Geoscience Frontiers 8 (2017) 851–867

HOSTED BY

ELSEVIER

Contents lists available at ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Research paper

Detrital zircon geochronology of quartzites from the southern Madurai Block, India: Implications for Gondwana reconstruction

CrossMark

Shan-Shan Li [a], M. Santosh [a,b,*], G. Indu [c], E. Shaji [c], T. Tsunogae [d,e]

[a] School of Earth Sciences and Resources, China University of Geosciences Beijing, 29 Xueyuan Road, Beijing 100083, China
[b] Department of Earth Sciences, University of Adelaide, Adelaide SA 5005, Australia
[c] Department of Geology, University of Kerala, Kariyavattom Campus, Trivandrum 695 581, India
[d] Graduate School of Life and Environmental Sciences, University of Tsukuba, Ibaraki 305-8572, Japan
[e] Department of Geology, University of Johannesburg, Auckland Park 2006, South Africa

A R T I C L E I N F O

Article history:
Received 8 June 2016
Received in revised form
11 July 2016
Accepted 16 July 2016
Available online 5 August 2016

Keywords:
U-Pb geochronology
Detrital zircon
Southern Madurai Block
Gondwana supercontinent

A B S T R A C T

Detrital zircons are important proxies for crustal provenance and have been widely used in tracing source characteristics and continental reconstructions. Southern Peninsular India constituted the central segment of the late Neoproterozoic supercontinent Gondwana and is composed of crustal blocks ranging in age from Mesoarchean to late Neoproterozoic–Cambrian. Here we investigate detrital zircon grains from a suite of quartzites accreted along the southern part of the Madurai Block. Our LA-ICPMS U-Pb dating reveals multiple populations of magmatic zircons, among which the oldest group ranges in age from Mesoarchean to Paleoproterozoic (ca. 2980–1670 Ma, with peaks at 2900–2800 Ma, 2700–2600 Ma, 2500–2300 Ma, 2100–2000 Ma). Zircons in two samples show magmatic zircons with dominantly Neoproterozoic (950–550 Ma) ages. The metamorphic zircons from the quartzites define ages in the range of 580–500 Ma, correlating with the timing of metamorphism reported from the adjacent Trivandrum Block as well as from other adjacent crustal fragments within the Gondwana assembly. The zircon trace element data are mostly characterized by LREE depletion and HREE enrichment, positive Ce, Sm anomalies and negative Eu, Pr, Nd anomalies. The Mesoarchean to Neoproterozoic age range and the contrasting petrogenetic features as indicated from zircon chemistry suggest that the detritus were sourced from multiple provenances involving a range of lithologies of varying ages. Since the exposed basement of the southern Madurai Block is largely composed of Neoproterozoic orthogneisses, the data presented in our study indicate derivation of the detritus from distal source regions implying an open ocean environment. Samples carrying exclusive Neoproterozoic detrital zircon population in the absence of older zircons suggest proximal sources in the southern Madurai Block. Our results suggest that a branch of the Mozambique ocean might have separated the southern Madurai Block to the north and the Nagercoil Block to the south, with the metasediments of the khondalite belt in Trivandrum Block marking the zone of ocean closure, part of which were accreted onto the southern Madurai Block during the collisional amalgamation of the Gondwana supercontinent in latest Neoproterozoic–Cambrian.

1. Introduction

Continental growth through vertical and horizontal accretion, recycling, and destruction are important processes associated with crustal evolution through time, including the assembly and disruption of supercontinents (Condie et al., 2009; Santosh et al., 2009a; Manikyamba and Kerrich, 2012; Santosh, 2013; Spencer et al., 2015). Recent studies also recognize that the early history of the Earth was characterized by the formation and amalgamation of micro-blocks through multiple subduction-accretion-collision processes (Santosh et al., 2009a, 2015). The late Neoproterozoic–Cambrian supercontinent Gondwana is one of the well-studied examples of amalgamation of continental blocks with distinct crustal evolution history, and involving subduction-accretion-collision and related magmatism and high grade metamorphism

* Corresponding author. School of Earth Sciences and Resources, China University of Geosciences Beijing, 29 Xueyuan Road, Beijing 100083, China.
E-mail address: msantosh.gr@gmail.com (M. Santosh).
Peer-review under responsibility of China University of Geosciences (Beijing).

http://dx.doi.org/10.1016/j.gsf.2016.07.002

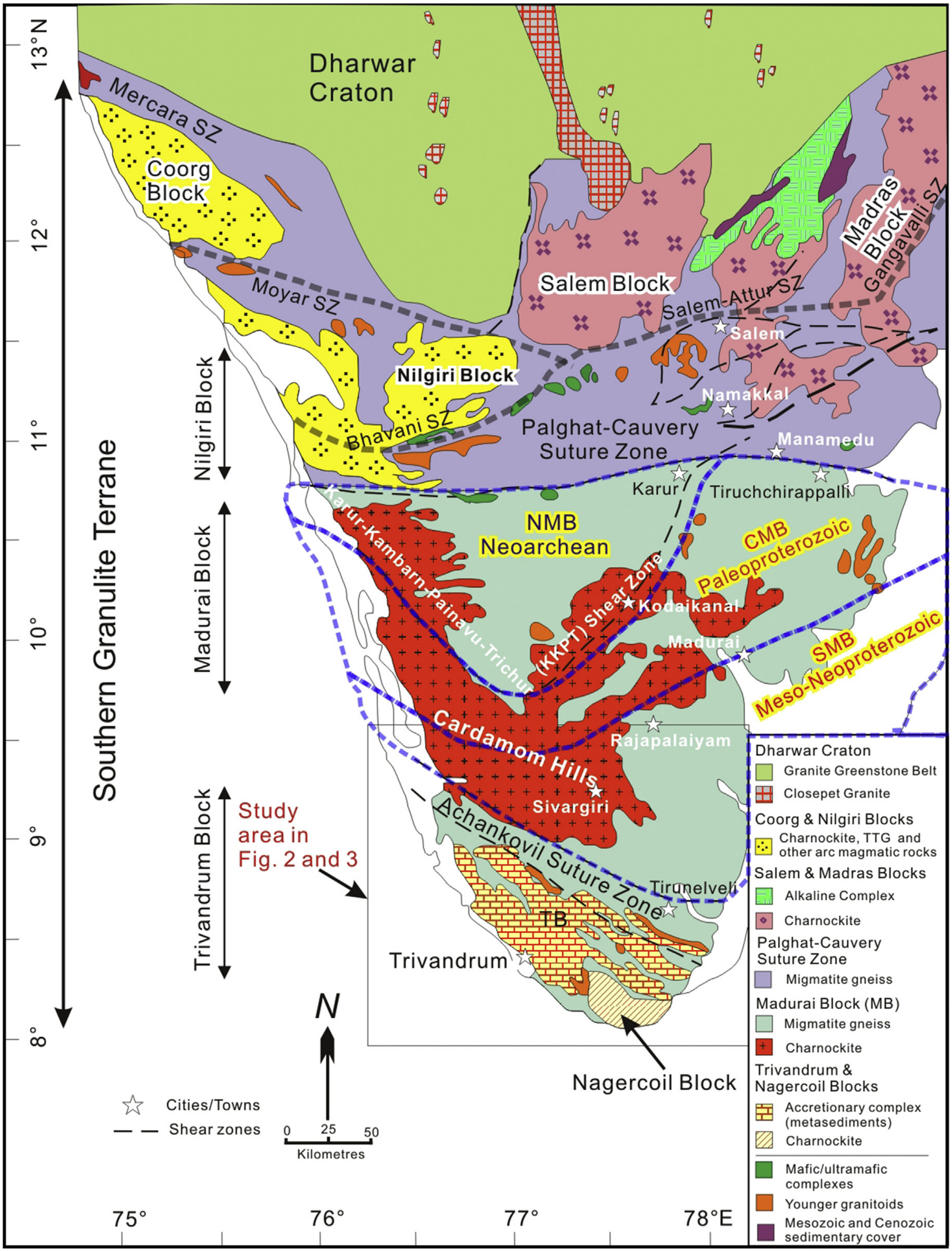

Figure 1. Generalized tectonic framework of the Southern India showing the major crustal blocks and intervening shear/suture zones (after Collins et al., 2014; Santosh et al., 2015).

(Harris et al., 1996; Kröner et al., 2003; Santosh et al., 2006, 2009b, 2012; Bingen et al., 2009; Collins et al., 2014; Clark et al., 2015; Takamura et al., 2016). The Gondwana-forming event involved the closure of a major ocean (the Mozambique ocean) and construction of multiple orogenic belts (e.g., Sommer et al., 2005; Bingen et al., 2009; Collins et al., 2014).

Located in the central part of the Gondwana supercontinent, the geological and tectonic history of Peninsular India have been central to discussions on Archean and Proterozoic crustal evolution models and paleogeography of the Gondwana supercontinent (Harris et al., 1996; Collins et al., 2007a, 2014; Santosh et al., 2009b, 2012, 2015; Saitoh et al., 2011; Sato et al., 2011b; Plavsa et al., 2014).

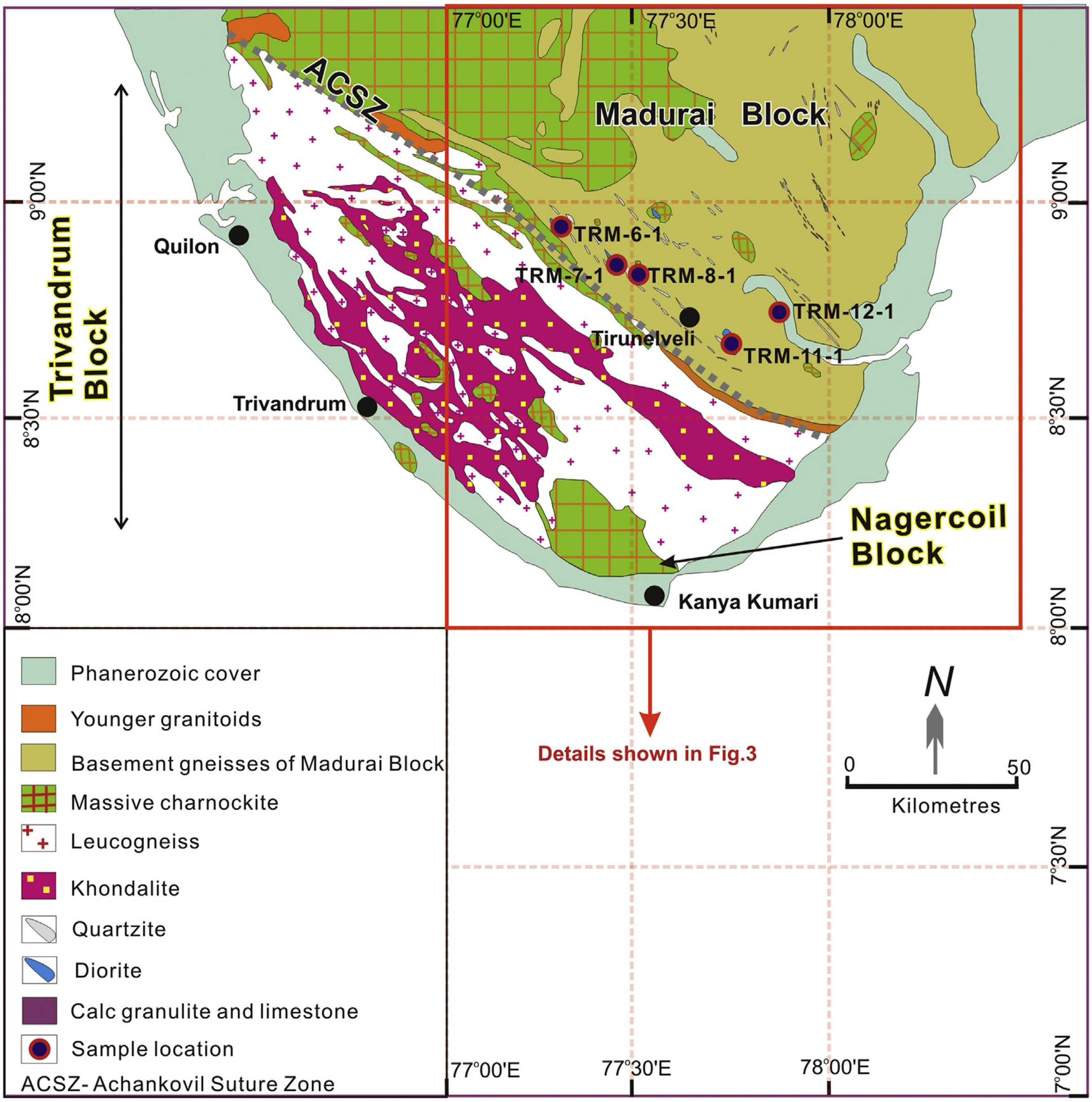

Figure 2. Geological sketch map of the southern part of the Madurai Block and adjacent Trivandrum and Nagercoil Blocks showing the sample locations.

