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REMARKABLE PETROGRAPHIC FEATURES OF SRI LANKAN GRANULITES; WITH SPECIAL REGARD TO UNEXPECTED OCCURRENCE OF “FELSITE-NANOGRANITE INCLUSIONS” IN GARNET

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ABSTRACT

Fine spherulitic intergrowths of quartz and feldspar in felsite inclusions (FIs) in garnet in five representative granulite-facies rocks from northern, central and southeastern parts of the Highland Complex (HC), Sri Lanka, are presented together with an experimentally reproduced spherulitic intergrowth of similar dimensions. FIs show characteristics indicative of unexpectedly rapid cooling after far-from-equilibrium crystallization of trapped partial melts formed during high-grade metamorphism, because granulite-facies rocks in continental collision orogens generally have been presumed to be cooled and exhumed slowly from the depths for more than millions of years. Sri Lanka is the key place to unravel the mystery of rapid cooling of huge granulite masses and relevant geological processes because of the most widespread but apparently restricted occurrence of FIs along the marginal part of the HC in addition to accumulated geological, geochemical, and geochronological data.

Keywords: spherulite, felsite-nanogranite inclusion, rapid cooling of granulite, continental collision orogen

INTRODUCTION

Sri Lanka extensively exposes high-grade regional metamorphic rocks, which show various notable features; (1) arrested charnockitization (e.g., Hansen et al., 1987; Hiroi et al., 1990; Yoshida and Santosh, 1994; Kehelpannala, 1999; Perchuk et al., 2000, and references therein), (2) high purity vein graphite deposits (e.g., Erdosh, 1970; Hapuarachchi, 1977; Dissanayake, 1986; Hewathilake et al., 2018; Touret et al., 2019, and references therein), (3) occurrence of ultrahigh-temperature (UHT) mineral assemblages such as sapphirine + quartz and orthopyroxene + sillimanite + quartz (e.g., Osanai, 1989; Hiroi et al., 1994, Kriegsman and Schumacher, 1999; Sajeev and Osanai, 2004; Dharmapriya et al., 2015; Osanai et al., 2016a, and references therein), and so on. I have carried out petrological study of them for more than thirty years and found such interesting features as follows; (1) occurrences of relict prograde kyanite and staurolite with or without sapphirine and spinel in khondalite and UHT pelitic granulites as well as retrograde andalusite in various rocks (e.g., Hiroi et al., 1987, 1990, 1994, unpublished data; Ogo et al., 1992), (2) occurrence of garnet preserving compositional growth zoning of major and trace elements in granulite-facies rocks (Hiroi et al., 1995, 1997a), (3) occurrence of Fe-rich kornerupine in pegmatite (Grew et al., 1995), (4) partial replacement of cordierite by andalusite + carbonate + quartz aggregates and ilmenite by rutile + siderite as the result of local infiltration of CO₂ (Hiroi et al., 1990, Ellis and Hiroi, 1997), (5) replacement of sillimanite and garnet by spinel + feldspar ± corundum intergrowths in some deformed khondalites (graphitic garnet-sillimanite gneiss) (Hiroi et al., 1997b), (6) metasomatic cordierite formation after plagioclase (Hiroi et al., unpublished data), and so on.

In particular, the occurrence of felsic volcanic rock-like inclusions (felsite inclusions, FIs) in garnet in various granulites is remarkable (Hiroi et al., 2014) (Table 1 and Fig. 1).
Table 1. List of samples containing felsite-nanogranite inclusions in garnet from Sri Lanka.

