Rb–Sr and Sm–Nd study of granite–charnockite association in the Pudukkottai region and the link between metamorphism and magmatism in the Madurai Block

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Pudukkottai region in the northeastern part of the Madurai Block exposes the garnetiferous pink granite that intruded the biotite gneiss. Charnockite patches are associated with both the rock types. Rb–Sr biotite and Sm–Nd whole-rock isochron ages indicate a regional uplift and cooling at ~ 550 Ma. The initial Nd isotope ratios ($\epsilon_{\text{Nd}}^t = -20$ to -22) and Nd depleted-mantle model ages ($T_{\text{DM}} = 2.25$ to 2.79 Ga) indicate a common crustal source for the pink-granite and associated charnockite, while the biotite gneiss and the charnockite within it represent an older crustal source ($\epsilon_{\text{Nd}}^t = -29$ and $T_{\text{DM}} = >3.2$ Ga). The Rb–Sr whole-rock data and initial Sr–Nd isotope ratios also help demonstrate the partial but systematic equilibration of Sr isotope and Rb/Sr ratios during metamorphic mineral-reactions resulting in an ‘apparent whole-rock isochron’. The available geochronological results from the Madurai Block indicate four major periods of magmatism and metamorphism: Neoarchaean–Paleoproterozoic, Mesoproterozoic, mid-Neoproterozoic and late-Neoproterozoic. We suggest that the high-grade and ultrahigh-temperature metamorphism was preceded by magmatism which ‘prepared’ the residual crust to sustain the high P – T conditions. There also appears to be cyclicity in the tectono-magmatic events and an evolutionary model for the Madurai Block should account for the cyclicity in the preserved records.

1. Introduction

A number of geochronological studies, during past couple of decades, has established the dominance of late-Neoproterozoic record of metamorphism in the Madurai Block (Ghosh *et al.* 2004; Santosh *et al.* 2009; Brandt *et al.* 2014 and references therein). In general, it is believed to be related to the Pan-African amalgamation of the Gondwana supercontinent along the Cauvery Shear Zone (CSZ), a site of Mozambique ocean closure (Collins *et al.* 2007; Santosh *et al.* 2009). However, a few studies suggested alternate locations to the south of the CSZ, for this late-Neoproterozoic suturing between the Archaean Dharwar craton and Proterozoic Southern

Granulite Terrain (SGT) (Ghosh *et al.* 2004; Plavsa *et al.* 2012; Brandt *et al.* 2014). Irrespective of the location of the late-Neoproterozoic–Cambrian terrane boundary, the broad tectonic framework for the evolution of the SGT remains that of the Pacific type of convergence, leading to Himalayan type of orogeny during the Pan-African accretion of the Gondwana supercontinent (Collins *et al.* 2007; Santosh *et al.* 2009).

Existing models explaining these processes are mainly based on monazite and/or zircon dating of different tectono-thermal events. However, the nature of magmatic protolith, sources of the younger magmatic episodes, and spatial and temporal links between the magmatism and metamorphism

Keywords. Granite; charnockite; Rb–Sr; Sm–Nd; geochronology; Southern Granulite Terrain; Madurai Block.

during the subduction-collision processes are still not well understood. The radiogenic isotopes of Sr and Nd help decipher the nature of protolith-source. The subsequent metamorphism of these rocks affects the Rb–Sr and Sm–Nd systematics, differently. Metamorphism is generally believed to affect the time-related accumulation of radiogenic isotopes of Sr and Nd in a mineral according to temperature dependent diffusion, resulting in higher ‘closure temperature’ of Nd than the Sr for most of the minerals. However, the effect of elemental fractionation of Rb/Sr during the melt-producing metamorphic reactions is seldom discussed while discussing the Rb–Sr and Sm–Nd results from rocks in a high-grade terrain.

We report results of Rb–Sr and Sm–Nd isotopic study from a new locality of granite–charnockite association near Pudukkottai region which falls within the northeastern part of the Madurai Block (figure 1a). We show that the late-Neoproterozoic ages as yielded by the granite–charnockite association refer to the time of regional retrogression and the peak P – T could have been significantly older than the late-Neoproterozoic. Taken together with the existing geochronological data from the other

parts, we attempt to explore the link between the magmatism and metamorphism during different time-periods finally culminating in a widespread late-Neoproterozoic metamorphic event.

2. Geological setting

Pudukkottai region is characterized by intrusive granites which are scattered in a wide area and the individual outcrops range from kilometer to less than a meter size (figure 1b). These granites are generally surrounded by gneissic rocks that vary from biotite-gneiss in the eastern part to the hornblende-biotite gneiss in the western part of the Madurai Block (GSI 2000). These are migmatized at several places within the Madurai Block. The western part of the Madurai Block, however, comprises several highlands which are generally charnockite massifs that are shown to be intrusions within the grey gneisses based on the presence of large inclusions of metapelites and calc-silicates (Rajesh *et al.* 2011; Rajesh 2012). In the eastern part, though, the charnockites occur as enclaves within the biotite gneisses, and are also intimately

Figure 1. (a) Geological map of the Southern Granulite Terrain (from Santosh *et al.* 2009) showing the study area of Pudukkottai district. The proposed boundaries within the Madurai Block by previous studies are also marked for comparison: KKPT (Ghosh *et al.* 2004), isotopic boundary (Plavsa *et al.* 2012). (b) Geological map of Pudukkottai district (GSI 2000) along with the sample locations.

associated with the intrusive K-feldspar rich granites which have plenty of coarse garnet grains.

The Palghat Cauvery Shear Zone (PCSZ) marks the northern boundary of the Madurai Block and has been interpreted variedly (Mukhopadhyay *et al.* 2003; Cenki and Kriegsman 2005; Chetty and Bhaskar Rao 2006; Brandt *et al.* 2014). Structural studies (Cenki and Kriegsman 2005) revealed refolding of the earlier gneissic foliations along the PCSZ which is consistent with the proposal that the PCSZ is a major crustal boundary between Archaean terrains in the north and Proterozoic Madurai Block. However, based on detailed geochronological studies across PCSZ, Ghosh *et al.* (2004) proposed Karur–Kambam–Painavu–Trissur (KKPT) shear zone, which lies further to the south of PCSZ, to be the terrane boundary.

Recently, based on the contrasting field-disposition of the gneisses and charnockites, Brandt *et al.* (2014) suggested that the eastern Madurai Block is a different crustal domain compared to the western Madurai Block. The eastern arm of the ‘V’ shaped KKPT shear zone separates these two domains of the Madurai Block (figure 1a). They further suggest that this NNE–SSW trending eastern arm of the KKPT marks the late-Neoproterozoic boundary between the eastern and western domains of the Madurai Block (figure 1a). In this framework, the Pudukkottai would be in the eastern Madurai domain south of the PCSZ. However, Plavsá *et al.* (2012) suggested that further to the south of KKPT, but almost paralleling it, was the boundary between

the Archaean and Proterozoic parts of the SGT. In this scenario, the Pudukkottai region would fall within the proposed ‘isotopic boundary’ (figure 1a).

