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LOCAL FORMATION OF HERCYNITE-PLAGIOCLASE SYMPLECTITE AFTER GARNET AND SILLIMANITE IN KHONDALITE FROM HABARANA, SRI LANKA: MINERAL TEXTURES

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Abstract: Khondalite (graphitic garnet-sillimanite-alkali feldspar-quartz granulite) is one of the characteristic rocks of the granulite facies Highland Series in Sri Lanka. Near Habarana occurs unusual khondalite in which both sillimanite and garnet are locally replaced by symplectitic intergrowths of hercynite and plagioclase to various degrees. Mineral textures suggest that the replacement reactions took place along pathways of fluid phase, most likely CO_2-rich fluid, which infiltrated from outside, and were triggered off by the breakdown of apatite with resultant formation of monazite.

key words: Highland Complex, khondalite, replacement, fluid infiltration, phosphate minerals

1. Introduction

Sri Lanka is inferred to have been located close to Lützow-Holm Bay in East Antarctica before the breakup of Gondwanaland (*e.g.*, OGO *et al.*, 1992; SHIRAISHI *et al.*, 1994), and is well-known among geologists for the spectacular "charnockitic veining" most probably due to CO_2 flushing (*e.g.*, NEWTON, 1989; NEWTON *et al.*, 1980). Khondalite closely associated with marble and quartzite is one of the characteristic constituents of the granulite facies Highland Series of Sri Lanka, and is composed mainly of sillimanite, garnet, alkali feldspar (perthite-mesoperthite), quartz, rutile, ilmenite and graphite without any hydrous minerals in the matrix. However, khondalite occurring near Habarana is unusual in that both garnet and sillimanite are replaced by symplectitic intergrowths of hercynite and plagioclase to various degrees as if the replacement reactions progressed in response to local fluid influx along foliation and deformation features (Figs. 1, 2a and 2b) (hereafter the rock is referred to as unusual khondalite). The aim of this paper is to describe the unusual khondalite to document the mineral textures in detail to assess the role of fluids in forming reaction textures. Bulk rock and mineral chemistry data and full discussion of the infiltrated fluid composition and fluid-rock interaction will be presented elsewhere. Mineral abbreviations used in this paper are after KRETZ (1983).

2. Geological Setting

Sri Lanka is underlain mainly by the late Precambrian-Cambrian high grade meta-

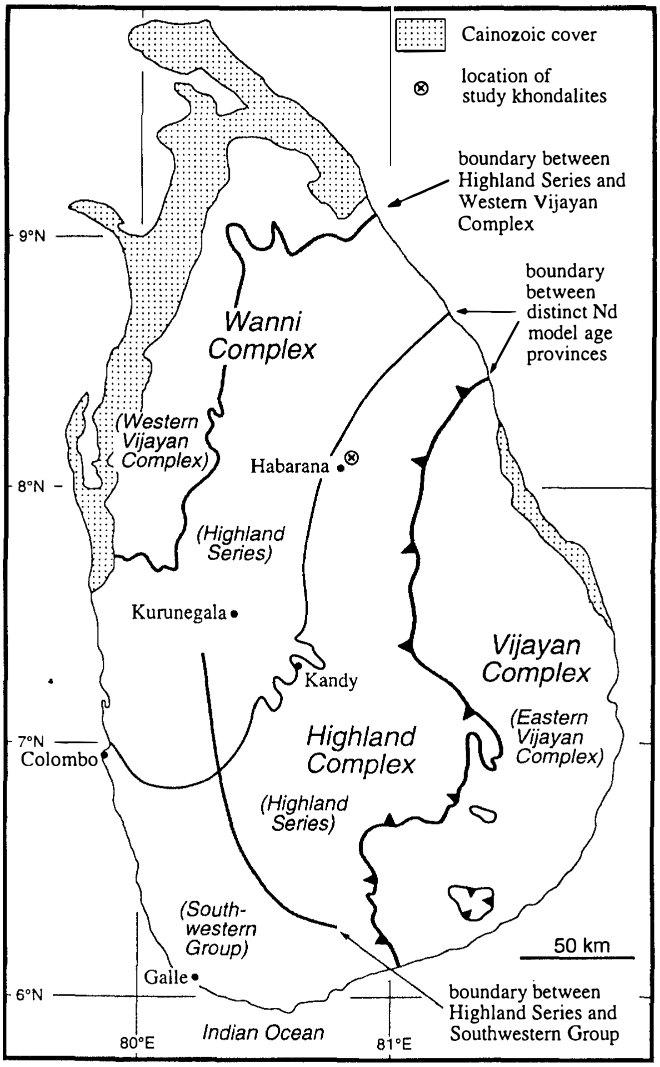

Fig. 1. Subdivision of the basement geology of Sri Lanka into the Wanni Complex (WC), Highland Complex (HC) and Vijayan Complex (after KRÖNER et al., 1991; COORAY, 1994). Also shown are the earlier boundaries and names (in parentheses) as given by the GEOLOGICAL SURVEY OF SRI LANKA (1982) on published maps.