| Locality in Fig. 1 | Sample number | Locality   | Rock type          | Notable minerals in FNI |
|--------------------|---------------|------------|--------------------|--------------------------|
| 1                  | 88112704A     | Habarana   | pelitic migmatite  | spherulite               |
|                    | H89082301A    |            | pelitic migmatite  | spherulite               |
| 2                  | 87C4'-3-2     | Dambulla   | pelitic migmatite  |                          |
| 3                  | 88112602      | Matale     | khondalite         | spherulite               |
| 4                  | 88112501B     | Matale     | pelitic migmatite  |                          |
| 5                  | Y85092909C    | Kandy      | pelitic migmatite  | dendrite                 |
| 6                  | Y85101511     | Digama     | khondalite         | dendrite, spherulite     |
| 7                  | 88111503A*    | Teldeniya  | pelitic migmatite  | dendrite, spherulite     |
| 8                  | YH10092802B   | Narangalla | pelitic migmatite  | dendrite, spherulite     |
| 9                  | 88120203B     | Moholawa   | pelitic migmatite  |                          |
| 10                 | H89081302A    | Nalla      | pelitic migmatite  |                          |
| 11                 | MK13101101A   | Peradeniya | pelitic migmatite  |                          |
| 12                 | 04090101I     |            |                    |                          |
| 13                 | 88112901A     | Victoria   | Grt-rich pelitic gneiss | spherulite |
|                    | 88112901H     | Reservoir  | Grt-rich pelitic gneiss | spherulite |
|                    | YH02121901    | west       | khondalite         | dendrite                 |
|                    | 04083103A, B  | (Talatuoya east) | khondalite | spherulite |
|                    | YH10092601    |            |                    | Sil                      |
|                    | YH10092602A   |            |                    | An, Ep                   |
|                    | H89082201B    |            |                    | An                       |
|                    | G89082202A    |            |                    |                          |
|                    | H89082204A    |            |                    |                          |
|                    | G89082204C    |            | Grt-rich pelitic gneiss | dendrite, spherulite |
|                    | G89082204C    |            | intermediate granulite | And, Sil, Gdd |
| 14                 | M88112606     | Karametiya | pelitic migmatite  | dendrite                 |
|                    | H89082601I    | Algama     | pelitic migmatite  | And                      |
| 15                 | Y85100105     | Wattappola | pelitic migmatite  | spherulite               |
| 16                 | Dlpt-1* (=88112401A, 03080801) | Delpitiya | UHT pelitic granulite | dendrite, spherulite |
|                    | 04083001B*    |            |                    | And, Sil, Spr, Spl, Opx,  |
|                    | 04083001E     |            |                    | Opx, Crd, Wag            |
|                    | 04083003D*    |            |                    | And, Crn                 |
|                    | 04083005B     |            |                    | Opx, Crd                 |
|                    | YH10092501A   |            |                    |                          |
| 17                 | Y88112205     | Kumbalgamuwa | pelitic migmatite | spherulite                |
|                    | 02121707C     | Nayapana   | Gt-bearing charnockite | spherulite |
|                    |                |            |                    | And                      |
| 18                 | YH18091203C   | Passara    | intermediate granulite | spherulite |
|                    | YH02121603B   | Bandarawela | intermediate granulite | spherulite |
| 19                 | YH18091305A   | Koslanda   | basic granulite    | And                      |
|                    | H890811510    | Kalupahana | pelitic migmatite  | An, Ep                   |
| 20                 | Y85111806     | Warakagoda | pelitic migmatite  |                          |
| 21                 | 88120504      | Mahagama   | pelitic migmatite  |                          |
|                    | 88120501B     | Matugama   | pelitic migmatite  | And                      |
| 22                 | Y85111806     | Warakagoda | pelitic migmatite  |                          |
|                    | 88120503      |             | pelitic migmatite  | And                      |
| 23                 | YH02120504-3  | Ginigal Pelessa | pelitic migmatite | dendrite                 |
|                    | YH02121506C   |             | pelitic migmatite  | dendrite                 |
| 24                 | YH02121506E   |             | pelitic migmatite  | dendrite                 |
| 25                 | YH18091402-1B | Kataragama | felsic migmatite   |                          |

The mineral abbreviations are after Whitney and Evans (2010). * Described by Hiroi et al. (2014)
They are characterized not only by far-from-equilibrium crystallization textures such as dendritic and spherulitic crystals of quartz and other minerals but also by porphyritic textures with euhedral-subhedral phenocrysts of quartz and other minerals. The occurrence of FIs is unexpected because granulites are widely inferred to be cooled and exhumed slowly over a period of millions of years (e.g., Spear, 1994; Jamieson and Beaumont, 2011). Cesare et al. (2009) first reported the occurrence of glass inclusions and nanogranites in garnet in a granulite from the Kerala Khondalite Belt, southern India. Nanogranites are cryptocrystalline inclusions consisting of a multiphase aggregate with equigranular, hypidiomorphic to allotriomorphic texture. However, nanogranites exhibit similar features to those of FIs when they are inequigranular and contain granophytic to micrographic intergrowths of quartz and feldspar (Cesare et al., 2011). Because of their similarities, both FIs and nanogranites will be collectively referred to as felsite-nanogranite inclusions (FNIs). FNIs are crystallized felsic and hydrous melt inclusions which were produced by dehydration incongruent melting of biotite and other hydrous minerals during high-grade metamorphism of
host granulites in continental collision orogens. Although Hiroi et al. (2014) already reported some examples of spherulitic intergrowths of quartz and feldspar in FNIs, additional examples from different localities in Sri Lanka will be documented in some detail together with an experimentally reproduced spherulitic intergrowth of equivalent dimensions to emphasize their importance in obtaining new insight into deep crustal processes in continental collision orogens in this paper.