The discoveries of ultrahigh-temperature metamorphism (UHT) during late-Neoproterozoic–Cambrian times, from various locations in the Madurai Block, have highlighted its complex metamorphic history (Bhaskar Rao *et al.* 1996; Raith *et al.* 1997; Sajeew *et al.* 2004, 2006, 2009; Tateishi *et al.* 2004; Santosh *et al.* 2006, 2009; Tsunogae and Santosh 2006; Braun *et al.* 2007; Sato *et al.* 2011). The eastern arm of the KKPT shear zone is in the alignment with the UHT locations (Brandt *et al.* 2014).

There have been a few reports of the early- to mid-Neoproterozoic ages now from the Madurai Block (Sato *et al.* 2011; Teale *et al.* 2011; Anderson *et al.* 2012; Brandt *et al.* 2014), since Santosh *et al.* (2009) made the compilation indicating a gap between early-Paleoproterozoic and late-Neoproterozoic (see figure 7 of Santosh *et al.* 2009). The available geochronological dataset indicates significant events during early to mid-Neoproterozoic period within the Madurai Block, though their importance in the broader framework of Wilson cycle, as proposed by Santosh *et al.* (2009) is yet to be established.

The intrusive granites in the Pudukkottai region are K-feldspar rich, pink in colour and are characterized by the presence of coarse garnet grains. Garnets, particularly, almandine rich, are generally present in S-type granite, however, there are also examples of garnetiferous meta-aluminous and A-type granites (Zhang *et al.* 2012). Major element

Figure 2. Field photographs showing patches of orthopyroxene-bearing charnockite within (a) biotite-gneiss near Pudukkottai region, (b) garnetiferous pink-granite, (c) coarse orthopyroxene grains in the charnockite within the biotite-gneiss, (d) coarse garnet grains within the quartzo-feldspathic portion in the pink-granite. Length of the hammer in figure (b) is about 45 cm.

Table 1. *Locations and details of samples analysed during the present study.*

Sl. no.	Sample name	Sample type	Location	GPS	Mineral assemblages	
					Major	Accessory
Pink granites						
1.	PDK-7B	Pink granite	Paraipatti	N10°36.588'; E078°47.323'	Kfs-Plg-Qtz-Bt-Grt	Mt-Ilm-Ms-Cal-Zrn-Mnz-Rt-Ank
2.	PDK-10B	Pink granite	Ammachatram	N10°31.448'; E078°46.739'	Kfs-Plg-Qtz-Bt-Grt	Opq-Zrn
3.	PDK-11B	Pink granite	Near Kudumyan Malai	N10°25.216'; E078°40.664'	Kfs-Plg-Qtz-Bt-Grt	Opq-Zrn
4.	PDK-11-8	Pink granite	Kudumyan Malai	N10°24.956'; E078°39.392'	Kfs-Plg-Bt-Qtz	Opq-Zrn
5.	PDK-13-7A	Pink granite	Panangudi	N10°26'01.4"; E078°43'16.7"	Kfs-Plg-Qtz-Bt-Grt	Opq-Zrn-Mnz
6.	PDK-13-13A	Pink granite	Narthamalai	N10°30'46.6"; E078°46'08.6"	Kfs-Plg-Qtz-Bt-Grt	Opq-Zrn-Mnz
7.	PDK-11-4	Pink granite	Paraipatti	N10°36.588'; E078°47.323'	Kfs-Plg-Qtz-Bt-Grt	Mt-Ilm-Ms-Cal-Zrn-Mnz-Rt-Ank
Charnockite patches in pink granites						
8.	PDK-11-5A	Charnockite	Paraipatti	N10°36.588'; E078°47.323'	Kfs-Plg-Qtz-Opx-Bt	Opq-Zrn
9.	PDK-13-7B	Charnockite	Panangudi	N10°26'01.4"; E078°43'16.7"	Kfs-Plg-Qtz-Opx-Bt	Opq
10.	PDK-13-14B	Garnetiferous Charnockite	Ammachatram	N10°31'34.7"; E078°46'37.1"	Kfs-Plg-Qtz-Opx-Bt	Grt-Opq-Zrn
Bt-gneiss						
11.	PDK-11-3	Bt-gneiss	Pallathupati	N10°35.961'; E078°46.574'	Plg-Kfs-Qtz-Bt	Mt-Ilm-Zrn
Charnockite patches in Bt-gneiss						
12.	PDK-8A	Charnockite	Pallathupati	N10°35.961'; E078°46.574'	Plg-Kfs-Qtz-Opx-Bt	Opq-Zrn

Abbreviations: Kfs: Potash feldspars; Plg: Plagioclase; Qtz: Quartz; Grt: Garnet; Opx: Orthopyroxene; Bt: Biotite; Mt: Magnetite; Ilm: Ilmenite; Zrn: Zircon; Ms: Muscovite; Opq: Opaque minerals; Cal: Calcite; Ank: Ankerite; Rt: Rutile; Mnz: Monazite; Ap: Apatite.

analyses of a representative sample from these pink granites, as published by Chandra Sekaran *et al.* (2015), indicate high SiO_2 (>70%), high $\text{K}_2\text{O}+\text{Na}_2\text{O}$ (>9%) and low CaO (~2%). The A/CNK ratio indicates meta-aluminous character of the pink-granites. Trace element results from our ongoing studies indicate that they have high Zr, Y and Ce. Therefore, by the criterion proposed by Whalen *et al.* (1987) these granites and also the charnockite patches within them would be classified as A-type granite. However, because detailed elemental data is not given in this manuscript, here they are called alkali-granites for the purpose of present discussion. Charnockites form patches within such granites and at places occur parallel to crude foliations (figure 2). Charnockite patches are

also present within the host biotite-gneiss where they make the gneissic foliations appear less prominent (figure 2a). Charnockites therefore occur in both, the biotite gneisses and the pink granites. Pudukkottai, however, is not the only region to have such charnockite–granite association within the Madurai Block. Similar types of charnockite associated with A-type pink-granite near Ayyer-malai from the northern (Sato *et al.* 2011) and near Mottamalai (Rajapalayam) in the southern parts of the Madurai Block (George *et al.* 2015) were reported earlier.

The patches of charnockite that are associated with the biotite-gneiss are similar to the various locations reporting ‘incipient charnockite’ from southern India (Pichamuthu 1960; Newton *et al.* 1980;

Figure 3. Thin section photomicrographs showing typical mineral assemblages of (a) and (b) biotite-gneiss, (c) retrogression of orthopyroxene in charnockite within the biotite-gneiss, (d) coarse garnet grain with inclusions within pink-granite, (e) inclusions of biotite within orthopyroxene in charnockite associated with the pink-granite, (f) retrogression of orthopyroxene in the charnockite associated with the pink-granite.

Ravindra Kumar *et al.* 1985; Hansen *et al.* 1987; Hansen and Harlov 2009).

