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Research Article

DEFORMATION, METAMORPHISM AND GEOCHRONOLOGY OF THE PALAEOPROTEROZOIC SALEM-NAMAKKAL FOLD THRUST BELT AND IMPLICATIONS FOR THE GONDWANALAND CONTINENTAL ASSEMBLY

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ABSTRACT
The granulite terrain of South India consists of three tectonically distinct terranes separated by ductile thrusts. The central terrane namely the Salem-Namakkal Fold Thrust Belt which forms the topics of the present paper is sandwiched between the Northern Archaean Granulite Terrane and southern Neoproterozoic Pandyan Mobile Belt. The Salem-Namakkal Fold Thrust Belt consists of a stack of imbricate thrust sheets showing N to NE vergence. The charnockitic mylonites produce an age of 2530±39 Ma. The imprint of Pan-African event is missing in the charnockitic mylonites. However, the shonkinite dyke emplaced in the ultramafic plutons has produced 801 Ma age. The southernmost Namakkal thrust sheet show isothermal decompression while the northernmost Salem thrust sheet show isobaric cooling history. The granulites are retrograded during shearing. In the Gondwanaland assembly, the Salem-Namakkal Fold Thrust Belt forms a contiguous terrane with the Antananarivo - Tsaratanana Belt of Madagascar and probably a complimentary unit to Usagaran Block of Tanzania craton; the Pandyan Mobile Belt -Mozambique Belt forms the central axis of the collisional orogen.

Key Words: *Southern Granulite Terrane, Salem-Namakkal Fold Thrust Belt, Palaeoproterozoic age of charnockitic mylonites, Antananarivo - Tsaratanana Belt of Madagascar*

INTRODUCTION
The granulites of South India are hosted in a collage of geologically distinct terranes (Fig. 1a inset) namely the Archaean Northern Granulite Terrane, the Palaeoproterozoic Salem-Namakkal Fold Thrust Belt, the Neoproterozoic Pandyan Mobile Belt (includes Madurai Belt and, the Kerala Khondalite Belt). These stacked granulite terrains have a transitional boundary with the Archaean greenstone-TTG terranes of the Dharwar Craton, popularly known as Fermor's line. The internal granulite belts are mutually juxtaposed along deep-seated ductile thrusts. Limited observations along the Palar river suggest that the Fermor's line may locally be marked by a low-angle thrust. The Northern Granulite Terrain consists of recently uplifted hills of charnockite, surrounded by low lying granite gneisses and migmatites (Devaraju *et al.*, 2007; Clark *et al.*, 2009). Sm-Nd model ages of the granulites within the Northern Granulite Terrain are 3.30 – 2.68 Ga suggesting that the Dharwar Craton was involved in their generation (Devaraju *et al.*, 2007). Geothermobarometric studies indicate that these rocks show an overall anticlockwise path, and formed at 700±30^{o} C and 5-7 kbar (Harris *et al.*, 1982). The Salem-Namakkal Fold Thrust Belt constitutes a mixed terrane comprised mainly of Palaeoproterozoic to late Archaean charnockites, mafic granulites and BIF (e.g. Nilgiri and Kanjamalai hills), surrounded by amphibolites, hornblende biotite schists, granite gneisses and migmatites. These rocks are emplaced as discrete thrust sheets such as

the Salem-Attur Thrust. Neoproterozoic granites and dunite-peridotite intrusives are associated with the Palaeoproterozoic granulites of the Salem-Namakkal Fold Thrust Belt. The Palghat-Cauveri Shear Zone has been interpreted as a Neoproterozoic – Cambrian suture, demarcating the southern limit of the Precambrian rocks. However, Ghosh et al. (2004) consider the Karur-Kambam-Painavu-Trichur Shear Zone to be the southernmost limit of Precambrian rocks. The Pandyan Mobile Belt occurs to the south of the Palghat-Cauveri Shear Zone and represents a Cambrian –Ordovician granulite belt comprised of a quartzite-pelite-carbonate dominated sequence (QPC) affected by multiple generations of folding. A U–Pb zircon age of 588±6 Ma from the Cardamom Hill charnockite (Miller *et al.*, 1996), as well as zircon U-Pb ages of 680±30 Ma and 570±10 Ma on core and rim respectively from pink metagranite and 1300 Ma-old detrital zircon from the same rock (Santosh *et al.*, 2003), all support a Neoproterozoic age of the Pandyan Mobile Belt. However, the surrounding gneisses and metasediments have produced older zircon of 1700 Ma, suggesting the presence of older basement (Collins *et al.*, 2003). The available geochronological data on magmatic phases within the Pandyan Mobile Belt indicate that the belt may have been assembled from a long-lived Neoproterozoic arc, and that the present day exposures reveal deeply eroded roots of this arc. The Achankovil Shear Zone separates the Kerala Khondalite Belt or Trivandrum Block from the Pandyan Mobile Belt. The Kerala Khondalite Belt is dominated by khondalites, calc-granulites and mafic granulites, with charnockites in the SE. Neoproterozoic–Cambrian metamorphism (600 to 400 Ma) overprints the rocks, while older ages of 1000 Ma, 1600 Ma, 2148± 94 and 3193 ± 72 have been reported from the relicts of some of the earliest forming continental crust (Bindu *et al.*, 1998; Braun *et al.*, 1998; Santosh *et al.*, 2006). There is only very limited evidence of any Mesoproterozoic events in the southern granulite belts.

In this paper we have studied the deformation patterns, metamorphic assemblages and possible P-T condition and present new zircon U-Pb SHRIMP geochronology of the mylonites of the Salem-Namakkal Fold Thrust Belt. Based on this, we investigate possible links with Palaeoproterozoic terranes of Madagascar and Tanzania and the East African Orogen.

REGIONAL GEOLOGY

The Salem-Namakkal Fold Thrust Belt is marked by multiple thrusts that form a flower structure (Chetty and Bhaskar Rao, 2006). Nilgiri, Kanjamalai and Godumalai are prominent hills in the area that expose various charnockites and are surrounded by granite gneiss and migmatite. Zircon cores from these charnockites near Salem show U-Pb ages of 2538±6 Ma and 2529±7 Ma, and rim ages of 2473±8 Ma and 2482±15 Ma ages (Clark *et al.*, 2009) indicating a Palaeoproterozoic origin. Mafic granulite of Kanjamalai hill shows metamorphic assemblages consistent with conditions of 750^0 C to 800^o C and 8-12 kbar, while U-Pb zircon ages of these granulites record a 2536.1±1.4 Ma magmatic age and a 2483.9 ± 2.5 Ma metamorphic age (Saitoh *et al.*, 2011). However, 900^o C and 14 kbar (Mukhopadhyay and Bose, 1994) and 760 – 780^o C and 7.4 kbar (Santosh *et al.*, 2010) have been reported. U-Pb and Sm-Nd ages of granulite facies metamorphism have been reported from the Nilgiri hill and dated at 2460 ± 81 Ma (Buhl, 1987; Raith *et al.*, 1999). The enderbitic charnockite from the Nilgiri hill shows the peak metamorphic condition of 730–750^0 C and 7-10 kbar (Srikantappa *et al.*, 1992). Nilgiri hill is considered to represent the deepest piece of exhumed crust on the Indian Peninsula (Raith *et al.*, 1999). The mafic granulites from the Namakkal area yielded the P-T of 731^0 C and 8.6 kbar (Manish *et al.*, 2005). The Salem-Namakkal Fold Thrust Belt is further marked by the Sittampundi anorthosite complex, the Sm-Nd whole rock age (Pl-Hbl-Grt) shows an emplacement at ca. 2935±60 Ma and resetting at 800-600 Ma, (Bhaskar Rao *et al.*, 1996) and peak metamorphic P-T condition is ca. 11.8 kbar and 830^0 C. Ultramafic rocks near Salem include dunite, peridotite and pyroxenite occur as intrusive bodies into the migmatite complex. These ultramafic bodies are locally intruded by lamprophyre and alkaline dykes which have been dated by Rb-Sr ischorn age of 808 ± 18 Ma (Reddy *et al.*, 1995). The younger components of the Salem-Namakkal Fold Thrust Belt are the Sangakiri and Tiruchengode granitic intrusives, which have yielded zircon U-Pb ages of 479±12 Ma to 534±15 Ma, and the pegmatoidal intrusions that record a zircon U-Pb age of 390±40 Ma (Pandey *et al.,* 1993; Nathan *et al.,* 1994; Ghosh *et al.,* 1996).

