Geochemical characteristics of Proterozoic granite magmatism from Southern Granulite Terrain, India: Implications for Gondwana

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Granitoid intrusions occur widely in the Southern Granulite Terrain (SGT) of India, particularly within the Cauvery Suture Zone (CSZ), which is considered as the trace of the Neoproterozoic Mozambique ocean closure. Here we present the petrological and geochemical features of 19 granite plutons across the three major tectonic blocks of the terrain. Our data show a wide variation in the compositions of these intrusions from alkali feldspathic syenite to granite. The whole rock geochemistry of these intrusions displays higher concentrations of SiO_2 , FeO^* , K_2O , Ba, Zr, Th, LREE and low MgO , Na_2O , Ti, P, Nb, Y and HREE's. The granitoids are metaluminous to slightly peraluminous in nature revealing both I-type and A-type origin. In tectonic discrimination plots, the plutons dominantly show volcanic arc and syn-collisional as well as post-collisional affinity. Based on the available age data together with geochemical constrains, we demonstrate that the granitic magmatism in the centre and south of the terrain is mostly associated with the Neoproterozoic subduction–collision–accretion–orogeny, followed by extensional mechanism of Gondwana tectonics events. Similar widespread granitic activity has also been documented in the Arabian Nubian shield, Madagascar, Sri Lanka and Antarctica, providing similarities for the reconstruction of the crustal fragments of Gondwana supercontinent followed by Pan-African orogeny.

Keywords. Southern granulite terrain; Cauvery suture zone; I-type and A-type granites; Neoproterozoic subduction; Gondwana.

1. Introduction

Granitoid intrusions represent a large part of the continental crust and occur in different tectonic environments (Pitcher 1993). The generation and emplacement of granitic magmas in space and time represent a major contribution to the growth and recycling of continental crust (Castro *et al.* 1999a; Patino Douce 1999). In general, the crustal melting and mixing of mantle are the major processes

that generate granitoids (Clark *et al.* 1997). The genetic classification of granites is based on the nature of origin considering those derived from sedimentary protolith as S-type, igneous protoliths as I-type, recycled and hydrated continental crust as A-type, and those evolved directly from subducted oceanic crust or overlying mantle as M-type (Chappell and White 1974; Collins *et al.* 1982; Whalen *et al.* 1987). Based on their tectonic environment, granitoids have been classified as island arc

granitoids (IAG); continental arc granitoids (CAG); continental collision granitoids (CCG); post-orogenic granitoids (POG); rift-related granitoids (RRG); continental epirogenic uplift granitoids (CEUG); and oceanic plagiogranites (OP). Among these, the IAG, CAG, CCG, and POG are considered as orogenic granitoids, whereas the RRG, CEUG and OP are considered as anorogenic granitoids (Maniar and Piccoli 1989). Granitic magmatism usually spreads over a wide range of settings including volcanic areas, continental shields and orogenic belts. It has been well established that during orogenesis, dynamic melting of anisotropic crust due to differential stresses leads to heterogeneous deformation which enables granite extraction, ascent and emplacement (e.g., Brown 1994; Sawyer 1994; Collins and Sawyer 1996; Rushmer *et al.* 1998). Granitoid formations associated with major collisional events have been traced around the world since Archean to Phanerozoic (Burg and Ford 1997). The Neoproterozoic Pan-African orogeny (850–550 Ma; Kroner 1980; Shackelton 1986) is one of the events where large-scale tectonics of continental convergence, deformation, metamorphism and granitic magmatic activity occurred within the Gondwana crustal fragments including South America, Africa, Australia, India and Antarctica (Kusky *et al.* 2003; Kroner and Stern 2004). This magmatism mainly represented by granites, alkaline granites and syenites is widely reported particularly from the Eastern Gondwana continents, i.e., India, Sri Lanka, Madagascar, East Antarctica and Western Australia (Rajesh *et al.* 1996; Collins 2003; Jacobs *et al.* 2003; Ghosh *et al.* 2004; Santosh *et al.* 2005). In India, the central domain of the Southern Granulite Terrain has witnessed widespread felsic alkaline magmatism during the Neoproterozoic period (Nathan *et al.* 2001; Ghosh *et al.* 2004). In addition, there are several Neoproterozoic–Paleoproterozoic granitoid intrusions, charnockites related magmatic suites occur in several parts of the terrain (Ghosh *et al.* 2004; Clark *et al.* 2009; Saitoh *et al.* 2011). The Neoproterozoic granitoids are mostly restricted to central and southern parts of Tamil Nadu and Kerala states. Further, several intrusions have occurred along the E–W trending Cauvery Suture Zone (CSZ) and towards its north as well as to its south as described by several workers (e.g., Gopalakrishnan 1994). Previous studies have correlated this magmatism to Archean crustal thickening (Drury *et al.* 1984), Precambrian continent–continent collision and southward subduction of Dharwar craton

(Rai *et al.* 1993) and crustal recycling. Based on isotopic ages of several granitic rocks from southern India, it is defined as two contrasting age provinces, the northern Dharwar craton of Archean age and the southern mobile belt of Proterozoic age with the CSZ marking the boundary between the two blocks (Harris *et al.* 1994). Some of the granitic rocks occur near the transition zone around Krishnagiri in the northern part of Tamil Nadu ranging in age from 3400 to 1000 Ma (Monard 1983) and have been classified into I-type and S-type (Condie *et al.* 1982, 1986; Dhanaraju *et al.* 1983; Chandrasekharan 2002). Whereas many of the granitoids occurring within the CSZ and south of the CSZ are of Neoproterozoic age. Recently, it is also described that the Mesoproterozoic granitoids of 3184.0 ± 5.5 Ma, 3170.3 ± 6.8 Ma (Santosh *et al.* 2015) and also the occurrence of Hadean felsic continental crust in the northwestern part of the terrain within the Coorg Block (Santosh *et al.* 2016). In this paper, we present the mean geochemical data of 19 granitic plutons, particularly of SGT in the three different tectonic blocks including Northern Block of the terrain, CSZ and Madurai Block (figure 1) and evaluated their petrogenesis and tectonic implications for Gondwana supercontinent.

2. Geological setting

The SGT in India is one of the largest exposed Precambrian deep continental crustal sections in southern India, consisting of multiple deformed Archean and Neoproterozoic high-grade metamorphic and magmatic rocks. The important lithologies comprise tonalitic gneisses, migmatites with high-grade assemblages of garnet-bearing felsic-mafic granulites, charnockites, dismembered mafic and ultramafic rocks, magnetite-rich quartzites and granitoids. The terrain has been divided into a number of distinct crustal blocks based on the structural and isotopic evolution from the north to south: (1) the Northern Block, (2) the Nilgiri Block, (3) the Salem–Madras Block, (4) Cauvery Suture Zone (CSZ), (5) the Madurai Block, and (6) the Trivandrum Block, (figure 1; Naqvi and Rogers 1987; Santosh 1996; Bartlett *et al.* 1998; Chetty and Bhaskar Rao 2006; Ramakrishnan and Vaidyanathan 2008; Clark *et al.* 2009; Santosh *et al.* 2009; Plavsa *et al.* 2012; Collins *et al.* 2014). The Northern Block is described below the ‘Fermor line’ and is dissected into three major blocks

Figure 1. Geological map of southern India showing the distribution of granite plutons in major tectonic blocks (modified after Santosh and Sajeew 2006 and source from Geological Survey of India maps). Shear Zones. M: Moyar, Bh: Bhavani, Me: Mettur, Pa-Ca: Palghat-Cauvery, Ga: Gangavalli CSZ: Cauvery Suture Zone, AKSZ: Achankovil Shear Zone, WDC: Western Dharwar Craton, EDC: Eastern Dharwar Craton, Tz: Transition Zone. Location of the granite plutons are also shown in the map.

by a central zone of faults and ultrabasic-alkaline magmatism (Ramakrishnan 2003). The block consists of massive charnockites that are interbedded with supracrustals, bands of fuchsite-kyanite-sillimanite quartzites, cordierite-sillimanite-kyanite schist, calc-granulites, limestones, several bands of amphibolites and banded iron formations. Several bodies of ultrabasic-alkaline-syenite-carbonatite complexes and granitoids have also emplaced within hornblende gneisses (Gopalakrishnan 1994; Ramakrishnan 2003). The Nilgiri Block, which occurs northwest of the terrain, predominantly consists of strongly deformed and migmatized garnetiferous rocks, enderbite granulites, charnockite masifs with minor contributions of kyanite-bearing gneisses, alkali granites, quartzites and metabasites

(Peucat *et al.* 1989; Janardhan *et al.* 1994) that form highland areas interspersed with low-lands consisting of felsic rocks generally in amphibolite facies. The Salem-Madras Block occurs in north-east of the terrain and consists of orthogneiss, charnockite, mafic granulite and ultramafic intrusions in association with metasedimentary units, a succession that continues up to the Palghat-Cauvery Shear Zone (PCSZ), and the entire zone is termed as Cauvery Suture Zone and is considered as the trace of the Cambrian suture zone of Gondwana (Collins *et al.* 2007). Based on the U-Pb SHRIMP ages from charnockites of Salem-Madras Block, Clark *et al.* (2009) described the magmatism at ca. 2530 Ma age and subsequent high-grade metamorphism and partial melting at

ca. 2480 Ma. The available geochronological data on the protoliths of the Salem Block indicate Mesozoic to Neoproterozoic rocks stretching as far south as the PCSZ, with metamorphic ages indicating a granulite facies event in the latest Archean to early Proterozoic times (Peucat *et al.* 1993). The Salem Block also represents the southernmost extent of the Archean Dharwar craton, which is separated from the Archean to Proterozoic Madurai Block by the Cauvery Suture Zone (CSZ, figure 1). The CSZ is made up of Neoproterozoic and Neoproterozoic oceanic type subduction complexes including ophiolitic melanges, high-pressure eclogites and ultra-high temperature sapphirine bearing rocks, mafic ultramafic complexes, charnockites, two pyroxene granulites, island-arc volcanic rocks, quartz-feldspathic hornblende gneisses with several events of granite (Viswanathan *et al.* 1990; Gopalakrishnan 1994; Hussain *et al.* 1996; Santosh *et al.* 2009, 2013; Yellappa *et al.* 2010, 2012). The CSZ extends from west coast to east coast with a distance of about 400 km and a width of ~60 km and comprises a network of shear zones. Chetty *et al.* (2003) described several shear networks of CSZ including Moyar–Bhavani Shear Zone (MBSZ), the Chennimalai–Noyil Shear Zone (CNSZ), the Dharapuram Shear Zone (DSZ), the Devattur–Kallimandayam Shear Zone (DKSZ) and the Karur–Oddanchatram Shear Zone (KOSZ) in the central part of the CSZ. While the Moyar–Bhavani–Attur Shear Zone represents the northern margin, the Palghat–Cauvery Shear Zone marks the southern margin. There are three ophiolitic complexes that have been described recently from the CSZ; (i) Neoproterozoic Manamedu Ophiolite Complex (MOC), occurring at the northern bank of the Cauvery river course, 40 km south east of Namakkal, (ii) Devanur Ophiolite Complex (DOC) of Neoproterozoic age (Santosh *et al.* 2012; Yellappa *et al.* 2012) located about 20 km north of MOC, and (iii) Neoproterozoic Agali Ophiolite Complex (AOC), that has been reported from the Agali hill near Attappadi, along the western extension of the CSZ/Bhavani Shear Zone (Santosh *et al.* 2013). The entire rock sequence of this Agali complex has been interpreted to represent a typical ‘Ocean Plate Stratigraphy’ sequence with arc and exhumed sub-arc mantle material (Santosh *et al.* 2013). Recently, Yellappa *et al.* (2014) also described the mafic and ultramafic complex of Aniyapuram near Mohanur as a dismembered ophiolite suite of Neoproterozoic to Paleoproterozoic age (Koizumi *et al.* 2014). All these ophiolite

complexes were evolved under two major events of suprasubduction zone tectonics ranging from Neoproterozoic to Neoproterozoic periods.

