UHT granulites of the Highland Complex, Sri Lanka II: Geochronological constraints and implications for Gondwana correlation

Yasuhito OSANAI*, Krishnan SAJEEV**, Nobuhiko NAKANO*, Ippei KITANO***, Wilbert K.V. KEHELPANNAL†, Ryosuke KATO***, Tatsuro ADACHI* and Sanjeewa P.K. MALAVIARACHCHI††

*Division of Earth Sciences, Faculty of Social and Cultural Studies, Kyushu University, Fukuoka 819-0395, Japan
**Centre for Earth Sciences, Indian Institute of Science, Bangalore 560 012, India
***Graduate School of Integrated Sciences for Global Society, Kyushu University, Fukuoka 819-0395, Japan
†Department of Geology, University of Botswana, Gaborone, Botswana
††Department of Geology, Faculty of Science, University of Peradeniya, Peradeniya 20400, Sri Lanka

The regional ultrahigh-temperature (UHT) metamorphism of the Highland Complex, Sri Lanka is well established and has an important role in our understanding of the tectonic history of the Gondwana supercontinent. U-Pb zircon dating of sapphirine-bearing Mg-Al granulites yielded two major metamorphic age populations at approximately 620–590 and 563–525 Ma with no evidence of older zircon cores. Pelitic granulite samples with a Grt-Sil-Spl-Crd assemblage have similar metamorphic ages with concordant data clusters at ~ 602, 563, and 526 Ma and inherited zircon cores aged from 2040 to 1600 Ma. The pelitic granulites also underwent two stages of metamorphism (565–520 and 622–580 Ma). Some of these pelitic granulite samples have inherited zircon cores ranging from 3060 to 760 Ma. Zircons in mafic granulite samples have age ranges of 566–533 and 620–578 Ma. A calc-silicate granulite sample also has similar age populations at 591, 541, and 524 Ma. Combining these new results with previously published ages from Sri Lanka and formerly adjacent continental fragments of Gondwana, we propose that the terranes in southern Madagascar (south of Ranotsara Shear Zone), Northern and Southern Madurai and the Trivandrum Blocks of southern India, the Highland Complex of Sri Lanka, and the Skallen Group in the Lützow-Holm Complex of East Antarctica represent a unique metamorphic belt that regionally experienced the Ediacaran-Cambrian UHT event during the amalgamation of the Gondwana supercontinent.

Keywords: U-Pb zircon LA-ICP-MS dating, Late Neoproterozoic, Ultrahigh-temperature granulite, Highland Complex, Sri Lanka

INTRODUCTION

The timing of UHT metamorphism in the Highland Complex in Sri Lanka is a topic of geological interest. However, given the limited amount of precise geochronological data available and the complex nature of events involved, the metamorphic evolution of the Highland Complex is still unclear. Sajeev et al. (2010) dated the sapphirine-bearing granulites of Sri Lanka using U-Pb zircon and monazite, which yielded multiple ages and linked several stages of metamorphic evolution. Peak metamorphism occurred at ~ 569 Ma and was followed by a stage of retrogression at ~ 551 Ma. Dharmapiya et al. (2015a) dated several new Spr granulite localities, describing detrital core ages ranging from 834-722 Ma with peak UHT metamorphism around ~ 567 Ma, which closely matches the results of Sajeev et al. (2010). However, the two Crn-bearing metapelites reported by Dharmapiya et al. (2015b) yielded metamorphic ages of ~ 530 and ~ 578 Ma and Paleoproterozoic ages of zircon cores were interpreted as detrital grains. Although these recent studies only dealt with specific rock types, the results implied the possibility of multiple stages of zircon growth associated with large-scale thermal episodes that affected the high-grade area in the Highland Complex. In
this contribution, we carried out LA–ICP–MS zircon U–Pb dating of granulite-grade rocks, which can be broadly grouped as Mg–Al granulites, mafic granulites, aluminous granulites, and calc-silicate granulites from the central Highland Complex. The detailed geology, petrography, mineral and whole-rock chemistry, as well as the pressure-temperature (P–T) estimations are described in Osanai et al. (2016 in this issue).

Multiple episodes of zircon growth and metamorphism have been reported from several East Gondwana fragments, including the Lützow-Holm Complex in East Antarctica (e.g., Dunkley et al., 2014; Tsunogae et al., 2015), southern Madagascar (e.g., Jöns and Schenk, 2011), the Madurai Block (e.g., Prakash, 2010), and Trivandrum Block in India (e.g., Taylor et al., 2014). Therefore, in this study, we also attempt to compile the geochronological datasets from these UHT terranes in order to discuss and realize the amalgamation of Gondwana fragments during the Ediacaran to Cambrian period.

**LA–ICP–MS DATING**

**Samples and analytical procedure**

Zircon grains were analyzed from 20 UHT metamorphic rocks in total: seven Mg–Al granulites (32001G, 32002A, 32002B-2, 32002C, 32002D, 32002F, and 32002G), six mafic granulites (32001A, 32001D, 32001F, 32002E, 32005F, and 31807H), five Fe-rich aluminous granulites (32003A, 32003B, 32006C, 31807E, and 31807F), and two calc-silicate granulites (32001B and 32001C). The localities of these samples are shown in Figure 1. Two non-UHT granulite-facies pelitic metamorphic rocks (122704G: Spl-bearing Grt-Sil-Crd gneiss and 40102A: Qz-rich Grt-Sil gneiss) were also analyzed for a geochronological comparison with the UHT metamorphic rocks.

The analytical procedure and conditions followed Adachi et al. (2012), and the zircon separation procedure followed Kitano et al. (2014, 2016). Standard zircon FC–1 (1100 Ma; Paces and Miller, 1993) was used to monitor internal consistency and gave a weighted mean 206Pb/238U age of 1099.4 ± 4.9 Ma (95% confidence intervals, n = 34, MSWD = 0.75) for the entire analytical period.

Representative CL images with apparent 206Pb/238U ages and their concordia diagrams of zircons from Mg–Al granulites and mafic granulites are shown in Figures 2–3 and Figures 4–5, respectively. All U–Pb data are shown in Supplementary Table S1 (available online from http://doi.org/10.2465/jmps.151230). We used the probability density curves for the concordant age populations to clas...
sify the metamorphic age groups. The zoning texture, shape, and size of analyzed zircon grains are summarized in Table 1 with obtained ages and Th/U ratios.