ROCK TYPES

The Salem-Namakkal Fold Thrust Belt has been mapped and comprises a wide variety of lithologies. The hilly terrains to the SE of Kandashramam, including the Thammampatti area, are dominated by charnockites, while near Kanjamalai and in the northern hills of Salem, there are abundant metagabbros, interlayered with banded magnetite-quartzite (BMQ), such as at Godumalai hill. The low lying areas are occupied by quartzofeldspathic gneisses, hornblende-biotite gneisses, granite gneisses and migmatites which are mylonitised in several places, especially along the shear zones occurring either side of Godumalai hill. The Sangakiri granite is a major intrusive that has developed calcareous skarn along the contact with surrounding marble. Minor anorthosite, dunite, peridotite, shonkinite, syenite and dolerite dykes are present throughout the area. Pseudotachylites are extensively developed along the Gangavalli Shear Zone.

The charnockites are comprised of clino- and orthopyroxene, calcic plagioclase, biotite and quartz. The metagabbro or mafic granulites are composed of clino- and orthopyroxene, calcic plagioclase and garnet, with biotite, rutile, spinel, ilmenite and hornblende as accessories. Hornblende biotite gneisses occur as retrograde products of metagabbro along the shear zones. The quartzofeldspathic gneisses show excellent development of layering structure with alternate BMQ and biotite-amphibole rich bands. These bands have developed chaotic folding patterns along the southern foothills of Kanjamalai. Syenites in the Umayalpuram Shear Zone range from course- to fine-grained, and are associated with dunite, peridotite and gabbro with veins of magnesite. In thin section, corundum-bearing syenites are also observed, while enstatite is found as accessory mineral.

STRUCTURES

The Salem-Namakkal Fold Thrust Belt consists of number of low-angle south-dipping thrust sheets demarcated by ductile shear zones (Fig. 1b inset). In many places they have been steepened by refolding, i.e. along the L. Kanavaipatti Shear Zone south of Namakkal (Fig. 2a). Mylonites are prominently developed in the foothills of Godumalai and Kanjamalai hill. These show kinematic indicators, mainly S-C fabrics, rotated porphyroclasts and intragranular faults, suggesting thrust-related tectonics with N to NE verging shear (Fig. 2b, c, d). However, in many instances the mylonites have undergone static recrystallisation (Fig. 2e). The mylonitisation is post-kinematic with granulite facies metamorphism. Peak granulite metamorphism has occurred during the F_1 stage of folding, which is characterised by isoclinal folds developed in bedding planes, represented by BMQ layers in quartzofeldspatic gneisses. The F_1 fold have produced penetrative gneissic fabrics and are coaxially refolded by open to tight upright F_2 folds producing type 3 interference patterns. The F_2 folds are accompanied by shear bands along the limbs that show mylonitisation and rootless folds in quartzite bands (Fig. 2f). Thus it is interpreted that the mylonitisation is synkinematic with F_2 stage of folding. The mylonitic foliation has been refolded by F_3 folds, which have probably removed the shear fabric to a large extent due static recrystallisation.

The Sangakiri Shear Zone separates the Idapadi Block from the Salem Block. The shear zone shows mylonitic foliation nearly E-W trend showing dip towards north (Fig. 1c). The Salem Block shows the dominants of metagabbro/mafic granulite. The outcrop shows synformal structure. The mafic granulites have been retrograded to amphibolite near Mallasamudram. The mylonitic foliation strikes NE-SW and dips toward E (Fig. 1d). The amphibolite shows nappe structure over the granite gneisses. The Kanjamalai Shear Zone near Kanjamalai hill takes an easterly trend. The mylonitic foliation shows NNW dip (Fig. 1e). The Udayapatti Shear Zone has an E-W strike and dips toward north (Fig. 1f). The

Udayapatti shear zone south of Godumalai shows extensive mylonite development. The mylonitic foliations are E-W and dip north and contain down dip stretching lineation (Fig. 1g). The Umayalpuram Shear Zone shows the emplacement of syenite and the mylonitic foliation shows the southerly dip (Fig. 1h). The L. Kanavaipatti Shear Zone is the southernmost shear zone. The mylonitic foliation shows both southerly and northerly dipping due to late stage folding (Fig. 1i). From the analysis of mylonites it is quite evident that the finite strain varies from one block to another. In Salem thrust sheet the static crsytallisation is very prominent while the Namakkal thrust sheet retains the assymetric fabric to a large extent.

METAMORPHISM

A limited metamorphic study has been conducted on metagabbro/mafic granulites from the Salem Block and from the Namakkal Block. Sample TKB-1 and TKB-28 represent the Salem and Namakkal thrust sheet respectively. Mineral chemistry of the coexisting phases in the mafic granulites was determined using a CAMECA – SX-100 electron microprobe at the Wadia Institute of Himalayan Geology, Dehradun. The operating conditions were: accelerating voltage of 15kv, specimen current of 20 nA and beam diameter of 1mm. Both synthetic and natural silicates and oxides were used as standards. Data correction was done using the PAP method (Pouchon and Pichoir, 1984). The data of these two samples are listed in Table 1.

a. The mafic granulite from the Salem thrust sheet shows assemblage opx + grt + pl + qtz ± bt ± hbl ± ilm. Prominently, orthopyroxene is rimmed by garnet at the close proximity of plagioclase (Fig. 3a). This suggests the following model reaction.

   Opx + Pl = Grt + Qtz ------------------------- (1)

   This reaction proceeds to the right in response to near isobaric cooling (Harley, 1989). Since the mafic granulite of the Salem thrust sheets is characterized by above corona texture, we interpret that garnet corona around orthopyroxene has resulted by isobaric cooling P-T path in a magmatic accretion setting.

   Mineral chemistry of the coexisting phases indicates that the garnets are Fe-rich with ~ 60 mol% almandine, ~19 mol% of grossular, ~19 mol% of pyrope and ~2 mol% of spessartine component (Table 1, Sample TKB-1). The orthopyroxene is Mg-rich and belongs to hypersthene variety and its X_{Mg} (Mg/Fe + Mg) value is ~ 0.56. The plagioclase is Na-rich and belongs to oligoclase variety with X_{Ca} content (X_{Ca} = Ca/(Ca+Na+K) of ~ 0.33.

