the Rock A. (d) porphyroblastic sapphirine in Rock B. (e) aggregate of saphirine in contact with plagioclase in Rock B. (f) coexistence of sapphirine-plagioclase at the rim of garnet in Rock C.

associated with plagioclase (Fig. 2d). The matrix, psuedo-porphyroblastic sapphirine (an aggregate of tiny sapphirine appearing as a porphyroblast) is surrounded by two feldspars (Fig. 2d). These sapphirine grains are highly pleochroic and light bluish in colour. Plagioclase is found in contact with sapphirine and orthopyroxene (Fig. 2e). Sapphirine and spinel occur in a modal percentage of <1%.

At the rim of garnet porphyroblasts in the Rock C, tiny sapphirine (0.1–0.5 mm) observed contact with plagioclase (Fig. 2f). These sapphirine grains are weakly pleochroic and light bluish in colour. Garnet has broken down forming orthopyroxene-cordierite symplectites. Sapphirine and spinel occur in a modal percentage of <1%.

5.2 *Spinel+Quartz assemblage*

Spinel+quartz assemblage occurs as inclusions within porphyroblastic garnet (Fig. 3a) and at margins of garnet porphyroblasts (Fig. 3b) in Rock D. This texture is mostly associated with Fe-oxides and secondary (retrograde) biotites. The rock contains abundant porphyroblastic garnet and Fe-oxide minerals in the matrix. Many of the garnet grains that have spinel+quartz texture contain biotite, plagioclase and quartz as inclusions. At some parts of the rock, spinel+quartz assemblage was observed in the matrix (Fig. 3b). Matrix spinel of this rock is mostly associated with Fe-oxide minerals.

5.3 *Exsolved rutile-ilmenite cluster within garnet*

In Rock E, tiny rutile-ilmenite inclusions are found as clusters in the core area of garnet porphyroblasts (Fig. 3c-d). These tiny inclusions show a preferred orientation (Fig. 3d). A considerable amount of biotite and plagioclase can also be observed as inclusions. These inclusions are mostly found in the near-core areas of garnet porphyroblats. Similar textures of exsolution of rutile from host garnet has been reported in many high to UHT ganulites (e.g Kawasaki and Motoyoshi, 2000; Osanai et al., 2001; Kawasaki et al., 2011).

5.4 *Kyanite inclusion within Grt*

Rare kyanite inclusion within garnet could be observed in Rock E (Fig. 3e). Kyanite occurs as clear-prismatic shapes in the core region of garnet