GEOLOGICAL OUTLINE

High-grade regional metamorphic rocks occupy most part of Sri Lanka, and have been divided into three geological units (e.g., Cooray, 1994), namely the Wanni Complex (WC) including the Kadugannawa Complex (KC), the Highland Complex (HC), and the Vijayan Complex (VC) from west to east based on Nd model ages (Milisenda et al., 1988, 1994; Kröner et al., 1991) (Fig. 1). However, the boundary between the HC and WC is not well defined, especially in the southwestern part, because of the scarcity of data, and the delineated boundary there appears to be discordant to geological structures. Moreover, there are different interpretations about the boundaries between the HC and WC (e.g., Sajeev et al., 2007; Santosh et al., 2014; He et al., 2016a, b); Osanai et al. (2016b), Takamura et al. (2016), and Kitano et al. (2018) presented comprehensive review and new geochronological data for the HC and WC.

THE HIGHLAND COMPLEX (HC)

The HC yields Nd-model ages of 3400-2000 Ma, and consists of granulite-facies metasedimentary and metaigneous rocks. In the central to northern part of the HC, marble and quartzite layers closely accompanied by khondalite are characteristic and traceable over the distance of 40 km. In contrast, in the southwestern part of the HC, marble and quartzite are scarce (Mathavan et al., 1999), and cordierite-bearing gneisses and orthogneisses are prominent (Perera, 1984; Prame, 1991). Based on such differences in lithology and mineralogy the HC was once subdivided into the Highland Series and Southwestern Group (Cooray, 1984, 1994), Faulhaber and Raith (1991), Raase and Schenk (1994), and Schumacher and Faulhaber (1994) showed an eastward gradual increase in pressure, while Sajeev and Osanai (2005) revealed a regional thermal structure regardless of the boundary between the HC and WC. UHT granulites occur sporadically in the high-temperature part (Osanai et al., 2016a, and references therein).

THE WANNI COMPLEX (WC)

The WC yields Nd model ages of 1800-1100 Ma, and comprises upper amphibolite- to granulite-facies rocks. Metaigneous rocks are predominant and range from granitic, granodioritic, monzonitic, to tonalitic (Pohl and Emmermann, 1991). The WC also contains non-metamorphic, post-tectonic granites at Tonigala and Galgamuwa (e.g., Cooray, 1984; Hözl et al., 1991; Cooray, 1994) and carbonatite at Eppawala (Weerakoon et al., 2001; Manthilake et al., 2008; Pitawala and Lottermose, 2012). The KC is often referred to as “arenas” and shows doubly plunging upright folds (Vitanage, 1972; Almond, 1991; Tani and Yoshida, 1996). Willbold et al. (2004), Santosh et al. (2014) and He et al. (2016a) showed that VC, especially the KC, was once a volcanic arc.

THE VIJAYAN COMPLEX (VC)

The VC yields Nd-model ages of 1800-1000 Ma, and consists mainly of amphibolite-facies rocks including granitic gneisses, migmatites and hornblende-biotite gneiss with rare quartzite and calc-silicate rocks (Kehelpannala, 1997; Mathavan et al., 1999; Kröner et al., 2013). Kröner et al. (2013) and He et al. (2016b) demonstrated that the VC was once a magmatic arc.