Results from Mg-Al granulites

32001G. This sample is Spr-Opx-Krn-Spl granulite collected from locality Ampitiya-1. The obtained ages yield a continuous range of 206Pb/238U ages from 616 to 518 Ma. These concordant data have been divided into two groups: ~620–610 Ma (n = 9; Th/U = 0.28–0.73) and ~550–520 Ma (n = 12; Th/U = 0.19–0.95), with the younger group defining a concordia age of 533.9 ± 4.7 Ma (MSWD = 1.9; probability = 0.16) (Fig. 3a).

32002A. Most of the zircon grains in Spr-Grt-Opx granulite from locality Ampitiya-2 show an age range between 622 and 540 Ma and have been split into three age groups of (1) 620–610 Ma (n = 3; Th/U = 0.37–1.78), (2) 606–572 Ma (n = 18; Th/U = 0.13–2.02), and (3) 558–540 Ma (n = 8; Th/U = 0.19–2.01) (Fig. 3c). Group (2) gives a concordia age of 587.1 ± 4.9 Ma (MSWD = 0.06; probability = 0.80). Although we could not obtain a concordia age from Group (3), the weighted mean 206Pb/238U age gives 548.8 ± 7.2 Ma (MSWD = 0.39; probability = 0.91).

32002B. Zircons in Spr-Grt-Opx granulite from locality Ampitiya-2 show an age range of 610–615 Ma (n = 4; Th/U = 0.11–0.23) and 584–538 Ma (n = 24; Th/U = 0.14–1.18) (Fig. 3d). The latter defines a concordia age of 563.5 ± 3.9 Ma (MSWD = 0.001; probability = 0.97).

32002C. A few zircon grains in Spr-Opx granulite from Ampitiya-2 show clear zonation of dark-CL cores
and wide bright–CL rims. All analyzed data are concordant, ranging from 626 to 495 Ma, and divided into three age groups: ~630–610 Ma (Th/U = 0.07–0.23; n = 2), 585–549 Ma (Th/U = 0.04–0.38; n = 9; concordia age of 565.0 ± 6.2 Ma and MSWD = 0.029), and 533–495 Ma (Th/U = 0.03–0.42; n = 16; concordia age of 516.8 ± 4.1 Ma with MSWD = 0.21) (Fig. 3e). No clear age difference is observed between dark–CL cores and bright–CL rims (Fig. 2e).

32002F. Ages from Spl–Opx granulite in Ampitiya–2 show a continuous spread of 206Pb/238U ages ranging from 622 to 518 Ma. These ages are split into two groups of 622–578 Ma (n = 8; Th/U = 0.02–0.39) and 560–518 Ma (n = 20; Th/U = 0.05–1.75). The weighted mean 206Pb/238U age of the older grains yields a weighted mean age of 594 ± 11 Ma (MSWD = 2.2; probability = 0.028).
The younger grains give a concordia age of 549.2 ± 4.3 Ma (MSWD = 0.051; probability = 0.82) (Fig. 3f).

32002G. Zircons in Spr-Grt-Opx granulite from Ampitiya-2 yield concordant ages ranging from 628 to 527 Ma, and the ages can be divided into two groups: 628-590 Ma (n = 6; Th/U = 0.15-0.17) and 570-527 Ma (n = 7; Th/U = 0.11-0.16, excluding one analysis of Th/U = 1.63) (Fig. 3g). These groups give concordia ages of 604 ± 11 Ma (MSWD = 1.3; probability = 0.25) and 552 ± 10 Ma (MSWD = 1.08; probability = 0.30), respectively.

Results from mafic granulites

32001A. Zircon grains in Grt-Opx-Cpx granulite from Ampitiya-1 show concordant ages ranging from 587 to 534 Ma (Th/U = 0.06-0.20), which gives a concordia age of 558.8 ± 3.1 Ma (MSWD = 1.4; probability = 0.23; n = 35) (Fig. 5a).

32001D. Hbl-bearing Grt-Opx-Cpx granulite in Ampitiya-1 contains zircon grains showing 206Pb/238U ages from 636 to 514 Ma. These concordant data have been split into age groups at 636-591 Ma (n = 8; Th/U = 0.01-0.06) and ~575-514 Ma (n = 18; Th/U = 0.01-0.26), such that the older group defines a concordia age of 605.9 ± 8.6 Ma (MSWD = 1.9; probability = 0.17) and the younger group gives a weighted mean 206Pb/238U age of 538.2 ± 5.7 Ma (MSWD = 2.2; probability = 0.002) (Fig. 5b).

32001F. This Grt-Opx-Cpx-Hbl granulite from Ampitiya-1 mostly has zircon grains with dark-CL cores (Fig. 4c) that yield discordant 206Pb/238U ages of 1633-700 Ma (n = 8; Th/U = 0.36-0.92) and sector-zoned portions with concordant ages of 639-539 Ma (n = 20; Th/U = 0.04-0.23) (Figs. 4c and 5c). The concordant ages have been split into two age clusters of >600 Ma (n = 5) and <590 Ma (n = 15). A concordia age of 566.9 ± 5.1 Ma (MSWD = 0.29; probability = 0.59) is calculated from the younger cluster (Fig. 5c). The discordant data fall along two different discordias (upper intercepts of 2205 ± 21 Ma and 2333 ± 31 Ma; Fig. 5c) anchored at the concordia age of 567 Ma.
570–560 Ma \((n = 4; \text{Th/U} = 0.04–0.28)\) and 549–523 Ma \((n = 13; \text{Th/U} = 0.08–0.40; \text{concordia age of 533.4 ± 4.0 Ma, MSWD = 0.43, and probability = 0.51) (Fig. 5d).\)

**32005A.** Grt–Opx–Cpx granulate from near Hanguranketa shows \(^{206}\text{Pb}/^{238}\text{U}\) zircon ages ranging from 623 to 516 Ma. These concordant data can be divided into three groups: ~620–610 Ma \((n = 2; \text{Th/U} = 0.07–0.24)\), 596–562 Ma \((n = 13; \text{Th/U} = 0.04–0.74)\), and 556–516 Ma \((n = 23; \text{Th/U} = 0.04–0.55)\). Concordia ages of 578.1 ± 4.8 Ma (MSWD = 0.55; probability = 0.46) and 537.0 ± 4.1 Ma (MSWD = 0.68; probability = 0.41) are calculated from the middle and younger groups, respectively (Fig. 5e).