Previous geological, petrological, geochemical, geochronological and geophysical studies have offered important information on the evolution of the crustal blocks and their amalgamation in the Southern Granulite Terrane (SGT) of Peninsular India (Sato et al., 2010; Plavsa et al., 2012; Collins et al., 2014; Koizumi et al., 2014). The Archean to Paleoproterozoic basement of the Dharwar Craton, Coorg Block, Salem Block and Nilgiri Block (Chadwick et al., 2000; Clark et al., 2009; Peucat et al., 2013; Ram Mohan et al., 2013; Samuel et al., 2014; Lancaster et al., 2015; Santosh et al., 2015, 2016), and the Paleoproterozoic to Neoproterozoic terranes in the Madurai, Trivandrum and Nagercoil Blocks have received much attention in recent studies (Santosh et al., 2006; Kooijman et al., 2011; Teale et al., 2011; Plavsa et al., 2014, 2015). The Palghat-Cauvery shear/suture zone (PCSZ) that marks the broad boundary between Archean blocks to the north with the Proterozoic blocks to the south in the SGT is considered as the trace of the Mozambique ocean suture (Chetty and Bhaskar Rao, 2006; Collins et al., 2007a; Saitoh et al., 2011; Santosh et al., 2012) (Fig. 1). Similarly, the Achankovil shear/suture zone separating the Madurai and Trivandrum blocks is also considered as a major tectonic zone (Collins et al., 2007b; Shimizu et al., 2009; Santosh et al., 2009b). The extension of the Mozambique ocean suture into Madagascar (Betsimisaraka suture) and central Tanzania have also been proposed (Möller et al., 1998; Kröner et al., 2003; Sommer et al., 2003, 2005, 2005; Collins, 2006). The tectonic correlation of India-Sri Lanka-Madagascar-Antarctic-Africa has been evaluated in several studies (Janardhan, 1999; Bingen et al., 2009; Santosh et al., 2009b; Collins et al., 2014; among others).

Detrital zircons from sedimentary rocks provide important insights into provenance protolith characteristics (Gebauer et al., 1989; Cawood et al., 2003), and isotopic data from detrital zircons have been widely applied to trace the crustal evolution history in Gondwana fragments including India, Sri Lanka, Madagascar, Africa and Antarctica (Cox et al., 1998, 2004; Rainaud et al., 2003; Plavsa et al., 2014; Tsunogae et al., 2015, 2016; Takamura et al., 2016). Takamura et al. (2016) linked the Archean magmatic units from Sri

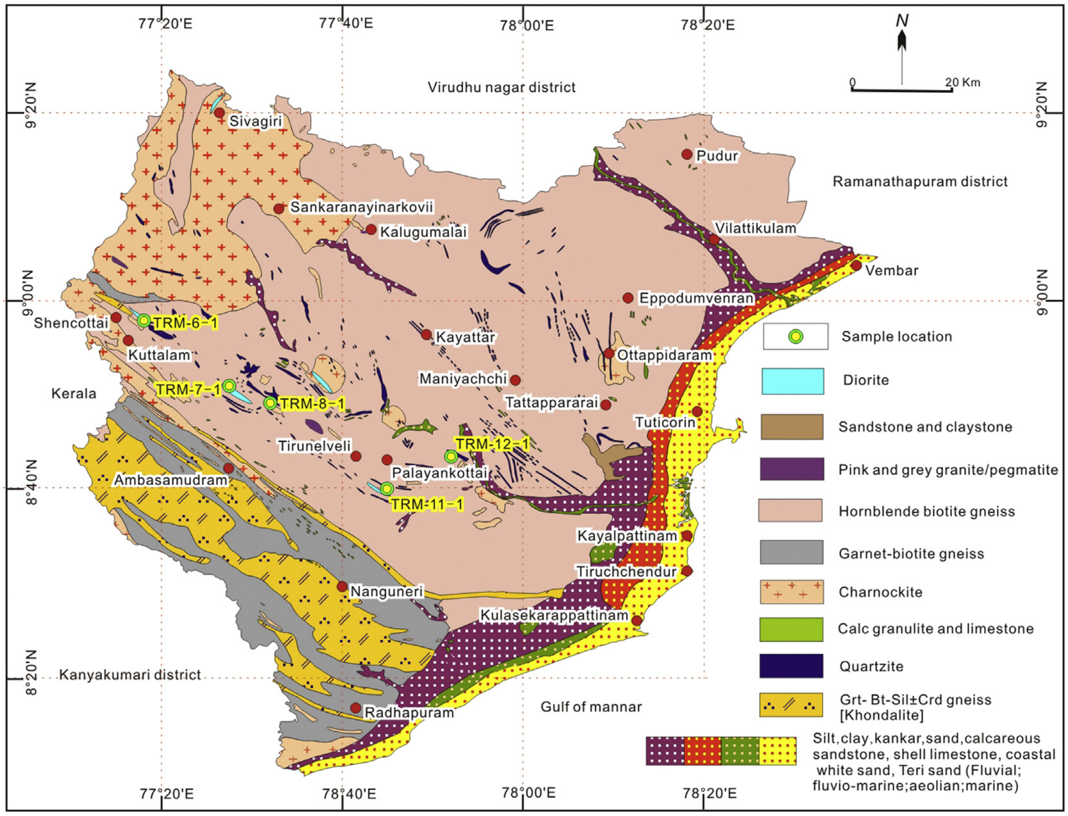

Figure 3. Detailed geological map of study area showing the rock type and groups, and sample locations of the southern Madurai Block (modified after Geological Survey of India, 2005).

Lanka with the Dharwar Craton, Coorg Block and Salem Block, and the Paleoproterozoic crust with Congo-Tanzania-Bangweulu Block of East Africa. Collins et al. (2007b) correlated the depositional age of Madurai Block and Trivandrum Block with the western Malagasy metasedimentary rocks (the Itremo and Molo Groups). Tsunogae et al. (2015, 2016) traced the arc related magmatic zircon from Lützow-Holm Complex of Antarctica from Kadugannawa Complex in Sri Lanka. Sommer et al. (2003) established correlations among the central Mozambique Belt of Tanzania, East Africa and Madagascar based on similar peak metamorphic events.

In this study, we investigate detrital zircons in a suite of metasediments (quartzites) from the southern margin of the Madurai Block, north of the Achankovil suture zone. We compare the results with previous data from southern Madurai Block as well as those from other adjacent Gondwana fragments and establish a coherent correlation with Sri Lanka, Madagascar and East Africa. We also confirm late Neoproterozoic–Cambrian high grade metamorphism possibly associated with the closure of Mozambique ocean and collisional assembly of crustal fragments within the Gondwana supercontinent.

2. Geological background

The Southern Granulite Terrane in India (Fig. 1), south of the Archean Dharwar Craton, is a collage of crustal blocks and intervening suture/shear zones ranging in age from Mesoarchean to late Neoproterozoic–Cambrian (Peucat et al., 1993; Chadwick et al., 2000; Jayananda et al., 2000; Clark et al., 2009; Santosh et al., 2009b, 2015, 2016; Collins et al., 2014). Towards the south part of Palghat-Cauvery Suture Zone (PCSZ, considered as the trace of the Mozambique ocean suture; Collins et al., 2007a,b; Santosh et al., 2009b) is the Madurai Block, which in recent studies is identified as a collage of three crustal segments, the northern, central and southern provinces (Plavsa et al., 2014). The Madurai Block is the largest crustal block in southern India and exposes hornblende-biotite gneiss, charnockites, diorites, pinkish and greyish granites and pegmatites, garnet-biotite gneiss, garnet-biotite-sillimanite gneiss, quartzite and metacarbonates (Santosh et al., 2009b; Plavsa et al., 2012) (Figs. 2 and 3). Previous geochronological studies suggest the Madurai Block is dominantly composed of Neoarchean to Paleoproterozoic basement in the northern part and dominantly Neoproterozoic rocks in the southern part (Collins et al., 2007b; Santosh et al., 2009b; Plavsa et al., 2014). The Madurai Block is considered as a collage of magmatic arcs developed through protracted subduction events and accreted together with intervening oceanic and supracrustal lithologies, with subsequent regional metamorphism during late Neoproterozoic–Cambrian during the orogeny event (Santosh et al., 2009b).

3. Geology of the study area and sampling

The major rock types in the study area at the southern margin of the Madurai Block are orthopyroxene-bearing mappable units of 'massive' charnockites, migmatitic TTG (tonalite-trondhjemite-granodiorite) gneisses, granulite facies metapelitic bands (khondalites and leptynites), metacarbonates, and younger felsic intrusions. Lenticular and linear and folded quartzite bands form ridges as well as mounds. Quartzites also occur as small conformable bands within garnet-biotite sillimanite gneisses.

In this study, we collected representative quartzite samples for zircon U-Pb geochronology. The sample locations are shown in Figs. 2 and 3, and their salient details are listed in Table 1. Representative field photographs are shown in Fig. 4, and a brief

Table 1
Sample numbers, localities, rock types, GPS reading from southern Madurai Block.

Serial no.	Sample no.	Locality	Rock type	Coordinates
1	TRM-6-1	Valibanpottai	Quartzite	N08°57′46.34″ E77°18′03.55″
2	TRM-7-1	Alangulam	Quartzite	N08°52′19.70″ E77°27′58.46″
3	TRM-8-1	Karumpuliyuth	Quartzite	N08°50′07.71″ E77°31′53.74″
4	TRM-11-1	Rettiyarpatti	Grt bearing quartzite	N08°40′36.20″ E77°45′25.30″
5	TRM-12-1	Infant Jesus Engineering College	Quartzite	N08°44′02.16″ E77°52′42.33″

description of the localities and dominant geological features are given below.

3.1. Quartzite (sample TRM-6-1)

Sample TRM-6-1 was collected from an outcrop in the Valibanpottai village (N08°57′44.61″, E77°18′04.05″) near a massive charnockite quarry. The quartzite band here is approximately 30 m in width and is coarse grained and white to pinkish in color. The band is folded and fractured and intercalated with weathered brownish clayey horizons corresponding to pelitic (aluminous) layers. These sedimentary bands appear to have been accreted onto the continental basement, as inferred from there juxtaposition with massive charnockites (Fig. 4a). The charnockite is greenish gray and shows granitic igneous texture and carries ca. 50 m wide zone retrogression and bleaching at the contact of intrusion of pegmatite veins (10–20 cm thick). The charnockite also carries melanocratic enclaves (mafic magmatic enclaves) which are subrounded and elongate and broadly corresponding to dioritic composition, resembling features of magma mixing and mingling.

3.2. Quartzite (sample TRM-8-1)

Sample TRM-8-1 was collected from a large ground level exposure near Kulampuliyuth (N08°50′07.71″, E77°31′53.74″). The quartzite band has a width of 100 m and is foliated. The rock shows light brownish to pinkish color and is medium to coarse grained. The pink color is attributed by fine grained ferruginous material. The band extends for 100 m and shows fracturing and folding. The basement rock here is also charnockite and is greenish, medium to coarse grained, with weak foliation. Visible clots of orthopyroxene and oriented biotites are present in this basement rock. Thin layers of hornblendite and some diorite enclaves occur within the charnockite.

3.3. Quartzite (sample TRM-12-1)

Sample TRM-12-1 was collected from the quartzite hillock opposite to Infant Jesus Engineering College (N08°44′02.16″, E77°52′42.33″), close to Tirunelveli-Tuticorin highway. The quartzite occurs as large ridge mostly covered by vegetation. Samples were collected from the foot of this hill, and medium to coarse grained, milky to light brownish in color and show weak foliation (Fig. 4b).

3.4. Quartzite (sample TRM-7-1)

Sample TRM-7-1 was collected from a folded and metamorphosed quartzite band near Alangulam (N08°52′19.70″, E77°27′58.46″). The rock is light brownish to pinkish in color,

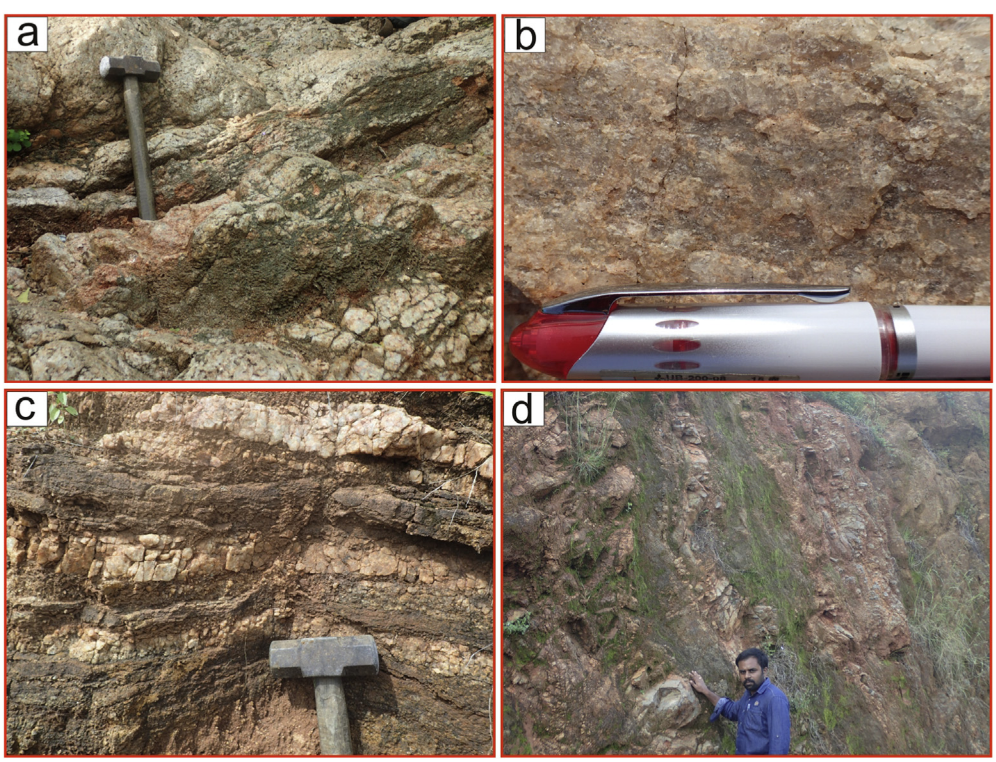

Figure 4. Representative field photographs: (a) TRM-6-1 pinkish coarse grained quartzite intercalated with thin pelitic layers; (b) TRM-12-1 medium to coarse grained quartzite showing milky to light brownish color; (c) TRM-7-1 coarse grained quartzite intercalated with dark brown pelitic layers; (d) TRM-11-1 pinkish medium grained garnet-rich quartzite intercalated with altered semi-pelitic rocks.