The Madurai Block/Madurai Granulite Block (MGB) occurs immediately south of the CSZ and is the largest crustal block in southern India. This block comprises dominantly of charnockite massifs intercalated with tonalitic/granodioritic gneisses and elongated narrow belts and slivers of metasedimentary rocks including quartzites, metamorphosed carbonates, iron formations and pelites, all suggesting an accretionary realm (Santosh *et al.* 2009). A N–S trending Karur–Kambam–Painavu–Trissur Shear Zone (KKPT) runs within the centre of MGB (Ghosh *et al.* 1998, 2004). The MGB can be lithologically divided into a western region and an eastern region (Cenki and Kriegsman 2005). The western part is characterized by two different groups of hornblende-biotite and orthopyroxene-biotite (charnockite) gneisses, one being quartz rich and the other is feldspar-rich rock, and alkali granites. The eastern part is composed of massive charnockites and enderbites with heterogeneously distributed quartzites and calc-silicate series of rocks (Cenki and Kriegsman 2005). The southern boundary of the Madurai Granulite Block is marked by the Achankovil Shear Zone (AKSZ), which also separates the Madurai Block from the Trivandrum Block in the south. The Trivandrum Block is sub-divided on lithological grounds into three tectonic units: the Kerala Khondalite Belt (KKB), the Nagercoil unit and the Achankovil metasediments. Trivandrum Block comprises dominantly of metasedimentary gneisses including garnet-bearing felsic gneisses (known locally as leptynites), orthopyroxene, hornblende, and biotite ($\pm$ garnet)-bearing intermediate to acid granulites of broadly granitic composition (charnockites to enderbites), granulite facies garnet+spinel+cordierite+sillimanite metapelites (termed khondalites) and garnet-bearing quartz-feldspathic gneisses interlayered with charnockites (Rajesh 2004; Ramakrishnan and Vaidyanathan 2008). Calc-granulites, quartzites and ultramafic rocks also occur as linear bodies parallel to the local structural trends. These lithologies constitute a vast sequence of continental margin sediments originally defined as the Kerala Khondalite Belt (KKB; Chacko *et al.* 1987). Achankovil Shear Zone (AKSZ) holds a key position in juxtaposing the member terrains in eastern Gondwana supercontinent and has been correlated with the sinistral Ranostara Shear Zone of Madagascar (e.g., Ramakrishnan 1991;

Paquette *et al.* 1994; Windley *et al.* 1994; Kriegsman 1995). Garnet- and biotite-bearing leucogranites are abundant throughout the KKB and formed from high-T dehydration-melting of the various KKB gneisses at granulite-facies conditions subsequent to the main stage of Pan-African ductile deformation. Neoproterozoic magmatic events and occurrences of 590–560 Ma age of granite within the shear zone have also been reported from AKSZ by several workers (Rajesh *et al.* 1996; Bohm *et al.* 2003; Santosh *et al.* 2005; Braun 2006).

2.1 Granitic magmatism

The southern granulite terrain was episodically active in the Neoproterozoic to early Paleozoic times with acid magmatism represented by granites spreading across the tectonic boundaries (Rajesh *et al.* 1996; Ghosh *et al.* 2004). The Neoproterozoic to Paleoproterozoic granitoids mostly confined to Northern Block are Tiruttani, Sholingar, Bisanattam, Ebbari and Krishnagiri (2500 Ma; GSI 1978; Krogh and Hanson 1988; Peucat *et al.* 1993). Some of the granites including Veppanapalli, Vaniyambadi, Krishnagiri, Bargur and Jakkampatti from this block also occur similar to the above granites. In Salem–Madras Block, there are several occurrences of Neoproterozoic and Neoproterozoic granites. Metamorphosed granite of Salem, Kanjimalai, Tiruvannamalai and Tirukovilur granites are of Neoproterozoic to Paleoproterozoic in age, and are mostly associated with peninsular gneiss and migmatitic complex. It is also described that some of the granites at Kullampatti and younger granites of Chalk Hills belongs to Neoproterozoic age. In the CSZ there are several occurrences, some important plutons of Neoproterozoic granites such as Kangayam, Palladam, Aravakurchi, Dharapuram, Sankari, Tiruchengodu, Karamadai, Udhiyur, Puliampatti and Kabilar-malai (figure 1). Many of these intrusions are small (<20–40 km² exposures) and trending E–W or NW–SE, in the form of elongated elliptical bodies emplaced within the older migmatized felsic gneisses and charnockites. There are two phases of these varieties: a leucocratic medium-grained pegmatoidal granitic phase of Sankari–Tiruchengodu, and Puliampatti coarse-grained pink pegmatoidal granites of Karamadai and Marudamaili whose composition ranges from alkali granite to quartz-monzonites (Nathan *et al.* 1994). In general, many of the granites from the CSZ are medium- to

coarse-grained and contain various amounts of mafic minerals, biotite and hornblende along with felsic minerals, and are mostly granodioritic to monzogranitic in composition with few granites (e.g., Pollachi–Udumalpet) belong to syenite, syenodiorite and monzogranite to tonalitic varieties (Mallikharjuna Rao *et al.* 2005). The Peralimala, Ezhimala, Kalpatta and Ambalavayal are some of the granites of Neoproterozoic age described in Nilgiri Block emplaced within the high-grade rocks and these are mostly in alkaline nature (Santosh *et al.* 1986, 1989; Miller *et al.* 1996; Rajesh 2008). In the Madurai Block, the Neoproterozoic granites include Palani, Oddanchatram, Madurai, Munnar, Pudukkottai, Usilimpatti, Roayanpatti, Vanjinagarm, Melur, Anagadimonar (Santosh *et al.* 1986, 1989; Nathan *et al.* 2001). All these granites are calc-alkaline to alkaline in nature and emplaced within the migmatitic gneiss/enderbitic gneiss and charnockitic association. In Trivandrum Block, similar Neoproterozoic granites like Kalipara granite near Pathanamthitta, Athiringal, Pathanapuram and Chenganoor (Santosh and Drury 1988; Rajesh and Santosh 1996) also occur. Though, the granite plutons are restricted to major tectonic segments, there are some transitional occurrences across the major tectonic boundaries including the intrusions at Salem, Nammakal, Karur and Mettupalliyam areas.

3. Petrography

The granites described in this study fall into three tectonic blocks. Northern Block represented by Veppanapalli, Vaniyambadi, Krishnagiri, Bargur and Jakkampatti plutons; the CSZ represented by Puliampatti, Tiruchengodu, Sankari, Udhiyur, Pollachi–Udumalpet, Kangayam, Palladam, Aravakurchi and Dharapuram granites; and Madurai Block represented by Palani, Oddanchatram, Madurai and Munnar granites. In general, all the granites are medium- to coarse-grained and contain quartz, feldspar, biotite and hornblende. The K-feldspar is either microcline or orthoclase with or without perthitic textures together with subordinate plagioclase. Marginal granulations and rare developments of garnet and myrmekite intergrowths are also noticed. Quartz occurs as large anhedral grains with undulatory extinction, as recrystallized grains and as inclusions in other minerals like feldspars, hornblende and biotite.

The granites in the Northern Block show distinct mineral and textural variations compared to those in the CSZ and Madurai block. In Veppanapalli granites, K-feldspar is the dominant mineral (44 vol.%) together with plagioclase (23 vol.%), hornblende (4 vol.%) and opaques (2 vol.%). The modal compositions (table 1) suggest that the rocks vary from alkali granite to granite (figure 3). The Vaniyambadi granites are coarse-grained with perthitic K-feldspar (42 vol.%; figure 2a) and plagioclase (32 vol.%). Muscovite and quartz also occur around feldspar grains and secondary sphene, epidote, chlorite and biotite are seen in the ground-mass (figure 2b). Modal percentages classify them as alkali granites (figure 3). The Krishnagiri granites are grey to light pink in colour and are coarse-grained with plagioclase as the dominant mineral (37 vol.%) followed by K-feldspar (32 vol.%). The K-feldspars are either perthite or microcline perthite and some of these minerals occur as inclusions in plagioclase (figure 2c). Alteration effects are common and fine-grained matrix of quartz-biotite-opaque is developed along grain boundaries. Bent cleavages and bent twin lamellae in plagioclase are well developed and strong undulatory extinction in feldspars and mafic minerals are common, which suggest that the deformation is subsequent to the emplacement. Modal compositional plot of Q–A–P diagram (figure 3) classifies the rocks as granites. The Bargur granites are medium- to fine-grained and show gneissic texture. The essential minerals are plagioclase (48 vol.%) followed by K-feldspar (24 vol.%), with no perthitic textures, although myrmekitic intergrowth textures are common. Biotite (4.5 vol.%) is the main mafic mineral and secondary epidote is seen in some deformed rocks. The Jakkampatty granites are coarse-grained with plagioclase (43 vol.%) and K-feldspars (26 vol.%).

In the CSZ, Kangayam, Palladam, Aravakurchi, and Dharapuram granites are light pink to grey in colour and vary from medium- to coarse-grained with well-developed hypidomorphic textures. These granite plutons are plagioclase poor (7–23 vol.%) and rich in K-feldspar (46–66 vol.%), which is mostly microcline and occasionally show perthitic texture. Biotite is the main mafic mineral (figure 2d). Modal classification suggests that these rocks are mainly syno-granites with marginal affinity to monzogranites. The Tiruchengodu–Sankari granites show no deformational effects except for the margins at few locations. They consist of dominantly K-feldspar (46.5 vol.%) with

subordinate plagioclase (31 vol.%). The K-feldspar occurs in two generations represented by microcline or microcline perthites. Thin rims of clear albite occur around the microcline (figure 2e). Biotite and muscovite are the accessory minerals along with opaques. The Puliampatti granites are leucocratic, medium- to coarse-grained and poor in mafic minerals. They contain plagioclase (25–35 vol.%), K-feldspars (31–50 vol.%), quartz (17–28 vol.%) and mafic minerals (1–5 vol.%). The K-feldspar is mostly microcline and shows myrmekitic texture (figure 2f) developed between plagioclase, quartz and K-feldspar. The Pollachi–Udumalpet granites are coarse-grained and unaltered and are dominantly composed of perthitic K-feldspar (41–63 vol.%), plagioclase (5–25 vol.%), quartz (7–38 vol.%) and opaques (0.4–4.6 vol.%). Mafic minerals are hornblende (1–7 vol.%) and biotite (0.3–7.5 vol.%) with secondary chlorite, sphene, calcite, epidote and allanite occurrence (figure 2g). Sphene corona structures are developed around opaque minerals and rare garnet is also found.

In the Madurai Block, the granites show some minor variations. The Madurai granites are medium- to coarse-grained and grey in colour with strongly developed gneissosity. K-feldspar is the dominant mineral represented by microcline or microcline perthite (62–66 vol.%), with modal composition (figure 3) ranging from granite to syenite. Different types of perthites including string, bleb and briard types are common (figure 2h). Plagioclase (12.5 vol.%) is less compared to other granites in the region. Both hornblende and biotites occur as mafic minerals in these rocks. The granites are poor in plagioclase (9 vol.%) and dominated by microcline perthites (65 vol.%). Palani granites are coarse-grained with K-feldspar, anti-perthitic and plagioclase is higher than K-feldspar. Biotite is the main mafic mineral with accessories of apatite and secondary epidote. Oddanchatram and Rayanpatti granites are light pinkish in colour with K-feldspar dominating and plagioclase is very less. Perthitic texture with string type is common. Clinopyroxene, biotite, zircon, apatite and secondary chlorite are other minerals in these rocks. The Munnar granites are rich in K-feldspars (67–73 vol.%) and are represented by microcline perthites. Plagioclase is very less (3.5 vol.%) and mafic minerals are hornblende and biotite. The Munnar granites and Oddanchatram granite plot in alkali feldspathic syenite field and Rayanpatti granite plots in syenite field (figure 3).

Table 1. Average model compositions of different granite plutons of the present study.