   The P–T calculations estimated by using conventional grt-opx geothermometer (calibrated by Wood and Banno, 1973; Dahl, 1980; Harley 1984) and TWQ2.02 software (Berman, 1991) and a grt-opx-pl-qtz barometer calibrated by Powell and Holland (1988) and Newton and Perkins (1982) suggest that the Salem thrust sheet has undergone the peak metamorphic temperature in range of 602–678º C and pressure in range of 8.3-9.4 kbar. The temperature estimated for opx-grt pair is relatively far below the temperature range of common granulite facies rocks. Since the garnet of the Salem granulites have grown from orthopyroxene by isobaric cooling, both mineral might have been reset their compositions at relatively low temperature condition as compared to granulite P-T field and this may be the reason for the low temperature yield by geothermometry of grt-opx.

b. The mafic granulites occur as lensoidal bodies within the quartzofeldspathic gneisses of the Namakkal thrust sheet. This bears the mineral assemblages of grt + opx + cpx + pl + hbl ± ilm ± rt. In many instances it was observed that the garnet is surrounded by opx and pl rim (Fig. 3b). Hence the following model reaction has been inferred.

   Grt + Qtz = Opx + Pl --------------------------- (2)

   This type of corona texture is reported from the Sittampundi anorthosite complex, South India (Santosh *et al.*, 2010) and from Eastern Ghats Mobile Belt, India (Dasgupta *et al.*, 1994). They interpreted that this corona texture has formed in decompression P-T environment. Presence of similar corona texture in the mafic granulite of the Namakkal thrust sheet show that these thrust sheets have undergone isothermal decompression P-T path under thrust tectonics environment.

   The EPMA analyses of corona forming phases shows that garnets are Mg and Ca richer with ~52 mol % almandine, 18 mol % of grossular, 29 mol % of pyrope and ~1 mol % of spessartine component (Table 1, Sample TKB-28). The pyrope content in garnet is relatively higher than the garnets of the Salem area. The clinopyroxene and hornblende is Mg-rich and its X_{Mg} value is ~ 0.7 and ~ 0.5, respectively. Two varieties of plagioclase are observed. Among these, one is Na-rich and of oligoclase variety with X_{Ca} value ranges between 0.32–0.44. In second variety, plagioclase is Ca-rich and of bytownite variety with X_{Ca} value of 0.81.

   The P–T value obtained by using grt-cpx conventional geothermometer calibrated by various workers (Ellis and Green, 1979; Powell, 1985; Krogh, 1988; Ai, 1994; Berman *et al.*, 1995; Krogh Ravna, 2000) and a grt-opx-pl-qtz barometer calibrated by Newton and Perkins (1982) and Powell and Holland (1988) suggest that the granulites of the Namakkal thrust sheet has attained the peak metamorphic temperature in range of 694–872º C and pressure in range of 9.4-11.1 kbar.

c. The mafic granulite and quartzofeldspathic gneisses from the mylonite zones have been studied. The rock shows alteration. The garnet is surrounded by alteration rim of biotite and hornblende with magnetite (Fig. 3c, d). This suggests the retrogression of granulites due to shearing. The possible reactions are

   Grt = Hbl + Pl ------------------------------------- (3)

GEOCHRONOLOGY

Zircons from the charnockitic mylonite from near the Kandashramam shear zone have been analysed by U-Pb SHRIMP method. The zircon separation was done in IIT Bombay using heavy liquid separation method and SHRIMP analyses conducted at the Perth Consortium facility at Curtin University of Technology (for techniques see Singh *et al.,* 2010).

Zircons from this sample range in size from 50 to 200μm and have aspect ratios between 1:1 and 3:1. The zircons are sub rounded to round in shape, but many preserve remnant crystal faces indicative of a magmatic character. Cathodo-luminescence (CL) imaging shows that the majority of zircon comprises a zoned inner rim domain with oscillatory or sector-zoning pattern, overgrown by often extensive bright CL rim domains. U and Th content on core data are in the ranges 90–488 and 67–413 ppm respectively, with

Th/U ratios between 0.5 and 3.8, consistent with magmatic zircon. The rim data are characterised by low U and Th contents, in the ranges 18–80 and 8–182 ppm respectively, with Th/U ratios between 0.2 and 3.8. These values are characteristic for zircon growing from small volumes of partial melt or metasomatic fluids, but not consistent with growth during metamorphism. The data on core appear to define two separate populations, an older group of six analyses that define a weighted mean $^{207}Pb/^{206}Pb$ age of 2604±28 Ma (Table 2) and a younger group of four analyses giving a weighted mean $^{207}Pb/^{206}Pb$ age of 2530±39 Ma. The eleven rim data define a cluster of analyses that appear to be aligned along a regression line with lower intercept at $712^{+780}/_{-540}$ Ma and upper intercept at $2533^{+73}/_{-27}$ Ma (Fig.4). The poor precision of the lower intercept is due to the fact all data are concentrated along the upper part of the regression, and using only the six concordant data points, a weighted mean $^{207}Pb/^{206}Pb$ age of 2518±21 Ma can be calculated. We interpret the oldest age group on core to represent xenocrystic components in the rock derived from a uniform source with an age of 2604±28 Ma. The younger core population is interpreted as the emplacement age of the protolith charnockite at 2530±39 Ma. The low U rims are constraining crystallisation of the latest-stage fluids during cooling of the magma at 2518±21 Ma, or alternatively growth of zircon rim during shearing or mylonitisation.

DISCUSSION

Fold thrust belt: The Salem-Namakkal Fold Thrust Belt constitutes a Neoarchaean-Palaeoproterozoic terrane, and consists of a stack of imbricate thrust sheets showing N to NE vergence (Fig. 1 inset). The northernmost imbricate records an isobaric cooling history, suggesting magmatic underplating. The Namakkal block, where the mafic granulites are interlayered with quartzofeldspathic gneisses, shows an isothermal decompression path suggesting the rocks have come from deeper levels by thrusting. We interpret the occurrence of various metamorphic scenarios in adjacent imbricates to reflect different level of exposure across a thrust belt. The zircon geochronology from the mylonites of the Kandashramam shear zone show ca. 2530 Ma crystallisation age, and possible 2520 Ma overprint. There is no younger imprint to suggest late-Neoproterozoic events, such as those recorded further south. However, emplacement of pegmatite veins along the mylonites in the Namakkal section could indicate that thrusting may be a younger event or that the Palaeoproterozoic thrusts were reactivated during the Neoproterozoic; the veins are yet to be dated.