morphic rocks formerly divided into three major units—the Highland Series, the Southwestern Group and the Eastern and Western Vijayan Complexes (COORAY, 1978, 1984; GEOLOGICAL SURVEY DEPARTMENT OF SRI LANKA, 1982). The Highland Series consists of pelitic and mafic through to felsic granulites and charnockite. Khondalite (graphitic garnet-sillimanite-alkali feldspar-quartz granulite) closely associated with dolomitic marble and quartzite is characteristic. The Southwestern Group mainly consists of granulite facies metasediments and charnockite but is somewhat dissimilar to the Highland Series lithologically, and khondalite is absent. The Vijayan Complex is a composite unit of metamorphic rocks, migmatites and granites. KRÖNER *et al.* (1991) and COORAY (1994) renamed these units with different boundaries as the Highland Complex, the Vijayan Complex and the Wanni Complex essentially on the basis of Nd model age mapping by MILISENDA *et al.* (1988, 1994). The boundaries for both the older and newer divisions in

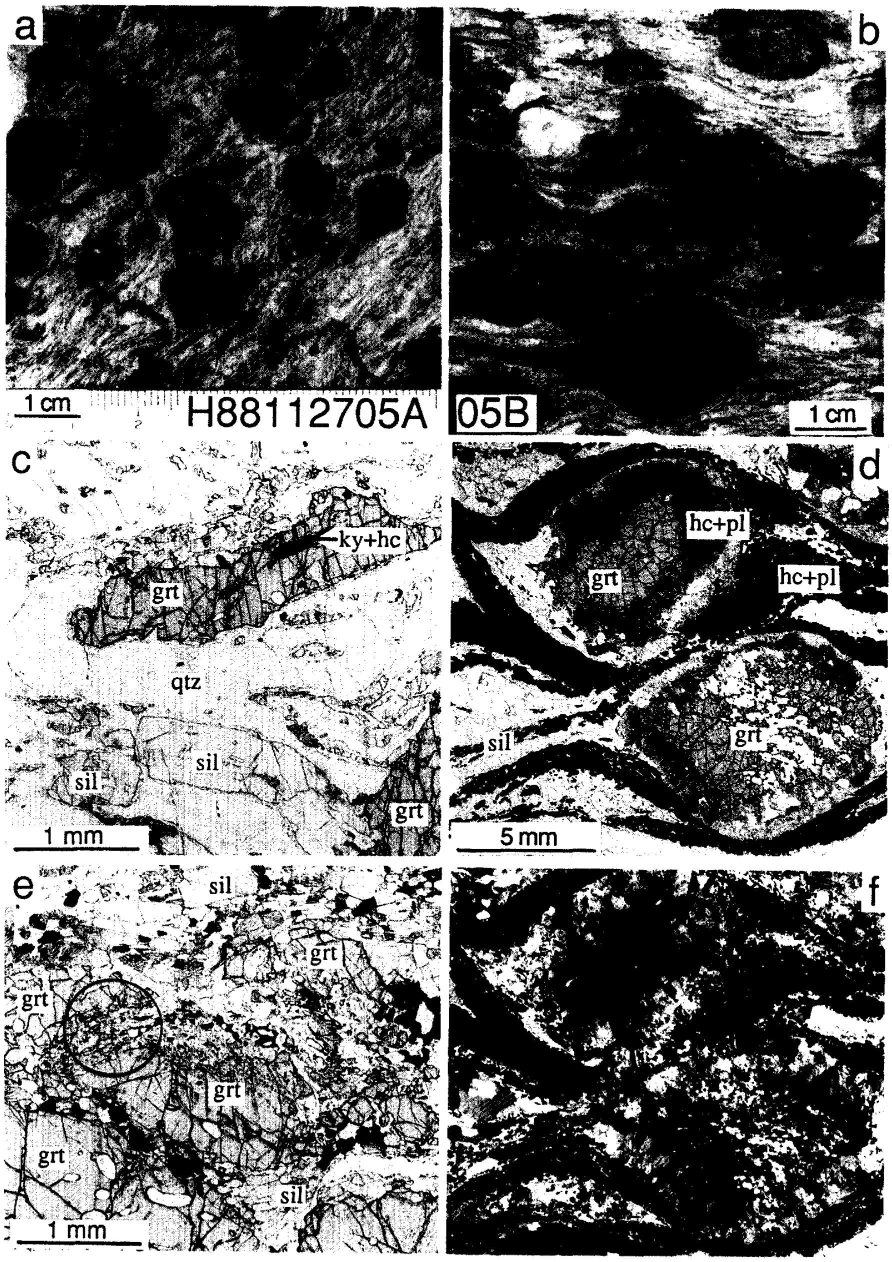

Fig. 2. Photographs and photomicrographs of matrix hercynite-bearing unusual khondalites from Habarana. a) Polished surface of Sp. H88112705A. Garnet porphyroblasts up to 1 cm in diameter occur in the sillimanite-alkali feldspar-quartz-graphite matrix. b) Polished surface of Sp. H88112705B. Reddish garnet porphyroblasts and sillimanite swarms in the matrix are replaced by dark greenish symplectitic intergrowths of hercynite and plagioclase to various degrees. Note that the replacement reactions took place locally along foliation and certain deformation features. c) Alkali feldspar film developed between quartz and the other minerals in Sp. H88112705A. Kyanite + Zn-rich hercynite association after staurolite occurs as a relic inclusion in garnet. (Plane polarized light) d) Garnet and sillimanite in Sp. H88112705B extensively replaced by symplectitic intergrowths of hercynite and plagioclase. (Plane-polarized light) e) Sporadic development of matrix hercynite in Sp. H88112705A . The portion in the circle is shown in Fig. 3a. (Plane-polarized light) f) Garnet and sillimanite in Sp. H88112705B. Same as d (Crossed polars).