Location	Veppanapalli	Vaniyambadi	Krishnagiri	Bargur	Jakkampatti	Kangayam	Palladam	Aravakurchi	Dharapuram	Sankari
No. of samples	3	3	6	3	3	4	6	4	8	5
Quartz	20.5	20.5	22.8	19.6	21.8	27.7	18.0	19.8	20.8	20.1
Plagioclase	22.8	31.7	36.8	48.1	43.3	10.5	11.7	7.7	22.7	24.6
K-feldspar	43.7	42.2	32.2	24.2	26.1	55.5	66.4	66.2	45.8	46.6
Biotite	4.1	4.1	3.1	4.5		3.5	1.1	3.3	5.8	3.3
Amphibole	3.6		2.1		4.7				0.8	
Opakes	1.9	1.5	1.5	2.4	1.9	0.6	1.1	0.7	1.7	1.8
Others	3.8	1.9	2.1	2.2	3.5	1.6	2.1	1.8	2.5	4.2

Location	Tiruchengodu	Udhiyur	Puliyampatti	Pollachi-Udumalpatt	Palani	Oddanchattram	Madurai	Rayanpatti	Munnar
No. of samples	2	7	10	20	3	3	4	4	3
Quartz	10.9	15.4	21.7	19.7	24.0	16.0	19.7	20.2	16.8
Plagioclase	31.4	18.1	34.9	13.6	39.2	1.5	12.8	8.9	3.5
K-feldspar	46.5	60.5	38.1	55.6	26.4	71.9	64.2	65.1	71.1
Biotite	3.6	2.4	2.3	2.8	7.2	1.6	1.2	1.3	1.6
Amphibole				5.3			0.6	1.2	2.7
Opakes	1.2	0.8	0.2	1.9	1.5	2.8	1.1	0.9	1.4
Others	2.3	2.8	2.4	2.1	1.6	6.4	1.4	1.4	2.7

Figure 2. Microphotographs of the granitic rocks from the different blocks of southern granulite terrain showing: (a) microcline perthite in Vaniyambadi granite, (b) presence of secondary sphene, epidote, chlorite and biotite within ground mass of Vaniyambadi granites, (c) presence of inclusions and recrystallized quartz in plagioclases of Krishnagiri granite, (d) predominance of biotite occurrence in Dharapuram granite, (e) thin rims of clear albite occur around the microcline Sankari granite, (f) myrmekitic intergrowth texture in Puliampatti granite, (g) presence of hornblende, secondary chlorite, sphene in Pollachi–Udumalpet granite, and (h) presence of orthoclase perthite as string type in Madurai granite.

Figure 3. AFM diagram of different granitoids from the SGT.

4. Geochemistry

A total of 167 samples from 19 different granite plutons from the three tectonic blocks (figure 1) have been selected for major, trace and rare earth element studies. The major oxide determinations were done on a Philips Magi X PRO model PW2440, wave length dispersive X-ray fluorescence spectrometer with suitable software SUPER Q 3.0 used at NGRI laboratory and about 50 samples were analyzed at Wadia Institute of Himalayan Geology, Dehradun. The accuracy and precision of the NGRI data were given in Krishna *et al.* (2007). The trace elements and rare earth elements (REE) were determined by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) at NGRI, Hyderabad. The samples were prepared in open acid digestion method 7:3:1 (HF, HNO₃, HClO₄) and for overall accuracy and other details see Roy *et al.* (2007). The ferrous iron was determined by

titration method. The geochemical dataset of ranges and averages of major, trace and rare earth elements of each granite pluton was given in table 2. A careful inspection and plots of chemical compositions of various granites indicate that the major and trace elemental contents of different granite plutons vary considerably within the same granite pluton and also vary between granites across the major three tectonic blocks, namely the Northern Block, CSZ and Madurai Blocks.

The granites of Northern Block namely Veppanapalli, Vaniyambadi, Krishnagiri, Jakkampatty and Bargur are poor in SiO₂ (66.9–70.4 wt.%), K₂O (0.8–4.1 wt.%) and relatively more in Al₂O₃ (15.5–16.8 wt.%), CaO (1.9–3.7%), MgO (0.4–0.9 wt.%) and TiO₂ (0.2–0.4 wt.%) than the granites of CSZ and Madurai Block (table 2). In the CSZ, Sankari and Tiruchengodu granites show less SiO₂ (64.2–74.4 wt.%), Na₂O (3–6.4 wt.%) and K₂O (1.3–5.2 wt.%) compared to the Kangayam,

Table 2. Average concentrations of whole rock geochemistry of different granite plutons of the present study.

Location Avg. no	Veppanapalli Avg(3)		Vaniyambadi Avg(2)		Krishnagiri Avg(13)		Bargur Avg(2)		Jakkampatty Avg(2)	
SiO ₂	66.67–67.12	66.93	67.52–69.54	68.53	66.71–73.98	70.37	67.29–71.28	69.29	61.21–66.24	63.73
TiO ₂	0.37–0.4	0.38	0.18–0.37	0.28	0.1–0.58	0.19	0.14–0.33	0.24	0.38–0.59	0.49
Al ₂ O ₃	16.54–16.92	16.79	16.13–16.39	16.26	14.7–16.81	16.01	15.18–15.89	15.54	15.4–15.57	15.49
Fe ₂ O ₃	3.02–3.22	3.15*	1.64–1.73	1.69	0.07–3.74	1.60	2.72–4.11	3.42*	3.65–4.97	4.31
FeO			1.12–1.12	1.12	0.2–0.28	0.22			1.56–1.92	1.74
MnO	0.04–0.05	0.05	0.02–0.04	0.03	0.01–0.05	0.03	0.01–0.04	0.03	0.04–0.07	0.06
MgO	0.83–0.94	0.88	0.49–0.95	0.72	0.01–1.04	0.41	0.45–0.78	0.62	1.49–2.48	1.99
CaO	3.59–3.75	3.67	2.39–3.11	2.75	0.25–3.61	1.87	2.22–3.26	2.74	4.1–5.8	4.95
Na ₂ O	5.48–5.82	5.66	4.51–5.11	4.81	3.45–6.26	4.81	3.7–4.73	4.22	4.42–4.51	4.47
K ₂ O	1.78–2.07	1.92	3.42–3.66	3.54	1.52–7.8	4.08	1.44–3.87	2.66	0.78–0.84	0.81
P ₂ O ₅	0.15–0.17	0.16	0.06–0.21	0.14	0.01–0.3	0.09	0.08–0.13	0.11	0.18–0.53	0.36
Total	99.58		99.3		99.54		99.83		98.37	
Trace elements in ppm										
Sc	2.1–5	4	1.1–1.2	1	0.34–5	2	2.01–2.4	2	4.1–7.9	6
V	5.1–42	24	29–29	29	1.4–38	16	14.2–34.9	25	53–74	64
Cr	2.1–25	17	25–25	25	12–158	60	111.6–124	118	110–148	129
Co	4.1–66	44	41–47	44	0.6–72	23	5.5–8.1	7	11.4–15.5	13
Ni	2.1–11	8	8.1–10	9	1.9–12	6	9.1–11	10	14.2–27.6	21
Cu	2.1–3	3	3.1–3.2	3	0.3–2.4	1	1.6–3.6	3	3.8–4.6	4
Zn	14–64	39	26–26	26	5.3–73	27	32.–52	43	57.2–90	74
Ga	8.1–25	17	24–24	24	10.4–25	15	16–19	17	20.3–21.2	21
Rb	50–273	134	64–70	67	12–115	70	52–84	69	2.6–4	3
Sr	24–496	303	328–350	339	228–610	379	466–495	480	797–947	872
Y	12–122	50	2.0–8.1	5	1.1–18	6	5.2–7	6	12.1–29	21
Zr	126–249	180	101–119	110	13–238	84	105–106	105	33–109	71
Nb	4.7–15.7	9	2.1–2.6	2	0.2–7.5	2	2.5–3.3	3	1.8–3.8	3
Cs	1.2–7.1	4	0.3–0.3	0.3	0.04–2.8	1	1.1–1.5	1	0.1–0.2	0.1
Ba	464–760	652	716–820	768	210–3158	913	303–1274	789	527–634	581
Hf	3.2–10	6	2.2–2.8	3	0.4–5.4	2	2.4–2.5	2	1.2–2.1	2
Ta	0.7–2.2	1.3	0.9–1.1	1	0.02–1.2	0.3	0.14–0.22	0.2	0.1–0.4	0.1
Pb	13–32	22	22–22	22	16–103	49	18–26	22	8.3–11.4	10
Th	n.d		n.d		0.2–5.6	1	0.8–2.3	1.6	0.3–1.5	0.9
U	n.d		n.d		0.6–0.8	0.3	0.3–0.3	0.3	0.1–0.2	0.2
REE in ppm										
La	18.10–20.70	19.40	5.05–5.05	5.05	0.82–61.28	15.53	4.36–10.61	7.49	23.51–55.93	39.72
Ce	44.63–44.77	44.70	9.73–9.73	9.73	1.36–97.11	28.02	8.98–22.68	15.83	55.63–145.7	99.67
Pr	6.43–7.18	6.81	1.17–1.17	1.17	0.15–11.91	3.50	1.2–2.81	2.00	7.77–21.8	14.82
Nd	22.09–26.16	24.13	3.97–3.97	3.97	0.52–31.63	10.49	4.28–8.77	6.53	26.3–78.4	52.36
Sm	3.77–8.18	5.98	0.78–0.78	0.78	0.51–4.64	2.07	1.26–1.64	1.45	5.03–12.9	8.97
Eu	0.09–1.02	0.56	0.82–0.82	0.82	0.2–1.12	0.75	0.68–0.86	0.77	1.63–2.57	2.10
Gd	2.91–6.92	4.92	0.67–0.67	0.67	0.1–3.83	1.34	0.68–1.21	0.95	4.59–12.24	8.41
Tb	0.48–1.93	1.21	0.08–0.08	0.08	0.02–0.52	0.19	0.12–0.21	0.17	0.61–1.62	1.11
Dy	2.07–12.43	7.25	0.35–0.35	0.35	0.09–2.33	0.85	0.6–0.9	0.79	2.3–5.62	3.96
Ho	0.36–2.56	1.46	0.07–0.07	0.07	0.02–0.39	0.15	0.11–0.18	0.14	0.33–0.73	0.53
Er	1.15–8.42	4.79	0.2–0.2	0.20	0.09–1.39	0.59	0.31–0.52	0.42	1.26–2.9	2.08
Tm	0.18–1.53	0.86	0.03–0.03	0.03	0.02–0.3	0.10	0.05–0.08	0.06	0.13–0.26	0.20
Yb	1.08–1.19	1.14	0.26–0.26	0.26	0.12–2.48	0.76	0.31–0.53	0.42	1.01–2.01	1.56
Lu	0.22–2.03	1.13	0.05–0.05	0.05	0.03–0.47	0.15	0.05–0.08	0.07	0.15–0.31	0.23
Σ REE	107.1–141.5	124.3	23.23–23.23	23.23	6.4–213.82	64.51	23.16–50.98	37.1	128.3–343.2	235.7

Table 2. (Continued.)