Regional implications: In Gondwanaland correlation, it has been viewed that India has been juxtaposed against Madagascar and Africa on its southwestern margin (Fig. 5). The geology of the neighbouring continents in combination with geochronology has supported this correlation. The Dharwar Craton has been equated with Antongil Craton and Masora Craton of eastern Madagascar (Peucat *et al.*, 1993; Tucker *et al.*, 1999, 2010; Collins and Windley, 2002; Collins, 2006; Jayananda *et al.*, 2006). Similarly, the rock groups in the southern Madagascar namely Vohibory, Graphite, Androyen and Molo units show matching with the Pandyan Mobile Belt. The above mentioned units show Palaeoproterozoic to Neoproterozoic sediments (2265 Ma to 841 Ma) that have been metamorphosed during Pan-African orogeny (531 Ma) (Collins *et al.,* 2012). Matching with that, in the Pandyan Mobile Belt, the Madurai Belt shows 1700 Ma sediments and ca. 570 Ma metamorphism and Kerala Khandalite Belt shows 2148 Ma sediment and ca. 500 Ma metamorphism (Collins *et al.,* 2003; Santosh *et al.*, 2003, 2006). The Palghat- Cauvery Shear Zone is considered to be the Cambrian suture which amalgamated the Neoproterozoic Pandyan Mobile Belt with Archaean-Palaeoproterozoic terranes to the north and, may be a contiguous feature with Ranotsara - and Betsileo Shear Zone of Madagascar (Fig. 5) (Collins, 2006; Santosh *et al.,* 2009; Collins *et al.,* 2012). In light of the present work a correlation may be attempted between Salem-Namakkal Fold Thrust Belt with Antananarivo Craton including Tsaratanana thrust sheets and Itremo Group of metasediments. Antananarivo Craton consists of Neoarchaean orthogneisses and paragneisses with Palaeoproterozoic tonalitic to granitic gneisses (2490–2590 Ma,Tucker *et al.,* 1999,

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Kröner *et al.*, 2000; Key *et al.*, 2011). The Itremo group that overlies the Antananarivo rocks with sheared

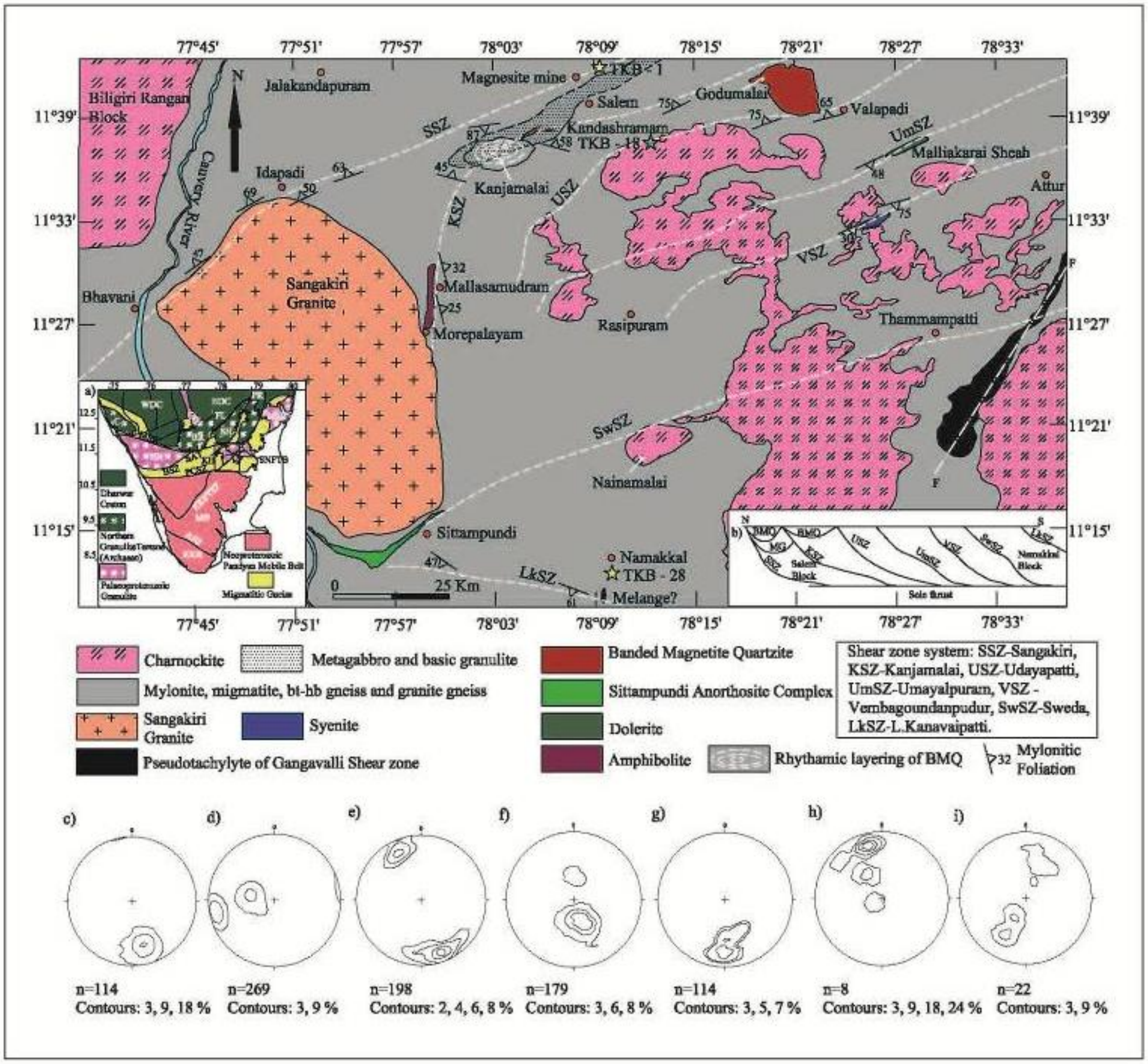

Fig.1 Sundaralingam et al.

Figure 1: Geological Map of the Study area.
Inset a: Simplified geological map of Dharwar Craton and Southern Granulite Terrains after Ramakrishnan and Vaidyanadhan (2008). Abbreviations: ASZ - Achankovil Shear Zone, BR-Biligiri Rangan, BSZ - Bhavani Shear Zone, C - Coorg, CG - Closepet Granite, EDC - Eastern Dharwar Craton, FL - Fermor's line, KH - Kanjamalai Hill, KKB - Kerala Khondalite Belt, KKPTSZ - Karur - Kambam - Painavu -Trichur Shear Zone, MB - Madurai Belt, MSB - Madras Block, MSZ - Moyar Shear Zone, NH - Nilgiri Hill, PR - Palar river, PCSZ - Palghat-Cauvery Shear Zone, SAT - Salem-Attur Thrust, SH-Shevroy Hill, SNFTB – Salem-Namakkal Fold Thrust Belt (Study area),WDC - Western Dharwar Craton.
Inset b: A schematic cross section of the study area, showing imbricate thrusts. The Salem and Namakkal Blocks represent two ends of the nappe belts.
Inset c-i: Stereoplots of mylonitic foliations from different part of the study area.