**31807H.** Zircons in Grt–Opx granulate in Haputale show age variation ranging from 636 to 517 Ma. These concordant data are split into age groups of 636–597 Ma \((n = 5; \text{Th/U} = 0.01–0.80)\) and 578–517 Ma \((n = 24)\).
17; Th/U = 0.01–1.04). The older and younger groups yield concordia ages of 614.9 ± 8.6 Ma (MSWD = 0.05; probability = 0.82) and 550.6 ± 5.7 Ma (MSWD = 0.03; probability = 0.87), respectively (Fig. 5f).

Results from aluminous granulites

32003A. Grt-Sil-Qz gneiss from near Talatuoya contains zircon grains showing 206Pb/238U ages of 621–531 Ma. These concordant data have been split into two groups at 621–594 Ma (n = 5; Th/U = 0.20–0.29) and 580–510 Ma (n = 17; Th/U = 0.20–0.36), which yield concordia ages of 613 ± 10 Ma (MSWD = 0.17; probability = 0.68) and 561.9 ± 4.5 Ma (MSWD = 0.36; probability = 0.55), respectively (Fig. 7a).

32003B. Zircons in Grt-Sil-Qz granulite from the locality near Talatuoya give concordant ages ranging from 617 to 519 Ma (Th/U = 0.15–1.23), which have been divided into the following three clusters: (1) an older group with a weighted mean 206Pb/238U age of 590.1 ± 4.8 Ma (n = 10; MSWD = 0.82; probability = 0.60), (2) a middle group with a concordia age of 566.3 ± 4.4 Ma (n = 10; MSWD = 2.0; probability = 0.16), and (3) a younger group with a weighted mean age of 530.9 ± 7.0 Ma (n = 9; MSWD = 1.7; probability = 0.10) (Fig. 7b).

31807E. Zircon grains in aluminous Grt-Crn-Spl granulite from near Haputale commonly show bright-CL cores with dark-CL from mantle to rim (Fig. 6c) and yield ages ranging from 809 to 529 Ma. The ages older than 655 Ma (n = 9; Th/U = 0.02–0.42) were obtained from the bright-CL cores and are likely to be inherited. Other ages obtained from both bright-CL cores and dark-CL mantle to rim areas have been split into two groups: 643–599 Ma (n = 11; Th/U = 0.03–0.57) and 587–529 Ma (n = 17; Th/U = 0.03–1.22). The older ages give a concordia age of 611.5 ± 7.9 Ma (MSWD = 1.4; probability = 0.23), and the younger ages yield a concordia age of 565.9 ± 5.7 Ma (MSWD = 1.4; probability = 0.24) (Fig. 7e).

31807F. Ages from zircons in Grt-Crn-Spl granulite from Haputale vary between 649 and 556 Ma and have been divided into two groups: 649–609 Ma (n = 8; Th/U = 0.29–0.85; concordia age of 622.5 ± 7.8 Ma with MSWD = 0.22) and 593–556 Ma (n = 22; Th/U = 0.17–0.92; weighted mean 206Pb/238U age of 577.5 ± 5.2 Ma with MSWD = 1.8; probability = 0.016) (Fig. 7d).

32006C. Grt-Sil-Bt granulite from near Hanguranketa contains zircons showing 577–529 Ma (n = 24; Th/U = 0.09–0.49) that give a weighted mean 206Pb/238U age of 546.1 ± 6.3 Ma (MSWD = 3.2; probability = 0.0) (Fig. 7e).

Results from calc-silicate granulites

32001B. The ages obtained from Ol–Cpx–Sph calc-silicate granulite in Ampitiya-1 range from 574 to 495 Ma (n = 6; Th/U = 0.07–0.43), yielding a concordia age of 524 ± 17 Ma (MSWD = 0.002; probability = 0.96) (Fig. 7f).

32001C. Opx-bearing Ol–Cpx calc-silicate granulite in Ampitiya-1 contains zircon showing ages of 606–520 Ma. These concordant data have been split into two groups: 606–578 Ma (n = 6; Th/U = 0.18–0.37) and 569–520 Ma (n = 24; Th/U = 0.14–0.44). Concordia ages of 590.8 ± 6.8 Ma (MSWD = 1.19; probability = 0.28) and 541.2 ± 3.9 Ma (MSWD = 0.095; probability = 0.76) are calculated from these groups (Fig. 7g).

Results from non-UHT granulites

Non-UHT granulite-facies metamorphic rocks of Spl-bearing Grt–Sil–Crd gneiss (122704G) and Qz-rich Grt–Sil gneiss (40102A) have metamorphic ages similar to the UHT metamorphic rocks described above (~ 603 and 527 Ma for 122704G in Fig. 3h and 630–580 Ma for 40102A in Fig. 7h). On the other hand, these non-UHT granulite-facies metamorphic rocks characteristically have various inherited ages (2040–1600 Ma for 122704G and 3060–1870 Ma for 40102A).

DISCUSSION

Timing of metamorphism in Highland Complex, Sri Lanka

The central part of the Highland Complex in Sri Lanka consists of high-grade rocks metamorphosed at UHT conditions (T> 900 °C). The P–T-evolution of these UHT granulites has been well demonstrated using phase-diagrams, experimentally, and theoretically well-constrained petrogenetic grids for Mg–Al granulite, mafic granulite, and aluminous granulite (Sajeev and Osanai, 2004a; Osanai et al., 2006; Sajeev et al., 2007, 2010 and references therein). Our geochronological results regarding the Spr bearing gneiss indicate that the pre-existing crystallization of Mg–Al granulites in Sri Lanka occurred between 660 and 510 Ma. The absence of detrital zircon cores could be because the protolith for the Mg–Al granulite contained very little or no detrital zircon. Alternatively, the progress of dissolution and re precipitation could also cause the ab-
sence of precursor zircons in these samples. This view can be supported by the silica-poor Mg–Al rich pelitic bulk chemical composition. It must also be noted that the mafic sample (32001F) and Grt–Crn–Spl granulite sample (31807E) with more silica rich compositions have detrital grains. Furthermore, the minor detrital cores present in the Mg–Al granulites might be also affected by the strong effect of zircon dissolution into melt during the prograde stage of very high-temperature (UHT) metamorphism.