3. Field relations and petrography

Samples of pink-granite and associated charnockites were collected from several quarries in the Pudukkottai region which are spread across, approximately, 30 × 20 km area (figure 1b). A couple of samples of the host biotite-gneiss and its associated charnockite patch were also analyzed. The details of sample locations, rock-types and mineral assemblages are given in table 1. The charnockites, thus occur in two different associations: (1) patches within the biotite-gneiss (figure 2a), (2) patches within the pink-granite (figure 2b).

3.1 Biotite-gneiss and associated charnockite

The biotite-gneiss, grey in colour, is the host rock for the pink-granites and has prominent gneissic foliations defined by biotite. The foliation is not very clear within the charnockite patches (figure 2a), though it appears to continue. The patches range from centimeter to meter scale. Major minerals in the biotite-gneiss are quartz, plagioclase, biotite, K-feldspar and Fe-Ti-oxides, while zircon and monazite are common accessory minerals (figure 3a, b). Perthitic feldspars and myrmekite textures are common (figure 3a, b). Rarely, biotite surrounds magnetite. Charnockite patches associated with biotite-gneiss is greenish coloured, medium to coarse grained with prominent euhedral to subhedral coarse orthopyroxene embedded in it (figure 2c). Contact between biotite-gneiss and the charnockite patches is not very sharp.

Charnockite patches consist of plagioclase, K-feldspar, quartz, orthopyroxene and biotite as major mineral constituents and opaque and zircon as minor minerals. Development of orthopyroxene at the fringe of coarse biotite grains indicates biotite dehydration reactions (figure 3c). In contrast, biotite development is seen at the boundary of few orthopyroxene grains indicating retrogressive breakdown reactions.

3.2 Pink-granite and associated charnockite

Pudukkottai granites are pink in colour, medium- to coarse-grained and crudely foliated with foliation planes marked by the alignment of biotite flakes. The granites mostly consist of K-feldspar, plagioclase, quartz, biotite and garnet with minor amounts of magnetite, ilmenite, muscovite, zircon, monazite, apatite and rutile. Although the granite is homogenous in appearance, they have some quartz-feldspar rich pegmatitic portions and biotite grains form small segregations at some

places. Garnet is medium- to coarse-grained, sub-rounded and have quartz inclusions. Notably, most of the garnets are seen within larger quartzo-feldspathic portions and along the boundary of smaller such portions (figure 2d), indicating entrainment of garnets during the melt-generation and flow (Brown 2013). Microscopic examination reveals that garnet grains have inclusions of quartz, feldspar, biotite and zircon (figure 3d). Embayed boundary of garnet grains confirm reaction with melt and inferred to represent entrainment either from the residual solid or from the early crystallized assemblage.

Charnockite patches within pink granites are medium- to coarse-grained and have gradational contact with pink granite. The charnockite patches are both parallel to foliation and oriented randomly. In some patches, grain size increases from the margin of patch to the center. K-feldspar, plagioclase, quartz, orthopyroxene and biotite are the major minerals with minor presence of magnetite, ilmenite, zircon, apatite, calcite, siderite, pyrite, chalcopyrite and chlorite. Garnet is not present in the charnockite patches, except some rare occurrences in smaller (few-centimetre size) patches. Biotite and quartz inclusions within coarse orthopyroxenes indicate biotite dehydration reactions caused the formation of orthopyroxene (figure 3e). The biotite + quartz intergrowth within orthopyroxene is considered to represent retrogressive breakdown of orthopyroxene (figure 3f). Perthite textures and myrmekites are common in the charnockites.

4. Materials and methods

Samples were prepared by conventional procedures of chipping, washing and crushing in hardened steel mortar. From the bulk samples, about 100 g of homogenized samples were taken and powdered to less than 75 microns in hardened tungsten pulveriser. For the Rb-Sr and Sm-Nd isotope studies, about 0.1 g of whole-rock samples were precisely weighed in Savilex[®] vials and a mixture of double-distilled HF+HNO₃+HCl was added to the vials and digested in high pressure steel bombs at a temperature of 150°C for about >12 hours. The samples were taken out and digested on hot plate with HNO₃+HCl mixture till clear solutions obtained. The clear solutions were made in 2N HCl. The digested samples were split into two aliquots, one part is used for isotopic composition (IC) measurement and to other part known quantity of pre-calibrated isotope tracer solution (mixed Rb-Sr and Sm-Nd solutions) were added and homogenized. The isotope tracer solution contains 6.45 µg/g of Rb, 0.92 µg/g of Sr, 0.7316 µg/g of Sm and 0.4383 µg/g of Nd. The tracer solution has the isotopic ratios of 51.6316 for ⁸⁵Rb/⁸⁷Rb, 10.1642 for ⁸⁴Sr/⁸⁶Sr, 0.00587 for ¹⁵⁴Sm/¹⁵²Sm and

Table 2. Rb–Sr and Sm–Nd isotopic compositions of samples from granite–charnockite association near Pudukkottai. The $\pm 1\sigma$ values given in the columns of $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ are errors at the last decimal place. Errors on Rb, Sr, Sm and Nd concentrations and their concentration ratios are to the order of 0.5% or better.

Sl. no.	Sample name	Sample type	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$ ($\pm 1\sigma$)	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$ ($\pm 1\sigma$)	$\epsilon_{\text{Nd}}^{t=550}$	T_{DM} (Ga)
Granite												
1	PDK-7B	Pink granite	185.5	116.9	4.617	0.767281 ± 4.2	9.371	55.69	0.1086	0.511238 ± 4.1	–21.15	2.76
2	PDK-10B	Pink granite	296.0	134.0	6.442	0.788822 ± 5.5	6.267	39.54	0.1023	0.511249 ± 3.1	–20.49	2.59
3	PDK-11B	Pink granite	147.1	113.0	3.783	0.752199 ± 3.9	0.7541	2.528	0.1926	0.511484 ± 2.5	–22.25	
4	PDK-11-8	Pink granite	200.6	231.5	2.515	0.739235 ± 6.6	8.076	66.62	0.0783	0.511133 ± 1.7	–21.1	2.26
5	PDK-13-7A	Pink granite	127.9	337.8	1.097	0.722638 ± 9.6	1.303	7.926	0.1061	0.511254 ± 1.6	–20.7	2.67
6	PDK-13-13A	Pink granite	162.8	131.9	3.588	0.755271 ± 6.4	3.272	20.49	0.1031	0.511266 ± 2.0	–20.2	2.53
7	PDK-11-4	Pink granite	148.9	93.49	4.633	0.764138 ± 4.2						
Mineral separate												
8	PDK-11-4	Biotite from Pink granite	913.2	4.859	951.14	8.3657 ± 1.7						
Charnockite in granite												
9	PDK-11-5A	Charnockite	141.7	140.4	2.932	0.751353 ± 5.8	13.24	77.61	0.1101	0.511244 ± 1.9	–21.1	2.89
10	PDK-13-7B	Charnockite	181.8	325.3	1.620	0.728071 ± 5.6	2.104	18.94	0.0717	0.511112 ± 2.0	–21.0	2.18
11	PDK-13-14B	Garnetiferous Charnockite	209.4	70.73	8.645	0.802769 ± 7.1	4.886	20.34	0.1551	0.511412 ± 2.0	–21.0	
Biotite-gneiss												
12	PDK-11-3	Bt-gneiss	71.94	498.8	0.418	0.717737 ± 6.4	0.2937	1.806	0.1050	0.510843 ± 3.5	–28.6	3.21
13	PDK-8A	Charnockite in Bt-gneiss	53.75	556.9	0.279	0.716231 ± 3.2	1.360	7.253	0.1210	0.510868 ± 3.0	–29.25	3.72
Mineral separate												
14	PDK-11-3	Biotite from Bt-gneiss	511.1	7.73	222.740	2.3901 ± 6.3	0.0800	0.3600	0.1382	0.510961 ± 5.5

Figure 4. (a) Rb–Sr whole-rock ‘apparent isochron’ indicating inheritance of initial correlated distribution of Rb/Sr and isotopic ratio. In the bottom-panel (b) is shown the linear relationship between the Sr isotope and inverse of the Sr concentrations.

