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New evidence for Palaeoproterozoic High Grade Metamorphism in the Trivandrum Block, Southern India

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ABSTRACT

In-situ zircon U-Pb isotopic and monazite Th-U-Pb chemical ages from leucosome in migmatitic paragneiss at Kanjampara in the Trivandrum Block, India, demonstrate the occurrence of high-T metamorphism and anatexis at 1.92 Ga. This Palaeoproterozoic tectonothermal event was strongly overprinted by the main Neoproterozoic-Cambrian granulite facies tectonism which itself involved significant partial melting and formation of garnet-bearing assemblages at 0.65 GPa and >820-860ºC. Monazite grains, which enclose zircon grains and locally preserve Palaeoproterozoic chemical age domains, were extensively reset and recrystallized at 565 ± 6 Ma. These monazite grains were further modified to form high-Th cuspate rims at 517 ± 15 Ma, equivalent to the lower intercept age for extensive Pb-loss from the highly discordant 1.92 Ga zircon, 528 ± 18 Ma. These results confirm that at least some of the metasedimentary paragneisses in the Trivandrum Block are polymetamorphic, initially metamorphosed in the Palaeoproterozoic in an event older than the 1.89-1.85 Ga granitic orthogneisses recognised from the area. The nature of the relationship between the paragneisses and older (2.0-2.1 Ga) granitic and charnockitic orthogneisses of the Trivandrum and Nagercoil Blocks, in particular whether they share the same Palaeoproterozoic history or were interleaved after 1.92 Ga, requires further investigation focussed on the presence or absence of the isotopic imprint of this event in both rock suites throughout the area.

The growth or recrystallisation of monazite at ca. 565 Ma and its further modification at ca. 520 Ma indicates that the high-T metamorphism in the Pan-African was long-lived, with a duration of at least 45 Myr. This adds further weight to recent proposals, based on zircon-monazite isotopic studies from other localities in the Trivandrum Block, that the region formed the mid- to deep-crust of a long-lived collisional hot orogenic belt that welded Gondwana from ca. 580-510 Ma.

Keywords: zircon, monazite, geochronology, Gondwana, Trivandrum Block

INTRODUCTION

Definition of the complex polyphase tectonothermal histories of the distinct and formerly separate crustal blocks that amalgamated in the late Neoproterozoic-Cambrian to form Gondwana is central to the recognition of crustal sutures and elucidation of the sequences of events through which Supercontinent amalgamation was achieved (Collins et al., 2007, 2014). Recognition of former tectonic relationships between blocks, their affinities, and potential correlations with crustal blocks elsewhere that have survived the fragmentation of older Supercontinents, relies on detailed evidence for local and regional event sequences tied to geochronology and isotopic fingerprinting, informing models for the configuration of continents through time.

Many of the crustal blocks that share late Neoproterozoic-Cambrian orogenesis in Southern India, Sri Lanka, Madagascar and East Antarctica are reworked polymetamorphic terrains and as such preserve, to varying extents, records of older orogens that may have been linked in former Supercontinents. For example, in East Antarctica the Prydz Belt, a region affected by intense 550-510 Ma tectonism, nevertheless preserves convincing evidence for tectonothermal and magmatic events in the period 990-930 Ma that allow its identification as a intensely reworked extension of the nearby Rayner Complex (Liu et al., 2009, 2013; Grew et al., 2012, 2013; Harley et al., 2013) rather than it being a tectonically 'juvenile' orogen characterised by new crust and paragneisses derived from late-Neoproterozoic basinal sediments (Kelsey et al., 2008a).