Location	Kangayam		Palladam		Aravakurchi		Dharapuram		Sankari	
Avg. no	Avg(8)		Avg(8)		Avg(4)		Avg(7)		Avg(5)	
SiO ₂	65.05–74.06	71.54	70.13–73.88	71.92	72.38–76.16	73.36	58.78–74.17	69.06	69.8–74.46	72.67
TiO ₂	0.01–0.14	0.07	0.01–0.28	0.09	0.03–0.12	0.07	0.01–0.79	0.21	0.04–0.08	0.06
Al ₂ O ₃	14.54–18.24	15.81	14.43–15.87	15.17	14.29–15.2	14.85	14.94–18.24	15.69	14.9–16.59	15.38
Fe ₂ O ₃	0.3–2.27	0.91	0.13–2.04	1.07	0.92–1.11	1.01	0.72–5.75	2.03	0.71–1.71	1.16
FeO	0.52–0.92	0.75	0.2–0.28	0.24	0.24–0.48	0.36	0.48–3.64	1.43	0.40–0.60	0.48
MnO	0.01–0.04	0.02	0.01–0.03	0.01	0.01–0.01	0.01	0.01–0.09	0.02	0.01–0.02	0.01
MgO	0.04–0.6	0.18	0.01–0.43	0.13	0.1–0.2	0.16	0.1–0.97	0.43	0.05–0.20	0.10
CaO	1.04–3.78	1.54	0.37–2.22	1.16	1.02–1.53	1.18	1.83–3.86	2.59	0.67–1.28	1.02
Na ₂ O	3.03–5.34	4.39	1.97–6.32	4.02	3.04–4.08	3.71	3.11–5.34	4.27	3.83–6.4	4.46
K ₂ O	2.73–6.17	4.68	3.31–5.96	5.08	2.96–6.05	4.97	2.73–6.03	4.13	1.62–5.17	4.32
P ₂ O ₅	0.01–0.1	0.03	0.01–0.11	0.03	0.02–0.02	0.02	0.02–0.37	0.11	0.01–0.03	0.02
Total	99.43		98.8		99.5		99.34		99.49	
Trace elements in ppm										
Sc	1.2–6.4	2	0.4–3.1	2	0.7–3.8	2	1.8–12.3	5	2.5–3.2	3
V	3.2–31	13	1.3–16.2	7	1.9–6.7	4	2.3–63.6	22	6.5–27.3	11
Cr	28–119	75	8.2–137.9	68	32–204	96	14.7–168.9	78	59–138.5	104
Co	0.78–73	26	0.8–63.1	11	1.5–2.3	2	1.5–14.3	5	1.03–3.1	2
Ni	3.7–25	10	2.1–5.1	3	2.3–7.2	4	2.9–9.4	7	0.8–1.5	5
Cu	0.9–3.1	2	1.2–9.4	3	1.1–1.9	2	0.3–3.5	2	20.8–48.3	1
Zn	11.1–42.2	27	13.1–25	15	12.9–24.5	17	9.7–91.3	38	16.5–24.9	32
Ga	11.2–26.3	18	23–97	17	14.1–24.9	20	16.2–27.5	21	64.4–155–9	21
Rb	26–111	81	23.1–97	70	22–120	86	26–129	71	64–156	116
Sr	101–893	392	113–869	440	196–304	238	311–1152	653	118–892	284
Y	3.4–19	10	1.2–20	6	0.5–5.4	3	0.9–145	29	3.9–18.7	8
Zr	18–140	73	10–471	127	24–217	136	16–512	108	33–269	163
Nb	0.23–6.4	2	0.07–12.2	3	0.11–5.2	3	0.8–25.1	6	2.5–10.9	5
Cs	0.03–0.47	0.2	0.01–0.1	0.1	0.08–0.16	0.1	0.03–0.2	0.1	0.26–0.7	1
Ba	193–1655	851	748–6864	3298	822–2971	1962	1188–9187	3145	305–1271	577
Hf	0.6–3.5	2	0.43–11.1	3	0.64–7.7	4	0.52–12.5	3	0.99–8.8	6
Ta	0.01–6.2	1.1	0.01–1.4	0.3	0.01–0.09	0.03	0.06–1.3	0.3	0.05–1.05	0.34
Pb	34.1–55	42	22.3–55	36	17.4–92.1	66	22.9–44.1	34	22.7–82.9	68
Th	0.2–7.3	3	0.1–33	7	0.18–66.8	38	0.2–17.7	5.6	0.29–34.9	18
U	0.2–0.5	0.3	0.03–3.2	0.6	0.1–4.2	1.8	0.12–1.37	0.3	0.4–4.13	2.4
REE in ppm										
La	2.68–26.31	12.28	1.22–48.94	17.93	9.77–46.21	29.63	8.99–82.45	33.65	2.03–8.36	4.90
Ce	4.71–45.65	22.65	2.38–91.94	33.23	18.8–106.5	65.95	17.17–217.5	72.34	4.84–21.2	11.91
Pr	0.57–5.74	2.70	0.27–9.79	3.39	2.01–9.88	6.49	1.41–33.36	9.58	0.74–3.08	1.79
Nd	1.78–18.14	8.13	0.76–27.1	10.44	4.96–33.68	20.96	4.19–119.38	32.41	2.74–10.89	6.42
Sm	0.52–4.52	2.06	1.07–5.73	3.19	1.71–5.23	3.65	1.33–26.25	7.25	0.9–3.44	2.20
Eu	0.37–1.24	0.97	0.62–2.97	1.27	0.97–1.17	1.04	1.09–3.34	1.82	0.39–0.68	0.58
Gd	0.39–3.43	1.61	0.08–4.27	1.44	1.02–3.03	2.40	0.42–19.77	5.48	0.52–2.21	1.37
Tb	0.07–0.43	0.22	0.01–0.65	0.19	0.06–0.34	0.23	0.04–4.09	0.91	0.12–0.35	0.25
Dy	0.45–1.93	1.18	0.07–2.82	0.90	0.14–1.45	0.80	0.18–21.31	4.47	0.58–1.63	1.13
Ho	0.09–0.43	0.23	0.01–0.49	0.13	0.01–0.11	0.06	0.02–3.87	0.77	0.1–0.4	0.19
Er	0.38–1.58	0.89	0.06–1.51	0.46	0.09–0.37	0.25	0.05–11.59	2.41	0.30–1.46	0.58
Tm	0.05–0.3	0.15	0.01–0.21	0.07	0.01–0.02	0.02	0.01–1.81	0.35	0.04–0.29	0.10
Yb	0.4–2.35	1.19	0.06–1.64	0.70	0.04–0.22	0.14	0.07–11.78	2.37	0.28–2.28	0.75
Lu	0.06–0.41	0.21	0.01–0.34	0.15	0.01–0.04	0.02	0.01–1.82	0.37	0.05–0.38	0.13
Σ REE	14.58–106.6	54.45	10.01–184.01	73.5	39.8–208.1	131.64	35.7–558.2	174.2	18.41–52.62	32.3

Table 2. (Continued.)

Location	Tiruchengodu		Udhiyur		Puliyampatti		Pollachi-Udumalpet		Palani	
Avg. no	Avg(6)		Avg(11)		Avg(16)		Avg(33)		Avg(10)	
SiO ₂	48.43–72.61	64.2	71.4–73.82	72.3	68.17–73.59	71.79	62.89–76.19	70.36	63.15–72.07	68.02
TiO ₂	0.19–1.65	0.66	0.01–0.08	0.03	0.01–0.25	0.06	0.01–0.85	0.29	0.1–0.47	0.33
Al ₂ O ₃	13.72–17.94	15.03	14.36–16.51	15.36	15.07–17.15	15.85	13.13–19.96	14.87	14.87–16.78	15.97
Fe ₂ O ₃	2.4–14.74	5.81	0.15–0.82	0.44	0.03–2.33	0.42	0.25–4.55	1.81	0.91–4.35	2.48
FeO	3.28–3.76	3.58	0.12–0.28	0.15	0.20–0.80	0.32	0.2–2.08	0.71	0.68–3.1	1.45
MnO	0.01–0.1	0.05	0.01–0.08	0.03	0.01–0.04	0.01	0.01–0.09	0.02	0.01–0.06	0.03
MgO	0.39–8.38	2.11	0.01–0.15	0.06	0.01–0.89	0.14	0.01–1.18	0.41	0.26–1.61	0.83
CaO	1.46–4.43	2.50	1.04–1.69	1.28	1.03–3.05	2.17	0.52–4.69	1.68	1.44–5.54	3.32
Na ₂ O	3.01–4.94	3.12	3.55–6.42	5.18	3.91–8.12	6.5	2.62–6.26	3.85	3.03–5.48	4.42
K ₂ O	1.29–4.56	2.26	2.61–5.18	4.03	0.5–5.18	1.86	1.52–6.93	5.12	1.18–6.28	2.83
P ₂ O ₅	0.04–0.52	0.15	0.01–0.04	0.01	0.01–0.12	0.03	0.01–0.5	0.14	0.01–0.28	0.15
Total	85.65		98.8		99.16		99.11		99.23	
Trace elements in ppm										
Sc	2.9–21	7	1.2–2.25	1	0.4–21	3	0.7–12	3	2.3–8	4
V	24.5–182	62	0.96–31	8	4.2–14	8	2.3–41	20	20.5–57	36
Cr	92.8–301	149	4.1–128	36	9.1–161	104	8.1–158	94	10.7–139	81
Co	2.9–49	16	0.72–75	25	1.3–63	12	1.2–64	10	2.3–71	23
Ni	6.9–92	29	2.2–25	5	2.2–5	3	2.3–12	5	3.3–12.5	7
Cu	1.5–8.6	4	0.31–3.2	2	1.3–4	2	0.4–9	3	0.76–6	3
Zn	30.9–124	58	4.5–17	10	8.1–59	17	9.2–84	41	22.9–69	47
Ga	14.5–36	18	30.1–86	18	12.1–21	16	12.2–50	21	15.6–24	20
Rb	7.34–143	57	30–86	55	6.1–85	27	16–151	94	16–104	47
Sr	248–456	285	128–1026	416	217–1205	679	66–1955	662	461–1187	697
Y	6.1–96	25	1.2–13	4	0.6–4	2	1.2–91	19	4.2–23	10
Zr	16–130	76	2–109	28	37–322	115	11–285	118	12–106	46
Nb	2.1–47.5	11	0.17–1.5	1	0.4–8	2	0.18–26	8	1.6–11	4
Cs	0.02–1.8	0.4	0.03–0.22	0.1	0.01–0.3	0.1	0.02–0.23	0.1	0.02–0.22	0.1
Ba	478–1777	746	211–4286	1865	6.8–1821	447	295–8909	2301	359–3210	1102
Hf	0.39–3.1	2	0.08–3.5	1	0.7–9	3	0.2–9	3	0.34–3.2	1
Ta	0.03–2.9	1	0.03–1.1	0.3	0.01–0.9	0.2	0.03–1.3	0.4	0.01–1.3	0.4
Pb	26–66	39	31.8–38.5	36	4.2–389	58	11.3–80	44	11.0–85	30
Th	0.17–56.16	22	0.13–0.24	0.2	0.1–8.5	2.4	0.4–124	37	0.5–26	6.6
U	0.1–1.38	0.7	0.02–0.1	0.04	0.1–1.1	0.4	0.1–6	0.6	0.1–0.3	0.2
REE in ppm										
La	6.81–139.6	52.71	0.16–24.96	3.94	0.06–6.02	3.51	7.07–1171	134.6	4.24–51.78	25.88
Ce	15.45–319.8	115.2	0.27–36.21	6.22	1.10–13.03	7.09	10.3–2153	356.3	9.98–96.21	49.51
Pr	2.14–43.2	15.10	0.03–3.67	0.67	0.14–1.68	0.93	1.00–69.52	22.67	1.44–12.92	5.96
Nd	7.81–141.5	48.17	0.12–9.16	1.89	0.48–6.23	3.20	2.55–124.4	46.24	5.41–43.51	18.72
Sm	2.09–24.2	8.18	0.35–1.02	0.62	0.17–2.32	0.89	0.87–20.02	8.47	1.75–8.94	3.36
Eu	0.88–3.71	1.67	0.18–1.16	0.41	0.26–0.88	0.49	0.47–12.84	2.23	0.73–2.32	1.22
Gd	1.54–18.18	6.08	0.06–1.16	0.32	0.08–1.92	0.62	0.23–13.91	6.27	1.09–5.55	2.55
Tb	0.24–3.18	1.01	0.01–0.19	0.05	0.04–0.20	0.09	0.02–4.26	0.91	0.21–0.90	0.37
Dy	1.11–15.47	4.58	0.16–1.35	0.39	0.07–0.63	0.35	0.09–11.99	3.16	0.76–3.39	1.60
Ho	0.16–2.56	0.75	0.02–0.26	0.07	0.01–0.50	0.08	0.01–2.28	0.56	0.11–0.60	0.26
Er	0.49–7.48	2.25	0.10–1.12	0.31	0.04–0.32	0.16	0.05–7.5	1.54	0.43–1.72	0.82
Tm	0.03–1.06	0.32	0.02–0.20	0.06	0.01–0.05	0.02	0.01–1.19	0.23	0.04–0.23	0.11
Yb	0.18–6.62	2.16	0.16–1.55	0.51	0.05–0.32	0.16	0.05–8.09	1.35	0.28–1.48	0.71
Lu	0.03–1.01	0.36	0.03–0.30	0.10	0.01–0.05	0.03	0.01–28.0	1.20	0.04–0.22	0.12
Σ REE	47.57–727.6	258.5	1.87–78.13	15.6	2.6–30.79	18.33	23.5–3432	582.0	28.7–215.5	111.2

Table 2. (Continued.)

