

Geochronological evidence for multistage-metamorphic events in ultrahigh-temperature granulites from central Highland Complex, Sri Lanka

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Abstract: The ultrahigh-temperature (UHT) granulite from the central Highland Complex, Sri Lanka preserves histories of several metamorphic events. The application of geothermobarometries on sapphirine-garnet-orthopyroxene-sillimanite-quartz bearing granulites confirms that metamorphism occurred under the UHT condition. We report a middle Proterozoic age of 1478 ± 58 Ma from the internal isochron using a garnet core, whole rock and felsic fraction (quartz + plagioclase) in the Sm-Nd system from the same rock samples. As this granulite preserves several stages of orthopyroxene formation, the measured isotope composition of orthopyroxene give mixed values. The reference isochron plotted with orthopyroxene and whole rock give an age of 550 Ma. The present results can be interpreted to mean that the middle Proterozoic metamorphic event could have been the thermal peak. During the uplift stage, this granulite might have remetamorphosed at younger stages along with the adjacent rocks.

key words: central Highland Complex, Sri Lanka, UHT granulites, Sm-Nd geochronology, multistage metamorphism

1. Introduction

Geochronological characteristics of ultrahigh-temperature (UHT) granulites from the Highland Complex, Sri Lanka have not been well understood because of the complex reaction textures, probably formed through multistage metamorphic events. Since the first finding of sapphirine-bearing granulites occurrence in the central Highland Complex of Sri Lanka (Osanai, 1989), several successive petrological works have been done on these very high-grade granulites (e.g. Kriegsman and Schumacher, 1999; Osanai *et al.*, 2000; Sajeev and Osanai, 2002). They reconfirmed UHT metamorphism, namely temperature and pressure conditions above *ca.* 1050°C and 11–12 kbar. These conditions are contradiction with the other granulites in the surrounding area, which preserves a maximum temperature of 750–850°C at 6–7 kbar (e.g. Hiroi *et al.*, 1994; Raase and Schenk, 1994).

Previous geochronological studies on the high-grade metamorphic rocks from Highland Complex have been summarized by Hölzl *et al.* (1991, 1994). Hölzl *et al.*

(1991) reported 492 ± 7 Ma for metapelites using an internal Sm-Nd system. They also reported 561 ± 12 and 481 ± 8 Ma by using the Sm-Nd internal isochron method, and 465 ± 11 Ma by using the Rb-Sr isochron method, respectively, from metabasites. Hölzl *et al.* (1994) dated zircons in metapelitic granulites of the Highland Complex to be of 569 ± 33 and 556 ± 183 Ma by using the U-Pb conventional method and also dated monazite in the same rocks to be 592 ± 2 Ma and 555 ± 3 Ma. Moreover, U-Pb rutile (conventional method) yielded the similar age of 538 ± 6 Ma. Hölzl *et al.* (1994) explained metamorphic and subsequent cooling ages for the metabasites by using various methods, in which they considered 608 ± 4 Ma (U-Pb zircon age, conventional method) as the best estimate for the peak granulite metamorphism. Kröner *et al.* (1987) yielded a detrital zircon U-Pb age of 3200–2400 Ma from metapelitic rocks. They also argued for a possible Pb-loss during 1100 Ma, which may imply an older metamorphic event. Osanai *et al.* (1996) reported a *ca.* 670 Ma metamorphic event for mafic and sapphirine-bearing granulites by using the Sm-Nd whole rock isochron method. They have also presented the retrograde age of *ca.* 520 Ma based on the whole rock-Bt internal isochron dating method.

In this report, we attempt to derive the peak metamorphic age of UHT granulite from the central Highland Complex by using the Sm-Nd system.

2. Geology

Milisenda *et al.* (1988) and Kröner *et al.* (1991) determined the tectonic units of the Sri Lankan basement, which are classified into the Wannai Complex, Highland Complex, Vijayan Complex and Kadugannawa Complex (Fig. 1). Among the four major complexes, the Highland Complex consists of high-grade granulites to amphibolite-facies rocks. Within the Highland Complex the highest-grade granulites are exposed around the central part, near Kandy. The geology of the central Highland Complex is highly complicated, being an intercalation of mafic and pelitic granulites (Fig. 2). Pelitic granulites from the central Highland Complex were extensively migmatized, being exposed as intercalation with mafic granulites, granitic gneiss, quartzites, charnockites and disrupted exposures of calc-silicates and marbles. The samples used in this study were taken from a roadside exposure (Fig. 3a) toward the south of Gampola (Fig. 2). The exposure has about a 5 meter length along the roadside. In this outcrop, sapphirine-garnet-orthopyroxene-sillimanite-quartz (Spr-Grt-Opx-Sil-Qtz) bearing granulites (Fig. 3b) are exposed as thin disrupted layers within garnet-cordierite-sillimanite gneiss and garnet-biotite gneiss. Coarse- to medium-grained garnet and sillimanite can be identified in hand specimens. On close observation of the specimens, fine- to medium-grained orthopyroxene can also be identified. All the fine layers are exposed as parallel to each other and the general foliation varies from $N10^\circ W$ to $N3^\circ E$ with a dip of $75\text{--}85^\circ S$.