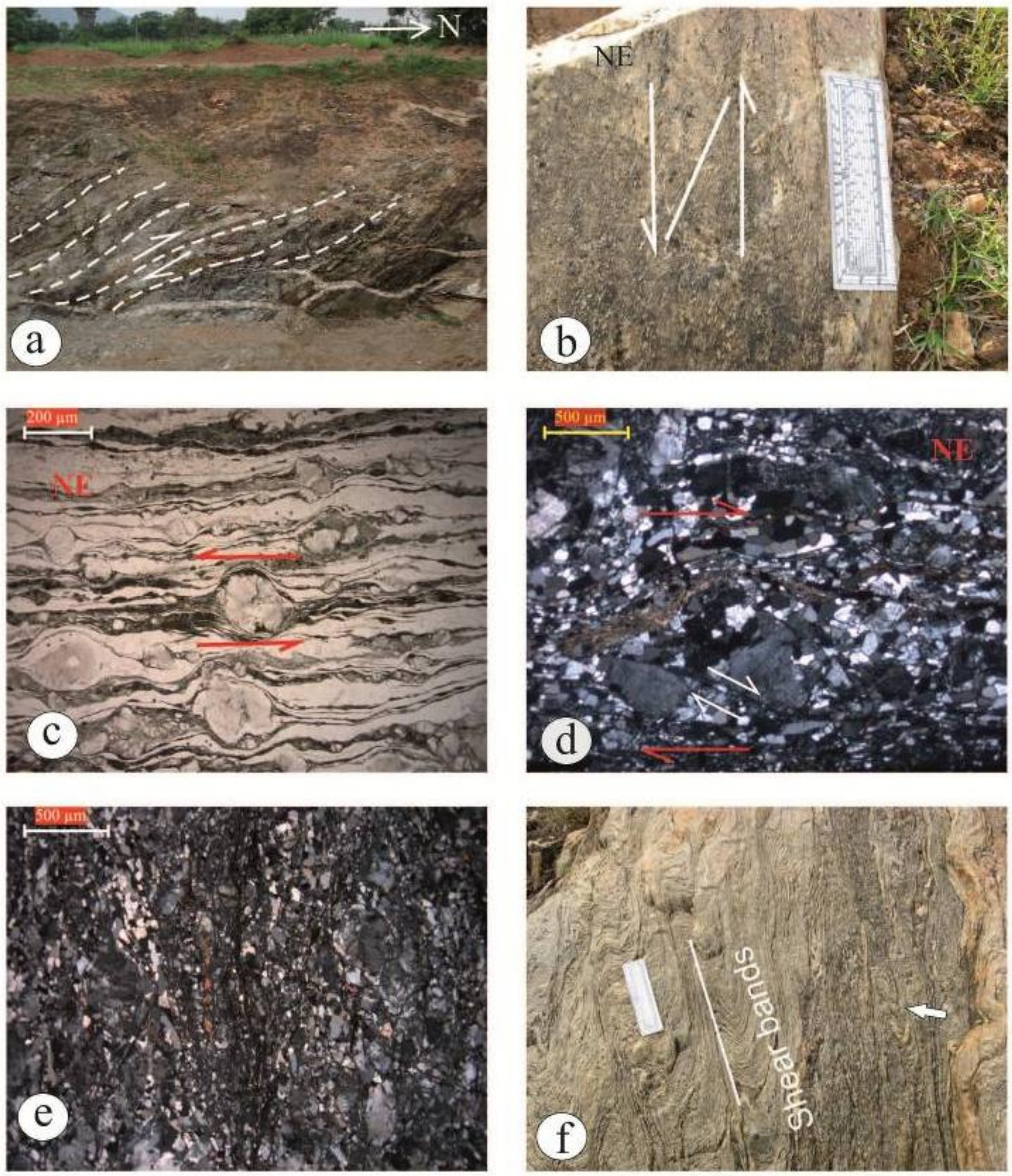

Fig. 2 Sundaralingam et al.

Figure 2: Field photograph and photomicrographs of the rocks. a. Low angle thrust in the mylonites exposed in the railway section south of Namakkal, b. S-C fabric in the Umayalpuram shear zone, c. Rotated porphyroclasts in the Udayapatti shear zone south of Godumalai, d. Intragranular fault, the main shear is opposite to intragranular shear, e. Static crystallization in the quartz grains of the mylonite, suggesting that the T (temperature) continued beyond deformation, f. Shear bands with mylonitisation associated with F_2 folds.

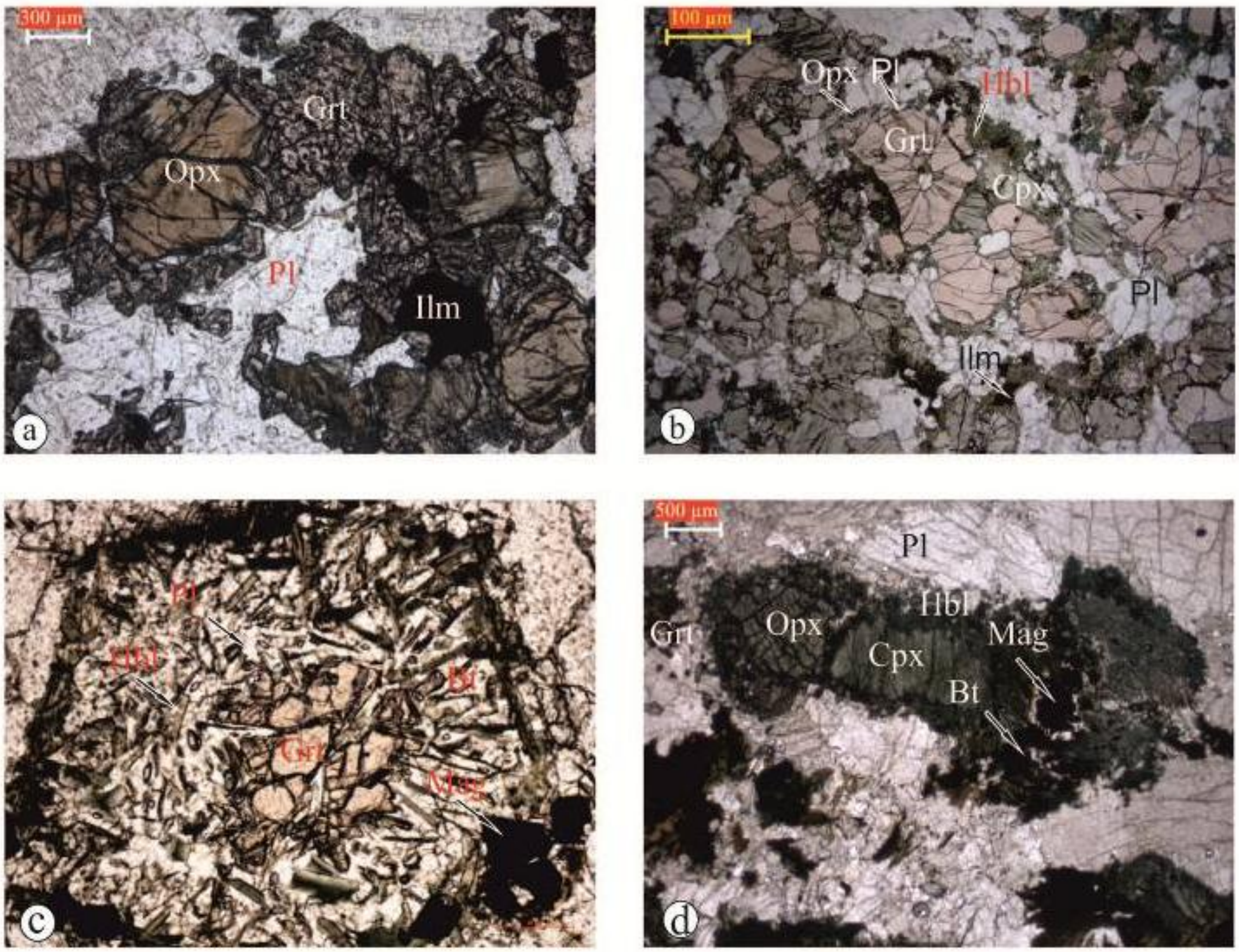

Fig.3 Sundaralingam et al.