Location	Oddanchattram		Madurai		Rayanpatti		Munnar	
Avg. no	Avg(6)		Avg(17)		Avg(3)		Avg(10)	
SiO ₂	66.84–74.81	69.31	68.92–74.24	72.48	72.12–74.44	73.2	67.64–73.36	71.72
TiO ₂	0.15–0.78	0.42	0.15–0.77	0.36	0.14–0.43	0.29	0.11–0.46	0.24
Al ₂ O ₃	1177–16.41	14.84	11.87–13.55	12.59	12.12–13.31	12.7	12.02–13.31	12.71
Fe ₂ O ₃	1.39–4.2	2.37	1.41–3.69	2.71*	1.24–3.59	2.35*	1.49–2.74	2.37*
FeO	0.72–1.92	1.11						
MnO	0.01–0.07	0.03	0.02–0.05	0.03	0.01–0.02	0.01	0.01–0.05	0.03
MgO	0.25–0.88	0.59	0.12–0.93	0.44	0.17–0.40	0.26	0.29–1.39	0.64
CaO	1.1–4.53	2.40	0.82–2.12	1.35	0.82–1.9	1.30	1.12–2.22	1.62
Na ₂ O	0.96–4.87	3.51	2.44–3.37	3.06	1.9–2.45	2.15	2.65–3.66	3.16
K ₂ O	1.04–8.09	3.90	4.71–5.85	5.31	5.31–6.43	5.75	3.79–7.06	5.6
P ₂ O ₅	0.05–0.29	0.17	0.01–0.22	0.11	0.01–0.10	0.05	0.06–0.52	0.17
Total	98.66		98.4		98.12		98.3	
Trace elements in ppm								
Sc	2.8–23	7	1.6–6	3	1.2–5	3	0.4–6	3
V	15.3–79	39	2.5–30	9	4.1–11	7	1.1–17	9
Cr	22.8–115	85	0.3–11	6	8.2–11	10	0.4–8	6
Co	2.9–14	8	1.2–7	4	3.3–6	5	0.5–8	4
Ni	7.1–26	13	1.7–7	3	2.2–3	3	1.1–5	3
Cu	0.38–16	4	0.3–2	1	0.3–0.4	0.1	0.1–2	0.7
Zn	30–80	53	11.8–39	24	13–23	20	2.2–34	19
Ga	13–26	20	1.8–25	20	13–21	17	2.1–24	15
Rb	19–189	87	1–377	230	228–253	241	11–189	90
Sr	61–1129	689	5–1554	366	7.2–71	29	60–795	259
Y	9.2–33	21	1.2–62	26	4.3–30	15	2.3–43	21
Zr	80–3544	793	8–269	106	166–2366	1521	3.4–1685	232
Nb	4.9–33	16	4.2–30	18	6.1–13	10	1.3–32	13
Cs	0.04–3.3	1	0.14–2.44	1	2.3–3	3	0.04–0.04	0.2
Ba	201–4447	1822	181–3595	793	322–564	448	239–2737	1191
Hf	2.45–71	16	0.24–8	3	5.1–8	7	0.08–5	2
Ta	0.24–2.8	1	0.2–2	1	0.3–0.5	0.4	0.04–2	0.6
Pb	10.1–153	65	30–43	38	33.8–36	35	4.2–65	37
Th	4.3–57	22	1.2–2606	262	2.1–54	30	16–1680	228
U	0.4–3.7	1.5	0.16–5.6	1.4	3.2–4.1	3.3	0.2–2.37	0.8
REE in ppm								
La	19.96–125.5	54.13	11.09–169	75.31	8.18–223	93.45	39.18–259	59.48
Ce	55.3–279.4	118.42	21.66–304	196.45	15.72–441	235.36	70.6–437	126.45
Pr	7.35–35.43	14.30	2.16–31.23	18.71	1.56–43.9	25.24	9.13–63.33	24.16
Nd	27.6–107.14	44.34	8.35–107.9	66.56	6.18–148.65	87.55	20.23–133.3	62.08
Sm	4.42–18.94	8.33	1.99–15.84	10.62	1.85–17.79	11.95	2.10–18.45	9.02
Eu	1.04–4.39	2.14	0.42–2.72	1.17	1.19–1.63	1.40	0.31–3.28	1.49
Gd	3.03–19.9	7.27	0.89–12.99	8.11	1.38–14.02	9.53	1.72–13.2	6.81
Tb	0.43–2.03	0.89	0.12–1.84	1.10	0.18–1.52	0.93	0.11–1.28	0.77
Dy	1.72–6.76	3.77	0.67–11.34	6.69	0.85–8.23	4.37	0.42–7.64	4.22
Ho	0.26–0.83	0.50	0.06–1.22	0.70	0.07–0.73	0.35	0.03–0.83	0.42
Er	0.70–3.55	1.80	0.21–3.97	2.32	0.17–1.97	0.97	0.11–2.85	1.39
Tm	0.09–0.31	0.21	0.02–0.51	0.29	0.02–0.16	0.08	0.01–0.36	0.16
Yb	0.55–2.76	1.62	0.16–5.14	2.81	0.21–1.36	0.69	0.09–3.69	1.58
Lu	0.10–0.45	0.26	0.02–0.81	0.44	0.04–0.19	0.10	0.01–0.59	0.25
Σ REE	127.7–606.8	257.9	48.2–687	391.2	37.6–884.5	471.2	135.6–917.2	248.2

Puliyampatti, Pollachi–Udumalpet granites. The Tiruchengodu granites have less silica and more iron compared to the Sankari granites. The grey and pink phases of granites are common and the pink phase contains higher K_2O than the grey types because of sub-solidus potassic fluid alteration. The Kangayam–Palladam granites from the CSZ show moderate SiO_2 (70.1–74.0 wt.%), Al_2O_3 (14.4–16.5 wt.%), Na_2O (2.0–5.2 wt.%), K_2O (3.3–6.2 wt.%) contents and are similar to the Dharapuram granites. The granites near Aravakurchi area are slightly higher in SiO_2 (72.4–76.1 wt.%), Na_2O (3.0–4.1 wt.%) than the Dharapuram granite, which contain higher Al_2O_3 (av. 15.7 wt.%) and lower amounts of Na_2O (av. 4.27 wt.%) and K_2O (av. 4.1 wt.%) compared to Kangayam, Palladam Tiruchengodu, Sankari and Udhiyur granites. Puliyampatti granites contain higher SiO_2 (70.1–73.6 wt.%, av. 72.79 wt.%), Al_2O_3 (15.1–17.2 wt.%, av. 15.85 wt.%), Na_2O (3.9–8.1 wt.%, av. 6.5 wt.%) and lower MgO (0.1 wt.%), CaO (1–2.8 wt.%, av. 2.2 wt.%), K_2O (0.5–5.2 wt.%, av. 1.9 wt.%) than the Pollachi–Udumalpet granites (table 2). The Munnar, Madurai, Palani, Rayanpatti and Oddanchatram granites from the Madurai Block vary in SiO_2 (68.0–73.2 wt.%), Al_2O_3 (12.59–15.97 wt.%) and CaO (1.3–3.32 wt.%) and they contain more alkalis.

Regarding trace elements concentrations, the Northern Block granites show more variation than the granites of CSZ (table 2) and these are poor in Rb (3–134 ppm), Ba (581–913 ppm), U (<1 ppm) and Th (<2 ppm), but Sr is moderate to high (303–872 ppm). In the CSZ, Sankari–Tiruchengodu granites contain moderate Sr (284–285 ppm), Rb (57–98 ppm) and Ba (578–746 ppm). The Kangayam and Palladam granites show higher Sr (392–440 ppm), Ba (1962–3298 ppm) and relatively moderate Rb (70–86 ppm) and Zr (127–136 ppm). The Aravakurchi granites also contain higher Sr (194–304 ppm), Zr (24–217 ppm), Ba (823–2971 ppm) and Th (up to 67 ppm). The Pollachi–Udumalpet granites contain higher in trace elements concentration Ga (12–50 ppm), Rb (16–151 ppm), Sr (66–1955 ppm), Y (4–19 ppm), Zr (11–256 ppm), Nb (1–26 ppm), Ba (290–5542 ppm), Th (0.4–124 ppm) and U (0.2–6 ppm) compared to the Puliyampatti granites (table 2). In the Madurai Block, the Palani, Oddanchatram granites show moderate Rb (47–87 ppm) Zr (46–793 ppm) and higher Sr (679–689 ppm) and Ba (1102–1822 ppm) concentrations. Madurai, Rayanpatti and Munnar granites also have higher concentrations of trace

elements like Rb (90–241 ppm), Sr (29–366 ppm), Zr (106–1521 ppm), Ba (448–1191 ppm), Hf (3–16 ppm) and Th (7–263 ppm) compared to the granites of CSZ and Northern Block.

In the normative An–Ab–Or plot (figure 4a), these granites define a compositional trend from albite end to orthoclase end and are confined mostly of granite–granodiorite fields and rarely trondhjemite field (Veppanapalli and Kangayam). But, the Barugur granite plot in tonalite field and the granites of Jakkampatty and Aravakurchi plotted in granodiorite fields. The R_1 and R_2 relation (Roche *et al.* 1980), also suggests that (figure 4b) most of the granites from the CSZ are granodioritic to monzogranite in composition, whereas the Pollachi–Udumalpet granite ranges from syenite, syenodiorite and is syn- or late-orogenic signature (Mallikharjuna Rao *et al.* 2005). The Jakkampatty granite plots in tonalite field. Many of the granites from the three blocks are having similar average A/CNK ratios, but the individual plutons show considerable spread in their A/CNK ratios. In binary A/NK against A/CNK plot (figure 5), the granite plots on either side of the demarcation line between metaluminous and slightly peraluminous suggesting that all the granites derived from a source of narrow chemical composition.

The REE patterns of the granitic plutons in Northern Block show wide range of rare earth elements (REE) and fractionation trends ($\sum REE$ 23–124 ppm, $La_N/Yb_N = 10.2$ –67.5). These granites show the slight enrichment of LREE and exhibit positive Eu anomalies except Jakkampatty and Veppanapalli granites (figure 6a). The Veppanapalli granites show slightly higher concentration of HREE and a strong negative anomaly (av. $Eu_N/Eu_N^* = 1.22$) (figure 4a). The Jakkampatty granites also show enriched REE patterns (av. $La_N/Yb_N = 17.67$) and show minor negative Eu anomaly (av. $Eu_N/Eu_N^* = 3.68$) (figure 6a). Both the LREE (av. $La_N/Sm_N = 2.77$) and HREEs (avg. $Gd_N/Yb_N = 4.46$) show almost flat trends of these two granitoids. The Vaniyambadi granites show strong fractionation trend and poorly concentrated REE ($\sum REE =$ up to 23 ppm) with strong positive Eu anomaly (av. $Eu_N/Eu_N^* = 4.96$) compared to the other granites like Veppanapalli ($\sum REE = 107$ –142 ppm) and Jakkampatty ($\sum REE = 128$ –343 ppm). The Krishnagiri granites also show variations in total REE content ($\sum REE = 6.4$ –214 ppm) and they also exhibit clear fractionation trend (figure 6a; av. $La_N/Yb_N = 14.13$) and (av. $Gd_N/Yb_N = 1.45$) with Eu positive anomaly.

Figure 4. (a) Normative An–Ab–Or plot for SGT granitoid (after O'Connor 1965) and (b) The R_1 – R_2 classification diagram (after De la Roche *et al.* 1980), the fields are defined as follows. A: Syenite, B: Quartz syenite, C: Alkali granite, D: Monzonite, E: Monzogranite, F: Granodiorite, G: Tonalite, H: Quartz monzonite, K: Diorite, L: Gabbro, M: Granodiorite, N: Nepheline Syenite, O: Syenodiorite, P: Syenogabbro, Q: Monzogabbro, R: Olivine Gabbro, S: Alkaline Gabbro, symbols as in figure 3.

The Burgur granites are poorly enriched in REE ($\sum \text{REE} = 23\text{--}51$ ppm) and show strong positive Eu anomaly (av. $\text{Eu}/\text{Eu}^* = 3.58$) comparatively. The strong positive Eu anomaly of these granites may be due to plagioclase rich source (figure 6a). However, the slight increase in HREE of Vaniyambadi, Veppanapalli and Krishnagiri granites may be due to accessory minerals like zircon and monazites (figure 6a).

Figure 5. Binary A/NK vs. A/CNK diagram showing metaluminous to slightly peraluminous character of granites (after Maniar and Piccoli 1989), symbols as in figure 3.