222.273 for $^{150}\text{Nd}/^{146}\text{Nd}$. The sample aliquots were passed through ion exchange columns and Rb, Sr, Sm and Nd were separated and loaded on metal ribbons, viz., tantalum for Rb and Sr and rhenium for Sm and Nd, and analysed in Thermal Ionization Mass Spectrometry (Make: Thermo Finnigan; Model: TRITON), the facility available in Department of Earth Sciences, Pondicherry University. Sr and Nd isotopic compositions were normalized to the values of 0.1194 ($^{86}\text{Sr}/^{88}\text{Sr}$) and 0.7219 ($^{146}\text{Nd}/^{144}\text{Nd}$). During the analysis, SRM-987 (A certified Standard Reference Material prepared by NIST) and AMES (Caro *et al.* 2003) were analysed to monitor the stability and accuracy of the measurements. Results are plotted and isochrons were calculated using Isoplot 2.49 version of Ludwig (2001).

5. Results

The results of Rb–Sr and Sm–Nd isotopic composition and concentrations measured by isotope-dilution thermal ionization mass-spectrometry (ID-TIMS) are tabulated in the table 2.

Figure 5. Rb–Sr biotite-whole rock isochron for the (a) pink-granite (b) biotite-gneiss. Note very high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the biotite and in comparison to that the whole-rock point is close to the initial ratio.

5.1 Isochron and biotite ages

The attempts to obtain whole-rock Rb–Sr ages for the intrusive pink granite and associated patchy charnockite resulted in interesting observations. Different combinations of the samples yielded good-fit straight lines in the isochron diagram (figure 4a) but failed the test for the mixing-line as the straight-line-fit was equally good in the plot of daughter isotope ratio ($^{87}\text{Sr}/^{86}\text{Sr}$) *vs.* concentration-inverse of daughter element ($1/\text{Sr}$) indicating a strong control of daughter element concentration, rather than the decay of parent isotope (figure 4b). However, this observation reveals an important aspect of the petrogenesis of these rocks, i.e., these rocks originated by the well correlated Rb/Sr ratios, either due to binary mixing or systematic metamorphic changes. However, the biotite separated from the pink-granite and from the host biotite-gneisses yield ages of ~ 563 Ma (figure 5a) and 527 Ma (figure 5b), respectively. These biotites have very high Rb/Sr ratios (~ 950 and ~ 222) compared to the whole-rock and therefore whole-rock point serves as an estimate for the initial $^{87}\text{Sr}/^{86}\text{Sr}$ (figure 5), choice of which, does not affect the age.

The charnockite associated with the pink granite on the other hand did not yield an isochron but

Figure 6. Sm–Nd whole-rock isochron for the charnockite-pink-granite association.

defined a three-point linear-array corresponding to an age of 550 Ma. Interestingly pink-granite samples when plotted in the Sm–Nd isochron diagram along with the charnockite samples defined a tight linear-array corresponding to the similar age. These samples are randomly distributed in the Nd isotope *vs.* $1/\text{Nd}$ diagram indicating that the isochron is not a mixing line unlike the Rb/Sr system. It clearly shows that the process that causes systematic and partial redistribution of Rb/Sr and Sr isotopes (discussed in detail in section 6) did not affect the Sm/Nd budget of the whole-rock. Three whole-rock charnockite samples along with a pink-granite sample define a relatively better isochron and yields an age of 550 ± 36 Ma (MSWD = 3.4; figure 6). The age is consistent with the obtained biotite ages from the associated granite and we interpret this time to be the age of the final stabilization of charnockite after decompression related cooling of the granite–charnockite association.

5.2 Sr–Nd isotope ratios

Rajesh *et al.* (2011), in case of Nagercoil charnockite, showed that Sr isotope ratios are affected by the metamorphic overprint but Nd isotopes can still be back calculated to match initial isotope ratio of the protolith. During the present study, we find that systematic redistribution of the Rb/Sr ratio during the metamorphic reactions involving biotite, as mentioned above and discussed in the next section, caused linearly correlated $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios resulting in a good pseudo-isochron. Nd isotopes, on the other hand, seem to be re-equilibrated completely during the metamorphic reactions yielding an isochron age of ~ 550 Ma. The Nd isotope ratios, therefore, are calculated for the $t = 550$ Ma, the time of metamorphism. $\varepsilon_{\text{Nd}}^{t=550}$ values from all the samples of pink-granite and associated charnockite fall in a narrow range of -20 to -22 ε units, while that of the biotite-gneiss and its

Figure 7. (a) Nd–Sr isotope plot for the ratios corrected for an age ~ 550 Ma. The horizontal array indicates the systematic partial equilibration of the initial Sr isotope and Rb/Sr ratios which did not affect the initial Nd isotopes resulting in narrow range of the Nd isotope ratios; (b) Evolution of the Nd isotopes with time. The subparallel trends of pink-granite and biotite-gneiss indicate distinct evolutionary histories.

associated charnockite is -29 ε units indicating a common parentage for the granite-charnockite association and a different source for the biotite-gneiss and its associated charnockite (figure 7a). The depleted mantle model ages (T_{DM}) for the pink-granite–charnockite associations range from 2.18 to 2.79 Ga, while for the biotite-gneiss and the associated charnockite, the T_{DM} are 3.21 and 3.72 Ga, respectively. Evolution of Nd isotope ratios with time, starting from the separation of source from the depleted mantle, also indicates that pink-granite with its charnockite had a different path than the biotite-gneiss and its associated charnockite (figure 7b). Initial Sr isotope ratios, unlike the Nd isotopes vary in wide range. The value for the $\varepsilon_{\text{Sr}}^t$ ranges from 150 to 550. The decoupling of the Nd and Sr initial isotope ratios has significant bearing on the ages and petrogenetic process as discussed below.