Figure 3: Photomicrographs: Reaction rims in the basic granulites a. Garnet rims around opx suggesting isobaric cooling, b. Garnet surrounded by opx and pl rims suggesting isothermal decompression, c. Grt breaking down to hbl, bt and qtz along the shear zone suggesting retrogression, d. Grt, opx, cpx retrograding to hbl and bt.

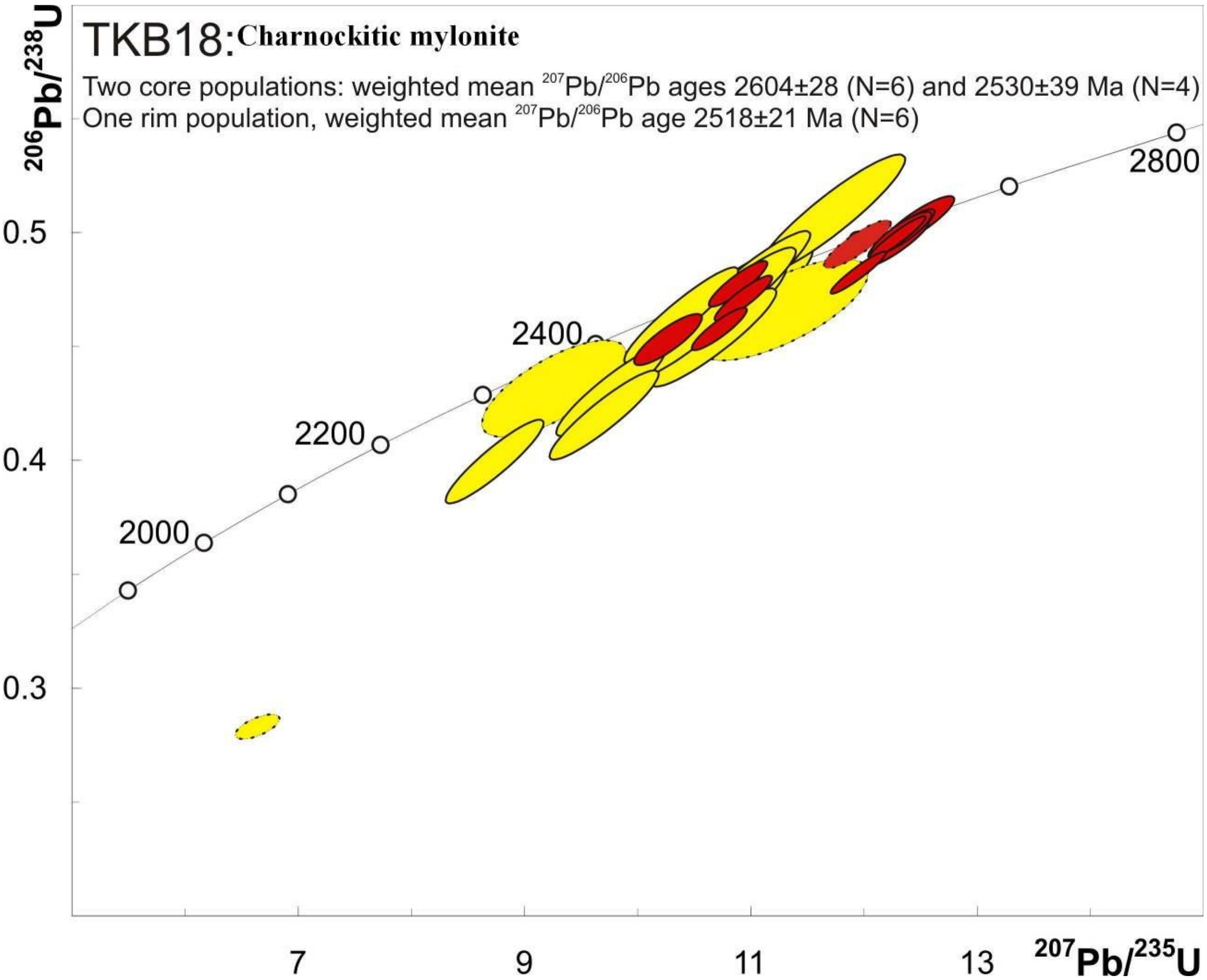

Figure 4: Concordia diagram of Sample TKB-18.

contact at the base consists of 2500 and 1800 Ma old metasediments that have been metamorphosed to different grade (Cox *et al.*, 1998, 2004; Fitzsimons and Hulscher, 2005; Tucker *et al.*, 2007; De Waele *et al.*, 2008). The rock assemblage has been intruded by 550 – 530 Ma old granites (Tucker *et al.*, 1999; Kröner *et al.*, 1999, 2000; Meert *et al.*, 2001; Goodenough *et al.*, 2010). Tsaratanana Complex occurs as isolated nappes on the Antananarivo Craton and Neoproterozoic Manampotsy Belt, suggesting the thrusting is post- Manampotsy age (Kröner *et al.*, 2000). The Tsaratanana Complex may be originally greenstones (de Wit, 2003), metamorphosed later to granulitic orthogneisses; the orthogneisses include gabbroic, tonalitic and granodioritic compositions, and have been dated at about 2520-2470 Ma (Tucker *et al.*, 1999; Kabete *et al.*, 2006; Key *et al.*, 2011) with evidence for high-temperature metamorphism at about 2500 Ma (Gonçalves *et al.*, 2003; Tucker *et al.*, 2010). However, a paragneiss from the Andriamena Belt (Tsaratanana Complex) contained detrital zircons in the range 2870 to 1750 Ma, suggesting the presence of Palaeoproterozoic or younger material (Kabete *et al.*, 2006). The Salem-Namakkal Fold Thrust Belt shows Neoarchaean-Palaeoproterozoic granulites that have been thrusted up in form of nappes over the Northern Archaean Granulite Terrane. The charnockites which has been mylonitsed show 2530±39 Ma, there is no sign of Neoproterozoic imprint.