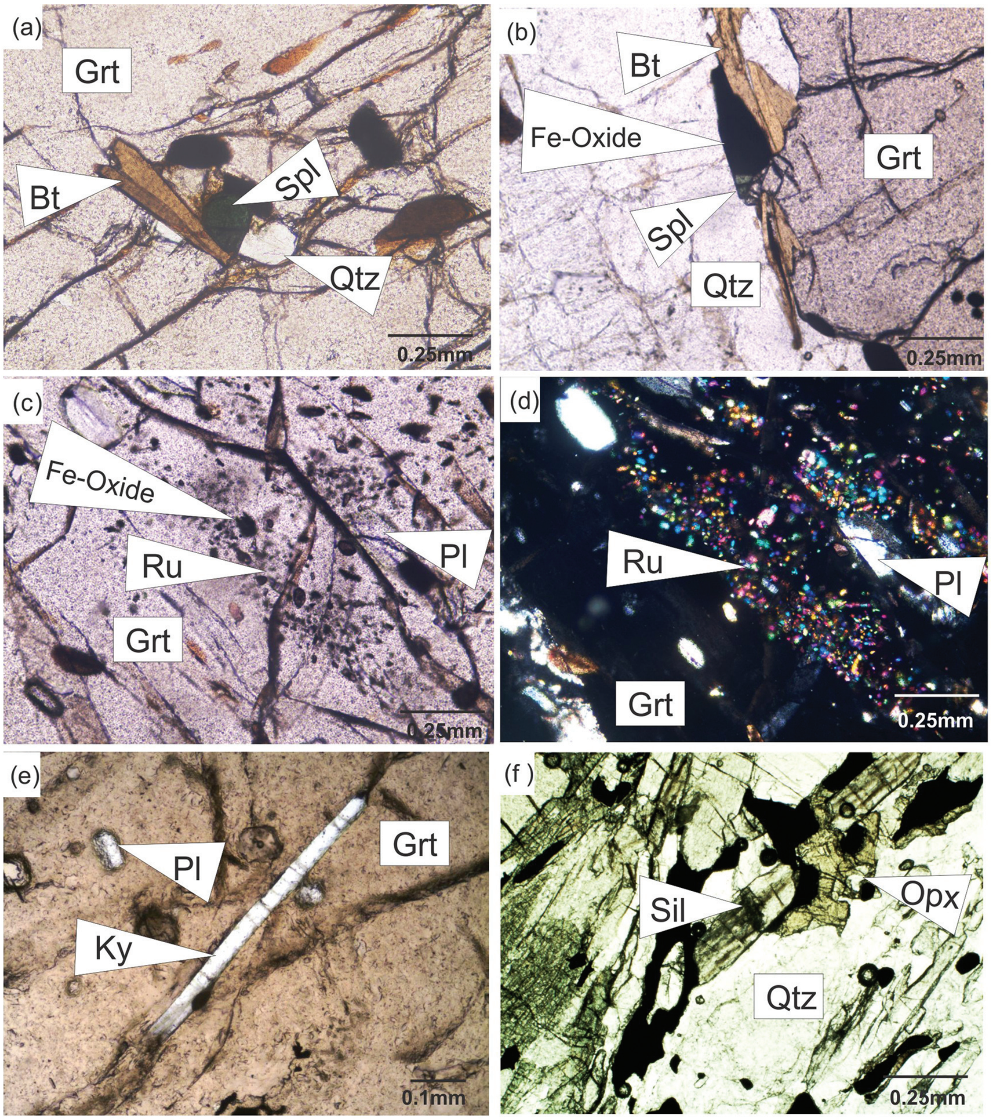

Figure 3: (a) Spinel+quartz assemblage occuring as inclusions within porphyroblastic garnet and (b) at margins of garnet porphyroblasts in the Rock D. (c) tiny rutile-ilmenite inclusions as clusters in the core area of garnet porphyroblasts showing a preffered orientation in Rock E (PPL view). (d) cross polarized view of (c). (e) tiny kyanite inclusions in garnet porphyroblasts in the Rock E. (f) orthopyroxene-sillimanite-quartz assemblage found in the matrix of the Rock B.