Similar issues surround interpretations of the high-grade crustal blocks that make up Southern India (Collins et al., 2014). Recent geological and isotopic studies in this region have identified the NW-SE trending Achankovil Shear Zone (AKSZ) as a major terrain boundary separating the Southern Madurai Block (SMB), with which it has strong protolith and event affinities, from the Trivandrum and Nagercoil Blocks to the SW. Detailed U-Pb and Hf isotopic analysis of granitic and charnockitic orthogneisses from the Trivandrum and Nagercoil Blocks that indicate the crystallisation of their magmatic precursors at 2.1-1.77 Ga (Whitehouse et al., 2014; Kroner et al., 2015; Johnson et al., 2015) support this distinction, as the felsic orthogneisses of the SMB and AKSZ were formed from 1.0-1.1 Ga magmatic rocks sourced from crust with model ages of 1.7-1.0 Ga (Plasva et al., 2012, 2014). These isotopic studies, however, do not resolve the original relationships between the Palaeoproterozoic orthogneiss precursors in the Trivandrum Block and the abundant metasediments with which they share late Neoproterozoic to Cambrian high-grade metamorphism and deformation. A number of relationships are possible. If the orthogneiss precursors were basement to some, or all, of metasedimentary precursors then those could be significantly younger and potentially related to the Neoproterozoic metasediments recognised from the SMB and AKSZ. Alternatively, some or all of the orthogneiss precursors in the Trivandrum Block may have been intrusive into metasediments or their precursor sediments, in which case the latter would be at least Palaeoproterozoic in depositional age, share a common history with the orthogneisses from at least 1.85 Ga and hence be entirely unrelated to the metasediments of the SMB and AKSZ. Finally, some or all of the metasedimentary packages and orthogneisses in the Trivandrum Block may have been separate and unrelated until interleaving, perhaps during the Neoproterozoic. In order to resolve these issues it is critical to determine not only the detrital mineral record of the Trivandrum Block metasedimentary gneisses but also establish the nature of any Palaeoproterozoic events that may be preserved within them.

This study reports the results of an integrated petrological, metamorphic and isotopic study of metasedimentary gneisses from Kanjampara quarry (KNJ) in the central area of the Trivandrum Block, with a focus on the chemical and isotopic age and event record preserved in monazite and zircon grains within a representative migmatitic leucosome. Zircon, and to a lesser extent monazite, is found to preserve strong evidence for a major metamorphic event involving anatexis and melt segregation at >1.9 Ga. This indicates that at least some of the metasediments in the Trivandrum Block are polymetamorphic, older than many of the orthogneisses with which they were co-deformed in the Neoproterozoic, and unrelated to the metasediments of the neighbouring crustal blocks to the NE of the TB.

GEOLOGICAL CONTEXT

The Trivandrum Block (Fig. 1; Santosh, 1996; Collins et al., 2014) is an elongate, NW-SE trending gneiss complex that forms part of the Southern Granulite Terrain of India. It is bounded to its NE and separated from the Southern Madurai Block (SMB) by the Achankovil Shear Zone (AKSZ), and bounded to the SW by the Nagercoil Block (NB). Each of these blocks share latest Neoproterozoic to Cambrian (ca. 570-515 Ma) high-grade metamorphic and deformational events associated with the amalgamation of East Gondwana (e.g., Braun et al., 1998; Braun, Kriegsman, 2003; Cenki, Kriegsman, 2005; Santosh et al., 2003, 2006, 2009; Collins et al., 2007; Collins et al., 2014; Clark et al., 2015; Johnson et al., 2015; Taylor et al., 2015).

The Southern Madurai Block (SMB), is comprised of orthogneisses whose magmatic precursors were formed in the late Mesoproterozoic and Neoproterozoic at 1.1-1.0 Ga (Plavsa et al. 2012) and metasedimentary gneisses with detrital zircon ages between 1.5 Ga and 670 Ma (Plasva et al., 2014). Neodymium model ages for SMB gneisses range between 2.0–1.2 Ga (Bartlett et al., 1998; Harris et al., 1994; Plasva et al., 2012), whilst zircon Hafnium model ages for the orthogneisses are 1.7-1.0 Ga (Collins et al., 2007, 2014; Plasva et al., 2014).

Like the SMB, the Achankovil Shear Zone (AKSZ) immediately to the NE of the Trivandrum Block contains Neoproterozoic metasediments (Collins et al., 2007, 2014; Taylor et al., 2015) that preserve Mesoproterozoic Nd model ages (1.4-1.3 Ga: Brandon and Meen, 1995; Bartlett et al., 1998; Cenki et al., 2004), U–Pb detrital zircon age spectra (Collins et al., 2007; Santosh et al., 2006, 2009; Taylor et al., 2015) and zircon Hf isotopic compositions (Plavsa et al., 2014). The Neoproterozoic metasedimentary packages of the SMB and AKSZ are interpreted as the fill of a juvenile late-Neoproterozoic rift-related basin formed on and adjacent to the Madurai Block proper (Plasva et al., 2012; Collins et al., 2014). Consequently, the AKSZ is recognised as a major structural and isotopic boundary separating the TB from the SMB.