The CSZ granites show REE considerable variation. The europium anomaly $\text{Eu}_N/\text{Eu}_N^*$ varies from 2.28 to 4.22 and show slight enriched patterns of LREE (av. $\text{La}_N/\text{Sm}_N = 2.77\text{--}9.95$) and flat HREE (av. $\text{Gd}_N/\text{Yb}_N = 1.12\text{--}14.35$) (figure 6b). The Kangayam granites show moderate concentration of REE ($\sum \text{REE} = 15\text{--}107$ ppm, av. $\text{La}_N/\text{Yb}_N = 7.16$) and exhibit slight Eu anomaly (av. $\text{Eu}_N/\text{Eu}_N^* = 3.66$) (figure 6b). Palladam granites show similar to Kangayam granites with positive Eu anomaly (av. $\text{Eu}_N/\text{Eu}_N^* = 4.19$) and HREE is moderately enriched (av. $\text{Gd}_N/\text{Yb}_N = 1.69$). The Puliampatti granites show enriched REE ($\sum \text{REE} = 2.6\text{--}30.8$, av. 18.3 ppm, av. $\text{La}_N/\text{Yb}_N = 15.11$), enriched LREE (av. $\text{La}_N/\text{Sm}_N = 2.46$) and depleted HREE (av. $\text{Gd}_N/\text{Yb}_N = 3.29$) and a strong positive Eu anomaly (av. $\text{Eu}_N/\text{Eu}_N^* = 2.84$; figure 6b). Udhiyur granites have varied similar REE patterns ($\sum \text{REE} = 2\text{--}78$ ppm) and exhibit positive Eu anomaly (av. $\text{Eu}_N/\text{Eu}_N^* = 2.99$) similar to Puliampatti granites. The Europium anomalies from these plutons may be due to non-removal of plagioclases from the melt compositions. In Pollachi–Udumalpet granites, majority of samples show enriched REE (around 600 ppm) with some abnormalities like very low or high concentration of REE ($\sum \text{REE} = 24\text{--}3432$ ppm, av. 582 ppm) and fractionated trends (av. $\text{La}_N/\text{Sm}_N = 9.95$ and av. $\text{Gd}_N/\text{Yb}_N = 3.83$) with slight positive Eu anomalies (av. $\text{Eu}_N/\text{Eu}_N^* = 4.22$; figure 6b). The Tiruchengodu granites are moderately enriched in REE ($\sum \text{REE} = 48\text{--}727$ ppm)

Figure 6. Rare earth element pattern of different granite plutons (averages): (a) Northern Block, (b) CSZ and (c) Madurai Block; normalized values are after [Sun and McDonough \(1989\)](#).

and show fractionation trends (av. $\text{La}_N/\text{Yb}_N = 16.93$) and exhibit negative Eu anomaly on average (av. $\text{Eu}_N/\text{Eu}_N^* = 3.21$; figure 6b). The Dharapuram granites are also similar to Tiruchengodu granites with enriched REE ($\sum \text{REE} = 35.7\text{--}558.2$ ppm) and show negative Eu anomaly on average (av. $\text{Eu}_N/\text{Eu}_N^* = 3.69$). The Sankari granites are poorly enriched in REE ($\sum \text{REE} = 18.41\text{--}52.62$ ppm) and show slight flat pattern with negative europium anomalies ($\text{Eu}_N/\text{Eu}_N^* = 0.75\text{--}2$, av. 2.21) on average. The Aravakurchi granites show fractionation trend and enrichment of REE ($\sum \text{REE} = 39\text{--}208$, $\text{Eu}_N/\text{Eu}_N^* = 132$ ppm) without much significance of negative Eu anomaly (av. $\text{Eu}_N/\text{Eu}_N^* = 3.04$; figure 6b). In general, the

granites of Sankari, Udhayur, Kangayam and Puliampatti are very poor in REE contents compared to other granites of CSZ.

From the Madurai Block, in the Palani and Oddanchatram granites, the av. REE concentration varies between 111 and 258 ppm (av. $\text{La}_N/\text{Yb}_N = 18.6\text{--}25.36$) with enrichment of LREE (av. $\text{La}_N/\text{Sm}_N = 4\text{--}4.8$, av. $\text{Gd}_N/\text{Yb}_N = 2.3\text{--}3.7$). The Palani granites are moderately enriched in REE ($\sum \text{REE} = 111$ ppm) and shows positive Eu anomaly (av. $\text{Eu}_N/\text{Eu}_N^* = 3.6$; figure 6c). The Oddanchatram granites are strongly enriched in REE ($\sum \text{REE} = 127.7\text{--}606.8$ ppm) and show strong fractionation trends (av. $\text{La}_N/\text{Yb}_N = 23.11$) with minor Eu anomaly (av. $\text{Eu}_N/\text{Eu}_N^* = 3.95$; figure 6c). The Madurai granites show (figure 6c) similar REE concentration and strongly enriched REE contents ($\sum \text{REE} = 48.2\text{--}687$ ppm) respectively and show strong negative Eu anomaly (av. $\text{Eu}_N/\text{Eu}_N^* = 1.95$) compared to Palani and Oddanchatram granites. The Munnar and Rayanpatti granites are also enriched in REE contents ($\sum \text{REE} = 135.6\text{--}917.2$ ppm, $\sum \text{REE} = 37.6\text{--}884.5$ ppm) with depleted HREE (av. $\text{Gd}_N/\text{Yb}_N = 3.5\text{--}11.4$) and show strong negative Eu anomaly (av. $\text{Eu}_N/\text{Eu}_N^* = 2.71$, av. $\text{Eu}_N/\text{Eu}_N^* = 2.91$; figure 6c). The early formed plagioclase removal from the early melts may cause for the observed strong negative Eu anomalies and showing strong alkaline character of the source of these granites.

5. Discussion

Generation of granitic magma is associated in space and time with the growth of the continental crust, rather than just recycling ([Patino Douce 1999](#)). Granites can result from partial fusion of continental crustal rocks at low pressure, without visible contribution of mafic magma. Partial melting of mantle peridotite produces basaltic magma that can undergo extensive fractional crystallization to produce granitic (non-orogenic) peralkaline granitoids and most Proterozoic TTG suites. Petrology and geochemical characteristics of granitic rocks from the study area are syenogranite to monzogranite in composition and few of them show alkali feldspathic syenite to syenitic composition. Quartz, K-feldspar and plagioclase are the major phases with ferromagnesian minerals like hornblende and biotite as accessories in these granites. The A/CNK molecular ratios of these granites range between 0.91 and 1.2 with predominantly

metaluminous character and I-type to S-type signatures (figure 5; Chappell and White 1974, 1992). The source for the I-type metaluminous granites are possibly mafic and metaigneous rocks (Chappell and White 1974; Frost *et al.* 2001), and for granites of slightly peraluminous nature (S-type), probably pure crustal melts that are uncontaminated by mantle material (Castro *et al.* 1999b; Ghani *et al.* 2013; El-bialy and Omar 2015). It is well described that the radiogenic and stable isotopic compositions of peraluminous leucogranites, their common field settings within medium- to high-grade regional metamorphic terrains show lack of spatial and temporal association between them, and the experimental studies have shown that melting of metasedimentary rocks generates peraluminous silica-rich melts (Patino Douce and Harris 1998). The slightly peraluminous and the metaluminous nature of these granites suggests their derivation from either melting of mafic rocks or amphibolites (Ellis and Thompson 1986; Patino Douce 1999). The REE patterns of these granites from all the three blocks show broad variations (figure 6a–c). The granites of Northern Block show both positive and negative Eu anomalies with moderately enriched REE contents and their sources may relate to melting of undifferentiated mantle-derived rocks. The Veppanapalli and Jakkampatty granites from this block show strong negative Eu anomalies that resemble the melts of upper continental crust. Vaniyambadi, Krishnagiri and Barugur granites show positive Eu anomalies that represent restites after partial melting (Rundick 1991). The REE patterns of the granites from CSZ suggest different modes of origin and evolutionary history. They show both positive and negative Eu anomalies of mixed characteristics. There is depletion of REE in the granites of Kangayam ($\sum \text{REE} = 14\text{--}106$, av. = 54 ppm) Palladam ($\sum \text{REE} = 10\text{--}184$, av. = 73 ppm), Puliampatti ($\sum \text{REE} = 2.6\text{--}31$, av. = 18.3 ppm), Udhiyur ($\sum \text{REE} = 1.87\text{--}78.14$, av. = 15 ppm) and show slight positive Eu anomalies that resemble possibly early intruded plutons of I-type. This positive Eu anomaly in these granites is due to feldspar accumulation or assimilation of feldspar-rich material (Ragland 1989). However, the granites of Madurai Block are highly enriched in REE ($\sum \text{REE} = 111\text{--}3853$ ppm) and exhibit strong fractionation trends with significant negative Eu anomalies (except for Palani) and show fractionated LREE with moderate enrichment of HREE that suggests they might have been generated from deeper source or due

Figure 7. Rock/primitive mantle spider plot of different granite plutons (average): (a) Northern Block, (b) CSZ and (c) Madurai Block; normalized values (after, Sun and McDonough 1989).

to addition of juvenile magmas, and data also reflect crustal contamination of source magma. The variations in REE concentrations and enrichment may be due to accessory minerals like allanite, monazite, sphene and zircon contents in the rock. In the primitive mantle-normalized spider plot (figure 7a–b), many of the granites from the Northern block and CSZ (Kangayam, Palladam, Puliampatti, Udhiyur) show positive Rb, Ba, Sr, Th, and light REEs anomalies and negative Nb, P and Ti anomalies resembling the characteristics of the average continental arcs (Condie and Kroner 2013). These high Ba, Sr granitoids are interpreted as tectonic regimes of elevated geotherms, including ridge subduction, rifting or subduction of young hot oceanic crust (Whalen *et al.* 1997). However, Madurai block granites and some of the granites of CSZ (Sankari, Tiruchengodu, Dharapuram, Aravakurchi and Pollachi–Udumalpet) show enrichment of Rb, Th, U and depleted Ti, Sr,

P, Eu anomalies (figure 7c) that resemble A-type characteristics (David and Chappell 1992).

Many distinguishing features have been outlined by Chappell and White (1974) for classifying granitoids into I- and S-types and for deciphering the tectonic environment. Several schemes and methods have been proposed by Pearce *et al.* (1984) and Maniar and Piccoli (1989). The scheme of Maniar and Piccoli (1989) indicates that the granitoid compositions are consistent with island arc, continental arc or continental collision. Tectonic discrimination diagrams of these granites show some of these are confined to volcanic arc granite types and show syn-collisional characteristics and some show post-collisional characteristics (Peace 1996). In spite of their chemical coherence on some variation diagrams (figure 8a–d), the plutons collectively exhibit incoherent trends for some major and trace elements. In the Rb *vs.* (Y+Nb), Nb *vs.* Y, Rb *vs.* (Yb+Ta) binary variation diagrams (figure 8a–c), some of the granites (Vaniyambadi, Bargur, Krishnagiri, Kangayam, Palladam, Udhayur, Puliampatti and Palani) are confined to the volcanic arc to syncollisional granite fields, and their genesis might have been associated with the Neoproterozoic subduction–accretion tectonics described in northern margin of terrain and that of CSZ and south of Madurai block (Yellappa *et al.* 2012; Santosh *et al.* 2009, 2012, 2013, 2015, 2017; Ratheesh Kumar *et al.* 2016; Bhadra and Nasipuri 2017). It is also described that the basement gneisses and intrusive granitic rocks near the transition zone around Krishnagiri as I-type and S-type (Chandrasekaran and Subrmanian 1996). The geochemical signatures of Veppanapalli, Vaniyambadi, Bargur and Jakkampatty granites from the present study are similar to Krishnagiri granites. The granites from the CSZ (Sankari, Tiruchengodu, Pollachi–Udumalpet, Dharapuram and Aravakurchi and Madurai Block (Munnar, Madurai, Oddanchetram and Rayanpatti) granites show syn-collisional to post-tectonic settings (figure 8a, d) and their evolution might be associated with extensional tectonics after post-collision. In Zr *vs.* Ga/Al diagram (figure 9a), majority of the granites from the present study show fractionated I-type, S-type and some are confined to A-type fields (Madurai, Rayanpatti, Munnar and Oddanchatram). Similarly in FeO*/MgO *vs.* Zr+Nb+Ce+Y diagram (figure 9b), most of the granites show fractionated I-type, while some like Sankari, Pollachi–Udumalpet, Oddanchatram, Madurai, Rayanpatti, and Munnar show A-type