6. Discussion

6.1 The late-Neoproterozoic retrogression of granite–charnockite association

The very high Rb/Sr ratio of the biotite makes it a robust geochronometer as the radiogenic Sr isotope dominates over the initial Sr akin to the U/Pb system in zircon. The choice of initial Sr isotope ratio to calculate the Rb/Sr age of a biotite is therefore not critical. However, the whole-rock Sr isotope ratio provides the best estimate for the initial Sr ratio, as isotopic equilibration between biotite and whole-rock on grain-size scale is achieved readily for the biotite. Therefore, biotite and whole-rock together provide the time at which the biotite equilibrated isotopically with the whole-rock Sr. The isotope equilibration is classically believed to be purely a temperature dependent diffusion process (Dodson 1973) and consequently, a minimum temperature, called ‘closure temperature’ can be assigned to a mineral, for a particular isotope, below which the isotope would not diffuse out of the mineral. The closure temperature concept allows assigning a temperature to the time enabling inference of T – t paths. Biotite is generally believed to have a closure temperature of $\sim 350^\circ\text{C}$ (Jager 1965; Jenkin *et al.* 2001; Nebel and Mezger 2008) for the Sr isotopes. However, this approach of closure temperature works best in the absence of fluid influx or deformation assisted recrystallization (Villa 1998). Glodny *et al.* (2008) further asserted that those minerals which were not affected by fluid-assisted recrystallization remained closed even when the rock remained above closure temperature for a significant time as shown for the relict minerals in the high-grade rocks of Norway. This implies that a generalized interpretation of isotopic age of a mineral as ‘cooling age’ needs to be relooked at and the ages needed to be interpreted in the textural and petrological context.

The petrographic observations indicate that the biotite has been part of the mineral reactions in the samples studied during the present study. Phase-equilibrium studies that we carried out for the bulk compositions of the similar granitoids (Chandra Sekaran *et al.* 2015) and some earlier studies (Endo *et al.* 2012) indicate that biotite-breakdown melting is a viable process to make orthopyroxene which is present in the charnockite patches within the granites. These studies reveal that the melt-free charnockitic assemblage having orthopyroxene and retrogressed biotite and orthopyroxene-free biotite-bearing granitic assemblage can both be stable below a pressure of ~ 6 kbar and temperatures $< 750^\circ\text{C}$. According to this model, granite-melt is generated, at higher temperature, by the biotite-dehydration reactions which form orthopyroxene.

The melt might not have been completely separated from the source thus retaining some restitic and/or peritectic phases. The melt-bearing source region when underwent cooling below 6 kbar and 750°C , crystallized granitic assemblage and at the same time some of the orthopyroxenes could have been retrograded back to the biotite. In this scenario, we interpret these biotite ages of ~ 527 Ma and ~ 563 Ma from biotite-gneiss and pink-granite respectively, the time of stabilization of retrograded mineral assemblages of granite and charnockite. The similar biotite ages from the intrusive pink-granite and from the host biotite-gneiss indicate that the stabilization is related to the regional uplift and cooling after the emplacement of pink-granite. This is further supported by the Sm–Nd whole-rock isochron age yielded by the charnockite and granite samples consistent with the proposed hypothesis of regional retrogression, affecting a large region in the eastern part of Madurai Block, between ~ 527 and 563 Ma. These ages are also similar to the only report from the Pudukkottai pink-granite which is Rb–Sr whole-rock isochron age of ~ 531 Ma (Nathan *et al.* 2001).

6.2 Evidence for the older crustal source

The Nd isotope ratios (calculated for ~ 550 Ma) of the pink-granites and associated charnockites fall in a very narrow range ($-20 \pm 2 \epsilon$ units), while the Sr isotope ratios range widely (table 2 and figure 7). The high negative values of ϵ_{Nd}^t and positive values of ϵ_{Sr}^t clearly point out a crustal source with a long residence time as reflected in depleted mantle model ages (T_{DM}) of > 2.2 Ga (table 2). The narrow range of the ϵ_{Nd}^t , further confirms that all the samples of pink-granite and associated charnockite studied were equilibrated for Nd isotope ratios at 550 Ma. The ϵ_{Nd}^t value of the biotite-gneiss is significantly different at -29ϵ units pointing towards a different source and crustal history of these rocks. Nd isotope evolution through time for the pink-granites and associated charnockites is distinctly different from the biotite-gneiss (figure 7b). Therefore, the biotite-gneiss could not have been the source for the magmas represented by pink-granites.

The T_{DM} ages of biotite-gneiss and associated charnockite are also older (3.21 and 3.72 Ga) compared to the pink-granite and associated charnockite which range between 2.25 and 2.78 Ga indicating that protolith for the biotite-gneiss was older than that of the pink-granite. However, the wide spread in initial Sr isotope ratios of the pink-granite and charnockite samples are not consistent with the model of a common source as observed by the tightly constrained Nd isotope ratios. There could be following possible reasons for initial Sr isotope ratios to have a wide range of values: (1)

mixing between the two different sources having different Rb/Sr and initial Sr ratios; (2) recent alteration causing loss of Rb to varied extents; (3) systematic partial equilibration of the Sr isotope ratios and modification of Rb/Sr ratio during the progressive biotite-breakdown dehydration and subsequent retrogression. Out of these the possibilities (1), i.e., mixing between the two sources can be ruled out by the fact that this would result in a corresponding wider range of Nd isotope ratios resulting in a mixing hyperbola on ϵ_{Nd}^t vs. ϵ_{Sr}^t diagram, instead, the sample-points define only a horizontal array (figure 7), (2) recent alteration can be ruled out as all the samples are collected from the fresh quarry surfaces and petrographic examination does not reveal any weathering related alteration and (3) systematic partial equilibration of Sr isotope during the mineral reactions in which biotite takes part. This remains a viable option as this is also consistent with the proposed petrologic evolutionary history of the granite–charnockite associations and with the earlier studies demonstrating the disturbance in Sr isotope ratios during metamorphic event (Rajesh *et al.* 2011). However, from the classical, thermal-diffusion-based understanding of the isotopic equilibration, it could be expected that a complete isotopic homogenization should have been achieved, while the final assemblage cools through the closure temperatures for Sr. But Jenkin *et al.* (2001) demonstrated that cation-exchange, which depends on the Rb and Sr concentrations in the phases involved, is an important factor in isotopic equilibration of Sr isotopes during the mineral reactions. Besides, presence of fluids, released during the dehydration reaction can also enhance the isotopic and elemental redistribution. Because the phases involved in these reactions do not control the Sm/Nd budget of the whole-rock which is mainly controlled by the phases such as garnet, monazite and zircon, the Nd isotope ratios remain unaffected by such systematic partial equilibration of Rb/Sr and Sr isotope ratios, reflecting in a decoupled relationship on ϵ_{Nd} vs. ϵ_{Sr} diagram. Further, the phases that control the Sm–Nd systematic of the whole-rock equilibrated with the melt generated during the biotite-dehydration reactions thus achieving complete isotopic equilibration as reflected in the isochron. Similar observation about Sr isotope partial equilibration was made by Glodny *et al.* (2008) for the Norwegian high-grade rocks. It, therefore, appears that the granite–charnockite samples represent different stages of Sr-isotopic equilibration through progressive mineral reactions and were not homogenized during the subsequent cooling, resulting in wide-spread Sr initial ratios. Zheng (1989) discussed this issue of partial homogenization and