The Nagercoil Block (NB), located to the SW of the Trivandrum Block, preserves massif type charnockites with emplacement ages of 2.1-2.0 Ga and Hf and Nd model ages ranging from Archaean to Palaeoproterozoic (2.8-2.2 Ga), identical to the protoliths of charnockites from within the Trivandrum Block itself (Ghosh et al., 2004; Cenki et al., 2004; Kröner et al., 2012; Kröner et al., 2015; Johnson et al., 2015). The protolith, model age and metamorphic age record of the Nagercoil Block (NB) indicates that it is essentially contiguous with the Trivandrum Block (TB) (Kröner et al., 2015; Johnson et al., 2015).

The Trivandrum Block (TB) itself is comprised dominantly of granulite-facies metasedimentary rocks including migmatitic garnet-biotite-quartz-feldspar gneisses and garnet-cordierite-sillimanite gneisses (khondalites), as well as granitic orthogneisses, charnockites and localised mafic granulites. Zircon grains in granitic and charnockitic orthogneisses indicate protolith ages of 2.1-2.0 Ga, 1.88-1.84 Ga and 1.76 Ga (Kröner et al., 2012, 2015; Whitehouse et al., 2014), and an augen granite gneiss has been dated at 1.55 Ga (Kröner et al., 2012). The TB metasedimentary gneisses record Archaean (3.3-2.7 Ga) to Palaeoproterozoic (2.0 Ga) model ages (Cenki et al., 2004; Choudhary et al., 1992; Harris et al., 1994). Detrital zircon cores preserved within strongly overprinted grains record Neoarchaean (2.7-2.5 Ga) to Palaeoproterozoic (2.2-1.9 Ga) $^{207}Pb/^{206}Pb$ ages, from which Collins et al. (2007) have inferred a maximum depositional age of 1.9 Ga, whilst Santosh et al. (2005, 2006) interpreted the maximum depositional age to be as young as 610 Ma based on chemical ages for zircon cores in their samples. In contrast, based on the observation that 2.07 Ga charnockite at Kottaram in the Nagercoil Block intrudes a paragneiss raft Kröner et al. (2015) suggested a minimum depositional age of 2.1 Ga for the sedimentary precursors of the paragneisses, similar to that suggested by Bartlett et al. (1998) from detrital zircon age data. Based on the presence of the 2.1-2.0 Ga and 1.77 Ga orthogneisses Kröner et al. (2015) further speculated that the TB may correlate with the North China Khondalite Belt, a region that records high-grade metamorphism at 1.92 Ga Ma to 1.85 Ga.

The generally preserved regional granulite-facies metamorphism and migmatisation in the TB is latest Neoproterozoic to Cambrian in age. Metamorphic ages defined from the lower intercepts of zircon U-Pb discordia and near-concordant zircon rims in orthogneisses lie in the range 570-515 Ma (e.g. Whitehouse et al., 2014; Kröner et al., 2012, 2015), with concordant soccerball-type zircon grains in leucogranites yielding ages of 544 ± 5 Ma (Kröner et al., 2015). Although Collins et al. (2007) found a significant proportion of metamorphic U-Pb zircon in the metasedimentary gneisses to lie in the age range 513 ± 6 Ma, most zircon ages obtained from migmatitic leucosomes are in the range 570-530 Ma (Braun et al., 1998; Braun and Bröcker, 2004; Braun, 2006; Cenki et al., 2004; Shabeer et al., 2005; Harley and Nandakumar, 2014; Taylor et al., 2014). These ages overlap broadly with monazite chemical and isotopic ages (Bindu et al., 1998; Braun et al., 1998; Santosh et al., 2003, 2006; Harley and Nandakumar, 2014) for the same groups of gneisses. Taylor et al. (2014) reported 585 ± 10 Ma monazite and 523 ± 7 Ma zircon grains from a garnet-biotite gneiss at Kottavattom, inferring from these that HT-UHT metamorphism lasted for some 60 Myr from its onset to late-stage melt crystallisation. This is consistent with Harley and Nandakumar (2014), who obtained ages of 545 Ma and 535 Ma for anatectic zircon and monazite grains respectively, and interpreted these to record cooling from peak metamorphism in the central TB. Taylor et al. (2014) also documented a later phase of post-peak fluid access associated with in-situ charnockitisation, which resulted in monazite dissolution-precipitation at ca. 495 Ma. This age is considerably younger than U-Pb titanite ages that indicate cooling to <600°C by 520 Ma in the TB (Shabeer et al., 2005).