Sri Lanka are shown in Fig. 1. The Highland Complex-Vijayan Complex boundary is a fault marking an abrupt change in lithology (*e.g.* COORAY, 1978, 1984), grade of metamorphism (*e.g.* RAASE and SCHENK, 1994) and Nd model ages (MILISENDA *et al.*, 1988, 1994). The boundary between the Highland Complex and the Wanni Complex is neither petrologically nor lithologically obvious (see KRIEGSMAN (1991) and HIROI *et al.* (1994) for discussion). The former Western Vijayan Complex is lithologically distinct from the Highland Series granulites, but Nd-model age data of MILISENDA *et al.* (1988) define a boundary such that the Wanni Complex includes part of the former Highland Series and Southwestern Group as well as all of the former Western Vijayan Complex.

The ages of the Sri Lankan granulite facies metamorphism and the overprinting effects of CO_2 on peak metamorphic mineral assemblages are not entirely resolved. SHIRAISHI *et al.* (1994) summarized the apparently conflicting isotopic interpretations. HÖLZL *et al.* (1994) have presented further isotopic data to confirm that sediments and igneous rocks of the two different Nd model age provinces (MILISENDA *et al.*, 1994) experienced a common Pan-African deformation and metamorphism at about 610 Ma (BAUR *et al.*, 1991). RAASE and SCHENK (1994) consider that this deformation and metamorphism led to the dominant mineral associations and regional variations in metamorphic grade. However, we note that opinion is still divided as to whether the Wanni Complex also records an earlier metamorphism at about 1000 Ma, as indicated by Nd-Sm and Pb-Pb whole rock-mineral isochrons (BURTON and O'NIONS, 1990a, b) and zircon U-Pb data (SHIRAISHI *et al.*, 1994). The incipient charnockitization affected both the Highland Complex and Wanni Complex after the end of the regional deformational history. The best estimate of this charnockitization is ~550 Ma (BURTON and O'NIONS, 1990b; BAUR *et al.*, 1991; HÖLZL *et al.*, 1994).

The peak *P-T* conditions during the regional metamorphism near Habarana have been estimated to be ≥ 800 °C and ≥ 8 kb (SCHUMACHER *et al.*, 1990; SCHENK *et al.*, 1991; RAASE and SCHENK, 1994; SCHUMACHER and FAULHABER, 1994; HIROI, unpublished data).

3. Petrography of Khondalites

3.1. Khondalite

Khondalite is usually composed of sillimanite, garnet, alkali feldspar (perthite-mesoperthite), quartz, rutile, ilmenite, apatite, monazite, zircon, graphite, pyrite and pyrrhotite. Corundum, kyanite, staurolite, Zn-rich hercynite, Ti-rich biotite and tourmaline additionally occur as inclusions in garnet (HIROI *et al.*, 1987, 1990, 1994; SCHUMACHER *et al.*, 1990; RAASE and SCHENK, 1994). The following are the general features of khondalite.

1) Relatively low bulk rock Mg/(Fe + Mg) ratio of *c.* 0.2, as is suggested by the ratio of the single Mg-Fe mineral garnet (HIROI *et al.*, 1994).
2) Saturation in SiO_2, Al_2SiO_5 and TiO_2, as is shown by the ubiquitous occurrence of quartz, sillimanite and rutile.
3) Clockwise prograde *P-T* trajectory as is suggested by the occurrence of kyanite ± Zn-rich hercynite ± corundum, staurolite and Ti-rich biotite as relic inclusions in garnet (HIROI *et al.*, 1994).
4) Relatively low H_2O fugacity, as is evidenced by the complete absence of hydrous

minerals in the matrix and by the lack of textures indicative of partial melting during high temperature (≥ 800 °C) metamorphism despite the minimum melting assemblage