The Spl-bearing Grt–Sil–Crd sample (122704G), collected from Udugama, the southwestern part of the Highland Complex that is far from the UHT area, contains zircons of similar metamorphic ages (~602, 563, and 526 Ma concordant clusters; Fig. 3h). However, inherited zircons ranging from 2040 to 1600 Ma are also present in this sample. The aluminous granulites [Grt–Sil–Qz (32003A, 32003B), Grt–Crd–Spl (31807E, 31807F), and Grt–Sil–Bt (32006C)] also experienced bimodal metamorphic events with similar ages to those of UHT granulites, ranging from 565–520 and 622–590 Ma. Some of these silica-rich samples contain inherited zircons ranging in age from 3060 Ma (40102A; Fig. 7h) to 760 Ma (UHT granulite 31807 E; Fig. 7c). It is also important to note the prominent concordant inherited zircon peak at ~1870 Ma (Fig. 7h). No inherited ages showing concordant ages were identified from the mafic granulites, however there are few discordant ages present in sample 32001. In this Grt–Opx–Cpx–Hbl granulite, the upper intercept ages are ~2333 and 2205 Ma. The metamorphic zircons in mafic rocks can be grouped again into age ranges of 566–533 and 620–578 Ma. Sajeev et al. (2007) reported ~570 Ma U–Pb zircon and ~532 Ma Sm–Nd mineral (Grt–Cpx–Whole–rock) isochron ages from one mafic granulite locality situated ~50 km southeast of Kandy City (Fig. 1a). Zircons in the calc-silicate granulite samples show the ages of 691, 541, and 524 Ma.

Overall, our conclusion is that all types of UHT granulites were formed by multiple thermal episodes during the Ediacaran to Cambrian period approximately at 620–580 and 563–525 Ma. Even though ages from two granulite samples (32002D and 32003B) yield intermediate age populations, they have older zircons around 610 Ma (Figs. 3e and 7b).

**Geochronological constraints from other Gondwana fragments**

It is also important to compare the present results with available datasets from formerly adjacent continental fragments of Gondwana to gain a better understanding of how these fragments might correlate and to test models of Gondwana formation.

**Lützow–Holm Complex.** Several recent geochronological studies of the high-grade metamorphic rocks of the Lützow–Holm Complex suggest that the timing of metamorphism was at ~520–560 Ma (Shiraishi et al., 1994; Hokada and Motoyoshi, 2006; Shiraishi et al., 2008). Fraser et al. (2000) reported 517 Ma as the melt crystallization age. Recently, Dunkley et al. (2014) suggested that the Ongul Group (1.1–0.63 Ga) and the Skallen Group (2.8–2.1 Ga) of the Lützow–Holm Complex should be sub-divided based on magmatic and detrital ages. Dunkley et al. (2014) also identified multiple zircon growth peaks at ~590, ~540, and ~520 Ma. Similar conclusions were also obtained in recent studies (Tsunogae et al., 2015; Kawakami et al., 2016): ~595–590 Ma zircon growth. Kawakami et al. (2016) also revealed multiple thermal histories at 595 and 525 Ma based on in-situ dating of monazite and zircon.

**Madagascar.** Goncalves et al. (2004) reported monazite U–Th–Pb ages from the Spr–Qz granulites of North–central Madagascar. Although the authors interpreted Archean ages from monazite cores as dating the peak metamorphic event, recent studies clearly show that monazite can also preserve detrital cores (e.g., Shazia et al. 2015). Thus, the major age peaks of 788–732 Ma and ~777 Ma can be reinterpreted as the detrital core and peak UHT metamorphism. The 788–732 Ma age group is reported as widespread granite magmatism in Madagascar (850–700 Ma Imorona–Itisindro Suite; Tucker et al. 2014), and the reinterpretation of the monazite core as detrital could be valid. Jöns and Schenk (2011) reported convincing evidence for clockwise metamorphic evolution of UHT samples with binomial metamorphic age groups of 650–600 and 560–530 Ma U–Pb ages from both zircon and monazite of southern Madagascar.

**Madurai Block.** Recent geochronological results from the Madurai Block, mainly using U–Th–Pb monazite, zircon, and Sm–Nd garnet methods, show metamorphic ages ranging between ~600 and 450 Ma (e.g., Bartlett et al., 1995; Jayananda et al., 1995; Santosh et al., 2003). Santosh et al. (2003) reported zircon cores from various ortho- and para-gneisses in the Madurai block with U–Th–Pb ages of 1700 Ma mantled by successive rims at 820 and 580 Ma. Shazia et al. (2015) identified similarly aged monazite cores, ~1700 Ma, from the Kodai kanal region. Santosh et al. (2006) reported peak metamorphic monazite EPMA ages in the range of ~550–520 Ma from the Spr-bearing granulites of Ganguvarpatti and the southern Palghat-Cauvery shear zone, which were interpreted as the timing of peak UHT metamorphism. Santosh et al. (2006) also reported the zircon inherited core age to be Paleoproterozoic to mid–Neooproterozoic (~2279 to 749 Ma). Prakash (2010) reported ~550 and
protoliths of Proterozoic age (1007 Ma) and (2) the southern Madurai Block with granitic protoliths of Neoarchaean age (2700–2500 Ma). Shazia et al. (2015) interpreted CHIME monazite ages of 540–520 Ma from metapelites of Kodaikanal as giving the time of peak metamorphism. George et al. (2015) used U–Pb zircon data to date peak UHT metamorphism of Spr–Qtz-bearing granulites from Rajapalayam at ~ 561 Ma, with detrital zircon ages ranging from 2300–800 Ma. Plavsa et al. (2012) used U–Pb zircon ages from Opx-bearing orthogneisses and charnockites to divide the Madurai Block into (1) the northern Madurai Block with granitic protoliths of Neoarchaean age (2700–2500 Ma) and (2) the southern Madurai Block with granitic protoliths of Proterozoic age (1007–784 Ma), and found that rocks in both regions were regionally overprinted by ~ 535 Ma metamorphism. Plavsa et al. (2014) found further support for this division from detrital zircons in metasedimentary rocks, which have Archean to Paleoproterozoic provenance (3200–1700 Ma) in the northern Madurai Block but Mesoproterozoic to Neoproterozoic provenance (1100–650 Ma) in the southern Madurai Block. Brandt et al. (2014) proposed an alternative subdivision of the Madurai Block into Western and Eastern Madurai Domains. The Western Madurai Domain consists of 2530–2460 Ma subduction-generated charnockites, re-worked during granulite facies metamorphism and partial melting at 2470–2430 Ma. In contrast, the eastern Madurai Domain comprises mainly meta-sediments deposited at 1740–1620 Ma. The major boundary between these domains is considered to be the Karur-Kambam-Painavu-Trichur (KKPT) shear zone (Ghosh et al., 2004), and the Kambum–Ganguvarpatti–Kodaikanal–Rajapalayam UHT metamorphic region in the central Madurai Block occurs along this major tectonic boundary (e.g., Sajeev et al., 2004, 2006; Sajeev and Santosh, 2006). Both domains were intruded by granitic and alkaline rocks at ~ 800 Ma, which is interpreted as a phase of extensional rifting (Brandt et al., 2014 and references therein).

