Internal texture and U-Th-total Pb isochron ages of monazite in metamorphic rocks from the Southwestern Highland Complex, Sri Lanka

D. Nuwan Sanjaya WANNIARACHCHI and Masahide AKASAKA

Department of Geoscience, Interdisciplinary Faculty of Science and Engineering, Shimane University, Nishikawatsu-cho 1060, Matsue 690-8504, Japan

The Chemical U-Th-total Pb isochron method (CHIME) dating was performed for internal domains and zones within monazites in garnet-biotite gneiss and garnet-biotite-cordierite gneiss from the Precambrian Southwestern Highland Complex (SWHC), Sri Lanka, to evaluate evolution of the metamorphic rocks which have been subjected to multiple thermal events during the Gondwana amalgamation. Monazites are abundant in garnet-biotite gneisses. The monazites have core-rim zoned, inherited core-bearing, complexly zoned, and oscillatory zoned type internal textures. The core domains of the core-rim zoned, inherited core-bearing, and complexly zoned type monazites show ages of 533–503, 1788–512, and 1686–678 Ma, respectively, and the rim domains show younger ages of 500–434 Ma. Even though its repeated zonings, oscillatory zoned type monazites show the only young age of 470 ± 45 Ma. The determined isochron ages are grouped into four clusters: group I of 1766 ± 140 and 1788 ± 30 Ma (at present 1686 ± 186 Ma age may be grouped into group I); group II of 679 ± 99 Ma; group III of ages in a range between 533 ± 22 and 481 ± 42 Ma; and group IV of ages in a range between 472 ± 17 and 433 ± 14 Ma. The ages of the group I may imply magma emplacement ages. The ages of the group II correspond to the stage of the most prominent thermal event recorded in the region. The groups III and IV can be identified as post-peak thermal events. The age data given for the monazites in the SWHC are consistent with the published data for the Central Highland Complex, and indicate that the SWHC has been subjected to the same thermal events as the Central Highland Complex.

Keywords: Sri Lanka, Monazite Internal textures, Geochronology, The chemical U-Th-total Pb isochron method

INTRODUCTION

Sri Lanka is a Precambrian terrain, and 90% of the basement consists of high-grade metamorphic rocks. In Gondwana reconstructions, closure of Mozambique Ocean and the birth of Mozambique Belt were active tectonic events, and Gondwana fragments have been undergone multiple thermal events (Kriegsman, 1993; Grunow et al., 1996; Dissanayake and Chandrajith, 1999; Hoffman, 1999). In the Gondwana supercontinent, Sri Lanka was placed along the Mozambique belt between East and West Gondwana, and was juxtaposed with East Africa (Tanzania, Madagascar) and South India in the west, and with East Antarctica (Lützow-Holm Bay area) in the east (Kriegsman, 1993; Grunow et al., 1996; Dissanayake and Chandrajith, 1999; Hoffman, 1999).

The Sri Lankan Precambrian basement consists of four major crustal units named the Highland, Vijayan, Wanni, and Kadugannawa Complexes (Cooray, 1994) (Fig. 1). The Highland Complex (previously known as the Highland Series and the Southwestern Group) is a central belt of granulite-facies rocks, which extends from the northeast to the southwest of the island. Inter-bedded pelitic gneisses, meta-quartzites, marbles, and charnockitic gneisses characterize the belt. The Vijayan Complex occupies eastern and southeastern Sri Lanka, and consists of amphibolite-facies migmatites, granitic gneisses, granitoids, and metasediments. The Wanni Complex lies to the west and northwest of the Highland Complex, and consists of migmatites, granitic gneisses, charnockitic
gneisses, minor metasediments, and granitoids. The Kadugannawa Complex consisting of hornblende gneiss, biotite–hornblende gneiss and migmatites occurs within elongate synformal basins around Kandy in central Sri Lanka (Cooray, 1994). Although a number of petrological studies have been carried out later on this terrain (e.g., Kehelpannala, 1997; Mathavan et al., 1999; Mathavan and Fernando, 2001; Kröner et al., 2003; Kröner et al., 2013; Dharmapriya et al., 2014; Santosh et al., 2014; He et al., 2016a), lithological nomenclature and petrology of the terrain introduced by Cooray (1994) is widely recognized.