METHODS

Whole-rock major element compositions of two leucogranitic gneisses (KNJ1, KNJ3) and one migmatitic gneiss (KNJ2) were determined by XRF at the National Centre for Earth Science Studies (NCESS), Thiruvananthapuram, using a Bruker S4 Pioneer sequential wavelength-dispersive x-ray spectrometer. CL and BSE imaging of textures and minerals (zircon, monazite, garnet) was carried out on the Phillips XL30 Scanning Electron Microscope (SEM) housed at the School of Geosciences, University of Edinburgh, complemented by further imaging on the FEG-SEM. CL images were collected at 15kV and BSE images at 20kV. Garnet X-ray element mapping was carried out at the Division of Earth Sciences, Department of Environmental Changes, Faculty of Social and Cultural Studies,Kyushu University, Japan, on a JEOL-8900 electron microprobe under beam conditions of 15 kV / 20 nA for major elements and 20 kV / 100 nA for selected REE and P.

EPMA Monazite Trace Element and Th-U-Pb chemical dating

Electron microprobe (EPMA) REE, Ca, Si, P and Th-U-Pb analysis of monazite was carried out using a five-spectrometer CAMECA SX-100 electron microprobe at the University of Edinburgh, employing the REE, Th, U and Pb analytical procedures of D.A. Steele (Kelsey et al., 2003; Berry et al., 2008). Standards used for peak calibration on the SX-100 were Th-oxide for Th, $ScPO_4$ for P, REE (and Y) phosphates for each of La, Ce, Nd, Pr, Sm, Gd, Dy and Y, wollastonite for Ca, Pb-bearing glass K227 for Pb and Si, and pure depleted UO_2 for U. Pb was analysed at 100 nA on two LPET spectrometers, each for 250 seconds on peak and 150 seconds on background, leading to detection limits of approximately 100 ppm. Analysis time for U was 180 seconds on peak and 120 on background. An age of 506 ± 5.8 Ma (2σ standard error of the mean, MSWD = 0.35; 50 analyses) was obtained for the Moacyr monazite standard over the session in which the Kanjampara monazite analyses were obtained (Harley and Nandakumar, 2014), which is in agreement with the accepted $^{207}Pb/^{235}U$ ID-TIMS age of 504.3 ± 0.2 Ma obtained by Gasquet et al. (2010) from fragments of the same Moacyr monazite grain (Itambe region, Brazil, provided by J.-M. Montel).

U-Th-Pb-REE analysis of KNJ monazite was also carried out in 2004 using a Camebax electron microprobe at the University of Edinburgh. In this set of analyses the suite of elements analysed was essentially the same as in that SX-100 protocol, but the use of a beam current maintained at 60nA coupled with the use of only 4 spectrometers with non-curved PET and LIF crystals resulted in lower count rates and hence lower overall precisions. Nevertheless, the Camebax data (20 analyses) referenced against the same Moacyr standard are consistent with the higher-precision data acquired on the SX-100 and are included here for completeness.

SIMS Trace element Microanalysis Protocol

REE and other selected trace elements within zircon and garnet were determined using the CAMECA ims-4f ion microprobe at the University of Edinburgh. Analytical conditions and correction procedures follow those of Kelly and Harley (2005), modified from Hinton and Upton (1991). Analyses were conducted using a 6 nA O^- primary beam with an accelerating voltage of -10 KeV, focused to a 20-25 μm spot. Secondary ions were extracted at a potential of 4500V and measured at a 120eV high-energy offset for zircon and 75eV energy offset for garnet, with a 19eV energy window. Trace element abundances were calculated relative to ^{28}Si and calibrated against the NIST-610 glass standard, with ion yields corrected by reference to the zircon standard SL1 (for zircon) and DDI garnet standard (for garnet). Analyses were performed for Si, P, Ca, Ti, Zr, Y, Nb, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er. Tm, Yb, Lu, Hf, Th, and U. Corrections for isobaric interferences on HREE arising from LREE oxide species were carried out using in-house software developed by R.W.Hinton. SIMS analysis of monazite followed similar calibration and correction procedures with ion yields adjusted by reference to the Moacyr standard and totals normalised to 100%.