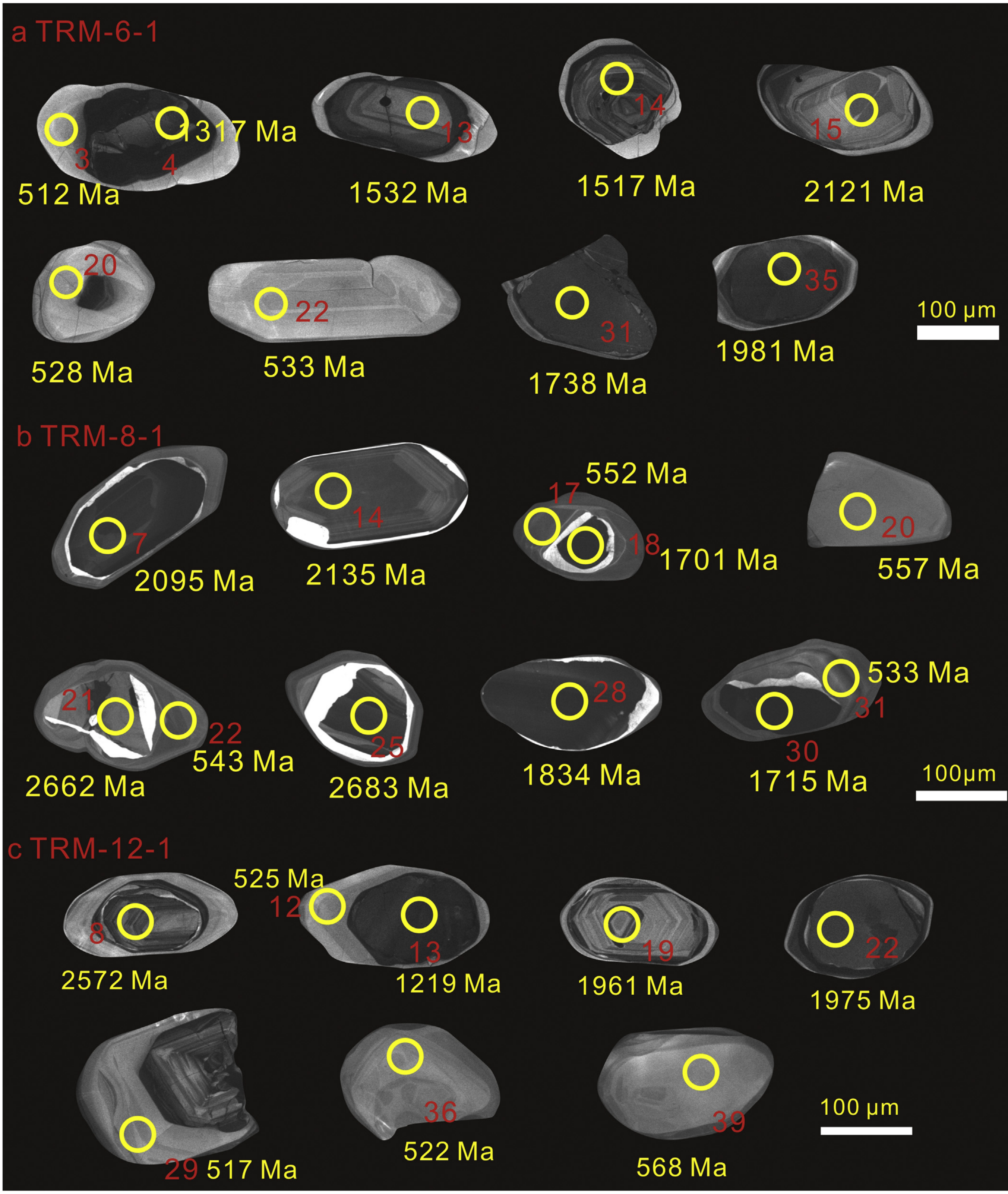

Figure 5. Representative Cathodoluminescence (CL) images of zircon grains from quartzite (TRM-6-1, TRM-8-1, TRM-12-1) of southern Madurai Block. Zircon U-Pb ages (Ma) are shown and the yellow circles represent spots of LA-ICP-MS U-Pb dating.

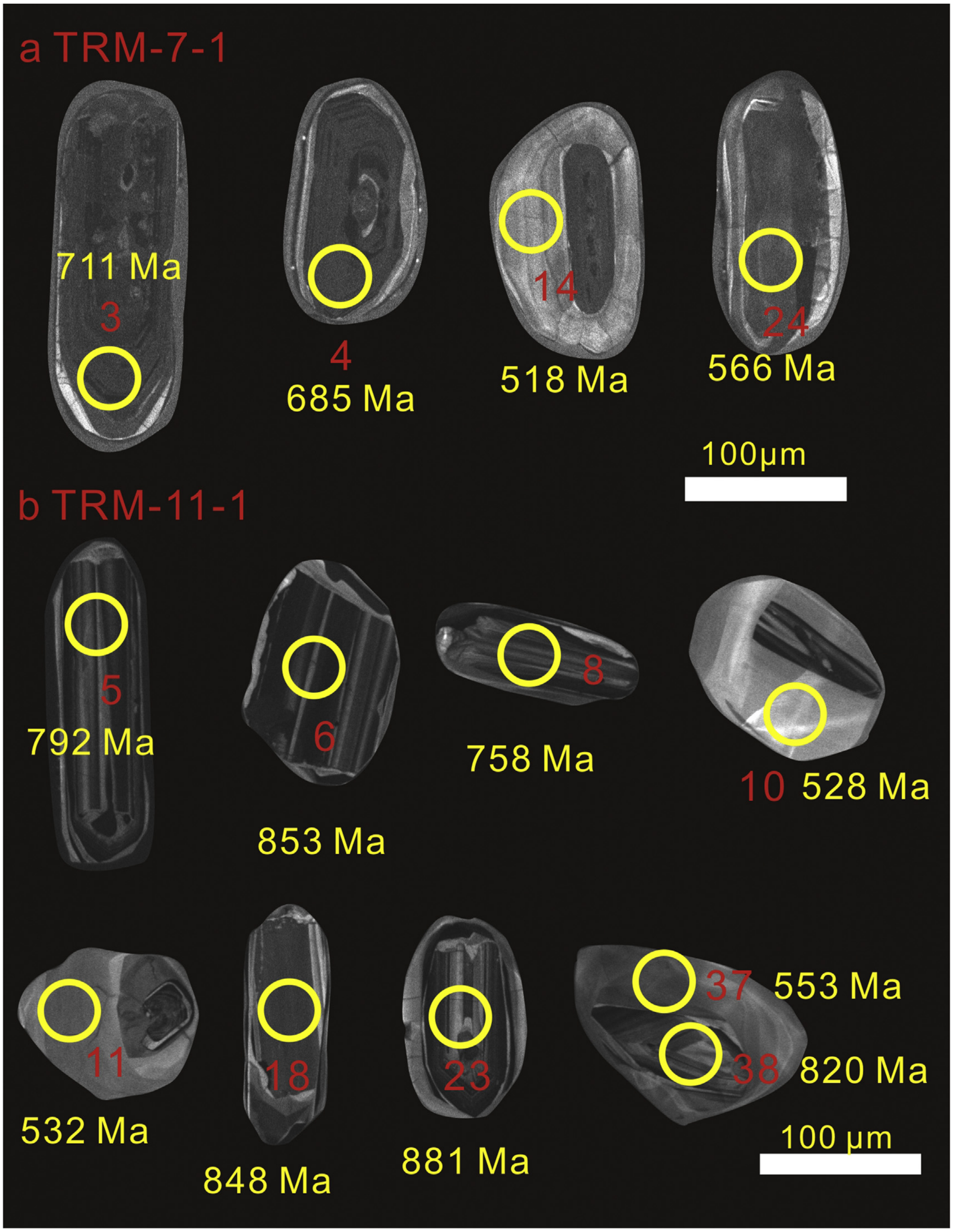

Figure 6. Representative Cathodoluminescence (CL) images of zircon grains from (a) quartzite (TRM-7-1) and (b) garnet bearing quartzite (TRM-11-1) of southern Madurai Block. Zircon U-Pb ages (Ma) are shown and the yellow circles represent spots of LA-ICP-MS U-Pb dating.

medium to coarse grained and intercalated with thin pelitic layers. The alternating psammitic and pelitic sequence are decimeter thick and show foliation (Fig. 4c). The quartzite is ferruginous with assemblage of quartz, hematite and magnetite. Within the band, a meter size block of greenish calc-silicate rock and occur as boudinaged lens. The basement rock is medium to fine grained melanocratic diorite and forms part of the TTG (tonalite-trondhjemite-granodiorite) gneiss suite in the area.

3.5. *Garnet bearing quartzite (sample TRM-11-1)*

Sample TRM-11-1 was collected from a vertical hill cutting near Ettiyarpatti (N08°40′36.20″, E77°45′25.30″), along the highway from Tirunelveli to Trivandrum. The quartzite is garnet-rich with rare biotite, and light brownish or pinkish in color, medium grained, and occurs as several meters thick (>20 m) bands intercalated with altered clay-rich semi-pelitic rocks (Fig. 4d). Within

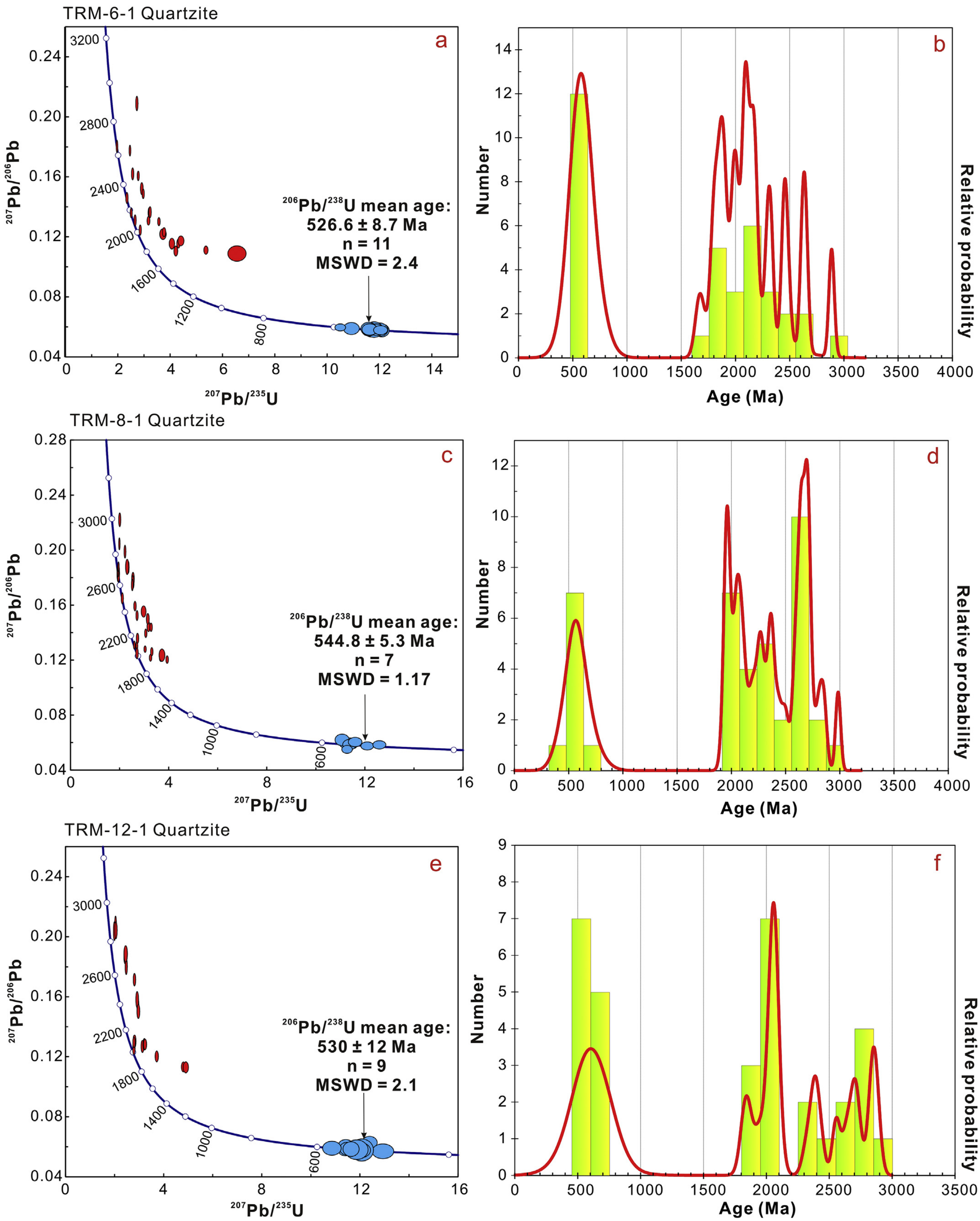

Figure 7. (a, c, e) U-Pb concordia diagrams of the analyzed samples (TRM-6-1, TRM-8-1, TRM-12-1). Red and blue circles in concordia diagrams imply core and rim respectively. (b, d, f) All the ages in histograms are ^{207}Pb/^{206}Pb ages.