According to studies by U–Pb zircon dating (Kröner et al., 1987; Santosh et al., 2014; Takamura et al., 2015; He et al., 2016a), Nd model ages (Milisenda et al., 1988, 1994), and Sr model ages (Crawford and Oliver, 1969), the detritus of the Highland Complex metasediments were derived from unidentified Archean to Proterozoic source terrains of 3.2–2.0 Ga, and peak metamorphism occurred around 610–550 Ma (Hölzl et al., 1991; Kröner et al., 1994; Hölzl et al., 1994; Sajeev et al., 2003; Santosh et al., 2014; He et al., 2016a, 2016b). Baur et al. (1991) and Hölzl et al. (1994) recognized zircon upper intercept ages around 1.9–1.8 Ga for orthogneisses, and interpreted them as the crystallization ages of the protoliths. However, Kröner et al. (1987, 2003) found lead loss in zircon and identified zircon growth events at 1.1–0.75 Ga. Sajeev et al. (2003, 2007) also proposed 1.4 Ga and 530 Ma thermal events in the Highland Complex, although Sajeev et al. (2007) pointed out that the 1.1 Ga and 1.4 Ga ages require reexamination. Sajeev et al. (2010) has given evidences of age clusters at about 1.7 Ga, episodes of zircon growth at 1.04–0.83 Ga and two generations of overgrowths in zircon at 569 ± 5 and 551 ± 7 Ma in quartz-saturated granulites.

On the other hand, Hölzl et al. (1994) reported ages (610–550 Ma) of monazite, indicating existence of thermal events older than 550 Ma. Malaviarachchi and Taka-su (2011) identified three types of internal textures in monazite: unzoned, core-rim-type zoned, and mesh-like zoned types. Moreover, they indicated three age ranges of 613–561 Ma (Group I), 728–619 (Group II) Ma, and 516–460 Ma (Group III).

In contrast to the detailed studies on the Central Highland Complex (CHC) noted above, the Southwestern Highland Complex (SWHC) has not been well studied, and the thermal events of the SWHC are not yet well understood. However, the location of the SWHC has been regarded to be close to the West Gondwana fragments of Madagascar and South India (Dissanayake and Chandrajith, 1999), and, thus, the SWHC is a critical place to gives a clear view of multiple thermal history and relationship among West Gondwana fragments. As mentioned by Parrish (1990), age dating using monazite is one of the most suitable methods to clarify multiple thermal history. In fact, mineral assemblages and textures of metamorphic rocks in Gondwana fragments were overprinted by Pan–African thermal events, but internal textures of monazite record older thermal events. Therefore, in the present study, age dating of monazite in metamorphic rocks from the SWHC was performed to evaluate multiple thermal events in the SWHC during the Gondwana amalgamation. To achieve the study purpose, internal textures of monazite were investigated in detail, and the chemical U–Th–total Pb isochron method (CHIME; Suzuki et al., 1991; Suzuki and Adachi, 1991) was applied to determine the ages of the internal domains.

**GEOLOGY OF STUDY AREA**

The study area is situated in the southwest of Sri Lanka (square area in Fig. 1). A geological sketch map (Fig. 2) shows the main structural features of the study area and the sample locations. The study area contains six major rock types: charnockitic gneiss, garnet–biotite gneiss, cordierite gneiss, hornblende–bearing gneiss, quartzite, marble, and calc-gneiss. Garnet–biotite gneiss is the most common rock type in the area, and the abundance of cordierite gneiss is greater than that in any other area of the
Highland Complex. The area contains several major synforms and antiforms, and several shear zones. Most of the rock units have an N-NW foliation, but in the northeastern part of the study area, foliation trends toward N-NE (Geological Survey and Mines Bureau of Sri Lanka: Geology Sheet 16, 1996; Geology Sheet 19, 2000).