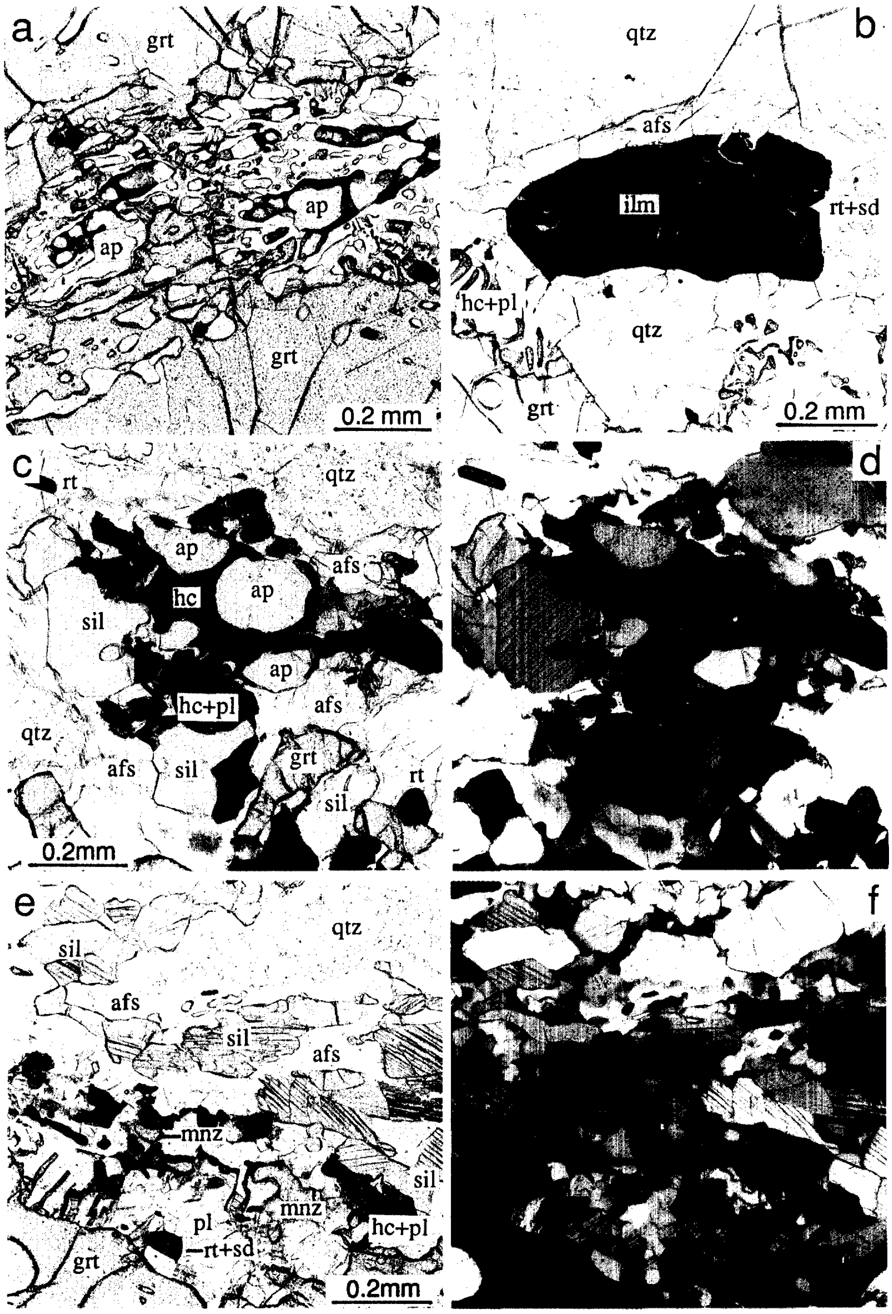

Fig. 3. Photomicrographs of Sp. H88112705A. a) Local formation of matrix hercynite surrounding apatite. (Plane-polarized light) b) Partial replacement of ilmenite by rutile + siderite association. Partial replacement of garnet by hercynite + plagioclase symplectite is also seen. (Plane-polarized light) c) Local formation of matrix hercynite surrounding apatite and partial replacement of nearby sillimanite by hercynite + plagioclase symplectite. (Plane-polarized light) d) Same as c. (Crossed polars) e) Local formation of matrix hercynite with monazite and partial replacement of nearby garnet and sillimanite by hercynite + plagioclase symplectite. Rutile + siderite association after ilmenite is also seen. (Plane-polarized light) f) Same as e. (Crossed polars)

quartz + alkali feldspar.

5) Relatively low oxygen fugacity, as is indicated by the presence of graphite, pyrrhotite and pyrite (OHMOTO and KERRICK, 1977; POULSON and OHMOTO, 1989).

3.2. Unusual khondalite

Two specimens of unusual khondalite (*Sp. H88112705A* and *B*) to be reported first in this paper were found as boulders near Habarana (Fig. 1; see also HIROI *et al.* (1990) for more detailed location), and therefore their mode of field occurrence is unknown. The mineral textures observed in these specimens will be described below separately.

Sp. H88112705A

This rock shows an incipient stage of matrix hercynite formation, and therefore is seemingly just an ordinary khondalite (Figs. 2a, 2c and 2e).