inherited Sr isotopes and showed that many of such cases may result in an apparent whole-rock Rb–Sr isochron. During the present study, we find that several pink-granite samples actually define an ‘apparent isochron’ with a very good fit (figure 4a). The good-fit line on an isochron diagram remains a good-fit line in the $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $1/\text{Sr}$ plot indicating a ‘mixing line’ (figure 4b). We suggest that this apparent ‘binary mixing’ actually represents systematic cation-exchange related Sr isotopic equilibration during the progressive mineral reactions that occurred along the evolutionary path of the granite–charnockite association. Zheng (1989) has demonstrated that such kinds of apparent isochrons generally represent a case between the two extreme situations of complete homogenization and complete retention of the protolith isotopic signatures. The protolith of these rocks, could be a orthogneiss or a meta-sediment. The possibility of a metasedimentary protolith cannot be completely ruled out based only on the isotopic ratios without the detailed elemental data. However, the metasedimentary source would have also given rise to more aluminous mineral assemblage having cordierite and/or muscovite. Further, the preliminary bulk-rock chemistry of these rocks (Chandra Sekaran *et al.* 2015) does not support them to be S-type granite. In the present case, the protolith is most-likely of a granitoid composition at mid-crustal levels (Endo *et al.* 2012; Chandra Sekaran *et al.* 2015).

The youngest homogenization event is dated by the biotite to be ~ 550 Ma, and therefore, the apparent isochron is expected to yield an age between age of protolith and timing of youngest metamorphic event which does not have any geological significance except confirming that the partial equilibration was a result of progressive mineral reactions.

6.3 Previous geochronological studies and link between magmatism and metamorphism

The geochronological data, from previous studies, using different geochronometers that record different events are compiled along with the ages that are being reported in this study (table A1 in Appendix). A compilation of the ages, from the whole SGT, was earlier presented by Ghosh *et al.* (2004), Santosh *et al.* (2009) and Plavsa *et al.* (2012). The ages of the felsic orthogneisses and granites of the Madurai Block were subsequently compiled by Brandt *et al.* (2014). We have included a few more data from other lithologies which were not included and also new data that were published recently from the Madurai Block (Bhattacharya *et al.* 2014; George *et al.* 2015). The data are categorized into the magmatic/emplacement ages and metamorphic/tectono-thermal ages as interpreted by the original authors. In order to make

Figure 8. Probability density plots of the compiled ages categorized into magmatic and metamorphic.

the salient features of the dataset clear, we first discuss probability density plots of the magmatic and metamorphic ages (figure 8) and then see their temporal and spatial relationships (figure 1).

The frequency plot of magmatic ages (figure 8) indicates several episodes of magmatism and interestingly, the most number of magmatic ages are recorded around ~ 800 Ma ago. At this stage, we would like to make it clear that we do not consider the peaks in the probability density plots to represent actual dominance, either temporally or spatially, because of inherent sampling-bias in the dataset. We are also going by the interpretation of these ages as made by the authors of the original papers and assume that all the alternative possibilities such as presence of inherited zircons have been considered while interpreting the ages. In spite of the possible sample bias and misinterpretations due to the inherited zircons, the data set provides a basis to infer the sequence of tectono-magmatic events and to decipher a link between the magmatic and metamorphic events, if any. The other dominant magmatic ages, in the compiled data, are 2490–2520 Ma. Comparatively, late-Neoproterozoic magmatic ages are smaller in number. There are also several Mesoproterozoic magmatic events reported between ~ 980 and ~ 1700 Ma. When these magmatic ages are compared with the metamorphic ages, we find the three age-peaks of metamorphism that affected the Madurai Block at 554, 784 and 2458 Ma. One interesting observation that can be made here is that the peaks in metamorphic ages closely follow, in time, the peaks in magmatic ages and, although a peak in late-Neoproterozoic is a minor one in the magmatic age data, but it is a dominant peak in the metamorphic age-data. In this context, it is interesting to note that most of the ages of the ultrahigh-temperature (UHT) metamorphic events

in the Madurai Block are reported to be late-Neoproterozoic (Santosh *et al.* 2006, 2008) except one which is mid-Neoproterozoic somewhere between 950 and 850 Ma (Braun *et al.* 2007). This observation of timing of UHT events relative to the granitoid magmatism is important for inferring tectonic setting of the Madurai Block. Kelsey and Hand (2015), while reviewing the world-wide occurrences of the UHT events pointed out that one important condition for achieving UHT, out of many others, is to have the crust ‘pre-conditioned’ by prior episodes of melt-extraction. This is consistent with the timing of magmatism relative to UHT in the Madurai Block. The late-Neoproterozoic UHT metamorphism followed the mid-Neoproterozoic magmatism.

The mid-Neoproterozoic period is the time of emplacement of granitoids and charnockites. Several ages of crystallization or emplacement falling between ~ 850 to 730 Ma are reported from the Madurai Block (Santosh *et al.* 1989; Ghosh *et al.* 2004; Pandey *et al.* 2005; Teale *et al.* 2011; Plavsa *et al.* 2012; Brandt *et al.* 2014; George *et al.* 2015). The garnet-bearing granite–charnockite association as reported by George *et al.* (2015) from the Mottamalai hills (Rajapalayam) is similar to what has been studied near Pudukkottai during the present study. Other than the granitoids, significant magmatism during this period at ~ 830 Ma is that of gabbro-anorthosite sequence near Kadavur (Kooijman *et al.* 2011; Teale *et al.* 2011).

Next to the mid-Neoproterozoic period, late-Paleoproterozoic–Neoproterozoic seems to be the period of wide-spread magmatism in the Madurai Block (table A1) (Bartlett *et al.* 1998; Ghosh *et al.* 2004; Plavsa *et al.* 2012; Bhattacharya *et al.* 2014; Brandt *et al.* 2014). Many of these granitoids are orthopyroxene-bearing or are associated with an orthopyroxene-bearing granitoid. Some of the locations, such as Kodaikanal (Plavsa *et al.* 2012), Dharapuram (Brandt *et al.* 2014) are shown to have experienced granulite-facies metamorphism coeval with the magmatism or soon after it. The late-Neoproterozoic metamorphism has affected almost all these locations.