SAMPLES

Twenty-four rock samples were collected from natural rock outcrops. Based on the preliminary petrographic study, six gneiss samples with monazite as accessory mineral were selected for detailed study: five garnet-biotite gneiss samples (17-24GB, 14-21GB, 07-10GB, 11-17GB, and 03-04GB), and one garnet-biotite-cordierite gneiss sample (23–32Co). Petrographic features of these samples are summarized in Table 1. The mineral assemblage of the garnet-biotite gneiss is garnet + biotite + plagioclase + K-feldspar ± cordierite ± sillimanite ± quartz + magnetite ± rutile ± spinel ± ilmenite ± calcite. Most of the garnet occurs as porphyroblasts (Figs. 3a–3f). Cordierite and sillimanite are characteristic minerals in the matrices of the samples 14-21GB (Table 1) and 11–17GB (Table 1; Fig. 3e), respectively. Monazite presents as an accessory mineral in all five samples of garnet-biotite gneiss (Figs. 3a, 3b, and 3d). Monazite occurs mainly in the matrix (Figs. 3a and 3d) and as inclusions in garnet (Fig. 3b). Monazite grain sizes range from 50 to 500 µm, and their abundances are characteristically high in quartz- and biotite-rich samples. The garnet-biotite-cordierite gneiss (22-32Co) consists of thin spinel-rich and extremely quartz-poor layers with the assemblage cordierite + plagioclase + magnetite + spinel ± corundum (Fig. 3g), and spinel-poor layers with garnet + biotite + K-feldspar + plagioclase + quartz ± magnetite ± spinel (Fig. 3h). In the former, cordierite occurs as a recrystallized phase. Monazite occurs mainly in the matrix (Fig. 3h).

METHODS

Petrographic study of thin sections of the samples was carried out using an optical microscope. The element distribution of U, Th, Pb, and Y in the monazite grains and the chemical compositions of monazite, zircon, garnet,
and biotite in the thin sections were analyzed using a JEOL JXA-8530F electron microprobe analyzer (EMPA) at Shimane University. The CHIME isochron method (Suzuki et al., 1991; Suzuki and Adachi, 1991) was performed using 'working standard' technique by Kato et al. (2005). By this technique, natural monazites were calibrated using well-characterized primary standards that are usable as working standard only with measurement of X-ray intensities. In the present study, natural Sri Lankan monazites with UO₂ = 1.682, ThO₂ = 6.93, and PbO = 0.261 wt%, and with UO₂ = 0.512, ThO₂ = 15.890, and PbO = 0.401 wt% were used as working standards for U and Th, respectively. The standard materials used for Y and Pb were synthetic Y₂Al₅O₁₂ and natural PbS, respectively. The compositions of natural Sri Lankan monazites were determined at Tsukuba Research Departments, National Museum of Nature and Science, Japan. The abundances of U, Th, Pb, and Y were measured using an accelerating voltage of 15 kV, a beam current of 200 nA, and a beam diameter of 3-10 μm. The X-ray interferences of ThMg and YLγ on PbMα, and ThMγ on UMβ were corrected along with the background interference corrections, using dwell time of 200 seconds at both peak and background positions. The ZAF method was used for data correction for all elements.

INTERNAL TEXTURES AND CHEMICAL COMPOSITIONS OF MONAZITE

Internal textures of more than 100 grains of monazite in

Figure 3. Representative petrographic images of garnet–biotite gneiss: (a), (b), (c), (d), (e), and (f), and garnet–biotite–cordierite gneiss: (g) and (h). (a), (b), (c), and (g) are optical microscopic images in plane-polarized light, and (e), (d), (f), and (h) are back-scattered electron (BSE) images. (a) monazite in matrix (17-24GB), (b) garnet with monazite inclusions (17-24GB), (c) garnet porphyroblasts with biotite (14-21GB), (d) garnet porphyroblasts with biotite and monazite in matrix (07-10GB), (e) garnet–biotite gneiss with sillimanite (11-17GB), (f) garnet porphyroblast in matrix (03-04GB), (g) cordierite bearing assemblage with spinal and magnetite in spinel rich layer (23-32Co), and (h) garnet porphyroblast and monazite in matrix (23-32Co). Bt, biotite; Crd, cordierite; Grt, garnet; Ilm, ilmenite; Kfs, K-feldspar; Mag, magnetite; Mnz, monazite; Pl, plagioclase; Qtz, quartz; Sil, sillimanite; Spl, spinel. Color version of Figure 3 is available online from http://doi.org/10.2465/jmps.160121.
of monazite in Figure 4 are available online from http://doi.org/10.2465/jmps.160121). The PbO against ThO2* diagrams of each domain and zone within the analyzed monazites are shown in Figure 6 along with isochron ages (Montel et al., 1996), where ThO2* is the recalculated ThO2 which correspond to measured ThO2 plus ThO2 equivalent of measured UO2 (Suzuki et al., 1991; Suzuki and Adachi, 1991).