3. Petrography and mineral chemistry of UHT granulite

The Spr-Grt-Opx-Sil-Qtz bearing granulite (3107B) consists of sapphirine, quartz, sillimanite, garnet and orthopyroxene as the peak assemblage. The minerals are mainly

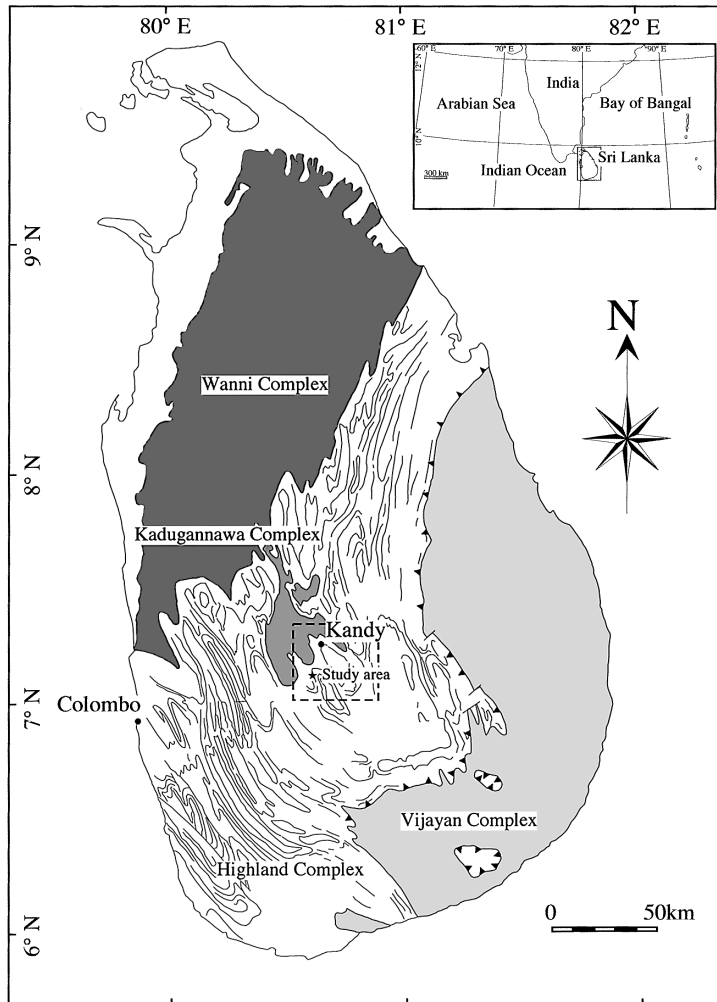


Fig. 1. Tectonic classification of Sri Lankan basement modified after Schumacher and Faulhaber (1994). The dotted square represents the area in Fig. 2. See the text for further explanation.

present as inclusions or as porphyroblasts. The significance of biotite inclusions in garnet may also indicate a peak assemblage along with sapphirine, due to its high-F content. Garnet is normally present as resorbed porphyroblasts with inclusions of sapphirine, quartz, biotite, orthopyroxene, cordierite and sillimanite. Sapphirine coexisting with quartz is present as rare inclusions in garnet (Fig. 3c). Orthopyroxene-sillimanite-quartz intergrowth is present as inclusions in garnet rims. Orthopyroxene-sillimanite-quartz intergrowth is also present in the matrix associated with garnet (Fig. 3d). Large porphyroblasts of orthopyroxene are present in the same rock (Fig. 3e). The rock preserves various retrograde symplectite and coronal textures consisting of orthopyroxene, cordierite, biotite and spinel. The major retrograde textures are fine moat of cordierite in the grain boundary of orthopyroxene-sillimanite and quartz and