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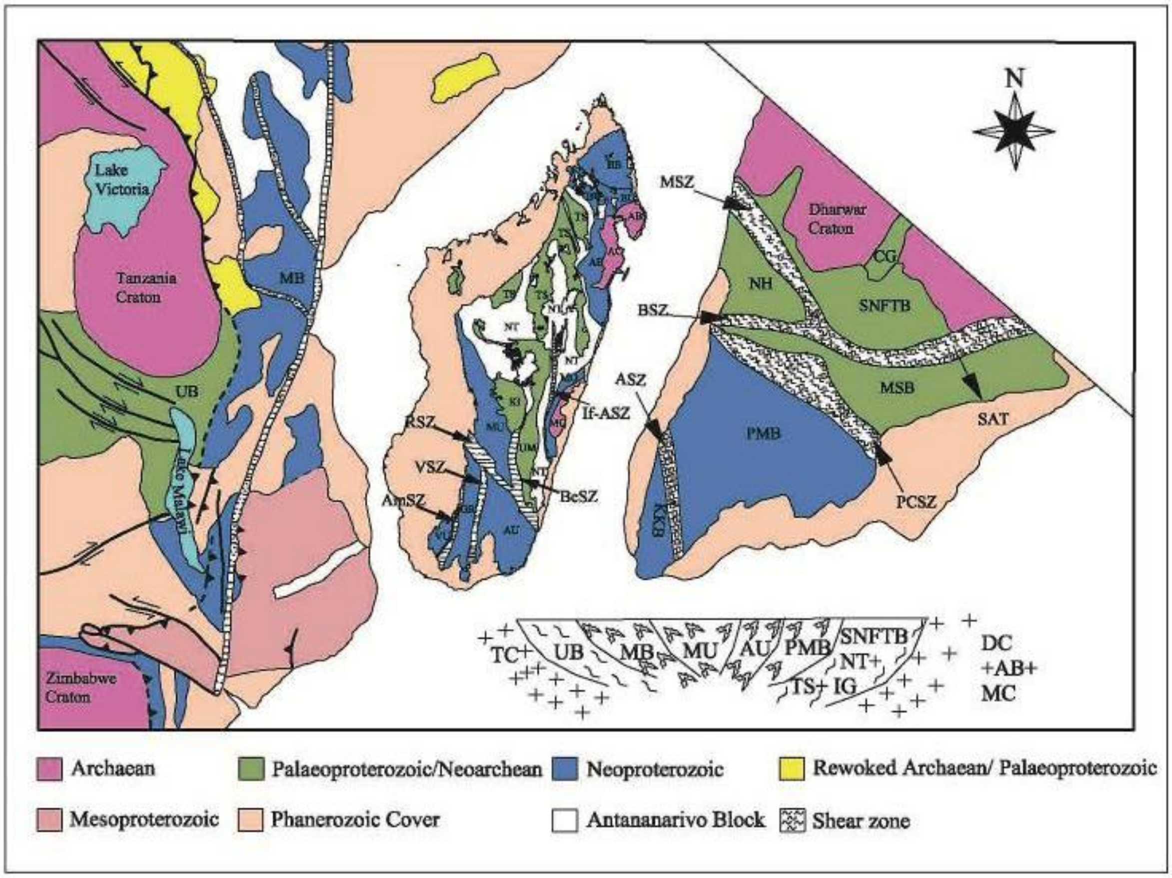

Fig.5 Sundaralingam et al.

Figure 5: Gondwanaland assembly showing juxtaposition of India, Madagascar and Africa. In the inset a schematic cross section is drawn to show the presence of Palaeoproterozoic fold thrust belt on either side of the Neoproterozoic Mozambique ocean (Figures are from Sommer *et al.*, 2003; Collins, 2006; Key *et al.*, 2011). Abbreviations: AB - Anaboriana Belt, AC - Antongil Craton; AmSZ - Ampanihy Shear Zone; ASZ - Achankovil Shear Zone; AU - Androyen Unit; BB - Bemarivo Belt; BeSZ - Betsileo Shear Zone; BSZ - Bhavani Shear Zone; BU - Betsimisaraka Unit; CG - Closepet Granite; GR - Graphite Unit; If-ASZ - Ifanadiana - Angavo Shear Zone; IG - Itremo Group; KKB - Kerala Khondalite Belt; MC - Masora Craton, MB - Mozambique Belt; MO - Manampotsy Belt; MSB - Madras Block; MSZ - Moyar Shear Zone; MU - Molo Unit; NH - Nilgiri Hill, NT - Antananarivo Craton; PCSZ - Palghat-Cauveri Shear Zone; PMB - Pandyan Mobile Belt, RSZ - Ranotsara Shear Zone; SAT - Salem-Attur Thrust; SNFTB - Salem-Namakkal Fold Thrust Belt; TS - Tsaratanana Sheet; UB - Usagaran Block; UM - Undated Sediments; VSZ - Vorokafotra Shear Zone; VU - Vohibory Unit.

However, an indirect interpretation towards a possible Neoproterozoic age for thrusting can be drawn from the magnesite deposits of Salem. The deposit is hosted in dunite-peridotite pluton that underlies the metagabbro/basic granulite nappe sheet. Further, pluton does not show any metamorphism, however, it has been sheared by the basal thrust and serpentinisation and magnesite mineralization have occurred along the shear zone. Hence thrusting is younger than the pluton emplacement. The pluton has been intruded by shonkinite dykes which apparently lack of deformational fabric, but show extensive intermingling with the magnesite veins at the contact zone. The shonkinite has yielded an age of 808±18 Ma (Rb-Sr isochron, Reddy *et al.*, 1995).

Table 1: Electron Probe Micro Analysis of selected rock samples

Sample No.	**TKB-1**				**TKB-28**					
Oxide %	**Grt**	**Opx**	**Pl**	**Ilm**	**Grt**	**Cpx**	**Hbl**	**Pl**	**Pl**	**Ilm**
SiO_2	38.29	51.70	60.25	0.10	39.47	51.45	45.38	60.73	47.69	0.17
TiO_2	0.10	0.11	0.03	53.43	0.09	0.36	0.64	0.00	0.03	47.94
Al_2O_3	21.38	1.00	25.55	0.04	21.58	3.08	10.21	24.61	33.28	0.08
FeO	28.44	26.83	0.00	45.71	24.7	8.75	14.72	0.07	0.54	45.12
MnO	0.95	0.35	0.00	0.20	0.63	0.09	0.00	0.07	0.00	0.10
MgO	4.91	19.21	0.01	1.30	7.67	12.49	11.45	0.00	0.01	2.10
CaO	6.82	0.79	7.08	0.02	6.62	22.8	12.22	6.7	16.71	0.03
Na_2O	0.01	0.00	7.67	0.00	0.05	0.42	1.11	7.76	2.13	0.02
K_2O	0.00	0.00	0.27	0.00	0.02	0.01	0.61	0.35	0.02	0.01
Total	**100.90**	**99.99**	**100.86**	**100.80**	**100.8**	**99.5**	**96.34**	**100.29**	**100.41**	**95.57**
Oxygen Basis	**12**	**6**	**8**	**3**	**12**	**6**	**23**	**8**	**8**	**3**
Si	2.99	1.97	2.66	0.00	3.02	1.93	6.79	2.70	2.18	0.00
Ti	0.01	0.03	0.00	1.00	0.01	0.01	0.07	0.00	0.00	0.95
Al	1.97	0.05	1.33	0.00	1.94	0.14	1.80	1.29	1.80	0.00
Fe	1.86	0.86	0.00	0.95	1.58	0.27	1.84	0.00	0.02	1.00
Mn	0.06	0.01	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00
Mg	0.57	1.09	0.00	0.05	0.87	0.70	2.55	0.00	0.00	0.08
Ca	0.57	0.03	0.34	0.00	0.54	0.92	1.96	0.32	0.82	0.00
Na	0.00	0.00	0.66	0.00	0.01	0.03	0.32	0.67	0.19	0.00
K	0.00	0.00	0.02	0.00	0.00	0.00	0.12	0.02	0.00	0.00
Total	**8.02**	**4.03**	**5.01**	**2.00**	**8.01**	**4.00**	**15.46**	**5.00**	**5.01**	**2.04**
Mg/(Mg+Fe)	0.24	0.56		0.05	0.36	0.72	0.58			0.08
Fe/(Fe+Mg)	0.76	0.44								
Ca/(Ca+Na+K)			0.33					0.32	0.81	
Na/(Ca+Na+K)			0.65					0.66	0.19	
K/(Ca+Na+K)			0.02					0.02	0.00	
Xalm	0.61				0.52					
Xgr	0.19				0.18					
Xpy	0.19				0.29					
Xsp	0.02				0.01					