1) Except for hercynite and sodic plagioclase locally formed in the matrix, the constituent minerals are essentially the same as those in ordinary khondalite.
2) Matrix hercynite occurs only sporadically in a small amount, and is not in direct contact with quartz. It shows three different modes of occurrence: (a) grains surrounding apatite and/or monazite (Figs. 3a, 3c, 3d, 3e and 3f), (b) grains forming symplectitic intergrowths with plagioclase and replacing sillimanite and/or garnet partially (Figs. 3c, 3d, 3e and 3f), and (c) grains intimately associated with ilmenite (Fig. 2e). Hercynites showing the former two modes of occurrence occur side by side.
3) Alkali feldspar (perthite) film has developed between matrix quartz and the other minerals (Figs. 2c, 3, 4d and 4f). It commonly shows a decomposition texture to K-feldspar and plagioclase (Figs. 4c, 4d, 4e and 4f). K-feldspar tends to be concentrated next to quartz whereas plagioclase occurs next to garnet and sillimanite (Figs. 4c, 4d, 4e and 4f).
4) Graphite is apparently more coarse-grained and probably there is more in this rock compared to non-reacted ordinary khondalite.
5) Ilmenite is sometimes replaced partially by rutile and goethite, most probably after siderite (Fig. 3b).

Sp. H88112705B

This rock shows an advanced stage of matrix hercynite formation as is evident by the development of dark greenish hercynite-rich zones or veins (Fig. 2b).

1) The mode of occurrence of the hercynite-rich veins is similar to the well-known "charnockitic veins" in amphibolite facies gneisses in Sri Lanka and some other areas (*e.g.*, NEWTON *et al.*, 1980; NEWTON, 1989) and to the "eclogitic veins" in gabbros and anorthosites in southwest Norway (*e.g.*, AUSTRHEIM, 1987; NEWTON, 1989).
2) Both garnet and sillimanite are replaced by symplectitic intergrowths of hercynite and plagioclase to various degrees (Fig. 2b). The shapes of precursor minerals are preserved well (Figs. 2d, 2f, 5a, 5b and 5e). In addition, the modal hercynite/plagioclase ratio of the symplectite is distinctly different between the pseudomorphs after sillimanite and garnet. Hercynite is much more abundant in pseudomorphs after sillimanite than in pseudomorphs after garnet (Figs. 2d, 2f, 5a, 5b, 6a, 6b and 6c). The symplectitic intergrowth after garnet is often subdivided into inner and outer parts (Figs. 5a and 5b). Hercynite is more coarse-grained in the outer part than in the inner