MATERIAL AND EXPERIMENTAL PROCEDURE

PETROGRAPHY AND MINERAL CHEMISTRY

Careful examination of more than 2000 thin sections of high-grade metamorphic rocks from various part of Sri Lanka (see Fig. 1) was first performed with a Nikon polarized-light microscope Eclipse E6TP-M32 to find FNIs in garnet at Chiba University, Chiba, Japan. Then, secondary electron (SE), backscattered electron (BSE), and cathodoluminescence (CL) images of FNIs were obtained, using a JEOL JSM-5600 scanning electron microscope (SEM) attached to a Link ISIS 300 energy dispersive X-ray spectrometer (EDS) system and an Oxford
Instruments MiniCL cathodoluminescence detector at Chiba University. X-ray compositional mapping was also performed with the SEM, using a 15 kV accelerating voltage and a 30 nA beam current. Fine-grained minerals (e.g., andalusite, kyanite, granidierite, and others) were identified with JASCO NRS-1000 and JASCO NRS-3000 laser-Raman spectrometers at the National Institute of Polar Research, Tokyo, Japan and Kyushu University, Fukuoka, Japan, respectively. Fine quartz + feldspar intergrowth textures were observed using a JEOL JXA-8530F field-emission EPMA at Kyushu University. Minerals were analyzed with a JEOL JXA-8230 wavelength dispersive electron probe microanalyzer (EPMA) at Chiba University, a JEOL JXA-8200 wavelength dispersive EPMA at the National Institute of Polar Research, and the JXA-8530F field-emission EPMA at Kyushu University. Analyses were performed using a 15 kV accelerating voltage and 12 nA beam current, with a 2 μm beam diameter. Synthesized oxides and natural minerals were used as standards for major elements. The obtained data were corrected using a JEOL oxide-ZAF correction program. X-ray composition maps were obtained on the same instruments using a 15 kV accelerating voltage, beam currents up to 300 nA, and a 1–2 μm beam diameter. Counting times were up to 50 ms.

**SAMPLE DESCRIPTION**

Constituent minerals of five representative samples containing FNIs with spherulitic texture are summarized in Table 2.

**Table 2. Constituent minerals of samples containing spherulitic felsite-nanogranite inclusions.**

| No | Sample number | Sil | Opx | Grt | Bt | Pl | Afs | Qz | Qt | Zrn | Mnz | Ap | Sr* | Hc* | Cm* | Ky* | And* |
|----|---------------|-----|-----|-----|----|----|-----|-----|----|-----|-----|----|----|-----|-----|-----|-----|
| 1  | 88112704A     | △   | ○   | ○   | ○  | ○  | △   | △  | △  | △   | △  | △  | △   | △  |
| 13 | 88112901A     | ○   | ○   | △   | ○  | ○  | △   | △  | △  | △   | △  | △  | △   | △  |
| 13 | 88112901H     | ○   | △   | ○   | ○  | ○  | △   | △  | △  | △   | △  | △  | △   | △  |
| 13 | G89082204A*1  | ○   | ○   | △   | ○  | ○  | △   | △  | △  | △   | △  | △  | △   | △  | △  |
| 20 | YH18091203C   | ○   | ○   | ○   | ○  | ○  | △   | △  | △  | △   | △  | △  | △   | △  |

The mineral abbreviations are after Whitney and Evans (2010).

Modal amount: ◎, abundant; ○, moderate; △, small.

* In garnet, *1 In FNI in garnet, *2 Some in matrix

**Sample 88112704A** is a migmatic pelitic to quartzose-feldspathic gneiss. Poikiloblastic garnet contains sporadic inclusions of sillimanite, plagioclase, alkali feldspar, quartz, biotite, ilmenite, and apatite in addition to FNIs (Fig. 2). FNIs in this sample are composed of spherulitic intergrowths of sodic plagioclase + quartz, which are accompanied by more coarse-grained biotite, apatite, and monazite. Biotite in FNIs is more magnesian and contains much less Ti and F than biotite in the matrix (Table 3). Estimated peak P-T conditions are 860-950°C and 0.8-0.9 GPa based on the biotite-garnet Mg-Fe exchange thermometers (Holdaway et al., 1997; Gessmann et al., 1997) and garnet-sillimanite-plagioclase-quartz-barometer (Hodges and Crowley, 1985).