SIMS U-Pb Microanalysis Procedures

U/Pb dating of zircon was carried out in-situ in thin section at the Edinburgh Ion Microprobe Facility (EIMF), using the CAMECA ims-1270 ion microprobe. The thin section and inserted standards were imaged in detail using transmitted and reflected light microscopes, as well as under SEM for CL and BSE imaging.

Analytical procedures were based on those used by Kelly et al. (2008), and similar to those described by Schuhmacher et al. (1994) and Whitehouse et al. (1997). Correction for in-situ common Pb was made using the measured ^{204}Pb counts above background at mass 204, and applying the present day common Pb composition. Correction of Pb/U ratios for instrument drift with time was made using the relationship between ln(Pb/U) vs ln(UO_2/UO) (e.g. Schuhmacher et al., 1994; Whitehouse et al., 1997; Kelly et al., 2008).

Elemental concentrations and Th/U ratios in unknown zircon grains were calculated by reference to measurements of Th/U and ^{208}Pb/^{206}Pb on the Geostandards 91500 zircon (Wiedenbeck et al., 1995, 2004: ^{206}Pb/^{238}U age of 1062.4 ± 10.3 Ma; assumed ^{206}Pb/^{238}U ratio = 0.17917; U = 81.2 ppm). Zircon U/Pb ratios were calibrated against measurements of the Plesovice zircon standard (Slama et al., 2008: ^{206}Pb/^{238}U age 337.1 ± 6.0 Ma (1σ); assumed ^{206}Pb/^{238}U ratio = 0.05369). 14 analyses of the Plesovice standard bracketing the KNJ analyses in this study yielded an average $^{206}Pb/^{238}U$ ratio of 0.5369 ± 0.0003 corresponding to a $^{206}Pb/^{238}U$ age of 337.1 ± 1.8 Ma (2σ; MSWD = 0.45).

Zircon data were reduced online using in-house data reduction spreadsheets developed by R.W. Hinton, and subsequently processed for age statistics using ISOPLOT/EX v3 (Ludwig, 2003). Uncertainties on ages quoted for individual analyses (ratios and ages) are at the 1σ level. The Inverse (Tera Wasserburg) Concordia diagram of Fig. 15 was calculated with $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ratios corrected for the minor common Pb present as calculated from measured ^{204}Pb; error ellipses presented in Fig. 15 are at 2σ level.

FIELD RELATIONS, PETROGRAPHY AND MINERAL CHEMISTRY

The field relationships and dominant rock types at Kanjampara quarry (KNJ) are similar to those throughout the metasedimentary gneisses of the Trivandrum Block. The gneisses are migmatitic on centimetre to decimetre width scales, and possess a sub-vertical gneissic fabric defined by the elongation of garnet, cordierite and sillimanite in mesosomes, platy quartz in felsic layers within the mesosomes, and alignment of leucosomes and leucogranitic sheets (Fig. 2). Migmatitic mesosomes (KNJ2) contain Grt + Crd + Sill ± Bt + Kfs + Plag + Qz + Fe-Ti oxides; green spinel may occur as a minor phase associated with the ilmenite in some sillimanite-rich foliae. Leucosome / leucogranite horizons and veins (KNJ1, KNJ3) contain Grt + Kfs + Plag + Qz + Ilm ± Sil, whilst leucosome KNJ2 and its sub-sample ED10 contain additional cordierite. Accessory zircon, monazite and apatite occur in both leucosomes and migmatitic mesosome, with zircon and monazite being significantly more abundant (by an order of magnitude) in the leucosomes.

The accessory mineral-rich KNJ2 leucosome sub-sample ED10 has been studied and analysed in depth in this work. ED10 preserves large porphyroblastic garnets (up to 5 mm in diameter) partially surrounded or replaced by radial symplectitic intergrowths of cordierite with quartz (Fig. 3a). The single large garnet porphyroblast in ED10 contains inclusions of zircon in its core regions but is strongly poikiloblastic and intergrown with quartz in its outer portions where those are not replaced by cordierite. This garnet is homogeneous in terms of its major element composition over most of its grain area ($Alm_{68.6}Prp_{27.8}Grs_{1.9}Sps_{1.6}$; X_{Mg} = 29), but is weakly zoned to lower X_{Mg} (27) and marginally higher Grs (2.4 mol%) within ca. 50 μm of rims adjacent to cordierite (Fig. 3a). Antiperthitic plagioclase, perthitic K-feldspar and quartz form a granoblastic polygonal to lobate texture, modified especially adjacent to garnet by the presence of grain-boundary films or rinds (up to 20 micron across) of homogeneous K-feldspar between plagioclase and quartz (Fig. 3b, c). Myrmekite is also present. Cordierite (<10 modal %) occurs within the quartzo-feldspathic matrix as clusters of granoblastic grains (X_{Mg} = 67-70) and as intergrowths at the margins of garnet (X_{Mg} (Crd) = 67-74). Sillimanite (1-2 modal %) occurs as rare grains in granoblastic cordierite within the quartzo-feldspathic groundmass. Zircon and monazite are abundant accessory phases, as described in detail below.