nature. Earlier studies have established (Condie *et al.* 1982, 1986; Dhanaraju *et al.* 1983; Chandrasekharan 2002) that the Sankari–Tiruchengodu granites from the CSZ are post-tectonic, calc-alkaline and slightly peraluminous in nature (Nathan *et al.* 2001). It is also described based on geochemical and mineralogical characteristics that the granites of Sankari–Tiruchengode are S-type and formed in continental collision tectonic setting showing later aborted rifting (Nathan *et al.* 1994). Recently, the granites of Sankari, Tiruchengodu, Puliampatti, Karamadai and Maruda Malai from the CSZ are described as A-type granites (GSI, 2009). A-type granitic melts occur in many continents and are of different ages and occur in a variety of tectonic settings (Whalen *et al.* 1987). These rocks result mainly by partial melting of F and/or Cl-enriched, dry granulitic residue remaining in the lower crust after extraction of anorogenic granites (Whalen *et al.* 1987). The origins of A-type granites were originally defined as anorogenic nature (Loiselle and Wones (1979). Later, it was also described that they can be formed in both anorogenic and post-orogenic settings (Whalen *et al.* 1987; Eby 1992). Geochemical characters of the granites from the Madurai block and some of granite of CSZ (described above) are broadly comparable with the A-type granites which indicated their possible post-orogenic nature. It is described that the granites south of Madurai at Ambasamudram and Rajapalayam intrude into the high-grade rocks showing the characteristics of A-type granites (Pandey *et al.* 1994). The granitoids at Kullampatti area, Salem district near Sankari and leucogranites of pegmatoidal granites within the CSZ were also described as A-type origin (Roy and Dhanaraju 1999; Nathan *et al.* 2001). From the present study the geochemical characteristics of Munnar, Rayanpatti and Oddanchatram of Madurai clearly show their A-type origin (figure 9a–b) in confirmation with the results of several other workers (Santosh and Nair 1983; Santosh *et al.* 1993; Thampi *et al.* 1993; Rajesh and Santosh 1996; Rajesh 2008).

It is well established that, the basement gneisses and intrusive granitic rocks occurring near the transition zone around Krishnagiri in the northern part of Tamil Nadu are predominantly of tonalitic-granodioritic in composition, Archean in age and are believed to have formed by partial melting of garnet-bearing amphibolites (Condie *et al.* 1982, 1986; Dhanaraju *et al.* 1983; Chandrasekharan 2002). It is also described that the

Figure 8. The tectonic discrimination diagrams: (a) Rb vs. (Y+Nb), (b) Nb vs. Y, (c) Rb vs. (Yb+Ta) for different granite plutons (after Pearce *et al.* 1984; Pearce 1996), and (d) R₁–R₂ tectonic classification diagram of plutonic rocks (after Batchelor and Bowden 1985) R₁ = 4Si – 11(Na + K) – 2(Fe + Ti); R₂ = 6Ca + 2Mg + Al; symbols as in figure 3.

pink granitic suite which is well-differentiated, calc-alkaline, metaluminous to mild peraluminous, late-kinematic granitoids is evolved by anatectic remelting of grey granitoids (Chandrasekharan 1996). The origin also implies for the evolution of several potash-rich feldspar granites during Archean–Proterozoic transition (Chandrasekharan 1996). The different granites in the SGT like Vaniyambadi, Bargur, Krishnagiri, Palladam, Kanyagayam and Puliampatti granites show +ve Eu anomalies suggesting that they may have affinity towards crustal component of TTG assemblages with subduction-related process, while the Vepanapalli, Jakkampatty, Aravakurchi, Pollachi–Udumalpet, Dharapuram, Rayanpatti, Munnar, and Madurai granites show negative Eu anomaly without much involvement of earlier TTG component and seem to be products of crustal anatectic melting after the Neoproterozoic post-collision. The generation of granite melts is at relatively

shallow depths and temperatures in the order of 600–900°C is recorded in experimental studies on silicate systems (Bonin *et al.* 2002). The Rb/Sr ratio is one of the indicators for magmatic differentiation, where it increases with higher degree of differentiation. The Rb vs. Sr plot (figure 9c) shows these granites have been derived from highly differentiated and more evolved granitic liquids of deeper origin (Condie 1973). Similarly, the curved trend of these granites on Al₂O₃/TiO₂ vs. TiO₂ (figure 9d) diagram represents well defined magmatic differentiation (Sun and Nesbitt 1978). However, in the normative Q–Ab–Or plot (figure 10), Puliampatti granite indicates a calc-alkaline trend of crystallization temperatures between 750 and 800°C, whereas the Pollachi–Udumalpet granitoids show wider scatter and range of crystallization temperatures between 700 and 800°C (Mallikharjuna Rao *et al.* 2005). The rest of the granite plutons in all the three tectonic blocks namely

Figure 9. The tectonic discrimination diagrams: (a) Binary Zr vs. Ga/Al diagram showing I- to A-type nature of granitic rocks (after Whalen *et al.* 1987); (b) FeO*/MgO vs. Zr+Nb+Ce+Y diagram (after Whalen *et al.* 1987); (c) Rb–Sr binary diagram, the dashed lines refer to the crustal thickness (after Condie 1973); (d) Al₂O₃/TiO₂ vs. TiO₂ magma differentiation diagram (after Sun and Nesbitt 1978); symbols as in figure 3.

Veppanapalli, Vaniyambadi, Krishnagiri, Sankari, Udhiyur, Aravakurchi, Palani, Oddanchatram and Madurai show between 700 and 760°C temperature for their crystallization of melts (figure 10). These lower temperatures might be the addition of more water or carbon dioxide during melt generation. Similar temperature range (650–700°C under 5 kb P_{H₂O}) of origin for potash feldspar granites in Northern Block is discussed by earlier workers (Chandrasekharan 1996).

5.1 Age constraints

The SGT has a complex evolutionary history from the early Archean to late Neoproterozoic (3500–550 Ma) with repeated multiple deformations, anatexis, intrusions and polyphase metamorphism. The summary of the available ages of granitoids from different tectonic blocks is given in table 3. The granites and tonalites of 2.5 Ga are common in the area of transition from amphibolite facies rocks of the Dharwar craton to the granulite facies rocks of the SGT as well as in the eastern

Figure 10. The normative Q–Ab–Or ternary diagram (after Tuttle and Bowen 1958) showing crystallization temperature of different granitoid melts; symbols as in figure 3.

Dharwar Block (Peucat *et al.* 1993). These granites extend across the major tectonic shear zones and occur at Salem, Namakkal, Karur, Mettupalliyam

Table 3. Brief summary of available ages of different granitoids in major tectonic blocks of the SGT.

Rock type	Method/technique	Age (Ma)	Interpretation	Reference
Northern Block				
Gneisses	U–Pb zircon	2963 ± 4	Protolith age	Friend and Nutman (1991)
Granite	U–Pb Zircon	2513	Crystallization age	Friend and Nutman (1991)
Granite-gneiss	Sm–Nd	3130	Crystallization age	Meissner <i>et al.</i> (2002)
Migmatitic gneiss	Nd–TDM model age	2780	Crystallization age	Peucat <i>et al.</i> (2013)
Krishnagiri granite	U–Pb zircon	2557 ± 16	Prootolith age	Peucat <i>et al.</i> (1993)
Gingee granite	K–Ar dating	2250 ± 76	Crystallization age	GSI (1978), Balasubrahmanyam <i>et al.</i> (1979)
Sholingar	K–Ar dating	~2302	Protolith age	Krogstad and Hanson (1988), Balasubrahmanyam and Sarkar (1981)
Gingee pluton	K–Ar dating	~2254	Protolith age	-do-
Pink Granite (Biligiri Rangan Hills)	U–Pb Zircon	2490 ± 21	Crystallization age	Ratheesh Kumar <i>et al.</i> (2016)
Nilgiri Block				
Enderbite gneiss	Sm–Nd model ages	~2620	Protolith age	Kohler and Srikantappa (1996)
Ambalavayal granite	Rb–Sr isochron	595 ± 20	Emplacement age	Santosh <i>et al.</i> (1986)
Kalpatta granite	U–Pb zircon	553 ± 5	Emplacement age	Miller <i>et al.</i> (1996)
Peralimali granite	Rb–Sr isochron	750 ± 40	Emplacement age	Santosh <i>et al.</i> (1989)
Salem Block				
Granite gneiss (Salem)	TIMS U–Pb zircon	2528 ± 2	Emplacement age	Ghosh <i>et al.</i> (2004)
Metamorphosed granite (Salem)	U–Pb zircon	~2650	Protolith and high-grade metamorphism	Sato <i>et al.</i> (2011)
Tirukovilur	K–Ar dating	~2440	Crystallization age	Balasubrahmanyam <i>et al.</i> (1979)
		~2254		
Kullamaptti granite	Rb–Sr isochron	534 ± 15	Emplacement age	Pandey <i>et al.</i> (1993)
Granite(Kanjimalai)	²⁰⁷ Pb/ ²⁰⁴ Pb age	2647 ± 11, 2442 ± 20	Crystallization, thermal event	Sato <i>et al.</i> (2011)
Quartzo-feldspathic gneiss	U–Pb Zircon	2475 ± 1.8	Emplacement age	Saitoh <i>et al.</i> (2011)
		2483 ± 2.5		
Cauvery Suture Zone (CSZ)				
Granite (Namakkal)	TIMS U–Pb zircon	2511 ± 28	Emplacement age	Ghosh <i>et al.</i> (2004)
A-type granite (Ayyermalai)	U–Pb zircon	~590	Magmatism high-grade metamorphism	Sato <i>et al.</i> (2012)
Rapakivi granite (Tangalamvaripatti)	U–Pb zircon	819 ± 26	Protolith ages	Sato <i>et al.</i> (2012)
Sankari, Tiruchengodu leucocratic granites	Rb–Sr isotope	534 ± 15	Crystallization age	Pandey <i>et al.</i> (1993)

Table 3. (Continued.)

Rock type	Method/Technique	Age (Ma)	Interpretation	Reference
Idappadi trondhjemite	Rb–Sr isotope	479 ± 12	Protolith age	Ghosh <i>et al.</i> (1996)
Puliyampatti (leucocratic granite)	K–Ar dating	471 ± 10	Protolith age	GSI (1978)
Marudamalai granite	Rb–Sr isotope	619 ± 35	Protolith age	Nathan <i>et al.</i> (2001)
Plagiogranite (Manamedu)	U–Pb Zircon	737 ± 23 , 513 ± 4.6	Crystallization age	Santosh <i>et al.</i> (2012)
Trondhjemite (Devanur)	U–Pb Zircon	2528 ± 61	Crystallization age	Yellappa <i>et al.</i> (2012)
Metagranite (Agali)	U–Pb Zircon	2545 ± 56 2535 ± 13	Crystallization age	Santosh <i>et al.</i> (2013)
Trondhjemite (Agali)	U–Pb Zircon	2547 ± 7.4	Crystallization age	-do-
Madurai Block				
Meta granite (Kodaikanal)	U–Pb zircon evaporation	2436 ± 4	Magmatism	Bartlett <i>et al.</i> (1998)
	Younger zircon over growths	~ 550	Metamorphism	-do-
Syntectonic granites, (south of KKPT shear zone)	U–Pb Zircon and Monazite	~ 790 , 600 and 570	Neoproterozoic thermotectonic event(s)	Ghosh <i>et al.</i> (1998, 2004)
Post-tectonic granitoids (south of KKPT shear zone)	U–Pb Zircon and Monazite	~ 525 , 550	Neoproterozoic metamorphism	-do-
Felsic gneiss(Kadavur)	U–Pb zircon	766 ± 8	Intrusion age Magmatism	Teale <i>et al.</i> (2011)
Vanji nagaram granite	Rb–Sr whole rock isochron age	620 ± 43	Emplacement age	Nathan <i>et al.</i> (2001)
Usilampatti Granite	Rb–Sr whole rock isochron age	823 ± 38	Emplacement age	Pandey <i>et al.</i> (2005)
NW Madurai	Rb–Sr whole rock isochron age	837 ± 34	Emplacement age	Pandey <i>et al.</i> (1994)
Pudukkottai Pink granite	Rb–Sr whole rock isochron age	563.3 ± 28	Emplacement age	Chandra Sekaran <i>et al.</i> (2016)
Munnar granite	U–Pb dating	740 ± 30 , 505 ± 56	Emplacement age	Odom (1982)
Melur granite	Rb–Sr dating	795 ± 17	Emplacement age	Nathan <i>et al.</i> (2001)
Granite (Theni)	U–Pb zircon	722 ± 11	Emplacement age	Plavsa <i>et al.</i> (2012)
Granite (Kotamangalam)	U–Pb zircon	567 ± 2	Protolith age	Ghosh <i>et al.</i> (2004)
Aklai granite (Sita- parappanallur)	U–Pb zircon	662 ± 20	Protolith age	Santosh <i>et al.</i> (2017)
Trivendrum Block				
Augen gneiss	U–Pb Zircon & Monazite Th–U–Pb	605 ± 37 ~ 470	Emplacement age Emplacement age	Braun <i>et al.</i> (1998) -do-
Granitic pegmatite	Flourapatite and Monazite	509 ± 25	Emplacement age	Berger and Braun (1997)
Pathanapuram granite	$^{207}\text{Pb}/^{204}\text{Pb}$	534 ± 5	Protolith age	Santosh <i>et al.</i> (2005)