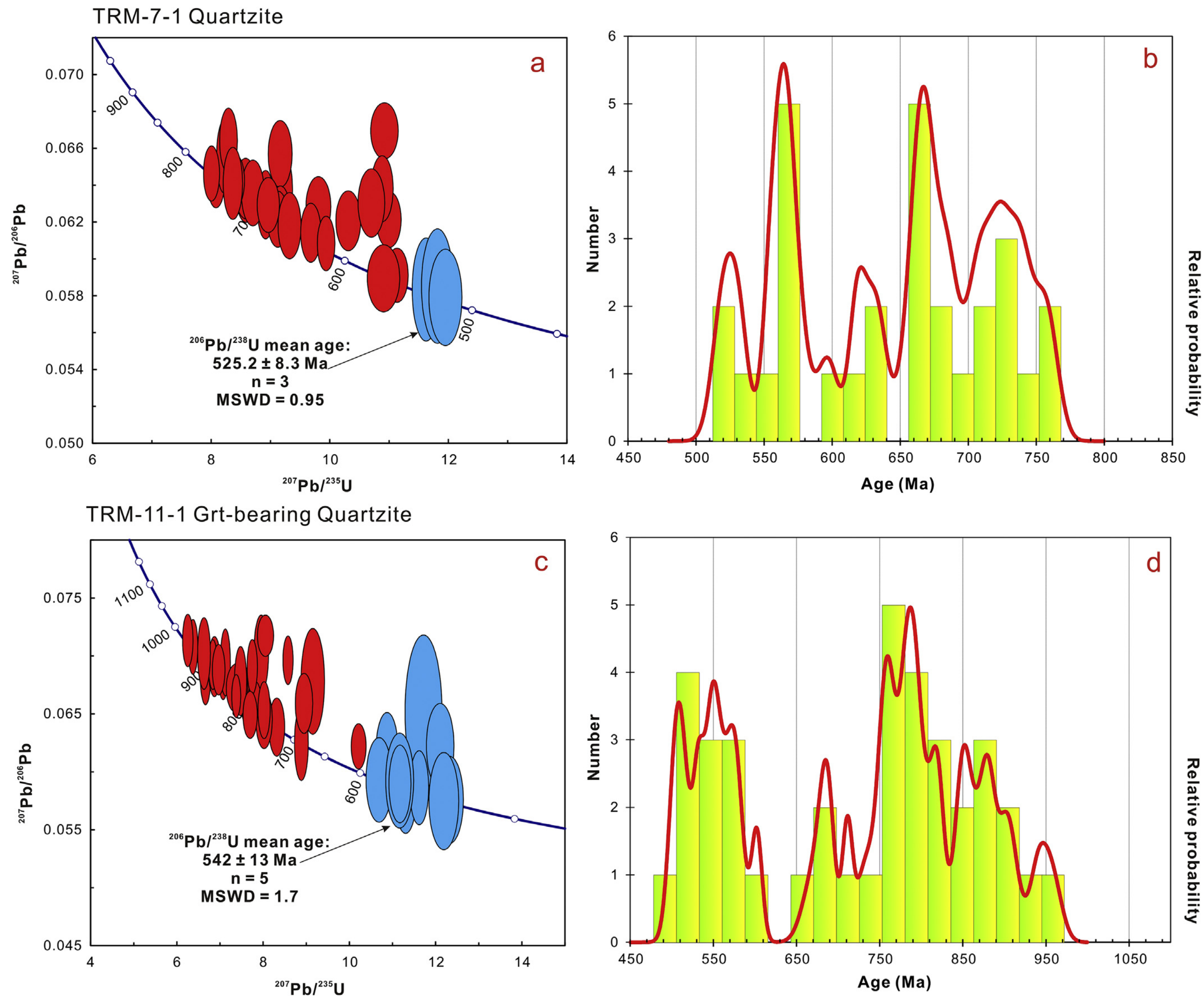

Figure 8. (a, c) U-Pb concordia diagrams of the analyzed samples (TRM-7-1, TRM-11-1). Red and blue circles in concordia diagrams imply core and rim respectively. (b, d) All the ages in histograms are $^{206}Pb/^{238}U$ ages.

the quartzite layers, boudinaged fragments of medium to fine grained mafic dykes are also found.

4. Analytical techniques for zircon U-Pb geochronology

Zircon grains were separated using standard procedures for U-Pb dating at the Yu'neng Geological and Mineral Separation Survey Centre, Langfang City, Hebei Province, China. The CL imaging was carried out at the Beijing Geoanalysis Centre. Individual grains were mounted along with the standard TEMORA 1, with $^{206}Pb/^{238}U$ age of 417 Ma (Black et al., 2003), onto double-side adhesive tape and enclosed in epoxy resin disks. The disks were polished to a certain depth to expose the cores of the grains and gold coated for cathodoluminescence (CL) imaging and U-Pb isotope analysis. Zircon morphology, inner structure and texture were examined by using a JSM-6510 Scanning Electron Microscope (SEM) equipped with a backscatter probe and a Chroma CL probe. The zircon grains were also examined under transmitted and reflected light images using a petrological microscope.

U-Pb dating and trace element analyses of zircon were conducted synchronously by LA-ICP-MS at the Wuhan Sample Solution Analytical Technology Co., Ltd. Detailed operating conditions for the laser ablation system and the ICP-MS instrument and data reduction are the same as description by Liu et al. (2008, 2010a,b). Laser sampling was performed using a GeoLas 2005. An Agilent 7500a ICP-MS instrument was used to acquire ion-signal intensities. Helium was applied as a carrier gas. Argon was used as the make-up gas and mixed with the carrier gas via a T-connector before entering the ICP. Nitrogen was added into the central gas flow (Ar + He) of the Ar plasma to decrease the detection limit and improve precision (Hu et al., 2008; Liu et al., 2010b). Each analysis incorporated a background acquisition of approximately 20–30 s (gas blank) followed by 50 s data acquisition from the sample. The Agilent Chemstation was utilized for the acquisition of each individual analysis. Off-line selection and integration of background and analyte signals, and time-drift correction and quantitative calibration for trace element analyses and U-Pb dating were performed by ICPMSDataCal (Liu et al., 2008, 2010a).

Zircon 91500 was used as external standard for U-Pb dating, and was analyzed twice every 5 analyses. Time-dependent drifts of U-Th-Pb isotopic ratios were corrected using a linear interpolation (with time) for every five analyses according to the variations of 91500 (i.e., 2 zircon 91500 + 5 samples + 2 zircon 91500) (Liu et al., 2010a). Preferred U-Th-Pb isotopic ratios used for 91500 are from Wiedenbeck et al. (1995). Uncertainty of preferred values for the external standard 91500 was propagated to the ultimate results of the samples. Concordia diagrams and weighted mean calculations were made using Isoplot/Ex_ver3 (Ludwig, 2003). Trace element compositions of zircons were calibrated against multiple-reference materials (BCR-2G and BIR-1G) combined with internal standardization (Liu et al., 2010a).

5. Results

Representative cathodoluminescence (CL) images of zircons from the quartzite samples TRM-6-1, TRM-7-1, TRM-8-1, TRM-11-1, TRM-12-1 are shown in Figs. 5 and 6, together with the analytical spots. The U-Pb age data are presented in Supplementary Table 2, and are plotted in concordia diagrams together with age data histograms (Figs. 7 and 8). The morphological characteristics of the zircon grains and age data in individual samples are briefly described below.

5.1. Zircon morphology

5.1.1. Sample TRM-6-1

In CL images, the zircons from this sample are colorless or dark brownish, transparent to translucent. Most grains are irregular euhedral to anhedral, and show prismatic or stumpy morphology (Fig. 5a). The zircons grains show a size range of 80–150 μm × 100–300 μm with aspect ratios of 3:1 to 1:1. They display core-rim texture. The detrital cores mostly show clear oscillatory zoning, with some show patchy zoning or sector zoning, and are surrounded by a dark overgrowth rim, suggesting multiple thermal events. The dark rim is often also surrounded by a bright metamorphic rim with width ranging up to 100 μm. The metamorphic rims are sometimes surrounded by another dark rim, suggesting recrystallization or overgrowth from fluids. Few grains show dark cores without structure. Some grains show abundant inclusions. Discrete structureless metamorphic grains are also common.

5.1.2. Sample TRM-8-1

Most grains from this sample are well grown and are transparent, colorless or brownish. The grains are euhedral to subhedral, rounded to subrounded, and few are prismatic or stumpy (Fig. 5b). The grain size shows a range of 80–200 μm × 80–200 μm with aspect ratios of 2:1–1:1. While core-rim texture is common, structureless grains also occur. The detrital cores are surrounded by bright white colored metamorphic rims or white domains, and some metamorphic rim mantled by a thin rim suggesting recrystallization. The detrital cores generally display oscillatory zoning or patchy zoning and some grains show very dark cores.

5.1.3. Sample TRM-12-1

Zircon grains in this rock are colorless or light brownish and transparent. They are irregular, euhedral to anhedral, with prismatic to stumpy shape. The grain size shows a range of 80–200 μm × 100–220 μm with aspect ratios of 2:1–1:1. They show typical core-rim structure (Fig. 5c). The detrital cores show oscillatory zoning or patchy zoning and are surrounded by a bright metamorphic rim or thin luminescent boundary. The metamorphic rims show width up to 100 μm. Some grains show bright cores, which are surround by a dark overgrowth rim. Several grains in this sample carry mineral/fluid inclusions. Discrete metamorphic grains without any internal structure also occur.

5.1.4. Sample TRM-7-1

Zircons from this sample are mostly brownish or colorless, transparent and cracked. They show euhedral to anhedral morphology, and are prismatic and elongate in habit (Fig. 6a) with size range of 30–100 μm × 50–200 μm and aspect ratios of 2:1–5:3. In CL images, the core-rim structure is marked by a very thin luminescence rim or band. The metamorphic rims are mostly narrow but in some cases the rims range up to 80 μm in width. The oscillatory zoning of the core is weak and mineral inclusions are also present.

5.1.5. Sample TRM-11-1

In CL images, zircons from this garnet-bearing quartzite are transparent and colorless, with prismatic or elongated morphology (Fig. 6b). They show a size range of 50–120 μm × 50–200 μm and aspect ratios of 3:1–1:1. The grains display moderate core-rim texture with the detrital cores showing oscillatory zoning or luminescent banding, and are surrounded by bright metamorphic rims. The internal textures are much clear and some grains show mineral/fluid inclusions. In some grains the oscillatory cores are surround by a dark overgrowth rim, which is again bordered by a bright metamorphic rim, representing recrystallization.

5.2. U-Pb and REE data

5.2.1. Sample TRM-6-1

A total of 35 spots were analyzed both from the detrital cores and metamorphic rims of thirty one zircons from this sample and the data can be divided into two groups. The older group is composed of 23 spots and their Th contents range from 40.51 to 336.12 ppm and U contents show a range of 68.92–626.84 ppm. The Th/U ratios are high and in the range of 0.27–2.47, representing magmatic crystallization. Many of the analyzed spots from this group are detrital cores and are dominantly discordant suggesting significant lead loss (see Fig. 7a and Supplementary Table 2). The $^{207}Pb/^{206}Pb$ ages with the low concordance are from the cores and show Neoarchean to Paleoproterozoic spot ages in the range of 2887 ± 25 Ma to 1674 ± 43 Ma (Fig. 7b). Another group is composed of metamorphic zircons or rims and includes twelve spots. Their Th and U contents and Th/U ratio show wide ranges of 42–126.62 ppm, 50.61–355.43 ppm, and 0.28–2.35, respectively (Supplementary Table 2). They show $^{238}U/^{206}Pb$ ages in the range of 586 ± 7 Ma to 512 ± 8 Ma, and define weighted mean age of 526.6 ± 8.7 Ma (MSWD = 2.4, n = 11) when calculate based on the high concordance (>99%) spots (Fig. 7a,b).

Trace element data were obtained simultaneously from the same spots where U-Pb were analyzed. Totally 35 spots were analyzed including 23 cores and 12 rims. The zircons display salient variation of LREE depletion and HREE enrichment, positive Ce, Sm anomalies and negative Eu, Pr, Nd anomalies, excluding one zircon from the core with a spot age of 1674 Ma that shows positive Pr and Eu anomalies (Fig. 9a) (Supplementary Table 3).

5.2.2. Sample TRM-8-1

Forty spots were analyzed from 34 zircon grains and the results can be divided into two groups. The first group is represented by detrital cores and contains thirty one spots, and many of the analyzed spots are discordant suggesting lead loss (Fig. 7c). Their Th contents range from 9.93–2723.92 ppm and U contents show a range of 24.66–468.45 ppm, with a wide range of Th/U ratios

(0.05–9.89). Their $^{207}Pb/^{206}Pb$ ages have relatively low concordance with spot ages spread from 2985 ± 23 Ma to 1950 ± 29 Ma, suggesting dominantly Neoarchean to Paleoproterozoic source (Fig. 7d). Another group includes nine spots and shows Th contents 55.76–154.60 ppm, U contents 64.77–277.61 ppm, and Th/U ratio in the range of 0.26–1.07 (Supplementary Table 2). These are mostly metamorphic zircons and yield $^{238}U/^{206}Pb$ ages in the range of 557 ± 9 Ma to 493 ± 7 Ma, and weighted mean age of 544.8 ± 5.3 Ma when calculate using the high concordance age spots (MSWD = 1.17, n = 7) (Fig. 7c,d).

The trace element data on 40 spots including 31 cores and 9 rims on zircons from this sample display obvious fractionated REE patterns with LREE depletion and HREE enrichment, positive Ce, Sm anomalies and negative Eu, Pr, Nd anomalies. Three zircon cores (2376 Ma, 2713 Ma, 2587 Ma) show slightly LREE enrichment and HREE depletion and slightly positive Pr anomalies, negative Ce anomalies (Fig. 9b) (Supplementary Table 3).

5.2.3. Sample TRM-12-1

Thirty two spots were analyzed from 31 zircons and the data can be divided into two groups. The older group includes 20 spots and their Th contents range from 33.23 ppm to 579 ppm and U contents show a range of 85.2–416.17 ppm, with Th/U values in the range of 0.4–1.39. Many of the analyzed spots are discordant suggesting obvious lead loss (Fig. 7e). The cores define $^{207}Pb/^{206}Pb$ ages ranging from 2875 ± 35 Ma to 1839 ± 41 Ma, suggesting that the detritus was sourced from Neoarchean to Paleoproterozoic protoliths (Fig. 7f). The second group is composed of metamorphic zircons and contains 12 spots. Their Th and U contents and Th/U ratio show wide ranges of 73.82–108.64 ppm, 67.21–183.97 ppm, 0.22–1.21, respectively (Supplementary Table 2). The data yield $^{238}U/^{206}Pb$ ages in the range of 568 ± 13 Ma to 480 ± 10 Ma, and weighted mean age of 530 ± 12 Ma when calculate using high concordance age spots (>95%) (MSWD = 2.1, n = 9) (Fig. 7e,f).