PHASE EQUILIBRIUM MODELLING OF KNJ GNEISSES

Conventional garnet-cordierite geothermobarometry *P-T* estimates obtained by Nandakumar and Harley (2000) for sample ED10 are 0.53-0.66 GPa and 800-850 °C. To improve on these estimates the bulk rock compositions of KNJ1 and KNJ2 (Supplementary Table 1) have been recast into molar proportions and used to calculate equilibrium phase diagrams over the *P-T* range 4-10 kbar and 750-950°C, for bulk H_2O contents of 0.5, 1 and 1.5 wt% H_2O in each rock composition. These bulk H_2O contents cover the range from that necessary to ensure the presence of melt at minimum temperatures of at least 710ºC, as required by the Ti contents of zircon (see below), up to the amount based on loss on ignition. Theriak-domino (de Capitani and Petrakakis, 2010; updated domino 03-01-2012 version) was used in concert with THERMOCALC (Holland and Powell, 1998) database tcdb55c2d (Holland and Powell, 2011) to calculate phase diagrams in NCKFMASHT and isolines of garnet (X_{Mg}, X_{grs}) and cordierite (X_{Mg}) compositions. Activity-composition relations used for the phases were those White et al. (2007) for biotite, garnet and melt, White et al. (2002) for orthopyroxene and spinel-magnetite, White et al. (2000) for ilmenite, Holland and Powell (2003) for the feldspars, and Holland and Powell (1998) for hydrous cordierite. Whilst it is recognised that this dataset and the activity-composition relationships linked with it are now superseded by more recent models and do not adequately account for oxidation, this simplified approach is considered reasonable for the purposes of this study in which the *P-T* conditions are only of peripheral interest.

The KNJ2 phase diagram for 0.5 wt% H_2O, and calculated assuming no Fe^{3+}, is presented in Fig. 4. Varying bulk rock H_2O content from 0.5-1.5 wt% for this rock composition has only a very minor effect on the positions of the key reactions constraining the stability field of the observed garnet + cordierite + ilmenite + 2 Feldspars + quartz ± sillimanite ± biotite assemblage. Oxidising even 5% of the measured Fe to Fe^{3+} stabilises spinel and leads to magnetite appearing in most calculated assemblages, which is not seen in the analysed rock.

The Grt + Crd + Ilm + 2 Feldspars + Qz ± Sill ± Bt assemblage is constrained to lie at minimum *P-T* conditions of 0.55 GPa and 780°C. Isopleths of grossular (X_{grs} < 2 mol%), X_{prp} (garnet cores) of 26-28 and X_{Mg} (cordierite) of 66-68, the mineral compositions documented from a more leucocratic sub-sample of KLP2 (ED10), further constrain the P-T of garnet equilibration to lie in the field defined by the ellipse in Fig. 4 (*P* = 0.62-0.66 GPa; *T* = 840±20°C). The phase diagram calculations also suggest that peak temperatures are unlikely to have exceeded 950°C at these pressures as sillimanite is present rather than spinel (Fig. 4), and two moderately ternary feldspars occur rather than a single mesoperthitic feldspar (Fig. 3c, 3d). Similar conclusions can be drawn from analysis of the phase diagrams calculated for KNJ1 with 0.5 wt% and 1 wt% H_2O, which are presented in Supplementary Figure 1.