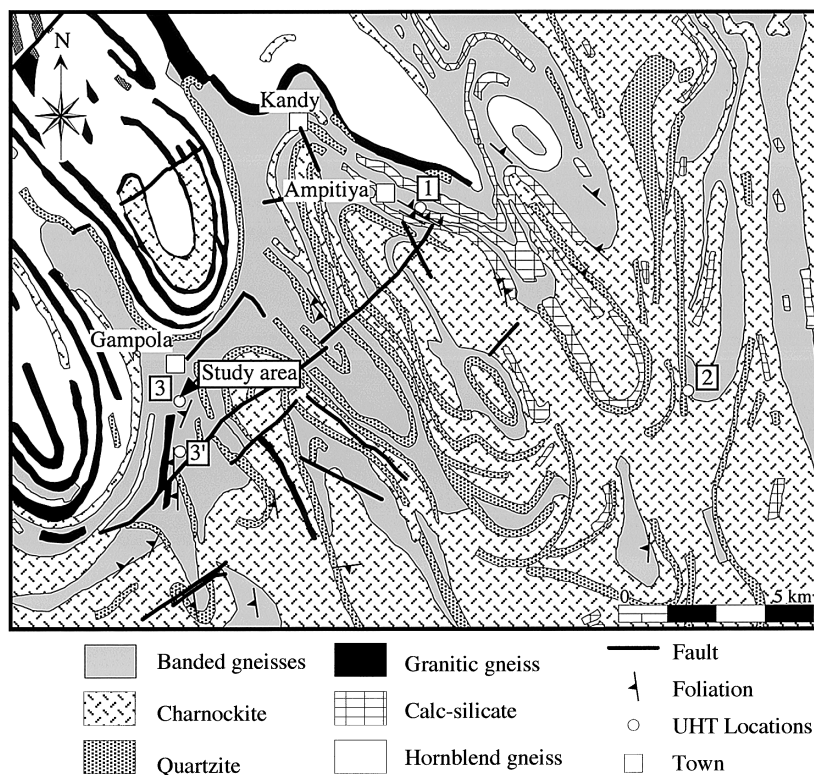


Fig. 2. Geology of central Highland Complex (map modified from Geological Survey Department of Sri Lanka (1982)).

1 corresponds to Osanai (1989), 2 is the location described by Kriegsman and Schumacher (1999) while 3 and 3' represent locations described by Sajeev and Osanai (2002). Samples from 3 are taken for this study.

orthopyroxene-cordierite \pm spinel symplectite (Fig. 3f). The rim of the biotite on orthopyroxene and rim of orthopyroxene on biotite are also present in the same sample. Several stages of orthopyroxene crystallization are presumed on the basis of textural variations.

The garnet porphyroblast composition slightly varies from core ($\text{Prp}_{54.1-53.2}$, $\text{Alm}_{42.8-42.1}$, $\text{Sps}_{2.4-1.5}$, $\text{GrS}_{2.2-1.2}$) to rim ($\text{Prp}_{53.3-48.2}$, $\text{Alm}_{44.5-49.8}$, $\text{Sps}_{2.5-1.3}$, $\text{GrS}_{2.1-1.1}$). Al_2O_3 content in orthopyroxene varies with respect to the textural variation. In the orthopyroxene inclusion as well as porphyroblast cores, Al_2O_3 content varies from 12.95–11.50 wt%, while the rim composition varies from 9.88–9.5 wt%. The X_{Mg} [$\text{Mg}/(\text{Mg}+\text{Fe})$] ratio of the initial orthopyroxene (inclusion phases as well as porphyroblasts) varies from 0.717–0.695. Orthopyroxenes in the retrograde symplectites contain relatively low Al_2O_3 (8.2–7.3 wt%) with X_{Mg} of 0.703–0.682. Sapphirine preserves composition near to 2:2:1, with X_{Mg} variation of 0.745–0.738. The spinels preserve an X_{Mg} range of 0.598–0.567. Pressure-temperature estimations using various garnet-orthopyroxene thermobarometers (Lee and Ganguly, 1988; Bhattacharya *et al.*, 1991; Harley, 1984a,b; Wood, 1974; Harley and Green, 1982) as