Core–rim zoned monazite

An anhedral core–rim zoned type monazite from garnet–biotite gneiss (17–24GB), shown in Figure 4a, is ~ 200 µm in size, and represents the simple zoning, where D1 core is rimmed by D2, ~ 10 µm in thickness. The D1 core is more abundant in U and Y (Figs. 5a–1 and 5a–4, respectively) but slightly poorer in Th than the D2 rim (Fig. 5a–2). As shown in a PbO against ThO2* diagram (Fig. 6a) and Table 2, the D1 and D2 have isochron ages of 503 ± 25 and 458 ± 19 Ma, respectively, and weighted average of apparent ages (abbreviated as WAVG ages) of 503 ± 5 and 457 ± 6 Ma, respectively (Table 2). An anhedral monazite from 17–24GB shown in Figure 4b is more than 300 µm in size, and consists of three zones, D1, D2, and D3. The D2 is brighter in the BSE image (Fig. 4b) and richer in Th than the D1 and D3 (Fig. 5b–2). The U and Y contents of the D3 are slightly less than those of the D1 and D2 (Figs. 5b–1 and 5b–4). The PbO against ThO2* diagram (Fig. 6b) shows isochron ages of 533 ± 14, 533 ± 22 and 498 ± 22 Ma, and WAVG ages of 533 ± 3, 534 ± 2, and 500 ± 5 Ma for the D1, D2, and D3, respectively (Table 2).

In a monazite in the garnet–biotite–cordierite gneiss (23–32Co), the core consisting of D1 and D2 and overgrowths of D3 and D4 are recognized in the BSE image of the grain (Fig. 4c). The D1 and D2 are richer in U and Y than the D3 and D4, respectively (Figs. 5c–1 and 5c–4, respectively); D3 is richer in Th than the D1, D2, and D4 (Fig. 5c–2), and more dominant in Pb than D4 (Fig. 5c–3); and D4 tends to be rich in Y as well as D1, although its content is variable (Fig. 5c–4). The D1 and D2 are 517 ± 43 and 525 ± 34 Ma in isochron age, respectively (Fig. 6c). The D1 and D2 are 522 ± 8 Ma and 525 ± 22 Ma in WAVG age, respectively (Table 2). On the other hand, the D3 and D4 yield isochron ages of 468 ± 50 and 450 ± 150 Ma, respectively, although the latter has a remarkably large error. The WAVG ages of the D3 and D4 are 467 ± 10 and 481 ± 60 Ma, respectively (Table 2).

Inherited core-bearing monazite

Three grains of the inherited core-bearing monazite from...
Figure 5. X-ray map images showing the distribution of U, Th, Pb and Y in the core–rim zoned monazites (a–1, a–2, a–3, a–4; b–1, b–2, b–3, b–4; c–1, c–2, c–3, c–4) and the inherited core-bearing type monazites (d–1, d–2, d–3, d–4; e–1, e–2, e–3, e–4; f–1, f–2, f–3, f–4). The samples of (a), (b), (c), (d), (e), and (f) are the same as those in Figure 4, respectively. Color version of Figure 5 is available online from http://doi.org/10.2465/jmps.160121.
the garnet-biotite gneiss are subhedral in form and fine in size (50–100 µm), where two of them are from 17–24 GB, and one from 11–17GB.

The monazite from 17–24GB shown in Figure 4d has D1 peripheral core and D2, D3 and D4 zones. In the monazite in Figure 4e, a peripheral core consisting of the D1 and D2 and D3 domains is overgrown by the D4 zone. The monazite in Figure 4f consists of a core made up of D1, D2 and D3 domains and three overgrowth zones of D4, D5 and D6. In the monazite shown in Figures 4d, the core D1 is characterized by higher U, Th and Pb contents than the zones D2, D3, and D4 (Figs. 5d–1 to 5d–3, respectively); the zone D2 is higher in U and Y and lower in Th than the zone D3 (Figs. 5d–1 and 5d–4), but low Th and Pb contents among the zones (Figs. 5d–2 and 5d–3). The D1 domain shows the isochron age of 512 ± 9 Ma and WAVG ages of 512 ± 5 Ma, and the D2, D3, and D4 zones yield younger isochron ages of 488 ± 40, 468 ± 18, and 469 ± 34 Ma (WAVG ages of 481 ± 30, 467 ± 6, and 467 ± 15 Ma), respectively (Figs. 6d; Table 2).