GARNET TRACE ELEMENT CHEMISTRY

In contrast to the lack of zoning in its major element composition, garnet in ED10 is heterogeneous in Y contents (430-130 ppm), and strongly zoned rimwards in terms of MREE and HREE (Yb_n/Gd_n: Fig. 5; also see Supplementary Figure 2). Selected REE abundances and ratios are plotted against distance in Figure 6, where distance is measured radially from the included zircon grain kz3, which is near the geometric centre of the garnet. Ten of the data points also lie on an approximately linear traverse across the garnet through this reference point. The data define an inner domain, 3000 μm in radius, in which the concentration of Y and HREE (Ho to Lu) decrease outwards, and an outer 2000 μm wide zone in which the concentrations of MREE in particular (Sm, Gd, Tb, Dy) increase. In detail:

a) Sm, Gd and Tb are near-constant in the inner domain but increase by a factor of 4 rimwards in the outer domain (e.g. to Sm_n = 20 and Gd_n = 160);

b) Dy, Y and Ho decrease outwards (by factors of 0.6-0.7) across the inner domain, and then increase across the outer domain by a factor of 3;

c) Er, Tm, Yb and Lu decrease markedly outwards across the inner domain, by factors of 0.35-0.25, and then are nearly constant or only increase slightly across the outer domain.

Chondrite-normalised garnet REE patterns highlight this marked change in MREE-HREE chemistry (Fig. 7). The inner domain is characterised by HREE at ca. 100-200 times chrondrite, a symmetrical but small 'hump' centred on Dy_n-Ho_n-Er_n, a shoulder defined by Gd_n<Tb_n<Dy_n, and very strong Eu depletion (Eu/Eu* = 0.035-0.015) with Eu_n generally less than 1. The combination of the individual MREE-HREE zoning features leads to a consistent decrease in Yb_n/Gd_n from 3.5 to 0.5 across this inner garnet domain (Fig. 6). The outer domain, in contrast, is typified by near-constant Yb_n/Gd_n of 0.5, a significant REE 'hump' from Gd_n to Ho_n that is centred on Dy_n, and lowered HREE from Er_n to Lu_n. Relative Eu depletion is also extreme (Eu/Eu* = 0.02-0.01), even though Eu_n is slightly higher than in the inner domain. These variations in P and the MREE-HREE are not evident in other trace elements: the garnet is unzoned in Zr (20-30 ppm).

EPMA trace element mapping of the garnet (Supplementary Figure 2) confirms the concentric character of the REE zoning, with high Y coupled with P in the core region defined from the SIMS analyses. Y is also observed to increase at the outermost rims of the garnet adjacent to cordierite. The EPMA maps also demonstrate that zircon inclusions are enriched in Er and Y relative to host garnet but similar to garnet in their Dy contents.

ACCESSORY MINERAL TEXTURES, CHEMISTRY AND GEOCHRONOLOGY

Monazite

Monazite Mineral Textures

Monazite occurs exterior to garnet as individual, inclusion-free, very coarse (300-700 μm length) subhedral-elongate grains at quartz-feldspar and quartz-cordierite contacts (Mnz2, Mnz5, Mnz8, Mnz9) or as more irregular and rounded poikiloblastic to xenoblastic grains that partially or wholly enclose 30-150 μm diameter multifaceted and equant zircon grains (e.g. Mnz10, Mnz11). High Th-Ca monazite (Cheralite) is preserved in one leucosome thin section.

BSE imaging reveals that all monazite grains are characterised by tessellated (Fig. 8: Mnz9) to irregular and cuspate-lobate internal domains, with darker and brighter BSE domains showing mutually truncating relationships (Fig. 5: Mnz2, Mnz5, Mnz9). 'Kernels', circular to oval bright-BSE domains, 10-40 μm in diameter, occur randomly located within most grains (Fig. 8: Mnz2, Mnz5, Mnz8, Mnz11). The tessellated to irregular and 'kernel' bearing internal zoning is truncated in several grains by bright curviplanar rim domains, 10-50 μm in width, that parallel grain boundaries (Fig 8: Mnz8, Mnz9, Mnz10). High-resolution BSE images of Mnz9, obtained on the Field Emission Gun SEM, reveals complexity in both the background 'tessellated' domains and the irregular to oval brighter BSE kernels. The darker tessellated domains display angular and linear BSE discontinuities and sub-areas suggestive of healed fractures, whereas the irregular and oval domains appear to truncate these. Micropores are associated with both types of texture.