The existing geochronological dataset, therefore, leads to the following generalized observations: (1) Granitic and associated charnockitic (orthopyroxene-bearing granitoid) magmatism occurred during Neoproterozoic–Paleoproterozoic, Mesoproterozoic and mid-Neoproterozoic periods within the Madurai Block. (2) The granulite-facies metamorphism and UHT metamorphic events followed the magmatic events and (3) the record of late-Neoproterozoic metamorphism has been preserved throughout the Madurai Block. With these observations it is difficult to suggest that the episodes of the metamorphism, earlier than the late-Neoproterozoic,

were not as widespread because the dataset more likely reflects the preservation of the records rather than the occurrences. These observations, however, clearly brings out the causal relationship between the magmatism and high-grade metamorphism. It is long-known from the experimental petrology and field-observations that increase in P – T conditions of the crust along the ‘normal’ geothermal gradient would cause crustal melting before the high-grade, and particularly UHT, metamorphic conditions are achieved (Kelsey and Hand 2015). Kelsey and Hand (2015), cite numerous studies (Vielzeuf *et al.* 1990; Brown and Korhonen 2009; Clark *et al.* 2011) to emphasize that mid-lower crust would start melting inhibiting the temperature rise to the UHT range. It, therefore, appears that the UHT and also the high-grade metamorphism are possible only in the crust which was made refractory by earlier episodes of melting. This provides explanation for the above observation of metamorphism following the magmatism in the Madurai Block which also has several locations of UHT metamorphic events. It also points out towards a common heat-source for the magmatism and metamorphism and could be related to the tectonic setting. In a recent paper, Clark *et al.* (2015) discussed this problem of heat source in detail. Based on the 1-D numerical modelling, they showed that radiogenic heat could be a potential heat source and needs to be evaluated against the other possibility of mantle upwelling. The two possible heat sources might be related to the two different tectonic scenarios. However, Kelsey and Hand (2015) reviewed all the possible tectonic settings that were proposed for the UHT metamorphism and concluded that P – T – t paths alone are not enough to infer the tectonic setting and neither any generalization can be made for it.

In the light of compiled geochronological data, any tectonic model has to account for the four main periods of magmatic and metamorphic activities. It is also noteworthy that the early-Neoproterozoic granitoids and associated charnockite indicate mantle inputs (Bhattacharya *et al.* 2014), while the similar association in the mid-Neoproterozoic indicates crustal reworking (George *et al.* 2015) which is also consistent with Sr–Nd results obtained during the present study on the Pudukkottai granite–charnockite association. Pudukkottai region also preserves the two generations of the granitoid–charnockite associations, the older biotite–gneiss–charnockite and the younger pink-granite–charnockite with clearly different Nd isotopic ratios and T_{DM} ages. These evidences indicate that even though an episode of magmatism would have left the residual crust ‘infertile’ and ready for the high-grade/UHT metamorphism, it could have also been hydrated again probably by subduction processes. A cyclic opening and closing within

the Madurai Block therefore could not be ruled out. In this regard, the two periods with significant magmatic and metamorphic activity are also marked by largely mantle-derived anorthosite–gabbro suite of rocks, Sittampundi (at northern extreme of the Madurai Block generally included within CSZ domain) in the Neoarchaeon (Bhaskar Rao *et al.* 1996; Ram Mohan *et al.* 2013) and Kadavur (Kooijman *et al.* 2011; Teale *et al.* 2011) in mid-Neoproterozoic. These episodes of mafic–ultramafic magmatism could be taken as evidences to support the hypothesis that the mantle-derived magma was the much sought after heat-source for the magmatism and metamorphism. Taking together all the evidences, as discussed above, we propose that Madurai Block might have experienced opening and closing of the oceans during the Neoarchaeon–Paleoproterozoic, Mesoproterozoic, mid-Neoproterozoic and late-Neoproterozoic periods. The locations of these openings and closures would require even more detailed dataset and careful correlations with the contemporary adjoining crustal blocks.

7. Conclusions

Pudukkottai region in the northeastern part of the Madurai Block exposes scattered outcrops of garnetiferous pink-granite intruding into biotite–gneiss which is the common country rock, particularly in the eastern Madurai Block. Orthopyroxene-bearing granites (charnockites) are associated with both generations of granitoids and are preserved as cm to m scale patches. Rb–Sr and Sm–Nd isotopic studies indicate that granite and charnockite both have experienced late-Neoproterozoic retrogression during which the charnockitic assemblage got preserved in patches which would have formed earlier during high-temperature breakdown of biotite causing dehydration melting. Further, the initial Sr and Nd isotopic ratios indicate a common source for the pink-granite and charnockites but systematic redistribution of Sr isotopes and Rb/Sr ratios occurred during the biotite-breakdown reactions.

The compilation of geochronological data from the Madurai Block indicates four major periods of magmatism followed by the metamorphism: late-Neoarchaeon–Paleoproterozoic, Mesoproterozoic, mid-Neoproterozoic and late-Neoproterozoic. We suggest that the magmatism prepared the residual mid-lower crust to undergo high-grade/UHT metamorphism which is reflected in the younger metamorphic ages. However, the metamorphic episodes either coeval with or preceding the magmatism cannot be ruled out as the present-dataset only indicate the preservation of the record.

Appendix 1

Table A1. Compilation of the available geochronological data from Madurai Block, Southern Granulite Terrain.

Sl. no.	Location	Rock type	Crystallization/ emplacement age (Ma)	Metamorphic/ thermal event age (Ma)	Isotope system	WR/Min	Reference
1	Kodaikanal	Meta-granite	2436 ± 11		²⁰⁶ Pb/ ²⁰⁷ Pb	Zircon evaporation	Bartlett et al. (1998)
2	Kadavur	Gabbro-anorthosite	829 ± 14		U-Pb	Zircon LA-ICP-MS	Teale et al. (2011)
3	Kadavur	Quartzite		843 ± 23	U-Pb	Zircon LA-ICP-MS	Teale et al. (2011)
4	Kadavur	Felsic gneiss	765.6 ± 8.1		U-Pb	Zircon LA-ICP-MS	Teale et al. (2011)
5	Cardamom	Charnockite	1565 ± 112		U-Pb	Zircon	Miller et al. (1996)
	Cardamom	Charnockite	588 ± 6		U-Pb	Zircon	Miller et al. (1996)
6	Theni	Qtz monzodiorite	2525 ± 25	518 ± 11	U-Pb	Zircon LA-ICP-MS	Plavsa et al. (2012)
7	Theni	Granite (Foliated)	795 ± 17	620 ± 16, 544 ± 34	U-Pb	Zircon LA-ICP-MS	Plavsa et al. (2012)
8	Kodaikanal	Opx bearing granodiorite	2689 ± 26	2494 ± 37, 525 ± 7	U-Pb	Zircon LA-ICP-MS	Plavsa et al. (2012)
9	Kodaikanal	Opx bearing granodiorite	2504 ± 20	512 ± 13	U-Pb	Zircon LA-ICP-MS	Plavsa et al. (2012)
10	Kodaikanal	Opx bearing granodiorite	2501 ± 19	540 ± 8	U-Pb	Zircon LA-ICP-MS	Plavsa et al. (2012)
11	Karur	Granodiorite	2520 ± 17	448 ± 59	U-Pb	Zircon LA-ICP-MS	Plavsa et al. (2012)
12	Near Kangayan	Qtz-diorite	2500	520	U-Pb	Zircon LA-ICP-MS	Plavsa et al. (2012)
13	Munnar	Granodiorite	2527 ± 8		U-Pb	Zircon LA-ICP-MS	Plavsa et al. (2012)
14	Sivagiri	Granodiorite	989 ± 21		U-Pb	Zircon LA-ICP-MS	Plavsa et al. (2012)
			798 ± 22	564 ± 9			
15	Sivagiri	Monzodiorite	781 ± 8	544 ± 8	U-Pb	Zircon LA-ICP-MS	Plavsa et al. (2012)
16	Sivagiri	Qtz monzodiorite	1007 ± 23	499 ± 50	U-Pb	Zircon LA-ICP-MS	Plavsa et al. (2012)
17	Dharapuram	Migmatitic Grt-Opx gneiss	2493 ± 10	2472 ± 15 to -17, 736 ± 55	²⁰⁷ Pb/ ²⁰⁶ Pb	Zircon LA-ICP-MS	Brandt et al. (2014)
18	Cardamom hill	Migmatitic charnockite	2464 ± 21 to -23	1024 ± 69, 550 ± 3	²⁰⁷ Pb/ ²⁰⁶ Pb	Zircon LA-ICP-MS	Brandt et al. (2014)
19	Pollachi	Migmatitic charnockite	794 ± 6	556 ± 4	U-Pb	Zircon LA-ICP-MS	Brandt et al. (2014)
20	Munnar granite	Hbl-Bt gneiss	804 ± 6	549 ± 10	U-Pb	Zircon LA-ICP-MS	Brandt et al. (2014)
21	Near Kadavur	Migmatitic Hbl-Bt gneiss	1739 ± 62	821 ± 33, 522 ± 160	U-Pb	Zircon LA-ICP-MS	Brandt et al. (2014)
22	Near Kodaikanal hill Near Kodaikanal hill	Migmatitic charnockite	2874-1835 1619 ± 8	557 ± 3	²⁰⁷ Pb/ ²⁰⁶ Pb Concordia age	Zircon LA-ICP-MS	Brandt et al. (2014) Brandt et al. (2014)