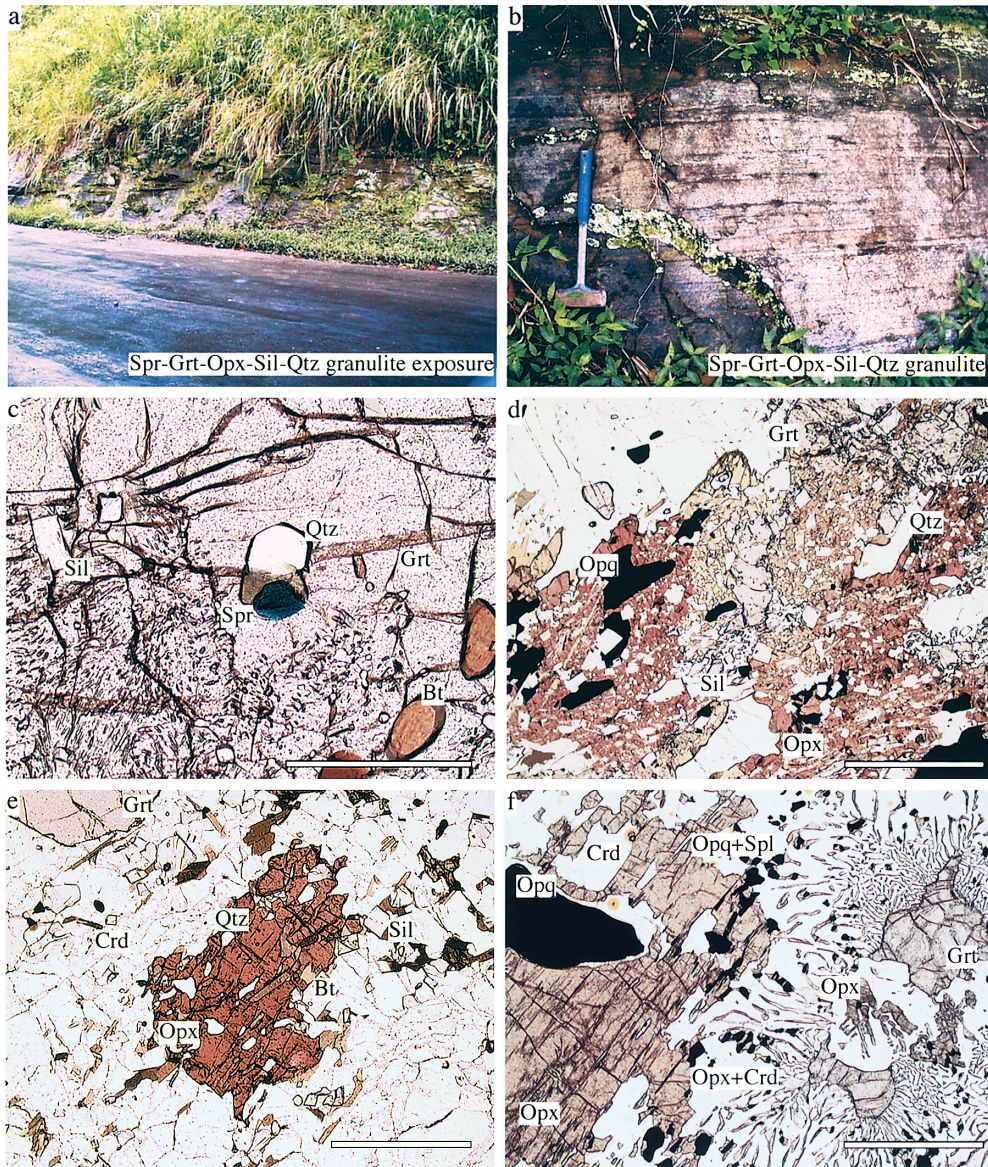


Fig. 3. Modes of occurrence and photomicrographs of UHT granulites. a) Roadside exposure of Grt-Spr-Opx-Sil-Qtz granulite, b) Close-up view of Grt-Spr-Opx-Sil-Qtz granulite exposure, c) Photomicrograph showing Spr-Qtz inclusion in garnet porphyroblast. d) Photomicrograph showing Opx-Sil-Qtz assemblage after Grt, e) Opx porphyroblast with Qtz inclusions present within the matrix of Crd, f) Opx-Crd symplectite after Grt. Note the porphyroblast of Opx in association. The scale bar in photomicrographs represents 0.5 mm for photo c, while for d, e and f as 1 mm.

well as Al_2O_3 isopleths (e.g. Harley and Motoyoshi, 2000) reveal the peak temperature, which must be between 1050–1150°C at pressure about 11–12 kbar. Representative mineral analyses are given in Table 1; their compositions are plotted in Al_2O_3 -FeO-MgO (AFM) and SiO_2 - Al_2O_3 -[FeO+MgO] (S-A-FM) diagrams (Fig. 4). The tie lines represent the reactions.