**Sample 88112901A** is a sillimanite-garnet gneiss. Poikiloblastic garnet contains numerous inclusions of sillimanite, plagioclase, alkali feldspar, quartz, biotite, spinel, rutile, ilmenite, monazite, and apatite in addition to FNIs. FNIs contain relatively coarse-grained biotite, sodic plagioclase and quartz surrounding fine spherulitic intergrowths of quartz + alkali feldspar (Fig. 3). Biotite in the FNIs is more magnesian and poor in Ti compared with biotite in the matrix (Table 3). Spinel in direct contact with quartz in garnet (Fig. 3c) is rich in Zn (Table 3). Estimated peak P-T conditions are 830-900°C and 0.9-1.0 GPa based on the biotite-garnet Mg-Fe exchange thermometers (Holdaway et al., 1997; Gessmann et al., 1997) and garnet-sillimanite-plagioclase-quartz barometer (Hodges and Crowley, 1985).
Fig. 2. Backscattered electron (BSE) images (a, d, and f), Plane-polarized light photomicrograph (b), cross-polarized light photomicrograph (c), and X-ray composition maps for Si, Al, Mg, Na, and K (e-1 to e-5) and for Si, Al, Ca, Na, and K (g-1 to g-5) of spherulitic In X-ray composition maps abundance increases from black to blue to green to yellow to red to white. The mineral abbreviations are after Whitney and Evans (2010). felsite-nanogranite inclusion in garnet in sample 88112704A from locality 1 in Figure 1. In X-ray composition maps abundance increases from black to blue to green to yellow to red to white.
| Sample | 88112704A | 88112901A | YH18091203C |
|--------|-----------|-----------|-------------|
| Mineral | Grt/Pl | Bt | Bt | Grt/Opx | Bt | Sp1 | Bt |
| SiO₂   | 39.80 | 62.23 | 35.03 | 38.10 | 39.46 | 62.31 | 35.17 | 35.99 | 0.04 | 38.20 | 50.65 | 57.34 | 36.53 | 39.27 |
| TiO₂   | 0.04 | 0.00 | 4.84 | 0.57 | 0.06 | 0.00 | 7.55 | 2.64 | 0.05 | 21.58 | 2.57 | 25.98 | 13.61 | 18.65 |
| Al₂O₃  | 22.25 | 24.68 | 16.94 | 17.65 | 22.08 | 23.13 | 15.96 | 19.87 | 61.86 | 0.04 | 0.00 | 0.00 | 0.08 | 0.03 |
| Cr₂O₃  | 0.04 | 0.00 | 0.06 | 0.06 | 0.00 | 0.09 | 0.01 | 0.01 | 0.10 | 29.64 | 28.33 | 0.14 | 17.12 | 8.27 |
| FeO*   | 28.93 | 0.05 | 14.78 | 10.54 | 31.36 | 0.02 | 15.32 | 13.25 | 24.91 | 0.32 | 0.00 | 0.00 | 0.06 | 0.00 |
| MnO    | 0.99 | 0.00 | 0.02 | 0.04 | 0.99 | 0.00 | 0.00 | 0.06 | 0.00 | 0.72 | 0.29 | 0.05 | 0.00 | 0.00 |
| MgO    | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| ZnO    | 9.27 | 0.00 | 13.04 | 18.55 | 7.70 | 0.00 | 12.12 | 13.62 | 7.19 | 6.95 | 17.94 | 0.03 | 12.58 | 16.50 |
| CaO    | 1.08 | 6.03 | 0.00 | 0.01 | 1.34 | 4.45 | 0.02 | 0.04 | 0.02 | 3.79 | 0.37 | 9.02 | 0.03 | 0.43 |
| Na₂O   | 0.00 | 8.30 | 0.07 | 0.41 | 0.03 | 9.49 | 0.09 | 0.08 | 0.00 | 0.01 | 0.02 | 6.74 | 0.05 | 0.74 |
| K₂O    | 0.01 | 0.46 | 9.83 | 8.51 | 0.00 | 0.24 | 9.84 | 9.87 | 0.01 | 0.01 | 0.01 | 0.25 | 9.78 | 8.53 |
| F      | n.d. | n.d. | 0.62 | 0.26 | n.d. | n.d. | 0.15 | 0.21 | n.d. | n.d. | n.d. | n.d. | n.d. |
| Cl     | n.d. | n.d. | 0.01 | 0.00 | n.d. | n.d. | 0.14 | 0.15 | n.d. | n.d. | n.d. | n.d. | n.d. |
| total  | 102.41 | 101.75 | 94.98 | 94.60 | 102.35 | 99.73 | 96.28 | 95.67 | 101.23 | 101.02 | 100.24 | 99.57 | 95.54 | 92.46 |
| O      | 12 | 8 | 22 | 22 | 12 | 8 | 22 | 22 | 4 | 12 | 6 | 8 | 22 | 22 |
| Si     | 3.003 | 2.721 | 5.296 | 5.562 | 3.007 | 2.773 | 5.255 | 5.316 | 0.001 | 2.966 | 1.935 | 2.589 | 5.532 | 5.770 |
| Ti     | 0.002 | 0.000 | 0.550 | 0.063 | 0.003 | 0.000 | 0.849 | 0.293 | 0.001 | 0.005 | 0.002 | 0.001 | 0.656 | 0.004 |
| Al     | 1.978 | 1.272 | 3.018 | 3.037 | 1.983 | 1.213 | 2.811 | 3.459 | 1.992 | 1.975 | 0.116 | 1.382 | 2.429 | 3.229 |
| Cr     | 0.002 | 0.000 | 0.007 | 0.007 | 0.000 | 0.003 | 0.001 | 0.001 | 0.002 | 0.002 | 0.000 | 0.000 | 0.010 | 0.003 |
| Fe     | 1.825 | 0.002 | 1.869 | 1.287 | 1.998 | 0.001 | 1.914 | 1.637 | 0.569 | 1.924 | 0.905 | 0.005 | 2.168 | 1.016 |
| Mn     | 0.063 | 0.000 | 0.003 | 0.005 | 0.021 | 0.000 | 0.000 | 0.008 | 0.000 | 0.047 | 0.009 | 0.002 | 0.000 | 0.000 |
| Zn     | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| Mg     | 1.043 | 0.000 | 2.939 | 4.037 | 0.875 | 0.000 | 2.700 | 2.999 | 0.293 | 0.805 | 1.022 | 0.002 | 2.840 | 3.614 |
| Ca     | 0.087 | 0.283 | 0.000 | 0.002 | 0.109 | 0.212 | 0.003 | 0.006 | 0.001 | 0.315 | 0.015 | 0.436 | 0.005 | 0.068 |
| Na     | 0.000 | 0.704 | 0.021 | 0.116 | 0.004 | 0.819 | 0.026 | 0.023 | 0.000 | 0.002 | 0.001 | 0.590 | 0.015 | 0.211 |
| K      | 0.001 | 0.026 | 1.896 | 1.585 | 0.000 | 0.014 | 1.876 | 1.860 | 0.000 | 0.001 | 0.000 | 0.001 | 1.889 | 1.599 |
| Cl     | 0.296 | 0.120 | 0.071 | 0.098 | 0.035 | 0.038 | 0.035 | 0.038 |
| total  | 8.005 | 5.007 | 15.599 | 15.702 | 8.000 | 5.035 | 15.438 | 15.61 | 3.001 | 8.042 | 4.006 | 5.022 | 15.544 | 15.514 |
| Mg/(Mg+Fe) | 0.364 | 0.611 | 0.758 | 0.305 | 0.305 | 0.585 | 0.647 | 0.340 | 0.295 | 0.530 | 0.567 | 0.576 | 0.581 | 0.781 |
| Aln    | 0.605 | 0.665 | 0.665 |
| Prp/An | 0.345 | 0.279 | 0.291 | 0.203 | 0.260 | 0.419 |
| Spv/Ab | 0.021 | 0.695 | 0.007 | 0.784 | 0.015 | 0.567 |
| Grs/Or | 0.029 | 0.025 | 0.036 | 0.013 | 0.102 | 0.014 |