and Kottamangalam areas. Neoarchean to Paleoproterozoic granites were described by several workers in the Northern Block (Balasubrahmanyam *et al.* 1979; Krogstad and Hanson 1988; Friend and Nutman 1991; Peucat *et al.* 1993, 2013). The tonalitic to trondhjemitic granite gneisses and charnockites from the Krishnagiri area in the north of Moyar–Bhavani described their protoliths age of $2550\text{--}2530\pm 5$ Ma (Peucat *et al.* 1993). However, the granitic rocks occurred near transition zone around Krishnagiri in the northern part of Tamil Nadu, described the age range from 3400 to 1000 Ma (Monard 1983). Similarly, in the Salem Block, 2528 ± 2 Ma granites gneiss and ~ 2650 Ma granites at Salem, 2647 ± 11 Ma granites at Kanjamalai, 2511 ± 28 Ma enderbite gneiss in Nilgiri block of Neoarchean ages were reported (Kohler and Srikantappa 1996; Ghosh *et al.* 2004; Sato *et al.* 2011). Some of the Paleoproterozoic granitoids are also described in the Northern Block, ~ 2221 Ma – Ebbari Malai, ~ 2302 Ma – Sholingar, ~ 2254 Ma – Gingee and ~ 2254 Ma – Tirukovilur granite (Balasubrahmanyam *et al.* 1979; Krogstad and Hanson 1988). The granites of the present study belong to two distinct age groups of Neoarchean–Paleoproterozoic and Neoproterozoic. The granites of Northern block including Vepanapalli, Vaniyambadi, Jakkampatty, and Bargur from the present study are possible equivalents of Krishnagiri of Neoarchean emplacements. Their emplacement sequence appears to be related the Neoarchean subduction–collision and accretionary tectonics (Saitoh *et al.* 2011; Yellappa *et al.* 2012; Santosh *et al.* 2012, 2013; Noack *et al.* 2013; Glorie *et al.* 2014; Samuel *et al.* 2014; Ratheesh Kumar *et al.* 2016) followed by crustal extension associated juvenile addition of magmas. In the Salem Block, the Neoproterozoic granites like Kullampatti granite is 534 ± 15 Ma and in Nilgiri block, the Ambalavayal granite of 595 ± 20 Ma, Kalpatta granite of 553 ± 5 Ma Peralimali granite of 750 ± 40 Ma are described by several workers (Santosh *et al.* 1986, 1989; Pandey *et al.* 1993; Miller *et al.* 1996). However, Neoproterozoic granitoids are predominantly described from the CSZ and Madurai Trivandrum Blocks. In the CSZ, the Rb–Sr isotope and U–Pb zircon dating of leucocratic granites (trondhjemitic) of Sankari, Tiruchengodu described as 534 ± 15 Ma (Rb–Sr isotope; Pandey *et al.* 1993) and 479 ± 12 Ma, respectively (U–Pb zircon; Ghosh *et al.* 1996). The age of the Puliampatti leucocratic granite is 471 ± 10 Ma (K–Ar GSI 1978) and that of Marudamalai granite is 619 ± 35 Ma (Rb–Sr

isotope; Nathan *et al.* 2001). The A-type granite of Ayyermalai is described as ~ 590 Ma (U–Pb zircon; Sato *et al.* 2012). It is also reported that 819 ± 26 Ma age of Rapakivi granite at Tangalam-varipatti and 737 ± 23 Ma age of palgiogranite from Manamedu Ophiolite complex (Santosh *et al.* 2012) is within the CSZ. In the Madurai Block, the granite plutons range in age from 550 to 850 Ma. The Munnar granites are of 740 ± 30 Ma age (U–Pb zircon; Odom 1982), Pudukkottai granite is of 563 ± 28 Ma (Rb–Sr isotope; Chandra Sekaran *et al.* 2016), Usilampatti granite is of 823 ± 38 Ma (Rb–Sr; Pandey *et al.* 2005), Vanjinagarm granite is of 620 ± 43 Ma, Melur granite is of 505 ± 56 Ma (Rb–Sr isotope; Nathan *et al.* 2001), Sitaparappanallur granite is of 722 ± 11 Ma (U–Pb zircon; Santosh *et al.* 2017) and Theni granite is of 795 ± 17 Ma (U–Pb zircon; Plavsa *et al.* 2012) as reported by earlier workers. Some of the Monazite ages of Vallamallai granite closer to Karur cluster around 500 ± 2 Ma has also been reported from this block. In the Trivandrum Block, the oldest zircons in the Pathanapuram granite pluton are in the range of 961–1149 Ma, with younger overgrowths at about 540–560 Ma, and at an age of 534 ± 5 Ma, the Pathanapuram granite in the central domain of Achankovil shear zone was established (Santosh *et al.* 2005). The granite pegmatite of 470 Ma and 509 ± 25 Ma granites from Ponmudi unit (Berger and Braun 1997) were also reported. All these age data indicates that the emplacement of alkali-granites and syenites in these tectonic blocks preceded calc-alkaline felsic magmatism around 500 Ma (Santosh *et al.* 1989, 2005) of Pan-African equivalents after the Neoproterozoic subduction–collision and accretionary events.

There are also several reports of Pan-African related magmatism and associated lithologies within the CSZ and several parts of the SGT (Santosh and Drury 1988; Rajesh *et al.* 1996; Nathan *et al.* 2001; Braun 2006). The CSZ has also been interpreted as the zone of closure of the Neoproterozoic Mozambique Ocean (Collins and Pisarevsky 2005; Collins *et al.* 2006, 2007; Santosh *et al.* 2009) and a prolonged subduction–collision–accretion history similar to Pacific-type of orogeny during Neoproterozoic–Cambrian periods along the craton-terrain margins (Santosh *et al.* 2009). Several imprints of Neoproterozoic arc related tectonics from the SGT, including oceanic remnants/ocean plate stratigraphy and ultra-high temperature metamorphism (UHT) is described by several

Figure 11. A schematic possible tectonic model showing Neoproterozoic subduction, continental convergence and emplacement of volcanic arc to syn-collisional granites of I-type and emplacements of A-type granites during extensional tectonics after post-collision.

workers (Tsunogae *et al.* 2008; Santosh *et al.* 2009, 2013; Yellappa *et al.* 2010). The occurrence of subduction mechanism during Neoproterozoic and Neoproterozoic periods is also described based on the study of the Devanur Ophiolite complex, Agali Ophiolite complex, and Manamedu Ophiolite complex from the CSZ (Yellappa *et al.* 2010, 2012; Santosh *et al.* 2012, 2013). These tectonic

events are correlated with major tectonic events in global scenario in terms of timing, deformation, magmatism, and metamorphism and evolution history. Recently, the occurrence of Neoproterozoic subduction and associated magmatism (Santosh *et al.* 2017) and crustal extensional events (Brandt *et al.* 2014) in southern Madurai Block has also been described. Geochemical characteristics of

studied granite plutons reveal I-type and A-type (figure 9a–b) with volcanic arc to syn-collisional and post-collisional signatures. I-type granitic magmatism probably associated with arc-continental collision of Neoproterozoic subduction (shown in figure 11). Their parental magma of these granitoids might have produced through mantle–crust source interaction which is typical of continental arc granities (Pearce 1996). The occurrence of A-type granites possibly related to anorogenic or transitional post-collision setting with large-scale crustal extensional events resulting recycling of crustal sediments, melting of crustal rocks and juvenile addition of fluids led to the emplacement of several granites (figure 11). Similar tectonics and extensional related origin of A-granites are well described by several workers (Whalen *et al.* 1987; Rajesh *et al.* 1996; Rajesh 2000, 2008; Elbially and Omar 2015). It is well known that basic and alkaline magmas related to extensional setting along the Mozambique suture of many segments including Malawi, southern Madagascar, southernmost India, Sri Lanka and part of Dronning Maud Land in Antarctica during the amalgamation between East and West Gondwana (Kroner *et al.* 1999; Collins *et al.* 2000). The high-temperature A-type granites, alkaline plutons and anorthosites, the high-temperature metamorphism of the granulites and the mantle-derived fluids associated with post-collisional extension along the Gondwana suture (Santosh and Yoshida 2001) have also been described.

Recent reviews on the formation of this Gondwana supercontinent suggest that the final amalgamation of Gondwana followed by the closure of the Mozambique Ocean, forming the East African orogen (Meert and Voo 1997; Kroner *et al.* 2000; Collins and Windley 2002; Meert 2003). Two Pan-African orogenesis have been described, an older orogeny resulted from the collision of Eastern Africa with an ill-defined collage of continental blocks including parts of Madagascar, Sri Lanka, Seychelles, India and east Antarctica during the interval 750–620 Ma, which they referred to as East African orogeny (Meert 2003). The pre-Pan-African signatures of south India, Madagascar and Sri Lanka are fundamentally important to characterize the Gondwana amalgamation tectonics around 500–550 Ma (McWilliams 1981; Unrug 1996; John *et al.* 2005). It is also described that several Pan-African domains/belts across the world expose upper to middle crustal levels and consist of ophiolites, subduction–collision related

granitoids, island arc or passive margin assemblages similar to Phanerozoic plate tectonics (e.g., Arabian Nubian Shield – Arabia and north-east Africa, Damara Kaoko-Gariep Belt & Lufilian arc – South central and south-western Africa, West Congo Belt – Angola and Central Republic, Tan – Sahara Belt of West Africa etc., Kroner and Stern 2004). The widespread Neoproterozoic granitic activity in SGT and other parts of India can be correlated with the other crustal fragments of Eastern Gondwanaland (Rajesh *et al.* 1996). The Pan-African Orogeny and its related alkaline granitic magmatism is well established by several workers in SGT (Santosh *et al.* 1989; Rajesh *et al.* 1996; Rajesh and Santosh 1996). The geochemical characteristics and ages of many of the granite plutons are of Pan-African equivalents, and similar geochemical characteristics of granites are well described in Arabian Nubian Shield, Brazilian shield and several parts of the world (Jackson *et al.* 1984; Eyal *et al.* 2004; Kroner and Stern 2004). The structural geometry of Neoproterozoic ophiolite complex of Manamedu and tectonic history is also correlated with ophiolite settings of Arabian Nubian Shield (Chetty *et al.* 2011).

6. Conclusions

- Petrological and geochemical characteristics of granitoids from the three distinct tectonic blocks of the southern granulite terrains show that they have feldspathic syenite to granite-ganodiorite compositions having metaluminous to slightly peraluminous nature.
- Geochemical characteristics of these granites suggest two distinct types of granitic magmatism: dominant I-type occurred along CSZ under continental volcanic arc settings to syn-collisional setting and A-type, dominant in Madurai block, possibly in post-tectonic setting of extensional mechanism.
- The varied REE pattern of these granitoids suggests fractional crystallization. Trace element characteristics, REE and the tectonic discrimination diagrams reveal that they were derived from a predominant crustal source of deeper origin with variable degree of mantle inputs. The crystallization temperatures of the melts range from 700 to 800°C, these lower temperatures might be the addition of more water or carbon dioxide during generation of melts.
- The available ages and the identified geochemical signatures of these granitoid rocks reveal

that the emplacement of these plutons might be a complex, multiple-stage of evolution during Neoproterozoic and Neoproterozoic periods. In terms of age and geochemistry, the Neoproterozoic granites are well co-relatable with Pan-African granites of Arabian Nubian Shield and Brazilian Shields.

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