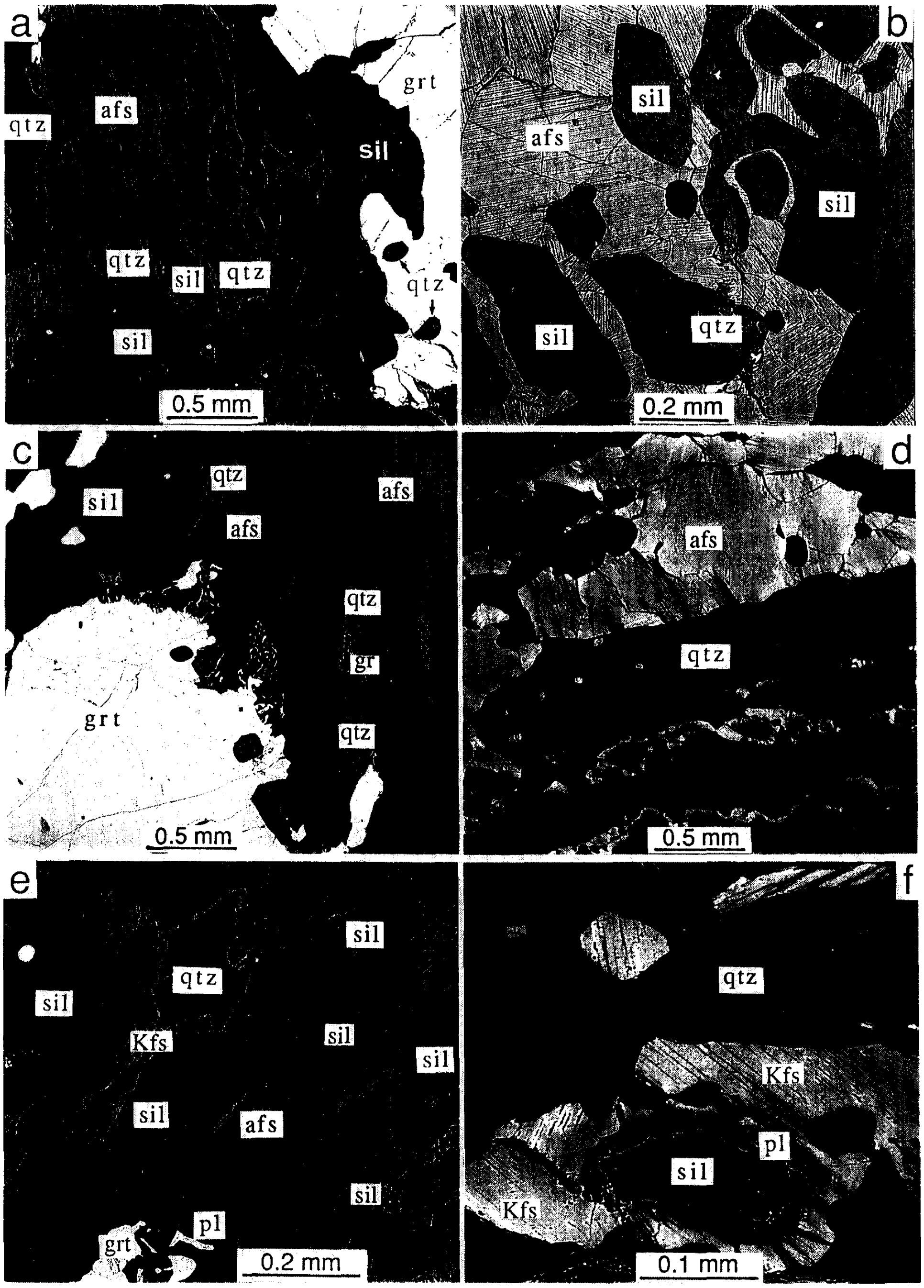

Fig. 4. *Backscattered electron micrographs. a) Alkali feldspar (perthite), garnet, sillimanite and quartz in khondalite (Sp. C2' from near Kandy). b) Closeup of lower central part of a. Note that alkali feldspar film is not developed between quartz and sillimanite in this case. c) Local development of symplectitic intergrowth of hercynite and plagioclase after garnet in Sp. H88112705A. d) Alkali feldspar (mesoperthite) and quartz in the matrix of Sp. H88112705A. e) Closeup of upper central part of c. Note that exsolved K-feldspar from alkali feldspar is concentrated next to quartz whereas exsolved plagioclase is next to garnet and sillimanite. f) Closeup of lower central part of d. Note that K-feldspar is concentrated next to quartz whereas sodic plagioclase is next to sillimanite.*