The trace element analysis of 32 spots including 20 cores and 12 rims display LREE depletion and HREE enrichment, positive Ce, Sm anomalies and negative Eu, Pr, Nd anomalies. One zircon from the core of a grain with an age 2384 Ma shows LREE enrichment and HREE depletion with obvious positive Pr anomalies and negative Eu anomalies (Fig. 10) (Supplementary Table 3).

5.2.4. Sample TRM-7-1

Twenty nine spots were dated from both the cores and metamorphic rims of 29 zircon grains in this sample and the data define two groups (Fig. 8a). The older group contains 26 spots and their Th contents range from 64.59 ppm to 306 ppm, U contents show a range of 1149.66–7527.95 ppm and Th/U values are in the range of 0.03 to 0.2. The cores of these grains display $^{238}U/^{206}Pb$ ages with high concordance (>90%) with spot ages ranging from 759 ± 8 Ma to 555 ± 6 Ma (Fig. 8b), Neoproterozoic magmatic sources. The second group includes three zircons and show Th contents 68.41–303.27 ppm, U contents 170.31–370.59 ppm, and Th/U ratio of 0.24–1.15 (Supplementary Table 2). These correspond to metamorphic rims having $^{238}U/^{206}Pb$ ages with high concordance (>99%) in the range of 532 ± 7 Ma to 518 ± 8 Ma, and yield weighted mean age of 525.2 ± 8.3 Ma (MSWD = 0.95, n = 3) (Fig. 8a,b).

Trace element data from twenty nine spots including 26 cores and three rims can be divided into two groups. One group shows obvious positive Pr, Eu anomalies, and negative Nd, Sm anomalies. Another group (including the metamorphic rims) show positive Ce, Sm anomalies, and negative Nd, Eu anomalies. The zircon grains slight REE fraction with minor LREE depletion (Fig. 11a, Supplementary Table 3).

5.2.5. Sample TRM-11-1

Thirty eight spots were analyzed from 36 zircon grains in this sample and can be divided into two groups (Fig. 8c). The first group includes 27 spots and their Th contents range from 41.65 to 522.50 ppm, U contents show a range of 103.39–642.94 ppm, and Th/U values in the range of 0.14 to 1.69. Their $^{238}U/^{206}Pb$ ages with high concordance (>90%) from the cores show Neoproterozoic crystallization ages in the range of 957 ± 11 Ma to 602 ± 6 Ma (Fig. 8d). The second group contains 11 spots and their Th contents range from 16.54 to 73.15 ppm and U show wide ranges of 48.54–168.29 ppm, Th/U ratio 0.14–1.51 (Supplementary

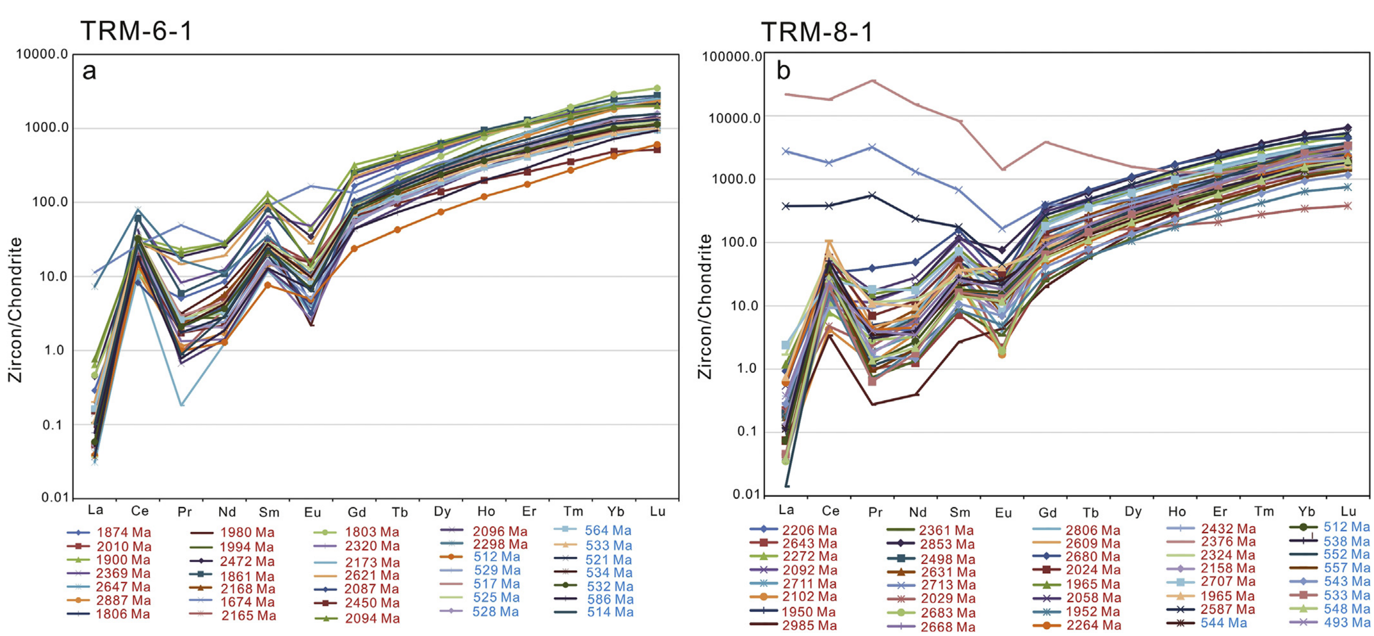

Figure 9. Chondrite-normalized REE diagrams showing the REE content of detrital cores and metamorphic rims. (a) TRM-6-1 (b) TRM-8-1. Chondrite values are after Sun and McDonough (1989). The zircon ages are shown below, red color represents $^{207}Pb/^{206}Pb$ age of the core, blue color represents $^{206}Pb/^{238}U$ metamorphic age.

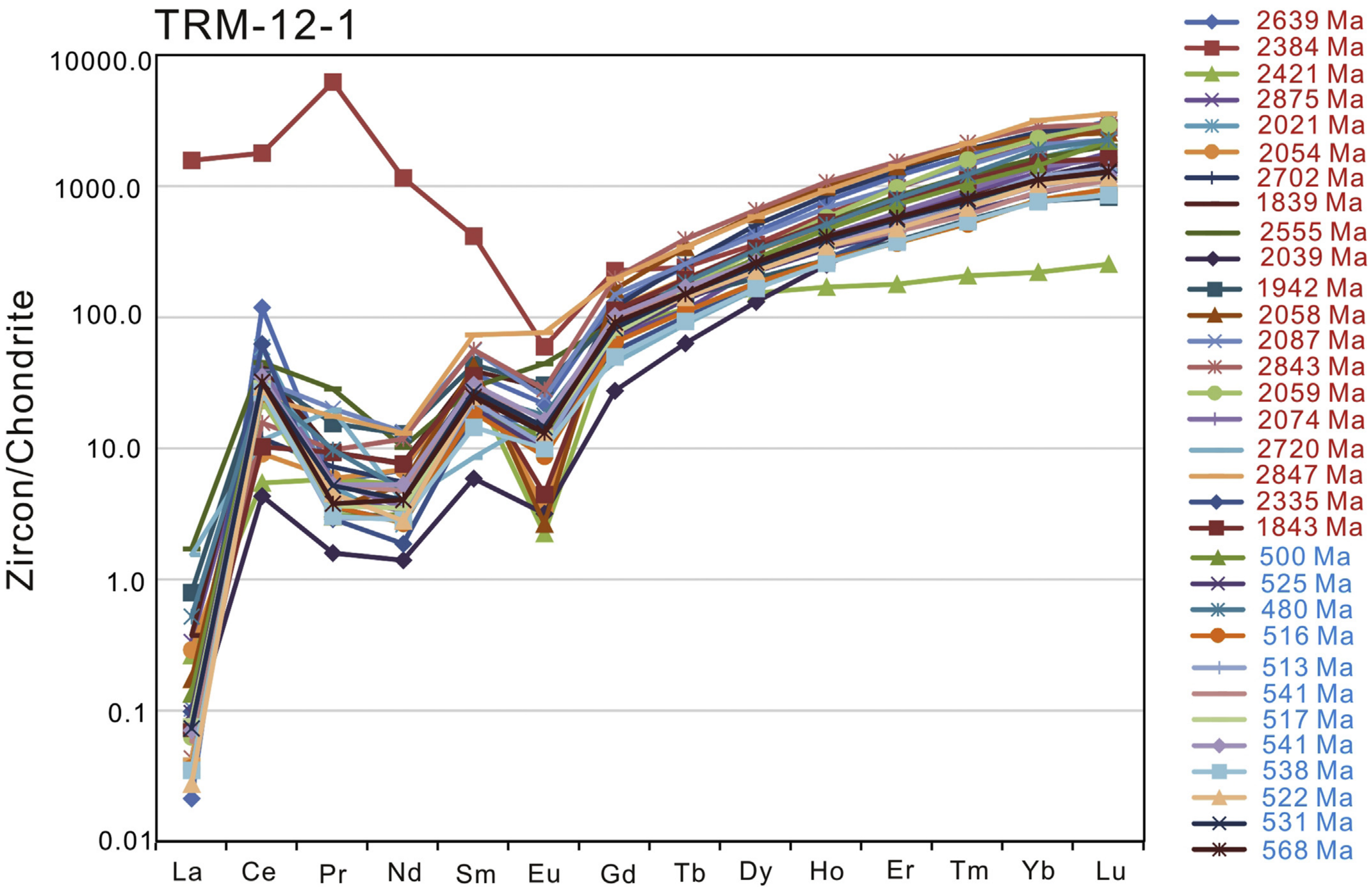

Figure 10. Chondrite-normalized REE diagrams showing the REE content of detrital cores and metamorphic rims for TRM-12-1. The zircon ages are shown in the right side, red color represents $^{207}Pb/^{206}Pb$ age of the core, blue color represents $^{206}Pb/^{238}U$ metamorphic age.

Table 2). These spots represent the metamorphic rims with $^{238}U/^{206}Pb$ ages in the range of 578 ± 8 Ma to 503 ± 8 Ma, and weighted mean age of 542 ± 13 Ma (MSWD = 1.7, $n = 5$) when calculated using high concordance age spots (Fig. 8c,d).

Thirty eight spots were analyzed for trace elements including twenty seven cores and eleven rims. The data show LREE depletion and HREE enrichment, positive Ce, Sm anomalies and negative Eu, Pr, Nd anomalies (Fig. 11b, Supplementary Table 3).

6. Discussion

6.1. Zircon U-Pb geochronology and REE data

Representative quartzite samples investigated in this study from the southern Madurai Block are dominantly medium to coarse grained, light brownish or pinkish color and mainly composed of quartz, although one sample (TRM-11-1) carries moderate content of garnet. Field features show that the quartzite bands have been metamorphosed, folded and fractured and accreted onto continental basement. Many of them are foliated and show intercalated pelitic layers (TRM-6-1, TRM-7-1, TRM-11-1).

The majority of zircons from our samples are detrital with a subordinate group of metamorphic zircons occurring either as rims or as discrete grains. Based on textural features and age relations, the zircon grains can be divided into two groups. The detrital cores from sample TRM-6-1 show $^{207}Pb/^{206}Pb$ ages from 2887 ± 25 Ma to 1674 ± 43 Ma (Fig. 7b), with metamorphic rims showing $^{238}U/^{206}Pb$ ages in the range of 586 ± 7 Ma to 512 ± 8 Ma and weighted mean age of 526.6 ± 8.7 Ma (Fig. 7a,b). Zircons from the core of sample TRM-8-1 show $^{207}Pb/^{206}Pb$ ages spread from 2985 ± 23 Ma to 1950 ± 29 Ma, and the metamorphic rim yielded $^{238}U/^{206}Pb$ in the range of 557 ± 9 Ma to 493 ± 7 Ma with weighted mean age of 544.8 ± 5.3 Ma (Fig. 7c,d). Zircon cores in sample TRM-12-1 show $^{207}Pb/^{206}Pb$ ages of 2875 ± 35 Ma to 1839 ± 41 Ma and the metamorphic rims yielded $^{238}U/^{206}Pb$ ages of 568 ± 13 Ma to 480 ± 10 Ma together with weighted mean age of 530 ± 12 Ma (MSWD = 2.1, $n = 9$) (Fig. 7e,f). However, the crystallized cores from TRM-7-1 show $^{238}U/^{206}Pb$ age distribution from 759 ± 8 Ma to 555 ± 6 Ma (Fig. 8b), with metamorphic ages showing 532 ± 7 Ma to 518 ± 8 Ma ages and $^{238}U/^{206}Pb$ weighted mean age of 525.2 ± 8.3 Ma (Fig. 8a,b). In sample TRM-11-1, there are no zircons with ages older than Neoproterozoic, with cores showing $^{238}U/^{206}Pb$ ages from 957 ± 11 Ma to 602 ± 6 Ma, and metamorphic ages are distributed from 578 ± 8 Ma to 503 ± 8 Ma with weighted mean age of 542 ± 13 Ma (Fig. 8c,d). In summary, the detrital cores of zircons in quartzites from the southern Madurai Block were mainly sourced from Neoarchean to Paleoproterozoic (ca. 2800–1670 Ma, with peaks at 2900–2800, 2700–2600, 2500–2300, 2100–2000 Ma) and minor Mesoarchean (ca. 2980–2800 Ma) suggesting multiple provenance (Fig. 7, Supplementary Table 2). However, zircons in samples TRM-7-1 and TRM-11-1 are dominated by Neoproterozoic population with magmatic zircons showing $^{238}U/^{206}Pb$ age of 950–550 Ma. The metamorphic ages mainly spread from 580–500 Ma (see Fig. 8 and Supplementary Table 2). Zircon trace element results mostly show LREE depletion and HREE enrichment with minor to moderate variation, suggesting different protoliths (Teale et al., 2011). The zircons dominantly display positive Ce, Sm anomalies and negative