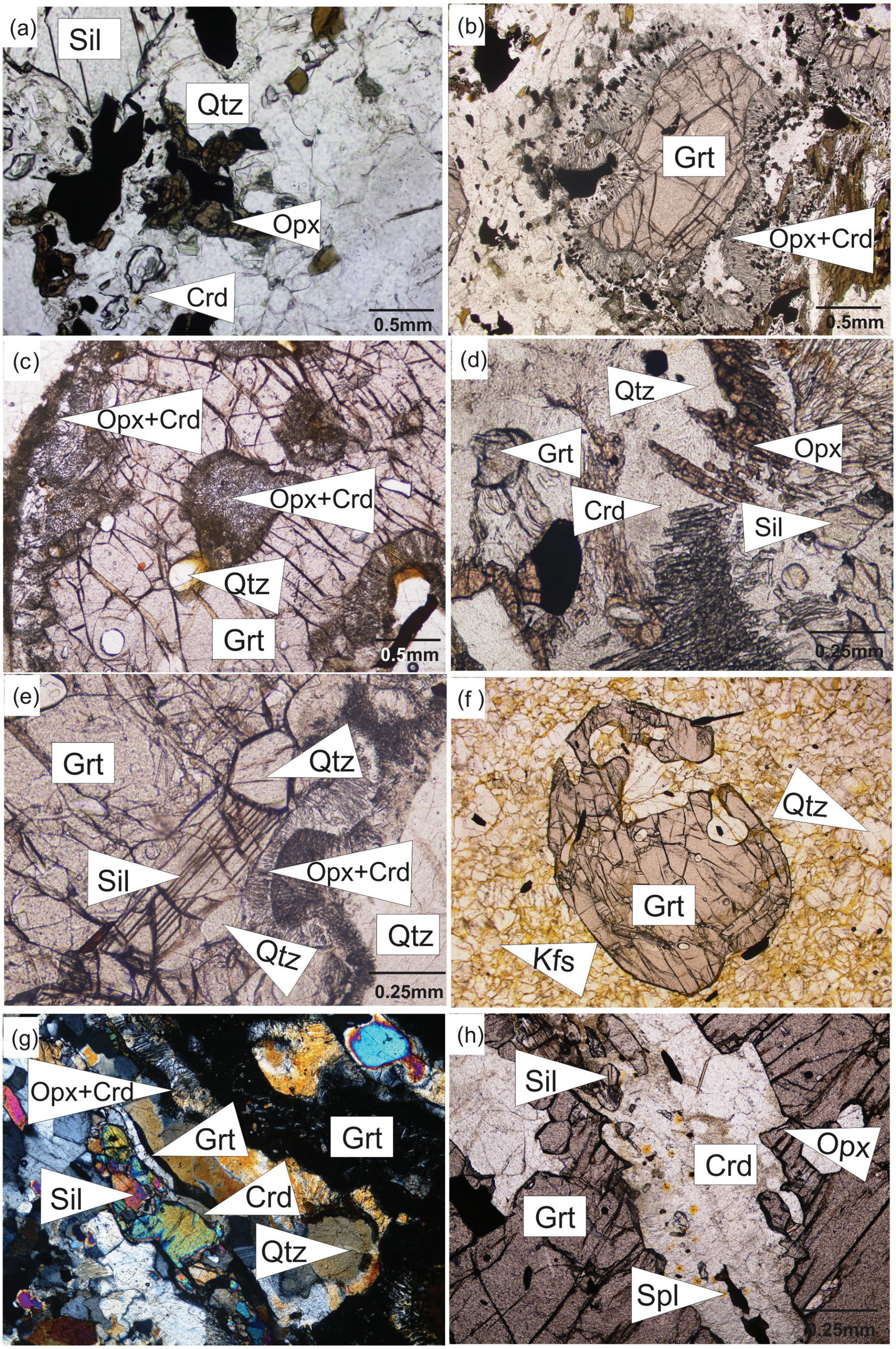

Figure 4: (a) Formation of tiny cordierite film among orthopyroxene, sillimanite and quartz in the Rock A, (b) orthopyroxene-cordierite symplectites at the rim of garnet porphyroblasts in the Rock A. (c) vermicular orthopyroxene-cordierite can be observed as inclusions within the core area of Grt in the Rock C. (f) garnets which do not show any reaction textures in the Rock B. (g) tiny garnet rim parallel to coarse sillimanite and formation of cordierite between the garnet rim and sillimanite of the Rock C. (f) formation of cordierite+spinel corona around garnet in the Rock F.

porphyroblasts, which also contains plagioclase inclusions. The matrix of this rock contains plenty of sillimanite.

5.5 *Orthopyroxene-sillimanite-quartz*

In Rock B, there are abundant orthopyroxene-sillimanite-quartz assemblages in the matrix (Fig. 3f). Further, at some domains the occurrence of thin film of cordierite between orthopyroxene, sillimanite and quartz (Fig. 4a and h) is observed. The orthopyroxene that coexist with sillimainite and quartz are relatively coarser (0.25 – 0.75 cm) in grain size and show typical pinkish colour and strong pleochorism (Fig. 3f) compared to the orthopyroxene grains that are found in symplectites around garnet (Fig. 4b, c, d and e respectively).

5.6 *Garnet-orthopyroxene-cordierite assemblages*

Orthopyroxene-cordierite symplectites at the rim of garnet porphyroblasts are abundantly observed in Rock B and C (Fig. 4b, c, d, and e). In some parts of Rock B, orthopyeoxene-cordierite symplectites after garnet are found where garnet is almost consumed totally. Vermicular orthopyroxene-cordierite can be observed as inclusions within the core area of garnet (Fig. 4c) in the same garnet of Rock C. At some domains in the Rock C sillimanite and quartz, which occur as inclusions within garnet, now coexist with retrograde orthopyroxene-cordierite symplectites (Fig. 4e). There are some garnets in the rock that do not show any reaction textures (e.g. Fig. 4f). In the same rock, tiny garnet rim parallel to coarse sillimanite can be observed, while cordietire can be observed between the garnet rim and sillimanite (Fig. 4g). Garnet-cordierite assemblage was observed in Rock F. In the same rock an assemblage of cordierite-spinel an also be observed as corona around garnet (Fig. 4h).

6 Discussion

6.1 *Prograde Reactions textures*

The presence of sapphirine inclusions in porphyroblastic garnet in spinel and sillimanite bearing Rock A suggest that the garnet and sapphirine could be formed the reaction

$$\text{Spl} + \text{Sil} \rightarrow \text{Grt} \pm \text{Spr} \qquad (1)$$

Presence of prismatic sapphirine inside garnet could be suggested that sapphirine-garnet was in equilibrium during high-grade metamorphism. Sharp grain contacts of sapphirine inclusions with host garnet clearly evidence for textural equilibrium at the metamorphism, most probably representing the near peak or peak metamorphic mineral phases at UHT conditions (e.g. Dharmapriya and Malaviarachchi, 2012). This is also confirmed from the spinel+quartz assemblage enclosed in garnet porphyroblasts in the Rock D also represent the UHT peak metamorphic conditions.

Presence of coarse orthopyroxene-sillimanite coronas around garnet (Fig. 3f) in Rock B are also probably a result of prograde reaction

$$\text{Grt} + \text{Qtz} \rightarrow \text{Opx} + \text{Sil} \qquad (2)$$

Occurrence of typical UHT assemblage of orthopyroxene-sillimanite-quartz implies UHT and relatively high-pressure conditions during the peak metamorphism (e.g. Annersten and Seifer, 1981). Direct grain contacts of spinel and quartz as inclusions in garnet (Figs. 3a and b) also an evidence of UHT metamorphism at relatively high-pressure conditions (e.g. Hensen and Harley, 1990). Rare kyanite inclusion within garnet (Fig. 3e) additionally supports the argument that the rock has evidence for equilibration at relatively higher-pressure conditions during the prograde metamorphism.