Trivandrum Block. Recent detailed studies of the Trivandrum Block (Kerala Khondalite Belt) and Achan Kovil Zone show a wide range of metamorphic zircon growth during the Neoproterozoic. Shabeer et al. (2005) reported that the peak metamorphism of the Trivandrum Block was between 530 and 525 Ma. Cenki et al. (2004) argued that peak metamorphism was between 590 and 550 Ma, while the recent results from Harley and Nandakumar (2014) show that peak metamorphism was sometime before 545 Ma through detailed texturally controlled zircon age results. Taylor et al. (2014) proposed that peak metamorphism was shortly after ~ 585 Ma based on monazite growth and demonstrated later zircon growth at ~ 523 Ma. The Achan Kovil Zone situated north of the Trivandrum Block experienced a relatively younger peak metamorphism (~ 545–512 Ma) and sediment source age ranging from 1100–650 Ma (Taylor et al., 2015). The southern tip of the Trivandrum Block, also known as the Nagercoil Block, shows a relatively older peak–metamorphic age at of ~ 560 Ma (Johnson et al., 2015), with a prograde age of ~ 570 Ma and retrogression at ~ 535 Ma. From these results, it is clear that in the Trivandrum Block there are also several stages of zircon growth and dissolution during high-temperature metamorphic evolution.

Kröner et al. (2015) reported that granitic rocks of the Trivandrum and Nagercoil Blocks were emplaced between 2100–1750 Ma and were intercalated with metasedimentary rocks that must have been older than 2100 Ma. However, Collins et al. (2007) and Taylor et al. (2014) reported 1800–1700 Ma detrital zircon ages from metasedimentary rocks of the Trivandrum Block, indicating that the sedimentary protoliths must be ~ 1800 Ma or younger. Therefore, more studies are required to understand the detailed provenance history of metasediments in the Trivandrum Block.

**Tectonic implications**

Sri Lanka, East Antarctica, the eastern and southern margins of Madagascar, and southern India were adjacent continental fragments of the Gondwana assembly (e.g., Reeves et al., 2002; Veevers, 2009). The general fit of these continents is well accepted, but precise correlations among these continental fragments are still debated. The Madagascar–India correlation has been widely discussed in several recent publications (e.g., Tucker et al., 2011a, 2011b; Ishwar-Kumar et al., 2013; Rekha et al., 2013, 2014; Tucker et al., 2014; Ishwar-Kumar et al., 2015). This discussion has been driven by the increased use of sophisticated analytical techniques leading to an improved understanding of the chronology and evolution of various rock-types. In the same way, there have been several geochronology-petrology focused studies of Sri Lanka published recently (e.g., Santosh et al., 2014; Dharmapiya et al., 2015a). However, even with a better understanding of the metamorphic ages, the paleo-position of Sri Lanka in Gondwana assembly with respect to southern India and eastern Antarctica is highly debated.

Boger et al. (2015) has recently proposed that a Neoproterozoic Gondwana suture extends from East Africa into Madagascar, Sri Lanka, and East Antarctica. This study suggested that the location of this suture in Sri Lanka is the tectonic boundary between the Highland Complex and Vijayan Complex (Fig. 8). According to Boger et al. (2015), the Highland Complex of Sri Lanka...
is part of the Indian Crust, along with the Trivandrum Block of southern India, the Lützow–Holm Complex in East Antarctica, and much of central Madagascar, while the Vijayan Complex, along with the Ser Rondane Mountains of Antarctica and southwest Madagascar, are an extension of the Arabian–Nubian Shield and represent an ocean arc domain between Indian and African Crusts. However, this model does not agree with the some of the geochronological or geological evidence (e.g., Shiraishi et al., 1997; 2008; Dunkley et al., 2014), such as the type and timing of metamorphism (Neoproterozoic UHT metamorphism) and province/protolith ages (~ 2.5 Ga). The Highland Complex of Sri Lanka can be petrologically and geochronologically correlated to the high-grade side of the Rundvågshetta and Skallevikshalsen regions of the Lützow–Holm Complex (Skallen Group) in East Antarctica (e.g., Shiraishi et al., 1994, 1997, 2008). Hence, based on the present results and a compilation of available geochronological and petrological datasets, the boundary between the Highland and Wanni Complexes must be an extension of the northern part of the Madurai Block and the boundary between the Skallen and Ongul Groups in East Antarctica (Fig. 8). It is also important to correlate all reliable petrological, geochronological, and structural datasets across the continental fragments. Mg–Al Spr + Qz bearing assemblages within garnet porphyroblasts are identified from the Highland Complex of Sri Lanka (Sajeev and Osanai, 2004a; Osanai et al., 2006), the Skallen Group in the Lützow–Holm Complex of East Antarctica (Yoshimura et al., 2008), the Madurai Block of southern India (Tateishi et al., 2004; Brandt et al., 2011), and Andriamena in northwestern Madagascar (Gonzalves et al., 2004) and Imamombo in southern Madagascar (Jöns and Schenk, 2011). Another rare assemblage, Spl + Qz, is also reported in most of these terranes (e.g., Kawakami and Motoyoshi, 2004; Morimoto et al., 2004; Sajeev and Osanai 2004b; Tadokoro et al., 2007; Kawasaki et al., 2011; Jöns and Schenk, 2011). Although the Spr + Qz assemblage is not identified from the Trivandrum Block of southern India, the Spl + Qz assemblage has been reported in this block (Morimoto et al., 2004; Tadokoro et al., 2007). All the above UHT terranes experienced multiple episodes of zircon growth and dissolution as part of metamorphism during the Neoproterozoic, and the $P-T$ paths of these terranes are similar to each other, with the exception of that obtained from the Ongul Group in the Lützow–Holm Complex (see Fig. 16 in Osanai et al., 2016 in this issue).