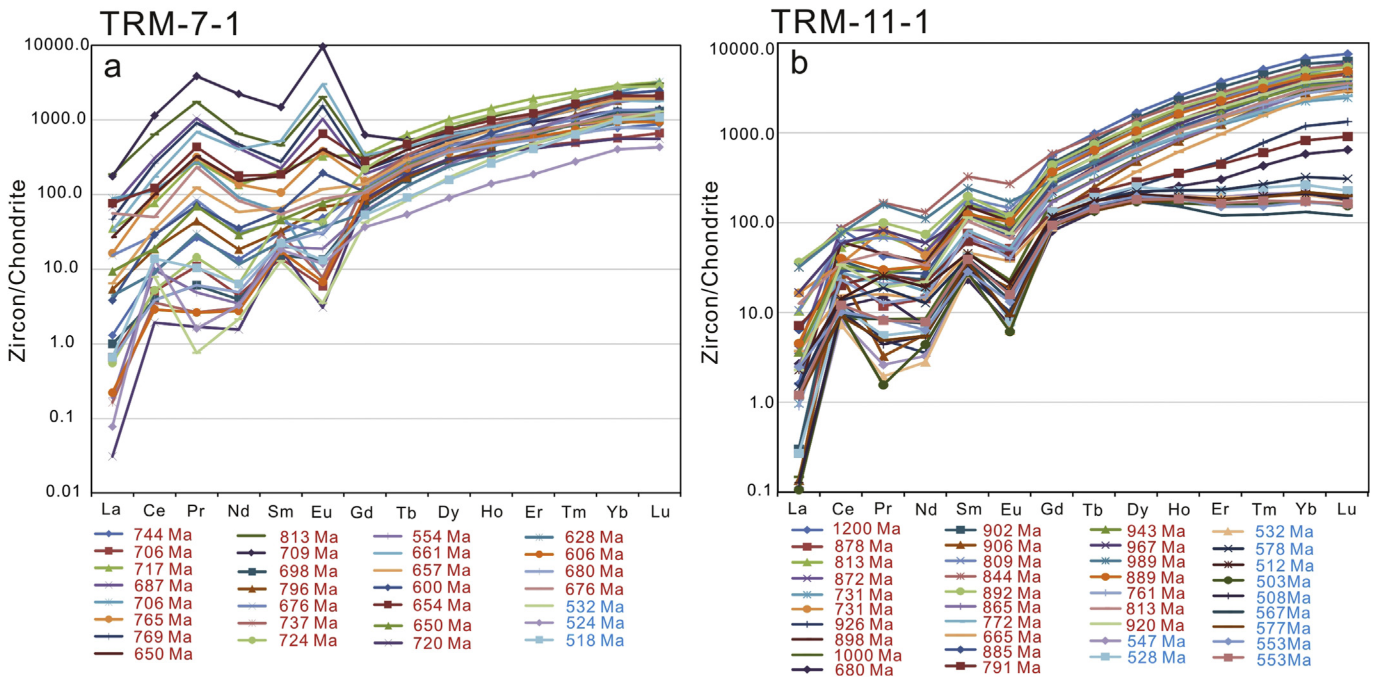

Figure 11. Chondrite-normalized REE diagrams showing the REE content of detrital cores and metamorphic rims. (a) TRM-7-1 (b) TRM-11-1. The zircon ages are shown below, red color represents $^{207}Pb/^{206}Pb$ age of the core, blue color represents $^{206}Pb/^{238}U$ metamorphic age.

Eu, Pr, Nd anomalies similar to those in previous reports on magmatic zircons (e.g., Kooijman et al., 2011).

Previous studies reported Paleoarchean to Paleoproterozoic (3.4–1.8 Ga, with age peaks at 2.7, 2.5, 2.4, 2.2–2.0 Ga and slightly lack of 1.8 Ga) detrital zircon from the southern Madurai Block (Santosh et al., 2003; Collins et al., 2007a; Kooijman et al., 2011; Teale et al., 2011; Plavsa et al., 2014). Kooijman et al. (2011) reported detrital ages of three quartzites and one metapelite from the Kadavur anorthosite complex south of Palghat Cauvery Shear Zone. The detrital cores yield Paleoarchean to Paleoproterozoic (3.4–1.8 Ga) ages and the rims display concordant ages at 955 ± 16 Ma and 810 ± 7 Ma. The younger ages are interpreted correlate with the timing of anorthosite intrusion, with subsequent metamorphism at 590–490 Ma. Plavsa et al. (2014) reported Archean to Paleoproterozoic (3.2–1.7 Ga, with major peak at ca. 2.65, 2.52, 2.4, 2.05 Ga) zircons in metasedimentary rocks from the northern part of Madurai Block whereas zircons from the southern part of the Madurai Block in their study show Mesoproterozoic to Neoproterozoic provenance (1.1–0.65 Ga, with major peak at ca. 1.02, 0.95, 0.78, 0.74, 0.67 Ga). Teale et al. (2011) reported zircon age data from one quartzite sample from Kadavur with maximum depositional age of 1926 ± 20 Ma. They also obtained zircons with crystallization age of 829 ± 14 Ma and 766 ± 8 Ma from gabbro-anorthosite and felsic gneiss. Collins et al. (2007b) reported similar detrital population (ca. 2700, 2260, 2100, 1997 Ma) from the Madurai Block. A detrital zircon with late Neoproterozoic age (695 ± 16 Ma) was also reported. These data show similar distribution with those from our study (Fig. 12).

Neoarchean to Mesoproterozoic zircons (2.7–1.4 Ga, with peak age at 2.2, 2.0, 1.9 Ga) were also reported from the granulite facies metapelites of the Trivandrum Block (Collins et al., 2007b) (Fig. 12). Santosh et al. (2003) reported Mesoarchean to Neoproterozoic zircons in a wide range of lithologies from different localities within the crustal blocks of the Southern Granulite Terrane including the Madras Block (3.2–2.8, 2.8–2.6, 2.5–2.4 Ga), Madurai Block (2.3, 1.7, 1.0–0.8 Ga), Trivandrum Block (2.8–0.4 Ga), and Nagercoil Block (0.61–0.50 Ga). Collins et al. (2007b) also reported Neoarchean to Mesoproterozoic ages (ca. 2.7 Ga, 2.0–1.3 Ga, with peak at 1.9–1.8, 1.7–1.6, 1.4 Ga) from one quartzite sample in Achankovil Shear zone (Fig. 12).

In the adjacent terrane of Sri Lanka, Kröner et al. (1987, 1994) and Takamura et al. (2016) reported Archean to Paleoproterozoic detrital zircons (3.2–1.8 Ga, with age peaks at 3.2, 2.8–2.6, 2.4, 2.2–2.0, 1.8 Ga) from the Highland Complex (Fig. 12). Sajeev et al. (2010) reported detrital cores showing ages in the range of 2.5–0.83 Ga from the UHT granulite of Highland Complex. In a recent study, Takamura et al. (2016) obtained Neoarchean to Paleoproterozoic ages (ca. 2700–1700 Ma, with minor Paleoarchean (ca. 3500 Ma), Mesoproterozoic (ca. 1200 Ma), as well as early to middle Neoproterozoic (ca. 800–600 Ma) components from the Highland Complex. Detrital zircons from southern Madurai Block in India and Highland Complex in Sri Lanka show broadly similar provenance.

Several Paleoarchean to Neoarchean basement rocks are reported from south India including the Dharwar Craton (3.4–2.5 Ga, Beckinsale et al., 1980; Chadwick et al., 2000; Jayananda et al., 2000; Collins et al., 2003; Yellappa et al., 2012), Coorg Block (3.4–3.0 Ga, Santosh et al., 2015, 2016), Salem Block (2.53 Ga, Ghosh et al., 2004; Clark et al., 2009; Sato et al., 2011a; Ram Mohan et al., 2013; Collins et al., 2014), Nilgiri Block (ca. 2.7 Ga, Samuel et al., 2014), and Neoarchean to Paleoproterozoic basement from Palghat-Cauvery Suture Zone (PCSZ) (2.5–2.1 Ga, Janardhan, 1999; Collins et al., 2007a; Saitoh et al., 2011; Santosh et al., 2012). These Paleoarchean to Neoarchean basement could have served as a major source of the detrital zircons of Madurai Block sediments.

The metamorphic ages from the quartzite of northern Madurai Block reported by Plavsa et al. (2014) range from early to latest Neoproterozoic (ca. 860 Ma, ca. 821–770 Ma, ca. 576 Ma). The dominant metamorphism of southern Madurai Block has been constrained as late Neoproterozoic–Cambrian (ca. 556 Ma and ca. 540 Ma). Collins et al. (2007b) also reported high-grade metamorphism from Trivandrum Block at 513 ± 6 Ma. In the Highland

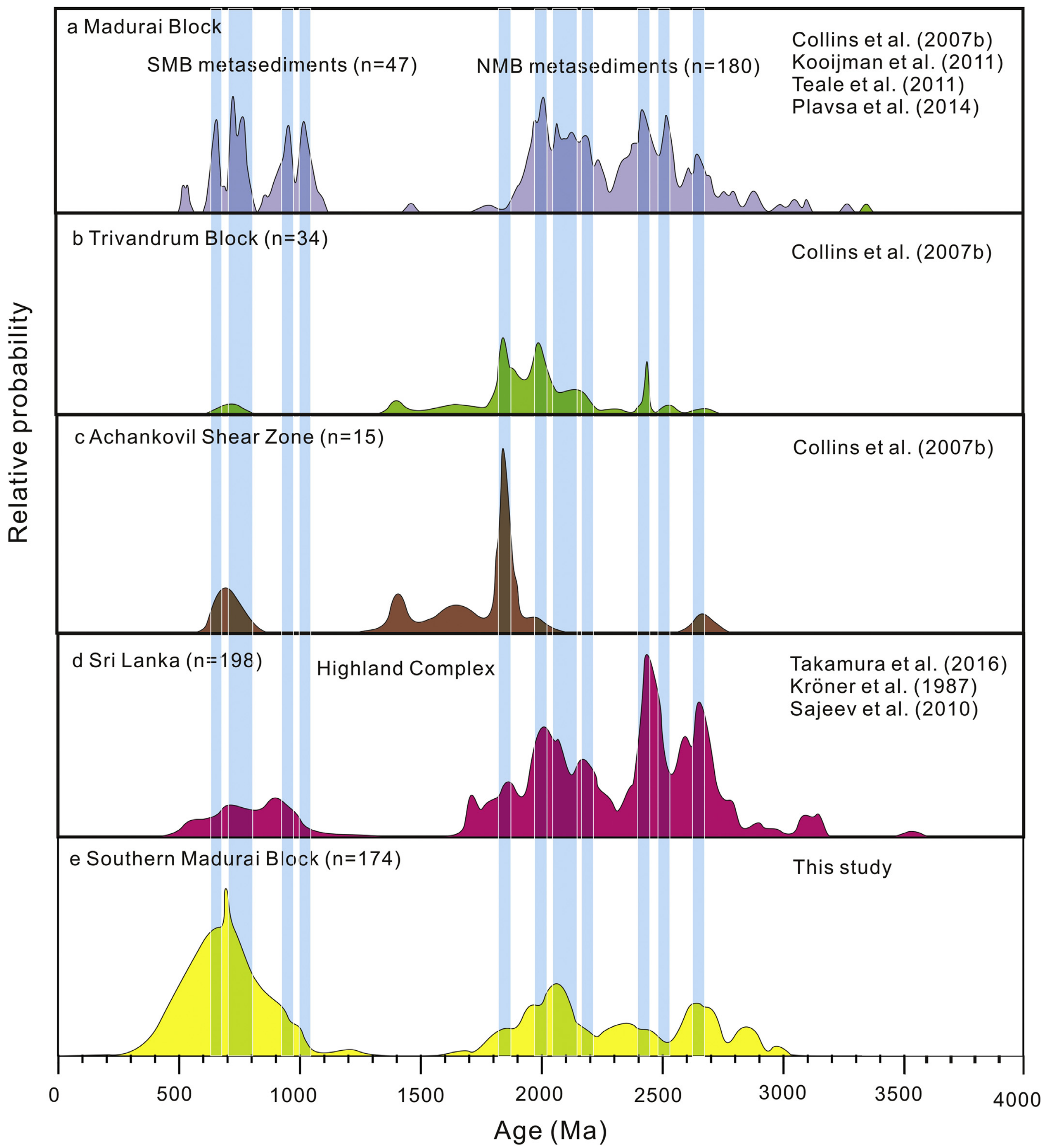

Figure 12. Probability density plots versus $^{207}Pb/^{206}Pb$ age (in Ma) of the metasedimentary rocks from the southern Indian terranes (northern and southern Madurai Block, and Trivandrum Block) and Sri Lanka (Highland Complex). Figure references: (a) Madurai Block (Collins et al., 2007b; Kooijman et al., 2011; Teale et al., 2011; Plavsa et al., 2014); (b) Trivandrum Block (Collins et al., 2007b); (c) Achankovil Shear Zone (Collins et al., 2007b); (d) Highland Complex (Kröner et al., 1987; Sajeev et al., 2010; Takamura et al., 2016); (e) Southern Madurai Block (this study).