* Total Fe as FeO  
  n.d. = not determined
Fig. 3. Plane-polarized light photomicrographs (a and c), BSE images (b, d, g, h, i, and k), X-ray composition maps for Si, Al, Mg, Na, and K (e-1 to e-5) and for Si (j), and scanning electron microscope cathodoluminescence (SEM-CL) image of spherulitic felsite-nanogranite inclusions in garnet in sample 88112901A from locality 13 in Figure 1.
Fig. 4. Plane-polarized light photomicrograph (a), cross-polarized light photomicrograph (c), BSE images (b, d, g and h), SEM-CL image (e), and X-ray composition maps for Si, Na, and K (f-1 to f-3) of spherulitic felsite-nanogranite inclusion in garnet in sample 88112901H from locality 13 in Figure 1.
Fig. 5. Plane-polarized light photomicrographs (a and b), BSE images (c, f, and g), SEM-CL image (d), and X-ray composition maps for Si, Mg, Na, and K (e-1 to e-4) of spherulitic felsite-nanogranite inclusion in garnet in sample G89082204A from locality 13 in Figure 1.
Fig. 6. Plane-polarized light photomicrographs (a and b), cross-polarized light photomicrograph (c), BSE images (d, f, and g), and X-ray composition maps for Si, Al, P, Mg, Ca, Na, and K (e-1 to e-7) of spherulitic felsite-nanogranite inclusion in garnet in sample YH18091203C from locality 20 in Figure 1.
**Sample 88112901H** is a sillimanite-free garnet-rich gneiss. Poikiloblastic garnet contains many inclusions of sillimanite, plagioclase, alkali feldspar, quartz, biotite, rutile, ilmenite, monazite, and apatite in addition to FNIs. It is noteworthy that some inclusion feldspars are coarse-grained mesoperthite in marked contrast with fine-grained FNIs with variable textures even in the same garnet (Fig. 4). In FNI showing spherulitic texture fine intergrowth of quartz + alkali feldspar is overgrown by more coarse-grained biotite, sodic plagioclase and quartz.