In summary, multiple metamorphic zircon growth and mineral assemblages along with their protolith ages convincingly show the Highland Complex correlates well with the Madurai and Trivandrum Blocks of southern India, extending to high-grade portions of the Lützow–Holm complex (Skallen Group) with metamorphic conditions up to UHT (e.g., Tadokoro et al., 2007; Yoshimura et al., 2008; Brandt et al., 2011; Kawasaki et al., 2011). Based on a compilation of newly available results including those presented here, we propose that the several terranes in southern Madagascar (south of Ranotsara Shear Zone), the Madurai and Trivandrum Blocks of southern India, the Highland Complex of Sri Lanka, and the Skallen group of East Antarctica indicate a unique terrane that metamorphosed by the Ediacaran–Cambrian regional UHT event during the amalgamation of the Gondwana supercontinent.

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SUPPLEMENTARY MATERIAL

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REFERENCES

Adachi, T., Osanai, Y., Nakano, N. and Owada, M. (2012) LA-ICP-MS U-Pb zircon and EPMA U-Th-Pb monazite datings on pelitic granulites from the Mt. Ukidake area, Sefuri Mountains, northern Kyushu. Journal of Geological Society of Japan, 118, 39-52.

Bartlett, J.M., Harris, N.B.W., Hawkesworth, C.J. and Santosh, M. (1995) New isotope constraints on the crustal evolution of south India and Pan-African metamorphism. In India and Antarctica during Precambrian (Yoshida, M. and Santosh, M. Eds.). pp. 412, Memoir, Geology Society of India, 34, 391-397.

Boger, S.D., Hirdes, W., Ferreira, C.A.M., Schulte, B., Jenett, T. and Fanning, C.M. (2015) From passive margin to volcanosedimentary forearc: The Tonian to Cryogenian evolution of the Anosyen Domain of southeastern Madagascar. Precambrian Research, 247, 159-186.

Brandt, S., Schenk, V., Raith, M.M., Appel, P., Gerdes, A. and Srikantappa, C. (2011) Late Neoproterozoic P-T evolution of HP-UHT granulites from the Palni Hills (South India): New constraints from phase diagram modelling. LA-ICP-MS zircon dating and in-situ EMP monazite dating. Journal of Petrology, 52, 1813-1856.

Brandt, S., Raith, M.M., Schenk, V., Sengupta, P., Srikantappa, C. and Gerdes, A. (2014) Crustal evolution of the Southern Granulite Terrane, South India: new geochronological and geochemical data for felsic orthogneisses and granites. Precambrian Research, 246, 91-122.

Cenki, B., Braun, I. and Bröcker, M. (2004) Evolution of the continental crust in the Kerala Khondalite Belt, southernmost India: evidence from Nd isotope mapping, U-Pb and Rb-Sr geochronology. Precambrian Research, 134, 275-292.

Collins, A.S., Clark, C., Sajeev, K., Santosh, M., Kelsey, D.E. and Hand, M. (2007) Passage through India: The Mozambique Ocean suture, high pressure granulites and the Palghat-Cauvery Shear Zone System. Terra Nova, 19, 141–147.

Dharmapriya, P.L., Malaviarachchi, S.P.K., Santosh, M., Li, T. and Sajeev, K. (2015a) Late-Neoproterozoic ultrahigh-temperature metamorphism in the Highland Complex, Sri Lanka. Precambrian Research, 271, 311-333.

Dharmapriya, P.L., Malaviarachchi, S.P.K., Galli, A., Su, B. Subasinghe, N.D. and Dissanayake (2015b) Rare evidence for formation of garnet + corundum during isobaric cooling of ultrahigh-temperature metapelites: New insights for retrograde P-T trajectory of the Highland Complex, Sri Lanka. Lithos, 200-201, 94-110.

Dunkley, D.J., Shiraiishi, K., Motoyoshi, Y., Tsunogae, T., Miyamoto, T., Hiroi, Y. and Carson, C.J. (2014) Deconstructing the Litözow-Holm Complex with zircon geochronology. Abstract of 7th international SHRIMP workshop program, 116-121.

Fraser, G., McDougall, I., Ellis, D.J. and Williams, I.S. (2000) Timing and rate of isothermal decompression in Pan-African granulites from Rundvågshetta, East Antarctica. Journal of Metamorphic Geology, 18, 441-454.

George, P.M., Santosh, M., Chen, N., Nandakumar, V., Itaya, T., Sonali, M.K., Smruti, R.P. and Sajeev, K. (2015) Cryogenian magmatism and crustal reworking in the Southern Granulite Terrane, India. International Geology Review, 57, 112-133.

Ghosh, J.G., de Wit, M.J. and Zartman, R.E. (2004) Age and tectonic evolution of Neoproterozoic ductile shear zones in the Southern Granulite terrane of India, with implications for Gondwana studies. Tectonics, 23, TC3006 (doi:10.1029/2002TC001444).

Goncalves, P., Nicollet, C. and Montel, J.M. (2004) Petrology and in-situ U-Th-Pb Monazite geochronology of ultrahigh-temperature metamorphism from Andriamena mafic unit, north-central Madagascar. Significant of a petrographical P-T path in a polymetamorphic context. Journal of Petrology, 45, 1923-1957.

Harley, S.L. and Nandakumar, V. (2014) Accessory mineral behavior in granulate migmatites: a case study from the Kerala Khondalite Belt, India. Journal of Petrology, 55, 1965-2002.

Hokada, T. and Motoyoshi, Y. (2006) Electron microprobe technique for U-Th-Pb and REE chemistry of monazite, and its implications for Pre-, Peak- and Post-metamorphic events of the Lützow-Holm Complex and Napier Complex, East Antarctica. Polar Geoscience, 19, 118–151.