Complex of Sri Lanka, the metamorphic ages range from 580 to 540 Ma with the ca. 550 Ma age interpreted as the peak of high-grade granulite facies metamorphism (Kröner et al., 1987, 1994; Sajeev et al., 2010; He et al., 2016a, b; Takamura et al., 2016). The ca. 550 Ma age is also regarded as the peak metamorphic event in southern India associated with the final amalgamation of Gondwana supercontinent (Santosh et al., 2003, 2006; Collins et al., 2007b; Sato et al., 2010; Plavsa et al., 2015).

In summary, the zircon data from our study are coherent with those from previous studies in the Madurai Block, Trivandrum

Block as well as in Sri Lanka as illustrated in Fig. 12. The Mesoarchean to Paleoproterozoic detrital zircon ages might have been sourced from the northern blocks of the SGT, whereas the Neoproterozoic to Cambrian zircons were mostly derived from proximal provenance in the southern Madurai Block.

6.2. Tectonic implications for the amalgamation of Gondwana

Peninsular India was located at the central domain of the Gondwana assembly surrounded by Madagascar, Africa, Sri Lanka, East Antarctica and Australia (Collins et al., 2014). Previous studies identified Archean to Proterozoic provenance in Gondwana fragments for the Neoproterozoic metasediments (Santosh et al., 2003; Collins et al., 2007a; Plavsa et al., 2014). Takamura et al. (2016) correlated the Archean (ca. 3.4–2.5 Ga) detrital zircons of Sri Lanka with source in the Dharwar Craton, Coorg Block and Salem Block, whereas the Paleoproterozoic zircons are thought to have been mostly derived from the Congo-Tanzania-Bangweulu Block. Tsunogae et al. (2015) reported Neoproterozoic (999–965 Ma) arc magmatism from Lützow-Holm Complex (LHC) and correlated it with the Kadugannawa Complex in Sri Lanka, suggesting that these terrane were formed in the same setting. The metamorphic ages from LHC (582–574 Ma) are also coherent with those from Sri Lanka (582–533 Ma) (Santosh et al., 2014; Dharmapriya et al., 2015; Tsunogae et al., 2015; Takamura et al., 2016). Cox et al. (1998, 2004) identified that the Itremo Group of Madagascar has a similar depositional age with correlative rock units in East Africa and India.

The Dharwar craton is dominantly composed of >3.0 Ga basement, with the Western Dharwar Craton (WDC) (ca. 3.4 Ga TTG and ca. 2.6 Ga), granulitic domain of Central Dharwar Province (CDP) (2.55 and 2.53 Ga) and TTG and calc-alkaline igneous protoliths Eastern Dharwar Craton (EDC) (Chadwick et al., 2000) as the major units. The Paleoarchean to Mesoarchean ages (2.98–2.8 Ga) in our quartzites might have been derived from the reworked Archean crust of the Dharwar Craton (Chadwick et al., 2000; Jayananda et al., 2000; Peucat et al., 2013). Prakash (2010) correlated the provenance of the continent crust in the NW of Madurai Block with southern Dharwar craton. The Mesoarchean basement detrital zircons of quartzite (3031–3007 Ma) and xenocrystic zircons of lapilli tuffs (3225–3169 Ma) from the Central African Copperbelt, as well as igneous rocks from east Antarctica (3800, 3000, 2800, 2500 Ma) (Harley and Black, 1997; Rainaud et al., 2003) also have Meso- and Neoarchean ages. These Archean basements in different Gondwana fragments show similar age distribution, and have served as multiple provenance.

Several studies reported Neoarchean magmatic rock from Salem Block at the southern part of the Dharwar Craton, the results suggest these rocks dominantly crystallized at ca. 2530 Ma with subsequent metamorphism at ca. 2480 Ma within an active convergent margin (Clark et al., 2009; Sato et al., 2011a; Ram Mohan et al., 2013). Plavsa et al. (2014) reported late Archean to early Paleoproterozoic (2.7–2.45 Ga) metasedimentary rocks from Salem Block together with positive Hf values of 0.3–8.8, indicating juvenile sources. Paleoproterozoic (2.4–2.1 Ga) protoliths are widely distributed in various crustal blocks of the Southern Granulite Terrane with a common peak metamorphic event at ca. 550 Ma identical to those in the adjacent Gondwana fragments. The Madurai Block exposes Archean basement rocks in the north and west and whereas the southern and eastern domains are mainly composed of Proterozoic basement (Collins et al., 2007b; Plavsa et al., 2012). Thus, the Archean to Paleoproterozoic detrital zircons in our samples might have been derived from distal sources in northern Madurai Block, Salem Block or Dharwar craton and Neoproterozoic ages are from more proximal sources of possible arc magmatic rocks. However, metasedimentary rocks carrying Archean to Paleoproterozoic zircons have also been reported from Madagascar (Itremo Group 2.69–1.85 Ga and Molo Group 1.7–1.5 Ga) (Collins, 2006). Cox et al. (2004, 1998) suggested that the Itremo Group might source from the East Africa, the central and southern Madagascar, the central Madagascar were linked with Tanzania, and the eastern and northern Madagascar were connected with India during Paleo- and Mesoproterozoic times. Thus, both north and east Madagascar terranes have been suggested as major sources of the Paleoproterozoic detrital zircons of southern Madurai Block.

Bartlett et al. (1998) reported Paleoproterozoic to Neoproterozoic Nd model ages (1500–1200 Ma) from the Achankovil Shear Zone, similar to the ages reported from the Itremo Group of central Madagascar, as well as the East Africa. The Neoproterozoic depositional ages obtained from zircon grains in the metasediments of Trivandrum Block show correlation with the western and southern Malagasy metasediments (Collins et al., 2007b).

Early to middle Neoproterozoic magmatic events were also reported from the SGT, such as those from Manamedu from the southern segment of the Palghat-Cauvery Suture zone (Santosh et al., 2012), Kadavur (Teale et al., 2011), and locations in the Madurai Block (Santosh et al., 2009b), correlated to mid Cryogenian subduction-related magmatism is prior to the closure of Mozambique ocean and amalgamation of the Gondwana supercontinent.

The late Neoproterozoic–Cambrian metamorphic ages from throughout the Mozambique belt together with adjacent terranes including Congo-Tanzania, Kalahari, East Antarctica India as well as other fragments including those identified in this study mark the final amalgamation of the Gondwana supercontinent.

In summary, the metasediments of the Trivandrum Block forming part of the khondalite belt appears to mark the zone of closure of the Mozambique ocean that separated the Paleoproterozoic basements of the Madurai Block to the north and Nagercoil block to the south. The quartzites investigated in this study possibly mark the northern boundary of this ocean forming part of a continental shelf sequence which were metamorphosed and accreted onto the southern part of the Madurai Block during the collisional tectonics associated with Gondwana assembly. The early Neoproterozoic proximal sources in the southern Madurai Block also contributed detritus to these sediments prior to the ocean closure, in addition to a mixture of detritus from multiple provenance similar to those in the Trivandrum Block sediments.

7. Conclusions

(1) Detrital zircon U-Pb data from metasediments (quartzites) in the southern Madurai Block show dominant Neoarchean to Paleoproterozoic ages (ca. 2800–1670 Ma, with peak at 2900–2800 Ma, 2700–2600 Ma, 2500–2300 Ma, 2100–2000 Ma) and minor Mesoarchean (ca. 2980–2800 Ma) components. Two samples also show exclusive Neoproterozoic ages (950–550 Ma) in the absence of older ages.

(2) The zircon trace element data dominantly display obvious REE fraction with LREE depletion and HREE enrichment, positive Ce, Sm anomalies and negative Eu, Pr, Nd anomalies.

(3) The Neoarchean to Paleoproterozoic detrital zircons from southern Madurai Block might have been sourced from the northern blocks of the Southern Granulite Terrane in India, as well as from distal provenance in Madagascar and Africa, similar to those in the khondalite belt of the Trivandrum block.

(4) The ages of metamorphic zircons in our samples from southern Madurai Block dominantly spread from 580 to 500 Ma, which are coherent with the ages reported from the adjacent Trivandrum Block (ca. 513 ± 6 Ma), Sri Lanka (582–533 Ma), and

NE Mozambique belt (570–530 Ma) and correspond to high grade metamorphism associated with the final amalgamation of the Gondwana supercontinent.

Acknowledgments

We thank Editor Prof. Sanghoon Kwon and two anonymous referees for constructive comments. This work is supported by funding to M. Santosh from China University of Geosciences, Beijing, China as Foreign Expert, and also contributes to Professorial support from the University of Adelaide, Australia. The work was also partly supported by a Grant-in-Aid for Scientific Research (B) from Japan Society for the Promotion of Science (JSPS) (No. 26302009) to Tsunogae.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.gsf.2016.07.002.

References

Bartlett, J.M., Dougherty-Page, J.S., Harris, N.B.W., Hawkesworth, C.J., Santosh, M., 1998. The application of single zircon evaporation and model Nd ages to the interpretation of polymetamorphic terrains: an example from the Proterozoic mobile belt of South India. Contributions to Mineralogy and Petrology 131, 181–195.

Black, L.P., Kamo, S.L., Allen, C.M., Aleinikoff, J.N., Davis, D.W., Korsch, R.J., Foundoulis, C., 2003. TEMORA 1: a new zircon standard for Phanerozoic U-Pb geochronology. Chemical Geology 200, 155–170.

Beckinsale, R.D., Drury, S.A., Holt, R.W., 1980. 3,360-Myr old gneisses from the south Indian craton. Nature 283, 469–470.

Bingen, B., Jacobs, J., Viola, G., Henderson, I.H.C., Shar, Ø., Boyd, R., Thomas, R.J., Solli, A., Key, R.M., Daudi, E.X.F., 2009. Geochronology of the Precambrian crust in the Mozambique belt in NE Mozambique, and implications for Gondwana assembly. Precambrian Research 170, 231–255.

Cawood, P.A., Nemchin, A.A., Freeman, M., Sircombe, K., 2003. Linking source and sedimentary basin: detrital zircon record of sediment flux along a modern river system and implications for provenance studies. Earth and Planetary Science Letters 210, 259–268.

Chadwick, B., Vasudev, V.N., Hegde, G.V., 2000. The Dharwar craton, southern India, interpreted as the result of Late Archaean oblique convergence. Precambrian Research 99, 91–111.

Chetty, T.R.K., Bhaskar Rao, Y.J., 2006. Constrictive deformation in transpressional regime: field evidence from the Cauvery Shear zone, southern Granulite Terrain, India. Journal of Structural Geology 28, 713–720.

Clark, C., Collins, A.S., Timms, N.E., Kinny, P.D., Chetty, T.R.K., Santosh, M., 2009. SHRIMP U-Pb age constraints on magmatism and high-grade metamorphism in the Salem Block, southern India. Gondwana Research 16, 27–36.

Clark, C., Healy, D., Johnson, T., Collins, A.S., Taylor, R.J., Santosh, M., Timms, N.E., 2015. Hot orogens and supercontinent amalgamation: a Gondwanan example from southern India. Gondwana Research 28, 1310–1328.

Collins, A.S., 2006. Madagascar and the amalgamation of central Gondwana. Gondwana Research 9, 3–16.

Collins, A.S., Clark, C., Plavsa, D., 2014. Peninsular India in Gondwana: the tectonothermal evolution of the southern Granulite Terrain and its Gondwanan counterparts. Gondwana Research 25, 190–203.

Collins, A.S., Clark, C., Sajeev, K., Santosh, M., Kelsey, D.E., Hand, M., 2007a. Passage through India: the Mozambique ocean suture, high-pressure granulites and the Palghat-Cauvery shear zone system. Terra Nova 19, 141–147.

Collins, A.S., Kröner, A., Fitzsimons, I.C.W., Razakamanana, T., 2003. Detrital footprint of the Mozambique ocean: U/Pb SHRIMP and Pb evaporation zircon geochronology of metasedimentary gneisses in eastern Madagascar. Tectonophysics 375, 77–99.

Collins, A.S., Santosh, M., Braun, I., Clark, C., 2007b. Age and sedimentary provenance of the southern Granulites, South India: U-Th-Pb SHRIMP secondary ion mass spectrometry. Precambrian Research 155, 125–138.

Condie, K.C., Belousova, E., Griffin, W.L., Sircombe, K.N., 2009. Granitoid events in space and time: constraints from igneous and detrital zircon age spectra. Gondwana Research 15, 228–242.

Cox, R., Armstrong, R.A., Ashwal, L.D., 1998. Sedimentology, geochronology and provenance of the Proterozoic Itremo Group, central Masagascar, and implications for pre-Gondwana palaeogeography. Journal of Geological Society, London 155, 1009–1024.

Cox, R., Coleman, D.S., Chokel, C.B., DeOreo, S.B., Collins, A.S., Kröner, A., De Waele, B., 2004. Proterozoic tectonostratigraphy and paleogeography of central Madagascar derived from detrital zircon U-Pb age populations. Journal of Geology 112, 379–400.

Dharmapriya, P.L., Malaviarachchi, S.P.K., Santosh, M., Tang, L., Sajeev, K., 2015. Late-neoproterozoic ultrahigh-temperature metamorphism in the Highland complex, Sri Lanka. Precambrian Research 271, 311–333.

Gebauer, D., Williams, I.S., Compston, W., Grünenfelder, M., 1989. The development of the central European continental crust since the Early Archaean based on conventional and ion-microprobe dating of up to 3.84 by old detrital zircons. Tectonophysics 157, 81–96.

Geological Survey of India, 2005. Resource Map of Tirunelveli, Tuticorin and Virudhnagar Districts,Tamil Nadu. Geological Survey of India, Calcutta.

Ghosh, J.G., de Wit, M.J., Zartman, R.E., 2004. Age and tectonic evolution of Neoproterozoic ductile shear zones in the southern Granulite Terrain of India,with implications for Gondwana studies. Tectonics 23, 297–319.