7 Retrograde Textures

Retrograde reactions are mainly observed as symplectites and reaction rims or coronae. Abundant retrograde reaction textures found in Rock B and C are cordierite + orthopyroxene symplectite and rarely cordierite film developed around garnet. This texture is typical of disequilibrium of the assemblages garnet-quartz and garnet-sillimanite-quartz where garnet start to break down forming vermicular orthopyroxene-cordierite symplectites. Such textures suggest the following FMAS continuous reactions:

$$\text{Grt} + \text{Qtz} \rightarrow \text{Crd} + \text{Opx} \qquad (3)$$

$$\text{Grt} + \text{Sil} + \text{Qtz} \rightarrow \text{Crd} \qquad (4)$$

In some domains, garnet is completely broken down to form vermicular orthopyroxene+ cordierite in the symplectite. In Rock F, Spinel occurs in cordierite coronae around garnet, which contains sillimanite inclusions (Fig. 4f). This texture may suggest the following continuous reaction:

$$\text{Grt} + \text{Sil} \rightarrow \text{Crd} + \text{Spl} \qquad (5)$$

The above reactions (3, 4 and 5) have been reported from many granulite terrines elsewhere in the world and are often taken as evidence in favor of near-isothermal decompression after the peak

UHT metamorphism (e.g. Harley, 1989, 2004). Rare occurrence of thin film of cordierite between orthopyroxene, sillimanite and quartz (Fig. 4a) suggest that the othopyroxene+sillimanite+quartz formed via the reaction.

$$\text{Opx} + \text{Sil} + \text{Qtz} \rightarrow \text{Crd} \quad (6)$$

In the Rock C, within the same garnet, which has orthopyroxene+cordierite symplectites at the rim, there are tiny orthopyroxene+cordierite symplectites as inclusions at the core region (Fig. 4b). This texture may have formed during a single decompression event, or else the symplectite in the core area may represent an early decompression event. Therefore, detailed mineral chemical and geochronological studies are underway to confirm its origin. Brownish biotite is closely associated with orthopyroxene, quartz, K–feldspar and garnet, suggesting the progress of the retrograde reaction, probably at the final stage of UHT metamorphism:

$$\text{Opx} + \text{Kfs} + H_2O \rightarrow \text{Bt} + \text{Qtz} \quad (7)$$

However, it is important to find mechanisms for the infiltration of H_2O-bearing fluids during the retrograde path. Orthopyroxene, which coexist with quartz, are relatively coarser in grain size showing typical pinkish strong pleochorism compared to the orthopyroxene which are found in symplectites around garnet (Fig. 4a and b respectively). Therefore, orthopyroxene of this rock may have been formed at multiple stages.

Two possibilities can be inferred for the texture of tiny garnet rim parallel to coarse sillimanite (Fig. 4g). The thin garnet rim could be a remnant of a coarse garnet porphyroblast. This assumption is due to the morphological continuation of the thin garnet rims parallel to the margin of the coarse garnet porphyroblast (see Fig. 4g). Or else, it could be the formation of garnet+cordierite, through the reaction (6). This is due to the presence of diffused margin of sillimanite and the occurrences of cordierite within the cracks of sillimanite. However, mineral chemical analysis of these two garnet textures is essential to elucidate the mechanism of formation of the thin garnet rim.

8 Conclusions

New petrological data from numerous samples (~400) of Al- and Mg-rich granulites of the Highland Complex of Sri Lanka provide further evidence for UHT metamorphic conditions. The mineral assemblages of sapphirine-garnet, with sharp grain contacts evidence the UHT peak metamorphism. Typical UHT assemblages of spinel+quartz and orthopyroxene-sillimanite-quartz also occur at peak or near peak UHT conditions. The UHT assemblage of orthopyroxene-sillimanite-quartz and kyanite in the garnet porphyroblast and presence of sillimanite in the matrix imply the clockwise P-T trajectory. Existence of orthopyroxene-sillimanite-quartz as peak assemblage may indicate that the UHT metamorphism to have taken place under relatively high-pressure conditions. Further, direct grain contacts of spinel and quartz as inclusions in garnet are also evidence of UHT metamorphism at relatively high-pressure conditions. Thus, we conclude that the peak mineral assemblages that were stable under UHT conditions of the considered rocks are garnet-sapphirine, orthopyroxene-sillimanite-quartz and spinel+quartz. Formation of sapphirine at garnet margins and widely observed orthopyroxene-cordierite bearing symplectites at garnet rims clearly indicate the retrograde evolution of UHT granulites in the Highland Complex. Further studies are underway to investigate the geochemical and geochrnological evolution of these rocks.

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