Ishwar-Kumar, C., Windley, B.F., Horie, K., Kato, T., Hokada, T., Itaya, T., Yagi, K., Jouzu, C. and Sajeev, K. (2013) A Rodinian suture in western India: New insights on India-Madagascar correlations. Precambrian Research, 236, 227-251.

Ishwar-Kumar, C., Sajeev, K., Windley, B.F., Kasyk, T.M., Feng, P., Rathee-Kumar, R.T., Huang, Y., Zhang, Y., Jiang, X., Razakamanana, T., Yagi, K. and Itaya, T. (2015) Evolution of high-pressure mafic granulites and pelitic gneisses from NE Madagascar: Tectonic implications. Tectonophysics, 662, 219-242.

Jayananda, M., Janardhan, A.S., Shivashubramanian, P. and Peucat, J.J. (1995) Geochronologic and isotopic constraints on granulite formation in the Kodaikanal area, southern India. In India and Antarctica during Precambrian (Yoshida, M. and Santosh, M. Eds.). pp. 412, Memoir, Geological Society of India, 34, 373-390.

Johnson, T.E., Clark, C., Taylor, R.J.M., Santosh, M. and Collins, A.S. (2015) Prograde and retrograde growth of monazite in migmatites: An example from the Nagercoil Block, southern India. Geoscience Frontiers, 6, 373-387.

Jöns, N. and Schenk, V. (2011) The ultrahigh temperature granulites of southern Madagascar in a polymetamorphic context: implications for the amalgamation of the Gondwana supercontinent. European Journal of Mineralogy, 23, 127-156.

Kawakami, T. and Motoyoshi, Y. (2004) Timing of attainment of the spinel + quartz coexistence in garnet-sillimanite leucogneiss from Skallevikshalsen, Lützow-Holm complex, East Antarctica. Journal of Mineralogical and Petrological Sciences, 99, 311-319.

Kawakami, T., Hokada, T., Sakata, S. and Hirata, T. (2016) Possible polynucleogenesis and brine infiltration recorded in the
garnet-sillimanite gneiss, Skallevikshalsen, Lützow-Holm Complex, East Antarctica. Journal of Mineralogical and Petrological Sciences, 111, 129-143.

Kawasaki, T., Nakano, N. and Osanai, Y. (2011) Osumilite and a spinel+quartz association in garnet-sillimanite gneiss from Rundvåghetta, Lützow-Holm Complex, East Antarctica. Gondwana Research, 19, 430-445.

Kitano, I., Osanai, Y., Nakano, N., Adachi, T. and Yoshimoto, A. (2014) Rapid techniques for zircon separation and the application for U-Pb dating. Bulletin of the Graduate School of Social and Cultural Studies, Kyushu University, 20, 1-10.

Kitano, I., Osanai, Y., Nakano, N. and Adachi, T. (2016) Detrital zircon provenances for metamorphic rocks from southern Sør Rondane Mountains, East Antarctica: A new report of Archean to Mesoproterozoic zircons. Journal of Mineralogical and Petrological Sciences, 111, 118-128.

Kriegerman, L.M. and Schumacher, J.C. (1999) Petrology of sapphire-bearing and associated granulites from central Sri Lanka. Journal of Petrology, 40, 1211-1239.

Kröner, A., Santosh, M., Hegner, E., Shaji, E., Geng, H., Wong, J., Xie, H., Wan, Y., Shang, C.K., Liu, D., Sun, M. and Nanda-Kumar, V. (2015) Palaeoecroterozoan ancestry of Pan-African high-grade garnetoids in southernmost India: Implications for Gondwana reconstructions. Gondwana Research, 27, 1-37.

Morimoto, T., Santosh, M., Tsunogae, T. and Yoshimura, Y. (2004) Spinel + quartz association from the Kerala khondalites, southern India: evidence for ultrahigh-temperature metamorphism. Journal of Mineralogical and Petrological Sciences, 99, 257-278.

Osanai, Y. (1989) A preliminary report on sapphirine/kornerupine garnet-sillimanite gneiss from Highland Series, Sri Lanka. Extended abstract with program of Seminar on recent advantages in Precambrian Geology of Sri Lanka, IFS Kandy.

Osanai, Y., Ando, K.T., Miyasita, Y., Kusachi, I., Yamasaki, T., Doyama, D., Prame, W.K.B.N., Jayatilake, S. and Mathavan, V. (2000) Geological field work in the southwestern and central parts of the Highland Complex, Sri Lanka during 1998-1999, special reference to the highest grade metamorphic rocks. Journal of Geoscience, Osaka City University, 43, 227-247.

Osanai, Y., Sajeev, K., Owada, M., Kehelpannala, K.V.W., Prame, W.K.B., Nakano, N. and Jayatilake, S. (2006) Metamorphic evolution of ultrahigh-temperature and high-pressure granulites from Highland Complex, Sri Lanka. Journal of Asian Earth Sciences, 28, 20-37.

Osanai, Y., Sajeev, K., Nakano, N., Kitano, I., Kehelpannala, W.K.K., Kato, R., Adachi, T. and Malaviarachchi, S.P.K. (2016) UHT granulites of Highland Complex, Sri Lanka: I. Petrological overview. Journal of Mineralogical and Petrological Sciences, 111, 145-156.

Paces, J.B. and Miller, J.D.J. (1993) U-Pb ages of Duluth Complex and related mafic intrusions, northeastern Minnesota: geo-chronological insights to physical, petrogenetic, paleomagnetic, and tectonomagmatic processes associated with the 1.1 Ga midcontinent rift system. Journal of Geophysical Research, 98, 13997-14013.

Plavsa, D., Collins, A.S., Fodena, J.F., Kropinska, L., Santosh, M., Chetty, T.R.K. and Clark, C. (2012) Delineating crustal domains in Peninsula India: Age and chemistry of orthopyroxene-bearing felsic gneisses in the Madurai Block. Precambrian Research, 198-199, 77-93.

Plavsa, D., Collins, A.S., Payne, J.L., Fodena, J.F., Clark, C. and Santosh, M. (2014) Detrital zircons in basement metasedimentary protoliths unveil the origins of southern India. Geological Society of America, Bulletin, 126, 791-811.