The inclusions of sapphirine-quartz coexistence in garnet porphyroblast, which is rimmed by aluminous orthopyroxene-sillimanite assemblage, represent the FMAS reac-

Table 1. Representative mineral analysis of garnet, orthopyroxene and sapphirine.

| Mineral Texture | Garnet | | | Orthopyroxene | | | Sapphirine | |
|-------------------------|---------|---------|--------|---------------|--------|---------|------------|--------|
| | Pb core | Pb core | Pb rim | Pb core | Pb rim | Opx-Crd | in Grt | in Grt |
| SiO_2 | 40.30 | 40.30 | 39.64 | 47.50 | 49.50 | 50.60 | 15.95 | 16.40 |
| TiO_2 | 0.00 | 0.00 | 0.00 | 0.30 | 0.00 | 0.20 | 0.20 | 0.00 |
| Al_2O_3 | 22.76 | 22.77 | 22.40 | 12.70 | 9.85 | 7.40 | 57.40 | 57.00 |
| Cr_2O_3 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| FeO | 20.55 | 20.40 | 22.97 | 15.80 | 16.70 | 17.90 | 10.50 | 10.70 |
| MnO | 0.00 | 0.20 | 0.30 | 0.00 | 0.10 | 0.00 | 0.00 | 0.00 |
| MgO | 14.86 | 14.75 | 12.89 | 22.40 | 23.10 | 23.60 | 16.30 | 16.30 |
| CaO | 0.90 | 0.90 | 0.90 | 0.40 | 0.60 | 0.10 | 0.00 | 0.20 |
| Na_2O | 0.00 | 0.00 | 0.00 | 0.20 | 0.10 | 0.10 | 0.00 | 0.00 |
| K_2O | 0.00 | 0.10 | 0.00 | 0.00 | 0.00 | 0.10 | 0.00 | 0.00 |
| Total | 99.37 | 99.42 | 99.10 | 99.30 | 99.95 | 100.00 | 100.35 | 100.60 |
| Oxygen | 12 | 12 | 12 | 6 | 6 | 6 | 10 | 10 |
| Si | 3.001 | 3.002 | 3.001 | 1.726 | 1.793 | 1.840 | 0.956 | 0.982 |
| Ti | 0.000 | 0.000 | 0.000 | 0.008 | 0.000 | 0.005 | 0.009 | 0.000 |
| Al | 1.998 | 1.999 | 1.999 | 0.544 | 0.421 | 0.317 | 4.057 | 4.022 |
| Cr | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Fe | 1.280 | 1.271 | 1.454 | 0.480 | 0.506 | 0.544 | 0.527 | 0.536 |
| Mn | 0.000 | 0.013 | 0.019 | 0.000 | 0.003 | 0.000 | 0.000 | 0.000 |
| Mg | 1.649 | 1.637 | 1.454 | 1.213 | 1.247 | 1.279 | 1.457 | 1.454 |
| Ca | 0.072 | 0.072 | 0.073 | 0.016 | 0.023 | 0.004 | 0.000 | 0.013 |
| Na | 0.000 | 0.000 | 0.000 | 0.014 | 0.007 | 0.007 | 0.000 | 0.000 |
| K | 0.000 | 0.010 | 0.000 | 0.000 | 0.000 | 0.005 | 0.000 | 0.000 |
| Total cation | 8.000 | 8.003 | 8.000 | 4.001 | 4.000 | 4.002 | 7.006 | 7.007 |
| Al^{IV} | - | - | - | 0.274 | 0.207 | 0.161 | 2.044 | 2.019 |
| Al^{VI} | - | - | - | 0.269 | 0.214 | 0.156 | 2.013 | 2.003 |
| Fe^{3+} | 0.000 | 0.010 | 0.000 | 0.003 | 0.000 | 0.005 | 0.017 | 0.020 |
| Fe^{2+} | 1.280 | 1.261 | 1.454 | 0.477 | 0.506 | 0.539 | 0.510 | 0.516 |
| Alm | 0.427 | 0.423 | 0.485 | - | - | - | - | - |
| Spe | 0.000 | 0.004 | 0.006 | - | - | - | - | - |
| Pyr | 0.550 | 0.549 | 0.485 | - | - | - | - | - |
| Grs | 0.024 | 0.020 | 0.024 | - | - | - | - | - |
| Adr | 0.000 | 0.004 | 0.000 | - | - | - | - | - |
| X_{Mg} | 0.563 | 0.563 | 0.500 | 0.716 | 0.711 | 0.701 | 0.734 | 0.731 |
| X^*_{Mg} | 0.563 | 0.565 | 0.500 | 0.718 | 0.712 | 0.703 | 0.741 | 0.738 |

Fe^{3+} calculated after charge balance.