In the monazite from 17–24GB shown in Figure 4e, D1 and D2 domains consisting of the peripheral core is characteristically richer in U and Th (Figs. 5e–1 and 5e–2, respectively), D3 is the poorest in U, Th, Pb and Y (Fig. 5e–1, 5e–2, 5e–3 and 5e–4, respectively), and D4 is characterized richly in Y (Fig. 5e–4). The D1, D2, D3, and D4 yield isochron ages of 462 ± 19, 472 ± 14, 449 ± 44, and 433 ± 14 Ma (WAVG ages of 472 ± 15, 467 ± 6, and 433 ± 6 Ma), respectively, indicating all domains have more or less similar age values (Fig. 6e; Table 2).
In the monazite of Figure 4f from 11–17 GB, the peripheral core is characterized by the D1 domain rich in Th and Pb (Figs. 5f-2 and 5f-3, respectively), D2 in U, Pb, and Y (Figs. 5f-1, 5f-3 and 5f-4, respectively), and D3 in U and Th (Figs. 5f-1 and 5f-2, respectively). The D4 and D5 zones are characterized by rather high Th content (Fig. 5f-2). The D6 is poor in U, Th, Pb, and Y (Figs. 5f-1, 5f-2, 5f-3 and 5f-4, respectively). The PbO against ThO₂* diagram shown in Figure 6f and Table 2 show the isochron ages of 1788 ± 30 and 1766 ± 140 Ma, and WAVG ages of 1787 ± 22 and 1783 ± 97 Ma for the D1 and D2, respectively; isochron age of 529 ± 41 Ma and WAVG age of 526 ± 14 Ma for the D3; and 481 ± 42, 495 ± 69 and 434 ± 59 Ma in isochron ages and 471 ± 21, 496 ± 13 and 436 ± 15 Ma in WAVG age for the D4, D5 and D6, respectively.

Complexly zoned monazite

The complexly zoned monazite grains from the garnet-biotite gneiss are anhedral in form, significantly resorbed, and relatively larger in size (500 µm). As shown by BSE image of a grain from 14–21 GB (Fig. 4g), internal texture is very complex and difficult to identify all sectors and zones. The complex occurrences of the brighter and darker zones in the BSE images are characteristic in the main part, which is rimmed by thin (10–20 µm) latest overgrowth zones. In the complexly zoned main part, quartz grains are included. In this study, the complex internal textures were categorized into five domains, based on the BSE image (Fig. 4g) and the determined age for each domain (Fig. 6g): D1 is the remarkably dark zone; D2 covers the D1; D3 is an overgrowth zone on the D2; D4 domains distribute outermost region of the D3 zone; and D5 is the outermost zone of the grain. The PbO against ThO₂* diagram (Fig. 6g) and Table 2 shows the oldest isochron age of 1686 ± 186 Ma and WAVG age of 1675 ± 35 Ma for the D1 domain; isochron age of 679 ± 99 Ma and WAVG age of 662 ± 68 Ma for the D2; isochron ages of 507 ± 49 and 503 ± 55 Ma and WAVG ages of 507.8 ± 7.7 and 499 ± 12 Ma for the D3 and D4, respectively; and 458 ± 64 Ma in isochron age and 458 ± 16 Ma in WAVG age for the D5.

Oscillatory zoned monazite

Figure 4h represents the BSE image of an oscillatory zoned monazite from garnet-biotite gneiss (07–10 GB). The grain is euhedral to subhedral in form and fine in size (100 µm). In the BSE image, alternating brighter and darker growth zones show different thicknesses. The surface of each generation shows euhedral to slightly resorbed subhedral shapes. The internal texture is categorized into a core D1 and three overgrowths of D2, D3, and D4 (Figs. 4h and 6h). The core and D2 zone are thicker than the overgrowth zones of D3 and D4. As shown by the PbO against ThO₂* diagram in Figure 6h, one age group of 470 ± 45 Ma in isochron age and 467 ± 8 Ma in WAVG age is given for the D1, D2, D3, and D4.

DISCUSSION

Internal textures of monazite in metamorphic rocks record growth process of monazite subjected to thermal events, and, thus, are important to elucidate the thermal history of the metamorphic rocks. In the study on monazites from the CHC, Malaviarachchi and Takasu (2011) identified three types of internal textures in the monazites, such as core-rim zoned, unzoned, and mesh-like.