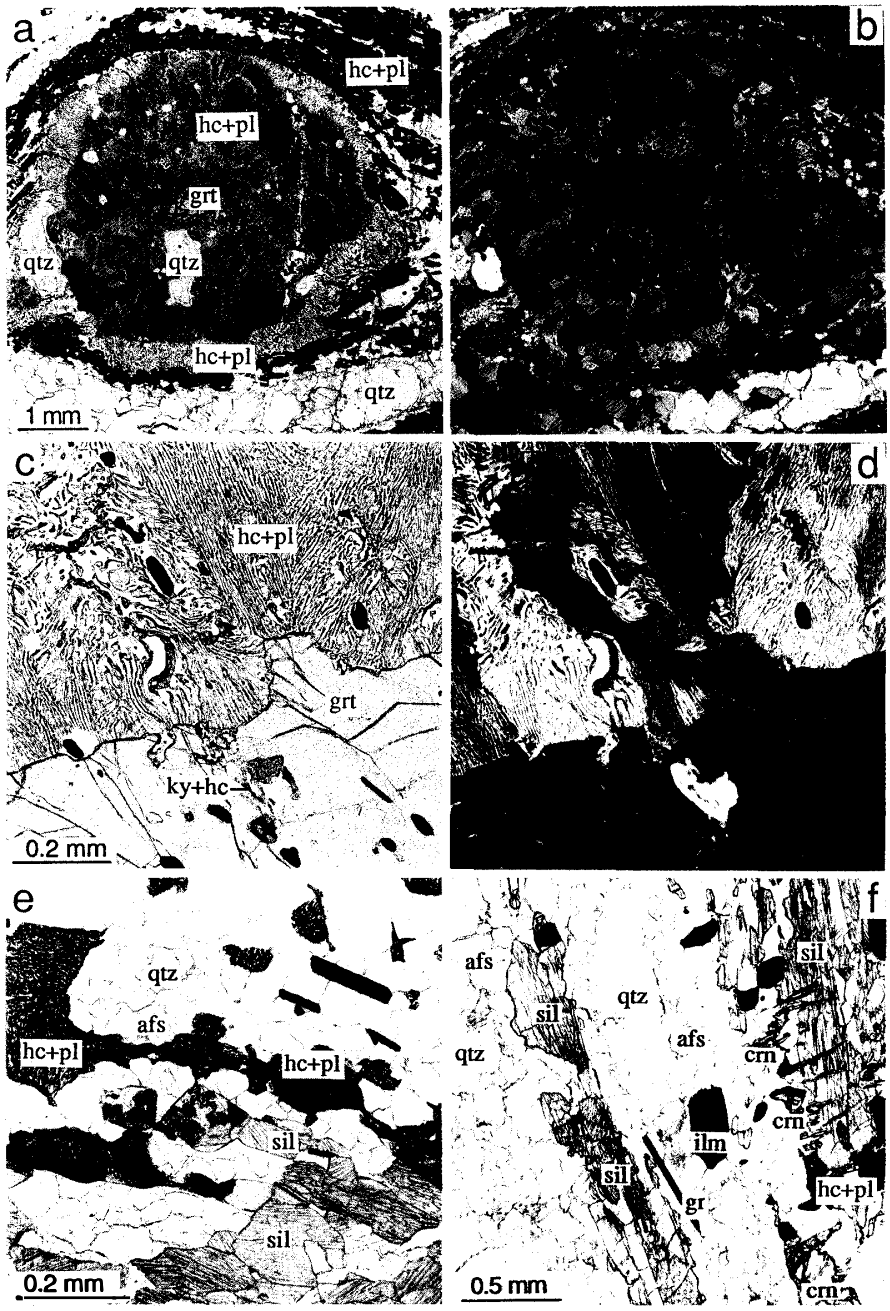

Fig. 5. Photomicrographs of Sp. H88112705B. a) Replacement of garnet and sillimanite by symplectitic intergrowths of hercynite and plagioclase (plane polarized light). Note that the modal hercynite/plagioclase ratio is distinctly different between symplectites after garnet and sillimanite, and that the symplectite after garnet is divided into outer coarser-grained and inner finer-grained parts. b) same as a (Crossed polars). c) Replacement of garnet by symplectitic intergrowth of hercynite and plagioclase. (Plane-polarized light) d) same as c. Note that replacing plagioclase is relatively coarse-grained. (Crossed polars) e) Arrested replacement of sillimanite by symplectitic intergrowth of hercynite and plagioclase at reaction front. Note the well-preserved shape of the precursor sillimanite. (Plane-polarized light) f) Rare occurrence of corundum replacing sillimanite near the reaction front where sillimanite is replaced by symplectitic intergrowth of hercynite and plagioclase. Quartz occurs nearby, but it is separated from the other minerals by alkali feldspar film. (Plane-polarized light)