Harley, S.L., Black, L.P., 1997. A revised Archaean chronology for the Napier complex, Enderby Land, from SHRIMP ion-microprobe studies. Antarctica Science 9 (1), 74–91.

Harris, N.B.W., Bartlett, J.M., Santosh, M., 1996. Neodymium isotope constraints on the tectonic evolution of east Gondwana. Journal of Southeast Asian Earth Sciences 14, 119–125.

He, X.F., Santosh, M., Tsunogae, T., Malaviarachchi, S.P.K., 2016a. Early to late Neoproterozoic magmatism and magma mixing-mingling in Sri Lanka: implications for convergent margin processes during Gondwana assembly. Gondwana Research 32, 151–180.

He, X.F., Santosh, M., Tsunogae, T., Malaviarachchi, S.P.K., Dharmapriya, P.L., 2016b. Neoproterozoic arc accretion along the 'eastern suture' in Sri Lanka during Gondwana assembly. Precambrian Research 279, 57–80.

Hu, Z.C., Gao, S., Liu, Y.S., Hu, S.H., Chen, H.H., Yuan, H.L., 2008. Signal enhancement in laser ablation ICP-MS by addition of nitrogen in the central channel gas. Journal of Analytical Atomic Spectrometry 23, 1093–1101.

Janardhan, A.S., 1999. Southern Granulite Terrain, south of the Palghat-Cauvery Shear zone: implications for India-Madagascar connection. Gondwana Research 2, 463–469.

Jayananda, M., Moyen, J.-F., Martin, H., Peucat, J.-J., Auvray, B., Mahabaleswar, B., 2000. Late Archaean (2550-2520 Ma) juvenile magmatism in the eastern Dharwar craton, southern India: constraints from geochronology, Nd-Sr isotopes and whole rock geochemistry. Precambrian Research 99, 225–254.

Koizumi, T., Tsunogae, T., Santosh, M., Tsutsumi, Y., Chetty, T.R.K., Saitoh, Y., 2014. Petrology and zircon U-Pb geochronology of metagabbros from a mafic-ultramafic suite at Aniyapuram: Neoarchean to Early Paleoproterozoic convergent margin magmatism and Middle Neoproterozoic high-grade metamorphismin southern India. Journal of Asian Earth Science 95, 51–64.

Kooijman, E., Upadhyay, D., Mezger, K., Raith, M.M., Berndt, J., Srikantappa, C., 2011. Response of the U-Pb chronometer and trace elements in zircon to ultrahigh-temperature metamorphism: the Kadavur anorthosite complex, southern India. Chemical Geology 290, 177–188.

Kröner, A., Jaeckel, P., Williams, I.S., 1994. Pb-loss patterns in zircons from a high grade metamorphic terrain as revealed by different dating methods: U-Pb and Pb-Pb ages for igneous and metamorphic zircons from northern Sri Lanka. Precambrian Research 66, 151–181.

Kröner, A., Muhongo, S., Hegner, E., Wingate, M.T.D., 2003. Single-zircon geochronology and Nd isotopic systematics of Proterozoic high-grade rocks from the Mozambique belt of southern Tanzania (Masasi area): implications for Gondwana assembly. Journal of the Geological Society, London 160, 745–757.

Kröner, A., Williams, I.S., Compston, W., Baur, N., Vithanage, P.W., Perera, L.R.K., 1987. Zircon ion microprobe dating of high grade rocks in Sri Lanka. Journal of Geology 95, 775–791.

Lancaster, P., Dey, S., Storey, C.D., Mitra, A., Bhunia, R.K., 2015. Contrasting crustal evolution processes in the Dharwar craton: insights from detrital zircon U–Pb and Hf isotopes. Gondwana Research 28, 1361–1372.

Liu, Y.S., Gao, S., Hu, Z.C., Gao, C.G., Zong, K.Q., Wang, D.B., 2010a. Continental and oceanic crust recycling-induced melt-peridotite interactions in the Trans-North China Orogen: U-Pb dating, Hf isotopes and trace elements in zircons of mantle xenoliths. Journal of Petrology 51, 537–571.

Liu, Y.S., Hu, Z.C., Gao, S., Günther, D., Xu, J., Gao, C.G., Chen, H.H., 2008. In situ analysis of major and trace elements of anhydrous minerals by LA-ICP-MS without applying an internal standard. Chemical Geology 257, 34–43.

Liu, Y.S., Hu, Z.C., Zong, K.Q., Gao, C.G., Gao, S., Xu, J., Chen, H.H., 2010b. Reappraisement and refinement of zircon U-Pb isotope and trace element analyses by LA-ICP-MS. Chinese Science Bulletin 55, 1535–1546.

Ludwig, K.R., 2003. ISOPLOT 3.00: A Geochronological Toolkit for Microsoft Excel. Berkeley Geochronology Center, California, Berkeley, 39 pp.

Manikyamba, C., Kerrich, R., 2012. Eastern Dharwar Craton, India: continental lithosphere growth by accretion of diverse plume and arc terranes. Geoscience Frontiers 3, 225–240.

Möller, A., Mezger, K., Schenk, V., 1998. Crustal age domains and the evolution of the continental crust in the Mozambique Belt of Tanzania: combined Sm-Nd, Rb-Sr, and Pb-Pb isotopic evidence. Journal of Petrology 39, 749–783.

Peucat, J.J., Mahabaleshwar, B., Jayananda, M., 1993. Age of younger tonalitic magmatism and granulitic metamorphism in the South India transition zone (Krishnagiri area): comparison with older Penisular gneisses from the Gorur-Hassan area. Journal of Metamorphic Geology 11, 879–888.

Peucat, J.J., Jayananda, M., Chardon, D., Capdevila, R., Fanning, C.M., Paquette, J.L., 2013. The lower crust of the Dharwar craton, southern India: patchwork of Archean granulitic domians. Precambrian Research 227, 4–28.

Plavsa, D., Collins, A.S., Foden, J.F., Kropinski, L., Santosh, M., Chetty, T.R.K., Clark, C., 2012. Delineating crustal domains in Peninsular 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., Foden, J., Clark, C., Santosh, M., 2014. Detrital zircons in basement metasedimentary protoliths unveil the origins of southern India. Geological Society of America Bulletin 126, 791–812.

Plavsa, D., Collins, A.S., Payne, J.L., Foden, J., Clark, C., Santosh, M., 2015. The evolution of a Gondwanan collisional orogeny: a structural and geochronological appraisal from the Southern Granulite Terrane, South India. Tectonics 34, 820–857.

Prakash, D., 2010. New SHRIMP U-Pb zircon ages of the metapelitic granulites from NW of Madurai, Southern India. Journal Geological Society of India 76, 371–383.

Rainaud, C., Master, S., Armstrong, R., Robb, L., 2003. A cryptic Mesoarchean terrane in the basement to central African Copperbelt. Journal of the Geological Society, London 160, 11–14.

Ram Mohan, M., Satyanarayanan, M., Santosh, M., Sylvester, P.J., Tubrett, M., Lam, R., 2013. Neoarchean suprasubduction zone arc magmatism in southern India: geochemistry, zircon U-Pb geochronology and Hf isotopes of the Sittampundi Anorthosite Complex. Gondwana Research 23, 539–557.

Saitoh, Y., Tsunogae, T., Santosh, M., Chetty, T.R.K., Horie, K., 2011. Neoarchean high-pressure metamorphism from the northern margin of the Palghat-Cauvery Suture Zone, southern India: petrology and zircon SHRIMP geochronology. Journal of Asian Earth Sciences 42, 268–285.

Sajeev, K., Williams, I.S., 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.

Samuel, V.O., Santosh, M., Liu, S.W., Wang, W., Sajeev, K., 2014. Neoarchean continental growth through arc magmatism in the Nilgiri Block, southern India. Precambrian Research 245, 146–173.

Santosh, M., Morimoto, T., Tsutsumi, Y., 2006. Geochronology of the khondalite belt of Trivandrum Block, southern India: electron probe ages and implications for Gondwana tectonics. Gondwana Research 9, 261–278.

Santosh, M., 2013. Evolution of continents, cratons and supercontinents: building the habitable Earth. Current Science 104, 871–879.

Santosh, M., Maruyama, S., Sato, K., 2009b. Anatomy of a Cambrian suture in Gondwana: Pacific-type orogeny in southern India? Gondwana Research 16, 321–341.

Santosh, M., Maruyama, S., Yamamoto, S., 2009a. The making and breaking of supercontinents: some speculations based on superplumes, super downwelling and the role of tectosphere. Gondwana Research 15, 324–341.

Santosh, M., Xiao, W.J., Tsunogae, T., Chetty, T.R.K., Yellappa, T., 2012. The Neoproterozoic subduction complex in southern India: SIMS zircon U-Pb ages and implications for Gondwana assembly. Precambrian Research 192–195, 190–208.

Santosh, M., Yang, Q.Y., Shaji, E., Tsunogae, T., Ram Mohan, M., Satyanarayanan, M., 2015. An exotic Mesoarchean microcontinent: the Coorg Block, southern India. Gondwana Research 27, 165–195.

Santosh, M., Yang, Q.Y., Shaji, E., Ram Mohan, M., Tsunogae, T., Satyanarayanan, M., 2016. Oldest rocks from Peninsular India: evidence for Hadean to Neoarchean crustal evolution. Gondwana Research 29, 105–135.

Santosh, M., Yokoyama, K., Biju-Sekhar, S., Rogers, J.J.W., 2003. Multiple tectonothermal event in the Granulite Block of southern India revealed from EPMA dating: implications on the history of supercontinents. Gondwana Research 6, 29–63.

Santosh, M., Tsunogae, T., Malaviarachchi, S.P.K., Zhang, Z.M., Ding, H.X., Tang, L., Dharmapriya, P.L., 2014. Neoproterozoic crustal evolution in Sri Lanka: insights from petrologic, geochemical and zircon U-Pb and Lu-Hf isotopic data and implications for Gondwana assembly. Precambrian Research 255, 1–29.

Sato, K., Santosh, M., Tsunogae, T., Chetty, T.R.K., Hirata, T., 2011a. Laser ablation ICP mass spectrometry for zircon U-Pb geochronology of metamorphosed granite from the Salem Block: implication for Neoarchean crustal evolution in southern India. Journal of Mineralogical and Petrological Sciences 106, 1–12.

Sato, K., Santosh, M., Tsunogae, T., Chetty, T.R.K., Hirata, T., 2011b. Subduction-accretion-collision history along the Gondwana suture in southern India: a laser ablation ICP-MS study of zircon chronology. Journal of Asian Sciences 40, 162–171.

Sato, K., Santosh, M., Tsunogae, T., Kon, Y., Yamamoto, S., Hirata, T., 2010. Laser ablation ICP mass spectrometry for zircon U-Pb geochronology of ultrahigh-temperature gneisses and A-type granites from the Achankovil Suture Zone, southern India. Journal of Geodynamics 50, 286–299.

Shimizu, H., Tsunogae, T., Santosh, M., 2009. Spinel+quartz assemblage in granulites from the Achankovil Shear Zone, southern India: implications for ultrahigh-temperature metamorphism. Journal of Asian Earth Sciences 36, 209–222.

Sommer, H., Kröner, A., Hauzenberger, C., Muhongo, S., 2005. Reworking of Archean and Paleaoproterozoic crust in the Mozambique belt of central Tanzania as documented by SHRIMP zircon geochronology. Journal of African Earth Scienses 43, 447–463.

Sommer, H., Kröner, A., Hauzenberger, C., Muhongo, S., Wingate, M.T.D., 2003. Metamorphic petrology and zircon geochronology of high-grade rocks from the central Mozambique Belt of Tanzania: crustal recycling of Archean and Palaeoproterozoic material during the Pan-African orogeny. Journal of Metamorphic Geology 21 (9), 915–934.

Spencer, C.J., Cawood, P.A., Hawkeswoth, C.J., Prave, A.R., Roberts, N.M.W., Horstwood, S.A., Whitehoue, M.J., EIMF, 2015. Generation and preservation of continental crust in the Grenville Orogeny. Geoscience Frontiers 6, 357–372.

Sun, S.-S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders, A.D., Norry, M.J. (Eds.), Magmatism in Ocean Basins, Geological Society of London Special Publication, pp. 313–345.

Takamura, Y., Tsunogae, T., Santosh, M., Sanjeewa, P.K., Malaviarachchi, E., Tsutsumi, Y., 2016. U-Pb geochronology of detrital zircon in metasediments from Sri Lanka: implications for the regional correlation of Gondwana fragments. Precambrian Research 281, 434–452.

Teale, W., Collins, A.S., Foden, J., Payne, J.L., Plavsa, D., Chetty, T.R.K., Santosh, M., Fanning, M., 2011. Cryogenian (~830 Ma) mafic magmatism and metamorphism in the northern Madurai Block, southern India: a magmatic link between Sri Lanka and Madagascar? Journal of Asian Earth Sciences 42, 223–233.

Tsunogae, T., Yang, Q.Y., 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.

Tsunogae, T., Yang, Q.Y., Santosh, M., 2016. Neoarchean-Early Paleoproterozoic and Early Neoproterozoic arc magmatism in the Lützow-Holm Complex, East Antarctica: insights from petrology, geochemistry, zircon U-Pb geochronology and Lu-Hf isotopes. Lithos. http://dx.doi.org/10.1016/j.lithos.2016.02.010.

Wiedenbeck, M., Alle, P., Corfu, F., Griffin, W.L., Meier, M., Oberli, F., Quadt, A.V., Roddick, J.C., Spiegel, W., 1995. Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses. Geostandards and Geoanalytical Research 19, 1–23.

Yellappa, T., Santosh, M., Chetty, T.R.K., Kwon, S., Park, C., Nagesh, P., Mohanty, D.P., Venkatasivappa, V., 2012. A Neoarchean dismembered ophiolite complex from southern India: geochemical and geochronological constraints on its suprasubduction origin. Gondwana Research 21, 246–265.