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### Table 2. Summary of U-Th-total Pb isochron age data for monazite domains

<table>
<thead>
<tr>
<th>Grain</th>
<th>Domains</th>
<th>Weighted average of apparent ages (Ma)</th>
<th>Isochron (CHIME) Ages (Ma)</th>
<th>Age group</th>
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<tr>
<td>Core-rim zoned</td>
<td>Fig. 4a D1</td>
<td>503±5</td>
<td>503±25</td>
<td>Group III</td>
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<tr>
<td></td>
<td>D2</td>
<td>456±6</td>
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<td></td>
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<td>533±22</td>
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<td>500±5</td>
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<td>Fig. 4c D1</td>
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<td>517±43</td>
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</tbody>
</table>
zoned types, and indicated three age ranges of 728–619 Ma (Group II), 613–561 Ma (Group I), and 516–460 Ma (Group III). Our study indicated that monazites in the metamorphic rocks of the SWHC in Sri Lanka have various internal textures, which can be categorized into four types: the core–rim zoned type, inherited core-bearing type, complexly zoned type, and oscillatory-zoned type. The core–rim zoned type monazite was common in the CHC and SWHC, but the unzoned type and mesh-like zoned type monazites were not observed in the SWHC. However, we newly defined three types of internal textural categories: inherited-core-bearing, complexly zoned, and oscillatory-zoned types. Finding of the inherited core-bearing type and complexly zoned type monazites are important, because, in monazites in these types, the core domains gave isochron ages of 1689 ± 186 Ma and 1788–1766 Ma which are older than the data by Malaviarachchi and Takasu (2011). According to the isochron ages of all the domains and zones in the present study, four distinct age groups can be proposed: group I defined by ages of 1689 ± 186 Ma and 1788–1766 Ma, group II of 676–559 Ma, group III of 533–507 Ma, and group IV of 481–434 Ma. As described already, ages of the groups I, II, and III in the present study were obtained from the core domains and inner core zones, whereas the group IV ages were mainly given from rim zones of the monazites. The group II ages of the SWHC monazite in this study coincide with the group I ages by Malaviarachchi and Takasu (2011), 613–561 Ma. We obtained the group II ages from the complexly zoned monazites, while Malaviarachchi and Takasu (2011) got their data from the unzoned type monazites. The groups III and IV ages in the present study, which were given from the rim zones of all kinds of monazites, seem to coincide with the group III ages, 516–460 Ma, of the mesh-like zoned monazite by Malaviarachchi and Takasu (2011). The group II ages by Malaviarachchi and Takasu (2011), 728–619 Ma, do not correspond to any group in our age group category at present, but partly overlap to the group II of the SWHC monazite, 676–559 Ma. After all, the internal textures in monazite in the SWHC show evidence of at least four stages of thermal events, which would be common in the CHC. Thus, the ages of monazites in the SWHC and CHC essentially show common features. Minor difference of the age data between the SWHC and CHC may be due to local variations of thermal events, which caused somewhat different growth processes of monazites in each metamorphic rock.

The chronological studies on monazites in the Sri Lankan basement, especially the SWHC, are few. In this study, we got ages of the group I (1689 ± 186 Ma and 1788–1766 Ma) in inherited-core-bearing type and complexly zoned type monazites from the garnet-biotite gneisses. This result proves that the detrital monazites were crystallized by thermal event at around 1.7 Ga. These ages may imply magma emplacement ages of the area. The ages close to the group I ages (1689 ± 186 Ma and 1788–1766 Ma) in this study have been reported by several studies on the CHC using zircon-geochronology. Sajeev et al. (2010) interpreted 1.7 Ga age clusters in quartz-saturated granulites from the CHC as episodes of zircon growth in the source region of the protolith sediments. The ages around 1.9–1.8 Ga (Baur et al., 1991; Hözl et al., 1994) for zircon upper intercept values were interpreted as crystallization ages of protoliths of orthogneisses in the CHC. The ages of the group II (676–559 Ma) correspond to the stage of the most prominent thermal event recorded in the region. The previous chronological studies of both zircon and monazite in the CHC confirmed that this age group corresponds to the peak metamorphic event in the region (Hözl et al., 1991, 1994; Kröner et al., 1994; Sajeev et al., 2010; Santosh et al., 2014; He et al., 2016a, 2016b). The groups III and IV in this study, 533–507 and 481–434 Ma, respectively, can be identified as post-peak thermal events. Such young ages have been also reported by chronological studies on zircons from the CHC, and have been interpreted to represent youngest thermal events (Hözl et al., 1994; Sajeev et al., 2003, 2007; Malaviarachchi and Takasu, 2011; He et al., 2016a, 2016b). However, as indicated in this study, most of these younger ages are recorded near and in the rim area of the monazites. According to Ayers et al. (1999), such growth patterns can be interpreted as later resetting of monazites due to longer heating period in the event of peak metamorphism. In this process, monazite crystals grew by Ostwald ripening to form rims and by coalescence, during which smaller crystals may move with grain boundaries by recrystallizing and reset the isotopic system. In this study, we assume the ages of the group IV at least represent the latest stage of the post-peak thermal events.