Texture description: 'in' inclusion, 'Pb' porphyroblast, symplectite represented by the involved minerals.

$X_{\text{Mg}} = [\text{Mg}/(\text{Fe} + \text{Mg})]$.

$X^*_{\text{Mg}} = [\text{Mg}/(\text{Fe}^{2+} + \text{Mg})]$.

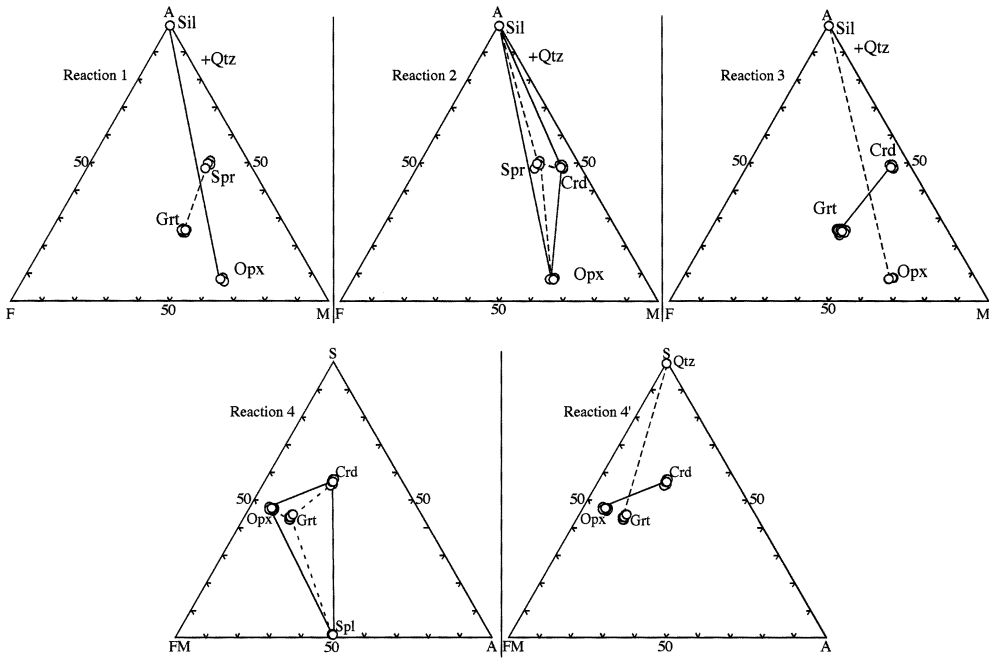


Fig. 4. $SiO_2-Al_2O_3-[FeO+MgO]$ (S-A-FM) diagram for the major mineral assemblages. Dotted tie lines represent reactants and normal lines for products of major mineral reactions. Textural variation is marked in the index. All sapphirine data are from the inclusion phase (e.g. see Fig. 3c). Orthopyroxene composition in the plot for reaction 1 is from the inclusion phase and porphyroblast cores (e.g. Fig. 2e), while for reactions 2 and 3 is represents the composition from orthopyroxene-sillimanite-quartz intergrowth (e.g. Fig. 2d). Reaction 4 represents orthopyroxene-cordierite symplectite composition (e.g. Fig. 2f). See the text for further description.

tion,



Although the initial sapphirine-quartz coexistence is present only as inclusion, cordierite + orthopyroxene + sillimanite assemblage in the matrix could have been formed by the reaction,



Minor inclusions of orthopyroxene-sillimanite intergrowth with quartz, inclusions in garnet rims and cordierite rim on the grain boundaries of orthopyroxene-sillimanite-quartz intergrowth are evidence for the FMAS univariant reaction resulting in garnet and cordierite,



Orthopyroxene-cordierite \pm spinel symplectite has been formed at the expense of garnet and minor quartz through the reactions,



The observed mineral reactions suggest isobaric cooling after peak metamorphism followed by isothermal decompression.