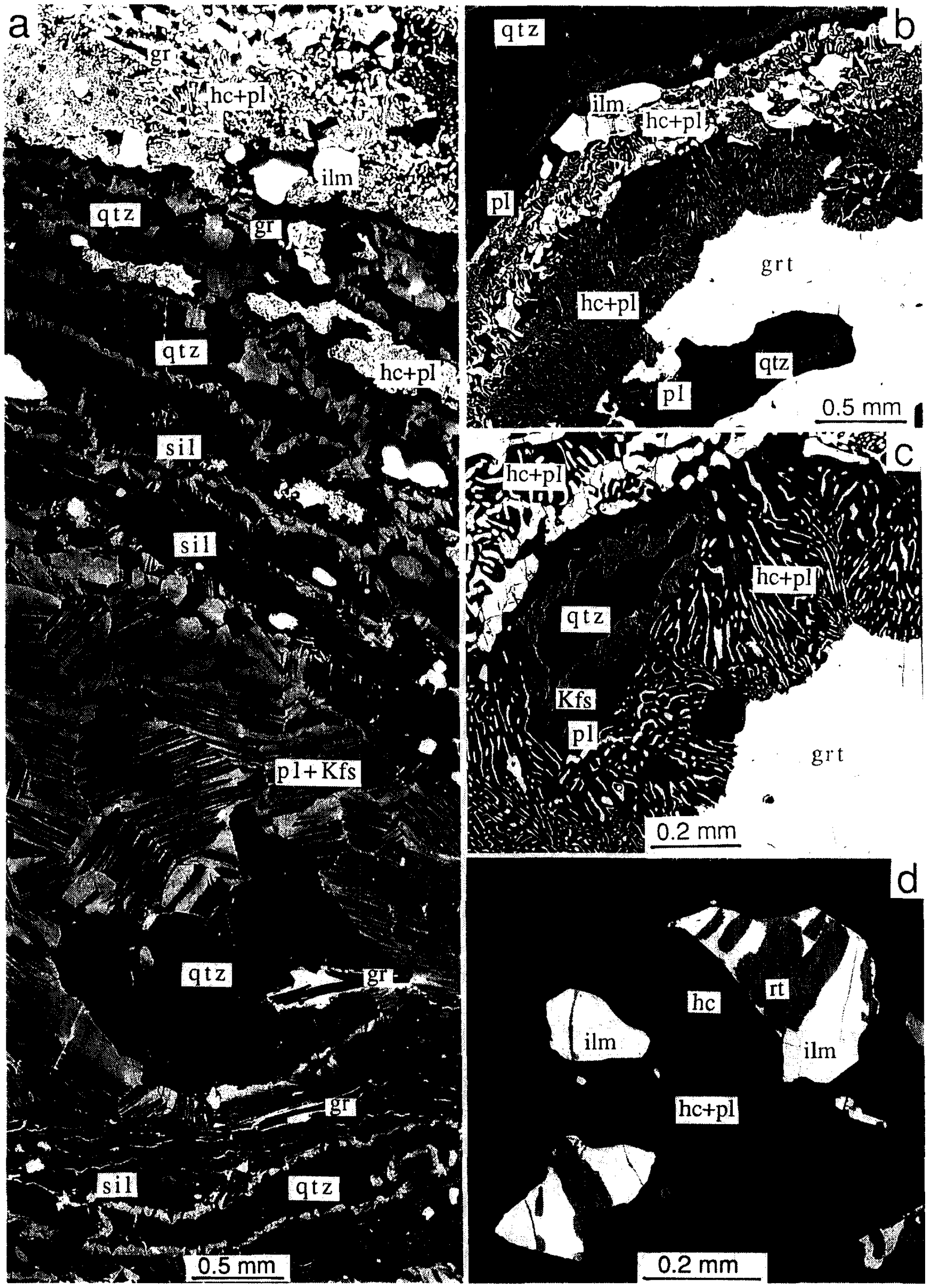

Fig. 6. Backscattered electron micrographs of Sp. H88112705B. a) Sillimanite, hercynite + plagioclase symplectite after sillimanite, extensively exsolved alkali feldspar, quartz and graphite in the matrix. Note that quartz is separated from the other minerals by alkali feldspar. b) Replacement of garnet and sillimanite by symplectitic intergrowths of hercynite and plagioclase. Note that modal hercynite/plagioclase ratio is distinctly different between the symplectites after garnet and sillimanite. The symplectite pseudomorph after sillimanite is much more enriched in hercynite that after garnet, most probably reflecting the original Al contents of precursor minerals. c) Closeup of central part of b. Note that K-feldspar is concentrated next to quartz. d) Partial breakdown of ilmenite to rutile and goethite, most probably after siderite.

part, though plagioclase is not necessarily fine grained in the inner part (Figs. 5a, 5b, 5c and 5d).
3) Apatite is absent in the matrix and occurs only as inclusions in garnet. Monazite is conspicuous in the matrix instead.
4) Alkali feldspar film has developed between matrix quartz and the other minerals (Figs. 5a, 5b, 5e, 5f, 6a, 6b and 6c).
5) Decomposition of alkali feldspar into K-feldspar and plagioclase is much more advanced compared to *Sp. H88112705A*. (Fig. 6a). K-feldspar is usually concentrated next to quartz (Figs. 6a, 6b and 6c).
6) Ilmenite is commonly replaced partially by rutile and goethite, most probably after siderite (Fig. 6d).
7) Corundum occasionally occurs in the reaction front where sillimanite is replaced by the symplectitic intergrowth of hercynite and plagioclase (Fig. 5f).
8) Trace amounts of biotite and muscovite occur near graphite.

4. Discussion and Conclusions

We may safely point out the following on the basis of the observed mineral textures in both the ordianry khondalite and unusual khondalite.
(1) Although the development of alkali feldspar film between quartz and the other minerals is conspicuous in the unusual khondalite, re-examination of all khondalite specimens at hand has revealed that it is not peculiar to the unusual khondalite but is rather a common phenomenon of khondalite in general.
(2) Replacement of garnet and sillimanite by symplectitic intergrowths of hercynite and plagioclase took place only locally along foliation and other deformation features.
(3) Apatite may have played an important role in giving rise to the replacement reactions, and itself reacted with the infiltrated fluid to form monazite.
(4) The replacement reactions took place in such a way that the symplectites produced occupy essentially the same volumes as the precursor minerals.
(5) The distinctly different modal hercynite/plagioclase ratios of the symplectitic pseudomorphs after garnet and sillimanite reflect the original difference in Al content of precursor minerals.
(6) Replacement of sillimanite by the hercynite + plagioclase symplectite attests to migration of Fe and Mg to the reaction site from a single Fe-Mg mineral garnet.
(7) Although quartz is present abundantly, formation of matrix hercynite and rare corundum that are not in direct contact with quartz suggests that silica was not necessarily saturated in the reaction sites.
(8) Coarsening and probable increase in amount of graphite indicate that the fluid-rock interaction resulted in the precipitation of graphite.
(9) Replacement of ilmenite by rutile and siderite is indicative of reaction (A), which is common in Sri Lankan cordierite granulites (*e.g.*, ELLIS and HIROI, 1997).

$$\text{Ilmenite} + CO_2 = \text{rutile} + \text{siderite}. \qquad (A)$$

Point (2) suggests that the replacement reactions were induced by local fluid infiltration along certain pathways. Point (3) suggests unknown but significant role of phosphate minerals in the reaction processes.

Points (4) and (5) may be ample evidence to indicate that Al was almost immobile during the symplectite-forming reactions, in marked contrast to Fe and Mg. This is apparently inconsistent with the alkali feldspar film formation between quartz and the other minerals, because alkali feldspar formation involves transportation of Al in addition to Si and alkalis. However, point (1) suggests that the stage of alkali feldspar film formation was different from and probably earlier than the stage of symplectite-forming reactions.

Points (8) and (9) suggest that the infiltrated fluid was probably rich in CO_2, which would be stable at relatively oxidized conditions (OHMOTO and KERRICK, 1977; POULSON and OHMOTO, 1989). Such a fluid is contrasting to the CH_4-rich reduced fluid that is expected in graphite-pyrrhotite-pyrite-bearing khondalite, as mentioned above. Reaction (A) is in contrast to the rutile-consuming reaction (B) which is commonly inferred to have taken place in khondalite upon decompression at high temperatures.

$$\text{Rutile} + \text{garnet} = \text{sillimanite} + \text{ilmenite} + \text{quartz}. \qquad \text{(B)}$$

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