**Sample G89082204A** is a sillimanite-garnet gneiss. Poikiloblastic garnet contains numerous inclusions of quartz, plagioclase, alkali feldspar, sillimanite, kyanite, corundum, staurolite, hertcynite, biotite, rutile, ilmenite, apatite, monazite, and carbonate minerals in addition to FNIs. Kyanite and staurolite are relict prograde minerals, while local andalusite + carbonate mineral association is of retrograde origin replacing garnet from outside and along cracks (Hiroi et al., 1994). Spherulitic FNI consists mainly of quartz + alkali feldspar intergrowth with minor quartz + sodic plagioclase intergrowth besides rutile and apatite (Fig. 5).

**Sample YH18091203C** is a well-foliated intermediate granulate containing orthopyroxene. Subidioblastic to xenoblastic and poikiloblastic garnet contains inclusions of plagioclase, quartz, biotite, ilmenite, monazite, and apatite in addition to FNIs, which show variable textures even in the same garnet grain (Fig. 6). It is notable that the spherulitic FNI is inhomogeneous, being composed mainly of alkali feldspar + quartz intergrowth with minor sodic plagioclase + quartz intergrowth. Biotite in the FNIs is more magnesian and poor in Ti compared with biotites showing different modes of occurrence, such as those included within garnet separately from the FNIs and in the matrix (Table 3). Estimated peak temperature by the biotite-garnet Mg-Fe exchange thermometers (Holdaway et al. 1997; Gessmann et al., 1997) is 970-980°C, while estimated pressure is about 0.9 GPa based on the garnet-plagioclase-orthopyroxene-quartz barometer of Perkins and Chipera (1985).

**DYNAMIC CRYSTALLIZATION EXPERIMENT**

Crystallization of melt takes place at various undercooling (ΔT), which is the difference between liquidus temperature and crystallization temperature, resulting in different morphologies of crystals (e.g., Sunagawa, 2005). Spherulitic texture is typically formed at large ΔT (> 200°C) (e.g., Maneta and Baker, 2014). Dynamic (time dependent) crystallization experiments have been performed from 1970s (e.g., Lofgren, 1974; Fenn, 1986; Swanson and Fenn, 1986; MacLellan and Trembath, 1991; Baker and Freda, 2001; Roskosz et al., 2005; London, 2008; Hammer, 2008; Maneta and Baker, 2014; Sirbescu et al., 2017, and references therein). Similar experimental study was conducted to reproduce observed mineral textures of FNIs with an internally heated, argon-pressurized vessel at Chiba University, Japan (Sun et al. unpublished data). The starting material is granitic (SiO$_2$ 79.41; TiO$_2$ 0.04; Al$_2$O$_3$ 11.41; total Fe as FeO 1.05; MnO 0.04; MgO 0.03; CaO 0.47; Na$_2$O 4.07; K$_2$O 3.45; P$_2$O$_5$ 0.02; total 100.00 wt%). The experimental procedure is schematically shown in Figure 7a. The starting material was first completely melted at 950°C and 0.2 GPa for 24 hours. Then, crystallization experiment started with cooling at various rates to the desired temperature ranging from 500 to 700°C. Then the experiment was held at the temperature for 0–1004 hours to accumulate data of variable textural development for the granitic composition with variable amounts of water. Obtained data are in harmony with the published experimental results with similar composition and ΔT (e.g., Maneta and Baker, 2014; Sirbescu et al., 2017, and references therein).