4. Geochronology

4.1. Sample preparation

Extreme care has been taken to separate garnet cores by cutting an approximate 0.5 mm rim from large garnet porphyroblasts. Zhou and Hensen (1995) and Unnikrishnan *et al.* (1995) pointed out problems due to contamination caused by inclusions in garnet in the Sm-Nd system. As explained above, the major inclusions in garnet are quartz, sillimanite and biotite with minor sapphirine, cordierite and orthopyroxene in the studied sample. Even the core part of garnet consists of similar inclusions. The core part of garnet was carefully separated as thin slabs (*ca.* 1 mm thick) by using an isomet micro cutter. The major part of the inclusions was eliminated using an isodynamic separator and by careful hand picking, then only clear garnet grains from the core part were selected for isotope analysis. The felsic fraction composed of feldspar and quartz was also separated with extreme care during hand picking to avoid contamination caused by zircon and monazite, which are present in minor amounts in the matrix. Zircons and monazites were taken out by hand picking from 100-mesh powder obtained after isodynamic separation. The remaining powder was used to pick out the fresh grains of felsic minerals. The major minerals in the matrix that can cause contamination are the opaque minerals, cordierite and spinel, which are separated by using a magnet, then an isodynamic separator and later by careful hand picking.

4.2. Analytical procedure

The thermal ionization mass spectrometer (TIMS: MAT-262) at the Graduate School of Science and Technology, Niigata University, Japan was used for measuring isotope compositions. Sm and Nd extractions follow the procedures explained by Kagami *et al.* (1982, 1987). Dissolution of garnet-bearing samples (garnet mineral sample and whole rock sample) was carried out after the procedure of Krogh (1973). The isotope dilution method using TIMS was used to measure the Sm and Nd concentrations by adding a ^{149}Sm - ^{150}Nd mixed spike. The measured $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of all samples were corrected to $^{143}\text{Nd}/^{144}\text{Nd} = 0.512116$ of JNdi-1 (Geological Survey of Japan standard), which corresponds to 0.511858 of La Jolla (Tanaka *et al.*, 1997). The internal isochron age and initial ratio were calculated by using the computer program of Kawano (1994) which follows the equation of York (1966). The decay constant: $\lambda(^{147}\text{Sm}) = 6.54 \times 10^{-12} \text{ y}^{-1}$ (Lugmair and Marti, 1978) was used to calculate the isochron. Analytical errors for $^{147}\text{Sm}/^{144}\text{Nd}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios are 0.1% (1σ) and 0.01% (1σ), respectively.

4.3. Analytical results

The Sm and Nd concentrations, isotope ratio and calculated age from the garnet core, whole rock and felsic fraction as well as reference age for orthopyroxene and whole rock are given in Table 2. The garnet core sample contains 9.820 ppm of Sm and 23.200 ppm of Nd. The felsic fraction gives the lowest values of 0.502 ppm of Sm and 2.070 ppm of Nd. The whole rock sample contains 10.100 ppm of Sm and 37.100 ppm of Nd. The orthopyroxene fractions contain 3.870 ppm of Sm and 11.800 ppm of Nd. The internal isochron using the garnet core, whole rock and felsic fractions gives 1478 ± 58 Ma with an initial ratio of 0.510556 ± 0.000075 (Fig. 5). It is noted that the orthopyroxene fraction does not fall on this isochron. However orthopyroxene and whole rock fractions give a reference age of 550 Ma (Fig. 5).

Table 2. Sm-Nd compositions and resulted ages for UHT granules of central Highland Complex.

| Spr-Grt-Opx-Sil-Qtz granulite | | | | | | |
|-------------------------------|--------|--------|-----------------------------------|------------|-----------------------------------|------------------------------|
| | Sm ppm | Nd ppm | $^{143}\text{Nd}/^{144}\text{Nd}$ | 2σ | $^{147}\text{Sm}/^{144}\text{Nd}$ | Age |
| Grt (core) | 9.820 | 23.200 | 0.513040 | 0.00001370 | 0.25591905 | 1478 ± 58 Ma |
| FF | 0.502 | 2.070 | 0.511990 | 0.00001410 | 0.14659021 | |
| Wr | 10.100 | 37.100 | 0.512142 | 0.00001379 | 0.16456392 | |
| Opx | 3.870 | 11.800 | 0.512263 | 0.00001392 | 0.19825700 | 550 Ma Reference isochron |