A geographical relationship among Sri Lanka, South India, Madagascar and Antarctica in Gondwana supercontinent has been proposed by Kriegsman (1993), Grunow et al. (1996), and Dissanayake and Chandrajith (1999), as shown in Figure 7. According to this model, the SWHC is closely related to Kerala Khondolite Belt (KKB) in South India and Androyan Complex of Madagascar. The result in the present study and the published data in KKB monazite by Santosh et al. (2005), shown in ThO2–PbO (wt%) diagram of Figure 8, proves the close relation between the SWHC and the KKB: in this diagram, plots of PbO (wt%) against ThO2 (wt%) of the SWHC monazites with ages of 1788–1689 and of 679–434 Ma form upper and lower
trends, respectively, and the trends by the data of the KKB monazites with 1967–1759 and 563–515 Ma (Santosh et al., 2005) are the same as those of the SWHC monazites. Moreover, the ages of early Pan–African thermal events in the South India have been reported as 1802 ± 16 Ma (Bartlett et al., 1998) and 1793 Ma (Choudhary et al., 1992), and Paquette et al. (1994) reported 1679 ± 04 Ma for zircon in Androyan Complex of Madagascar (Fig. 7). Therefore, the SWHC, the KKB and the Androyan Complex give similar ages of early Pan–African thermal events. On the other hand, the ages of 760–550 Ma given from zircons and monazite of the CHC have been interpreted in terms of Pan–African metamorphism with multiple thermal events (Hölzl et al., 1991, 1994; Kröner et al., 1994; Sajeev et al., 2010; Santosh et al., 2014; He et al., 2016a, 2016b). The ages of 484–440 Ma given from Rb–Sr isochron method in biotite, feldspar, and garnet from metamorphic rocks in South India, have been considered to represent Post–Pan–African thermal events (Choudhary et al., 1992; Unnikrishnan–Warrier et al., 1995; Unnikrishnan–Warrier, 1997). Thus, the lower trend in Figure 8 is interpreted to correspond to Pan–African and Post–Pan–African thermal events.

After all, the close relationship between the SWHC and other Gondwana fragments in the proposed model on Gondwana supercontinent can be confirmed by the chronological data in the present study and the published data.

**CONCLUSIONS**

The BSE images, element distributions, and CHIME age data of monazites in the garnet–biotite gneiss and garnet–biotite–cordierite gneiss from the SWHC, Sri Lanka, show several domains and zones even in one monazite grain. The internal domains and zones within monazites were categorized into four types: core–rim zoned, inherited core–bearing, complexly zoned, and oscillatory–zoned types. Among those categories, inherited core–bearing, complexly zoned, and oscillatory–zoned types are reported first time for Sri Lankan monazites. The determined ages are grouped into four clusters: group I of 1766 ± 140 and 1788 ± 30 Ma (at present 1686 ± 186 Ma age may be grouped into group I); group II of 679 ± 99 Ma; group III of ages in a range between 533 ± 22 and 481 ± 42 Ma; and group IV of ages in a range between 472 ± 17 and 433 ± 14 Ma. The rim areas of monazites show younger ages (533–433 Ma). Some monazite grains provided a wide variation in age (e.g., complexly zoned monazite). According to the results on the thermal history of the SWHC...
in this study and the published chronological data of the KKB in South India and Androyan Complex in Madagascar, the SWHC shows a close geochronological relationship with the KKB in South India and Androyan Complex. The synchronized studies of internal textures and geochronology of monazites are required to evaluate tectonic setting and evolution of the Gondwana amalgamation among those crustal blocks.

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**SUPPLEMENTARY MATERIALS**

Appendixes Tables S1–S6 and color version of Figures 3 and 5 are available online from http://doi.org/10.2465/jmps.160121.

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