Table A1. (Continued.)

Sl. no.	Location	Rock type	Crystallization/ emplacement age (Ma)	Metamorphic/ thermal event Age (Ma)	Isotope system	WR/Min	Reference
23	Sirumalai Hills	Meta-rhyolitic Grt-Cpx gneiss	1560 ± 41		U-Pb	Zircon LA-ICP-MS	Brandt <i>et al.</i> (2014)
24	Varshanad Hills	Migmatitic charnockite	821 ± 19	810 ± 13 to -15, 353 ± 120	U-Pb	Zircon LA-ICP-MS	Brandt <i>et al.</i> (2014)
25	Sirumalai Hills	Porphyritic charnockite	818 ± 51 to -54 1761 ± 28 795 ± 3	622 ± 9, 578 ± 7	U-Pb	Zircon LA-ICP-MS	Brandt <i>et al.</i> (2014)
26	Rangamalai Hills	Porphyritic charnockite	2700 788 ± 4	768 ± 69, 650 ± 46 662 ± 46 2520 ± 25 784 ± 6, 563 ± 33	²⁰⁷ Pb/ ²⁰⁶ Pb ²⁰⁷ Pb/ ²⁰⁶ Pb	Zircon LA-ICP-MS Zircon LA-ICP-MS	Brandt <i>et al.</i> (2014)
27	Southern slope of Sirumalai Hills	Meta-leucogabbro	1660 ± 29		²⁰⁷ Pb/ ²⁰⁶ Pb	Zircon LA-ICP-MS	Brandt <i>et al.</i> (2014)
28	Mottamalai Hills	Garnetiferous granite	811 ± 4	785 ± 4, 550 ± 8	U-Pb	Zircon LA-ICP-MS	George <i>et al.</i> (2015)
29	Mottamalai Hills	Charnockite	836 ± 76 831 ± 31		U-Pb	Zircon	George <i>et al.</i> (2015)
30	Mottamalai Hills	Incipient charnockite		722 ± 49	U-Pb	Zircon	George <i>et al.</i> (2015)
31	Usilampatti region	Calc-granulite	1339 ± 10		Rb-Sr	WR	Pandey <i>et al.</i> (2005)
32	Usilampatti region	Granite	823 ± 38		Rb-Sr	WR	Pandey <i>et al.</i> (2005)
33	Usilampatti region	Leptynite	894 ± 82		Rb-Sr	WR	Pandey <i>et al.</i> (2005)
34	Usilampatti region	Pegmatite		491	Rb-Sr	Muscovite	Pandey <i>et al.</i> (2005)
					(Model Age)		
	Usilampatti region	Pegmatite		532	Rb-Sr	Microcline	Pandey <i>et al.</i> (2005)
					(Model Age)		
35	Karur	Granite gneiss	2542 ± 17		U-Pb	Zircon TIMS	Ghosh <i>et al.</i> (2004)
36	Kotamangalam	Granite gneiss	2511 ± 27 571 ± 114		U-Pb	Zircon TIMS	Ghosh <i>et al.</i> (2004)
37	Kotamangalam	Granite	567 ± 2		U-Pb	Zircon TIMS	Ghosh <i>et al.</i> (2004)
38	Rangamalai	Charnockite	796 ± 1		U-Pb	Zircon TIMS	Ghosh <i>et al.</i> (2004)
39	Munnar	Charnockite	2634 ± 43	582 ± 25	U-Pb	Zircon LA-ICP-MS	Bhattacharya <i>et al.</i> (2014)
40	Munnar	Charnockite	2465 ± 56	543 ± 24	U-Pb	Zircon LA-ICP-MS	Bhattacharya <i>et al.</i> (2014)
41	Munnar	Granite	2499 ± 29	519 ± 87	U-Pb	Zircon LA-ICP-MS	Bhattacharya <i>et al.</i> (2014)

Table A1. (Continued.)

Sl. no.	Location	Rock type	Crystallization/ emplacement age (Ma)	Metamorphic/ thermal event age (Ma)	Isotope system	WR/Min	Reference
42	Munnar	Granite		519 ± 9	U-Pb	Zircon LA-ICP-MS	Bhattacharya et al. (2014)
				540 ± 9	U-Pb	Zircon LA-ICP-MS	Bhattacharya et al. (2014)
43	Kodaikanal	Enderbitic gneiss	2534 ± 9	646 ± 10	U-Pb	Zircon LA-ICP-MS	Bhattacharya et al. (2014)
44	Pudukkottai	Pink granite	531 ± 20	556 ± 4	U-Pb	Zircon LA-ICP-MS	Brandt et al. (2014)
45	Vanji Nagaram	Granite	620 ± 43		Rb-Sr	WR	Nathan et al. (2001)
46	Pettupparai (near Perumalmalai)	Spr-bearing granulite	2509 ± 12	550 ± 15	Rb-Sr U-Pb SHRIMP	WR Zircon	Nathan et al. (2001) Prakash (2010)
47	South of Perumalmalai	Grt-Crd bearing gneiss	2509 ± 30	530 ± 50	U-Pb SHRIMP	Zircon	Prakash (2010)
48	Kodaikanal	Charnockite		553 ± 15	Sm-Nd	WR+Grt	Jayananda et al. (1995)
49	Pudukkottai	Charnockite and pink granite		550 ± 36	Sm-Nd	WR	This study
50	Pudukkottai	Pink granite		563.3 ± 0.28	Rb-Sr	WR-Bt	This study
51	Pudukkottai	Bt-gneiss		527.8 ± 2.6	Rb-Sr	WR-Bt	This study

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