Grt (core) = garnet core fraction

FF = felsic fraction

Wr = whole rock fraction

Opx = orthopyroxene fraction

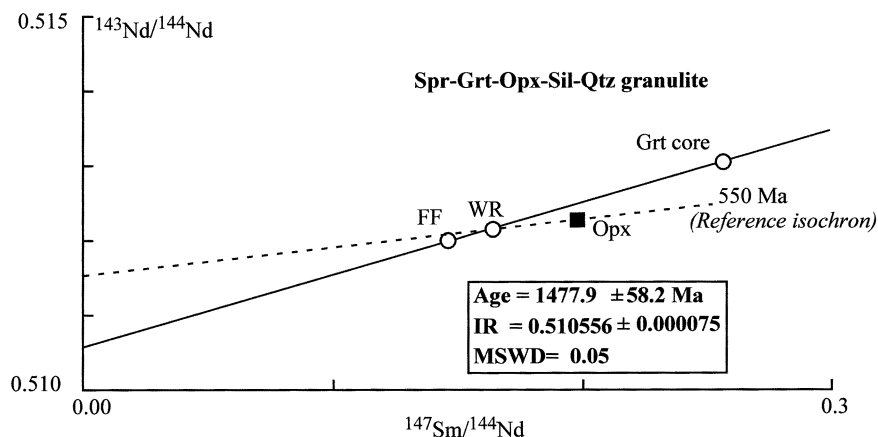


Fig. 5. Sm-Nd isochron diagram for UHT granulites.

FF represents felsic fraction and WR indicates whole rock.

5. Concluding remarks

The present result of 1478 ± 58 Ma is the oldest reported metamorphic age from the Highland Complex, Sri Lanka. Considering the closure temperature of garnet in the Sm-Nd system, the estimated age must indicate a cooling age after peak UHT metamorphism. This indicates that the peak UHT metamorphic event of the Highland Complex might have been undergone earlier than 1478 Ma.

From the petrographical observations, it is clear that the mode of later orthopyroxene is higher than that of prograde ones. Therefore the reference age of 550 Ma is considered to be a mixed age due to mixing of various stage orthopyroxenes. The age of *ca.* 550 Ma may be equivalent to the Pan-African metamorphic event, which is widely reported from Sri Lanka (*e.g.* Hölzl *et al.*, 1991) and also from other East Gondwana terranes (*e.g.* Shiraishi *et al.*, 1994; Soman *et al.*, 1995). This implies that the reference age (*ca.* 550 Ma) reported here may indicate that the studied UHT granulite has also been affected by Pan-African metamorphism. In considering other geochronological works, the suggested metamorphic event of the Highland Complex around *ca.* 1100 Ma (Kröner *et al.*, 1987) or *ca.* 670 Ma (Osanai *et al.*, 1996) metamorphism was not detected in this study.

Taking Sri Lanka as a part of the East Gondwana super-continent into account, it is also important to consider the relationship between metamorphism and isotope ages from the other continental fragments derived from the Gondwana super-continent. Many studies have correlated metamorphic complexes between Sri Lanka and East Antarctica or India (*e.g.* Laever and Scotese, 1987; Yoshida *et al.*, 1992). Among these comparisons, characteristic UHT metamorphism has also been reported from Rundvågshetta in the Lützow-Holm Complex, East Antarctica (Motoyoshi and Ishikawa, 1997) and Madurai Block, southern India (*e.g.* Brown and Raith, 1996). The metamorphic age of the Lützow-Holm Complex is considered to be during *ca.* 700–500 Ma (Pan-African era) (*e.g.* Shibata *et al.*, 1986; Shiraishi *et al.*, 1994; Fraser *et al.*, 2000). The metamorphic age of southern India is not well established, while the whole terrane is considered to be metamorphosed during the Pan-African event (*e.g.* Soman *et al.*, 1995). The results from numerous geochronological works (described above) from the Highland Complex, Pan-African metamorphic event in Sri Lanka is clearly established. However, the 1500 Ma metamorphic event has not been identified yet from any Pan-African metamorphic terrane, within East Gondwana, except from Sri Lanka. From this point of view we argue that geochronological studies on similar high-grade rocks from the adjacent terranes including the Lützow-Holm Complex, East Antarctica and southern Indian granulite belts (*e.g.* Madurai Block) could also provide evidence for early metamorphic events (1500 Ma).

This study is the first approach to resolve the problem for the timing of UHT metamorphism in the central Highland Complex, Sri Lanka. The present result indicates that UHT granulites are remnants of an old granulite basement preserved within the surrounding granulites.

Acknowledgments

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