In Figure 7b, a representative BSE image of the run product of isothermal crystallization of the granitic material with 2.4 wt% water at 700°C (ΔT ~ 230°C) and 0.2 GPa for 1004 hours is presented together with the natural example in sample YH18091203C for comparison. Both texture and grain size of the spherulitic intergrowths in Figure 7b are almost equivalent to each other, indicating that observed spherulitic textures of FNIs are well reproduced by the crystallization duration up to 1004 hours. Run products of shorter crystallization durations 134 and 30 hours are much more fine-grained, submicrometer- and micrometer-scale respectively. In general, the longer crystallization duration is, the more coarse-grained and larger run product is. The experimental method, procedure, and results will be presented elsewhere.
DISCUSSION AND CONCLUSIONS

A schematic model of FNI-forming and preserving processes is shown in Figure 8 after Hiroi et al. (2014, 2019). The ‘isobaric cooling of trapped melts in garnet’ of stage ① in Hiroi et al. (2014) should be changed to ② ‘cooling of trapped melts with substantial overpressure caused by the large difference in compressibility between melt inclusions and host garnet’ (Angel et al., 2014, 2015; Ferrero et al., 2016, 2018; Hiroi et al., 2019). The cracking of host garnet of stage ③ may have been caused by deviatoric stresses in the host garnet caused by overpressure (e.g., Angel et al., 2015; Ferrero et al., 2016). The decompression caused by cracking induces instantaneous H₂O loss from hydrous melt, which imposes effective undercooling of trapped melts resulting in far-from-equilibrium crystallization to form the characteristic mineral textures of FNIs. The significance of andalusite often present in FNIs is discussed by Hiroi et al. (2019). The observed spherulitic intergrowths of quartz + feldspar in FNIs are reproducible by experiments for the

Fig. 7a. Schematic illustration of dynamic (time dependent) isothermal crystallization experimental procedure (a) and BSE images of 1004 h isothermal crystallization run product at 700°C and 0.2 GPa and natural example (YH18091203C) (b). Run products of 138 and 300 h isothermal crystallization are submicrometer- and micrometer-scale spherulitic intergrowths, respectively.
duration up to 1000 hours, as shown above. If the run product is held at the same P-T conditions for longer duration, coarsening and recrystallization (Ostwald ripening) to destroy the fine spherulitic texture will take place. Therefore, rapid cooling is inevitable to preserve the fine textures of FNIs after their formation. The cooling history of metamorphic rocks is usually determined by measuring the ages of several different minerals, each with a different closure temperature. In general, slow cooling near the metamorphic peak is followed by rapid cooling (10–20 °C/Ma) between 550 and 300 °C (Spear, 1994). Numerical models of syn- and post-convergent ductile flow at T > 500 °C may reproduce the P-T path followed by granulites well (e.g., Jamieson et al., 2010; Jamieson and Beaumont, 2011), but the rapid cooling path ⑤ in Figure 8 has not been performed yet. In this connection, fluid released from crystallizing partial melts may play a significant role in reducing rock strength in discrete high-strain zones during cooling, as Hiroi et al. (2014) pointed out. Since crystallization of partial melts does not exactly reverse dehydration melting processes, crystallization inevitably leads to local fluid overpressures and hence hydraulic fracturing or fault lubrication.

The rapid cooling mechanism of huge granulite masses and relevant geological processes in the depths of continental collision orogens are yet to be solved. Sri Lanka is the key place to unravel the problems because of the most widespread but restricted occurrence of FNIs along the marginal part of the HC, as shown in Figure 1, in addition to accumulated geological, geochemical, and geochronological data.

Fig. 8. P-T diagram showing schematic P-T paths followed by melt inclusion (FNI) in garnet and host rock. Estimated peak P-T conditions of samples 88112704A, 88112901A, and YH18091203C based on the chemical compositions of minerals in Table 3, biotite-garnet Mg-Fe exchange thermometers (Holdaway et al., 1997; Gessmann et al., 1997), garnet-sillimanite-plagioclase-quartz barometer (Hodges and Crowley, 1985), and garnet-plagioclase-orthopyroxene-quartz barometer (Perkins and Chipera, 1985). FNI-forming and preserving processes consist of five stages ① to ⑤ (see text for more detail). Wet granite solidus and granite solidus for reduced H₂O activity are drawn to show the degassing effect on solidification temperature. Liquidus temperature also increases by degassing.
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