Prakash, D. (2010) New SHRIMP U-Pb Zircon Ages of the Metapelitic Granulites from NW of Madurai, Southern India. Journal of Geological Society of India, 76, 371-383.

Reeves, C.V., Sahu, B.K. and de Wit, M.J. (2002) A re-examination of the paleo-position of Africa’s eastern neighbors in Gondwana. Journal of African Earth Sciences, 34, 101-108.

Rekha, S., Viswanath, T.A., Bhattacharya, A. and Prabhakar, N. (2013) Mesos Neoarchean crustal domains along the north Konkan coast, western India: The Western Dharwar Craton and the Antongil-Masora Block (NE Madagascar) connection. Precambrian Research, 233, 316-336.

Rekha, S., Bhattacharya, A. and Prabhakar, N. (2014) Tectonic re-storation of the Precambrian crystalline rocks along the west coast of India: correlation with eastern Madagascar in East Gondwana. Precambrian Research, 252, 191-208.

Sajeev, K. and Osanai, Y. (2004a) Ultra-high-temperature Metamorphism (1150 °C and 12 kbar) and Multi-stage Evolution of Mg-Al-Garnet from Central Highland Complex, Sri Lanka. Journal of Petrology, 45, 1821-1844.

Sajeev, K. and Osanai, Y. (2004b) ‘Osumilite’ and ‘spinel+quartz’ from Highland Complex, Sri Lanka: a case of cooling and decomposition after ultra-high-temperature metamorphism. Journal of Mineralogical and Petrological Sciences, 99, 320-327.

Sajeev, K., Osanai, Y. and Santosh, M. (2004) Ultra-high-temperature metamorphism followed by two-stage decomposition of garnet-orthopyroxene-sillimanite granulites from Ganguvarpatti, Madurai block, southern India. Contributions to Mineralogy and Petrology, 148, 1, 29-46.

Sajeev, K. and Santosh, M. (2006) An unusual high-Mg garnet-spinel orthopyroxenite from southern India: Evidence for ultra-high-temperature metamorphism at high-pressure conditions. Geological Magazine, 143, 6, 923-932.

Sajeev, K., Santosh, M. and Kim, H.S. (2006) Partial melting and P-T evolution of the Kodaiakan Metapelite Belt, southern India. Lithos, 92, 465-483.

Sajeev, K., Osanai, Y., Connolly, J.A.D., Suzuki, S., Ishioka, J., Kagami, H. and Rino, S. (2007) Extreme crustal metamorphism during a Neoproterozoic event in Sri Lanka: a study of dry mafic granulites. Journal of Geology, 115, 563-582.

Sajeev, K., Williams, I.S. and Osanai, Y. (2010) Sensitive high-resolution ion microprobe U-Pb dating of prograde and retrograde ultrahigh-temperature metamorphism as exemplified by Sri Lankan granulites. Geology, 38, 971-974.

Santosh, M., Yokoyama, K., Biju-Sekhar, S. and Rogers, J.J.W. (2003) Multiple tectonothermal events in the granulite blocks of southern India revealed from EPMA dating: Implications on the history of supercontinents. Gondwana Research, 6, 29-63.

Santosh, M., Collins, A.S., Tamashiro, I., Koshimoto, S., Tsutsuji, Y. and Yokoyama, K. (2006) The timing of ultrahigh-temperature metamorphism in southern India: U-Th-Pb electron microprobe ages from zircon and monazite in sapphire-bearing granulites. Gondwana Research, 10, 128-143.

Santosh, M., Santosh, M., Prakash, D., Zhang, Z. and Ding, H.X. (2014) MesoNeoarchean crustal domains along the north Konkan coast, western India: The Western Dharwar Craton and the Antongil-Masora Block (NE Madagascar) connection. Precambrian Research, 233, 316-336.

Santosh, M. (2014) Palaeoproterozoic ancestry of Pan-African Gondwana. Precambrian Research, 233, 316-336.
Tateishi, K., Tsunogae, T., Santosh, M. and Janardhan, A.S. (2004) First report of Sapphirine + Quartz assemblage from southern India: implications for ultrahigh-temperature metamorphism. Gondwana Research, 7, 899-912.

Taylor, R.J.M., Clark, C., Fitzsimons, I.C., Santosh, M., Hand, M., Evans, N. and McDonald, B. (2014) Post-peak, fluid-mediated modification of granulite facies zircon and monazite in the Trivandrum Block, southern India. Contributions to Mineralogy and Petrology, 168, 1–17.

Taylor, R.J.M., Clark, C., Johnson, T.E., Santosh, M. and Collins, A.S. (2015) Unravelling the complexities in high-grade rocks using multiple techniques: the Achankovil Zone of southern India. Contributions to Mineralogy and Petrology, 169, 1–19.

Tsunogae, T., Yang, Q.-Y. and Santosh, M. (2015) Early Neoproterozoic arc magmatism in the Lützow-Holm Complex, East Antarctica: Petrology, geochemistry, zircon U-Pb geochronology and Lu-Hf isotopes and tectonic implications. Precambrian Research, 266, 467–489.

Tucker, R.D., Roig, J.Y., Delor, C., Amelin, Y., Goncalves, P., Rabarimanana, M.H., Ralison, A.V. and Belcher, R.W. (2011b) A new geological framework for south-central Madagascar and its relevance to the “out-of-Africa” hypothesis. Precambrian Research, 185, 109–130.

Tucker, R.D., Roig, J.Y., Moine, B., Delor, C., Amelin, Y., Armstrong, R.A., Rabarimanana, M.H. and Ralison, A.V. (2011a) Neo-proterozoic extension in the Greater Dharwar Craton: a reevaluation of the “Betsimisaraka suture” in Madagascar. Canadian Journal of Earth Sciences, 48, 389–417.

Veevers, J.J. (2009) Palinspastic (pre-rift and –drift) fit of India and conjugate Antarctica and geological connections across the suture. Gondwana Research, 16, 90–108.

Yoshimura, Y., Motoyoshi, Y. and Miyamoto, T. (2008) Sapphirine + quartz association in garnet: implication for ultrahigh-temperature metamorphism at Rundvågshetta, Lützow-Holm Complex, East Antarctica. Geological Society of London, Special Publications, 308, 377–390.

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