A far of and probable comparison can be visualized between Salem-Namakkal Fold Thrust Belt with Usagaran Block of Tanzania Craton. Tanzania Craton consists of Archaean Cratonic unit of 3.3 Ga and is surrounded to south by Palaeoproterozoic Usagaran Block. These two tectonic blocks are separated from granulites rocks of the Mozambique belt by westerly verging thrust. Mozambique belt consists of rocks of

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Table 2: Zircon U-Pb SHRIMP data

Spot Name	*f*206 (%)	U (ppm)	Th (ppm)	Th/U	$(^{238}U/^{206}Pb)_{total}$ (±1s abs)	$(^{207}Pb/^{206}Pb)_{total}$ (±1s abs)	$(^{238}U/^{206}Pb)_{204}$ (±1s abs)	$(^{207}Pb/^{206}Pb)_{204}$ (±1s abs)	$^{206}Pb/^{238}U$ Age (±1s Ma)	$^{207}Pb/^{206}Pb$ Age (±1s Ma)
TKB-18-C-1	0.03	135	67	0.51	1.97867 ± 0.02943	0.17933 ± 0.00145	1.97924 ± 0.02944	0.17907 ± 0.00146	2636 ± 32	2644 ± 14
TKB-18-C-2	0.06	195	91	0.48	2.09082 ± 0.02906	0.16571 ± 0.00115	2.09204 ± 0.02909	0.16520 ± 0.00117	2519 ± 29	2510 ± 12
TKB-18-C-4	0.04	417	352	0.87	2.00614 ± 0.02524	0.17932 ± 0.00080	2.00693 ± 0.02525	0.17897 ± 0.00081	2606 ± 27	2643 ± 7
TKB-18-C-5	0.11	426	413	1.00	1.99673 ± 0.02492	0.17979 ± 0.00128	1.99897 ± 0.02495	0.17879 ± 0.00129	2615 ± 27	2642 ± 12
TKB-18-C-6	0.05	152	77	0.52	1.99906 ± 0.02858	0.17929 ± 0.00123	2.00009 ± 0.02860	0.17883 ± 0.00125	2614 ± 31	2642 ± 12
TKB-18-C-7	0.10	359	320	0.92	2.06841 ± 0.02621	0.18035 ± 0.00079	2.07052 ± 0.02624	0.17944 ± 0.00081	2540 ± 27	2648 ± 7
TKB-18-C-8	0.22	287	200	0.72	2.01198 ± 0.02660	0.18190 ± 0.00102	2.01647 ± 0.02667	0.17991 ± 0.00108	2596 ± 28	2652 ± 10
TKB-18-C-9	0.07	247	211	0.88	2.18049 ± 0.02949	0.17034 ± 0.00112	2.18204 ± 0.02952	0.16970 ± 0.00114	2432 ± 27	2555 ± 11
TKB-18-C-10	0.06	212	119	0.58	2.11928 ± 0.02920	0.16862 ± 0.00109	2.12059 ± 0.02922	0.16807 ± 0.00111	2490 ± 28	2539 ± 11
TKB-18-C-11	-	90	327	3.75	2.20526 ± 0.03574	0.163922 ± 0.001633	2.20481 ± 0.03574	0.16411 ± 0.00164	2411 ± 33	2498 ± 17
TKB-18-C-12	0.25	266	149	0.58	2.01321 ± 0.02825	0.17695 ± 0.00133	2.01820 ± 0.02834	0.17475 ± 0.00142	2594 ± 30	2604 ± 14
TKB-18-C-13	2.53	488	396	0.84	3.43140 ± 0.04281	0.19177 ± 0.00210	3.52050 ± 0.04422	0.16920 ± 0.00251	1612 ± 18	2550 ± 25
TKB18-R-1	-	50	64	1.33	2.09132 ± 0.06457	0.16506 ± 0.00203	2.08868 ± 0.06451	0.16619 ± 0.00211	2522 ± 64	2520 ± 21
TKB18-R-2	0.28	64	79	1.28	2.31343 ± 0.06889	0.16679 ± 0.00197	2.31999 ± 0.06911	0.16427 ± 0.00213	2310 ± 58	2500 ± 22
TKB18-R-3	0.07	47	75	1.63	2.37649 ± 0.07220	0.16787 ± 0.00214	2.37814 ± 0.07226	0.16725 ± 0.00218	2263 ± 58	2530 ± 22
TKB18-R-4	2.37	42	8	0.21	2.25903 ± 0.07267	0.17640 ± 0.00292	2.31386 ± 0.07513	0.15532 ± 0.00492	2316 ± 63	2405 ± 54
TKB18-R-5	0.17	38	46	1.25	2.17957 ± 0.06740	0.16762 ± 0.00209	2.18322 ± 0.06753	0.16612 ± 0.00220	2431 ± 63	2519 ± 22
TKB18-R-6	0.07	44	63	1.50	2.49687 ± 0.07554	0.15881 ± 0.00204	2.49857 ± 0.07560	0.15820 ± 0.00209	2170 ± 56	2437 ± 22
TKB18-R-7	0.11	45	63	1.45	2.13877 ± 0.06476	0.16771 ± 0.00309	2.14112 ± 0.06484	0.16673 ± 0.00313	2471 ± 62	2525 ± 32
TKB18-R-8	0.04	39	75	1.99	2.19934 ± 0.06914	0.17059 ± 0.00229	2.20021 ± 0.06918	0.17024 ± 0.00232	2415 ± 63	2560 ± 23
TKB18-R-9	0.81	80	90	1.16	1.95114 ± 0.06608	0.17427 ± 0.00195	1.96710 ± 0.06669	0.16703 ± 0.00243	2650 ± 74	2528 ± 24
TKB18-R-10	0.09	18	14	0.79	2.12386 ± 0.07733	0.16804 ± 0.00347	2.12582 ± 0.07743	0.16722 ± 0.00356	2485 ± 75	2530 ± 36
TKB18-R-11	2.65	46	152	3.38	2.08572 ± 0.06493	0.19891 ± 0.00428	2.14245 ± 0.06710	0.17529 ± 0.00535	2469 ± 64	2609 ± 51
TKB18-R-12	0.14	49	182	3.84	2.11565 ± 0.06508	0.16786 ± 0.00210	2.11854 ± 0.06519	0.16665 ± 0.00219	2492 ± 64	2524 ± 22
TKB18-R-13	0.11	59	71	1.26	2.15171 ± 0.06438	0.16312 ± 0.00183	2.15401 ± 0.06446	0.16217 ± 0.00189	2458 ± 61	2478 ± 20

different ages that have been metamorphosed during NeoProterozoic -Cambrian period (Bingen *et al.*, 2009; Thomas *et al.*, 2010; Ueda *et al.*, 2012). The Usagaran Block is 1800 – 2000 Ma and consists of magmatic rocks (Wendt *et al.*, 1972; Maboko and Nakamura, 1996; Collins *et al.*, 2004) that have been metamorphosed to greenschist to eclogite facies and reworked during Neoproterozoic time (Sommer *et al.*, 2003, 2005 and Vogt *et al.*, 2006). The Pandyan Mobile Belt in India with southern belts of Madagascar and Mozambique belt of the Congo-Tanzania form the central axis of a symmetrical collisional orogen similar to Alpine orogen. Collision between Dharwar and Congo-Tanzania Craton gave rise to the Pan-African orogen and paired fold thrust belts in form of Salem-Namakkal and Usagarn Block on either side (Fig. 5 inset). Azania block may be an obducted central highland (Singh *et al.*, 2010).

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