Monazite Mineral Chemistry and EPMA Th-U-Pb Ages

KNJ monazite describes a wide range in terms of their Th+U+Si and REE chemistry (Fig.9: Th+U+Si = 0.3-0.8), though most analyses cluster at the lower Th+U+Si end of this range. ThO_2 for the whole analytical population varies between 6 and 15 wt%, with most analyses being in the range 6-10 wt%. UO_2 is generally relatively high, from 0.7 wt% to 1.8 wt%, leading to low Th/U. Yttrium (Y) and partial REE patterns obtained using EPMA (Table 2, Fig. 10) are characterised by moderate to strong HREE and Y depletions compared with LREE (Ce_n/Y_n = 30-150; Dy_n = 8000-25000; Fig. 10). Y_2O_3 (0.2-2.2 wt%) correlates with UO_2. Full REE analyses have been obtained by SIMS to complement the EPMA analyses (Table 3, Fig. 10). The SIMS results (Table 4) are consistent with EPMA and furthermore show that the monazite grains have strongly negative Eu anomalies (Eu/Eu* < 0.1) and strong Y and HREE depletions (Ce_n/Y_n = 500-2000; Gd_n/Yb_n = 60-300).

A sub-group of monazite analyses that plot within the main analytical cluster in terms of total REE+Y+P (7.4 in Fig. 9) have high Ce_2O_3/Y_2O_3 and ThO_2/UO_2 reflecting their relatively low UO_2 (0.44-0.73 wt%) and Y_2O_3 (0.44-0.55 wt%) contents. These monazite analyses, which also record old chemical ages from ca. 1266 Ma to ca. 1793 Ma (Table 2), are located within otherwise typical monazite grains with ages in the 570-550 Ma range (e.g. Mnz9) and show no evidence of overgrowth by the younger domains. For example, Mnz11 not only records several chemical ages from 564 Ma to 598 Ma, but also preserves chemical ages in lower-UO_2 domains from 1793 Ma to 1290 Ma, and 1077 Ma for a high UO_2 (>1.9 wt%) analysis site (Mnz11: Fig. 8).

KNJ monazite grains spanning the age range from 618 ± 15 Ma to 507 ± 20 Ma describe a trend of increasing Ce_2O_3/Y_2O_3 and ThO_2/UO_2 with decreasing age (Fig. 11), correlated with increasing Th+U+Si. Chemical age data for this monazite group are presented in the probability density diagram of Fig. 12a. The 49 analyses produce a broad probability density distribution with mean peak age at 557.6 ± 6.1 Ma and 2σ age spread of ± 20 Ma. The density distribution curve is slightly skewed by the presence of a sub-group of younger analyses between 507-530 Ma, all of which have been obtained from rims that have high or intermediate ThO_2 relative to the slightly older domains in this monazite population. When the chemical age data are evaluated excluding this younger age sub-group (6 analyses) and 4 older outliers (> 600 Ma) the remaining 39 analyses yield a weighted mean age of 559.5 ± 5.4 Ma (2σ, MSWD = 0.36; probability = 1; Fig. 12b). The higher- ThO_2 rim analyses (n = 6) yield a weighted mean age of 517 ± 15 Ma (2σ, MSWD = 0.16; probability = 0.98).

Zircon

Zircon Textures and Settings

Zircon is abundant in KNJ leucosome ED10. For example, more than 50 grains with diameters of 50-400 μm have been observed in one 2.5 cm^2 thin section. These zircon grains occur in four textural contexts: as individual prismatic to multifaceted, sub-elongate to equant grains located in the plagioclase + perthitic K-feldspar + quartz leucosome groundmass; as clusters of grains of similar form and size, partially enclosed by coarse irregularly-zoned monazite; included within granoblastic cordierite within the leucosome; and as equant grains included in coarse porphyroblastic garnet (e.g. z3, z4) or on garnet-quartz grain boundaries.

CL imaging reveals all zircon grains to have generally weak oscillatory (Fig. 13: z1, z3, z5, z10), sector and sector-planar zoning, with the latter being dominant in most grains (Fig. 13: zz3, z4, z13, z14). Bright CL, 10 μm thick partial rinds or lobate domains occur on some grains (Fig. 13: z5, z11), but overall the extent of modification of the planar and weak oscillatory zoning in the zircon is minor. The shared internal features of these zircon grains irrespective of their textural settings suggest that they form a single population, grown prior to or contemporaneously with enclosing garnet, cordierite and monazite.

Zircon Chemistry

The zircon grains are relatively homogeneous (Table 4). HfO_2 is 1.48 ± 0.05 wt% and Ti contents are 6.0 ± 1.2 ppm. These Ti contents indicate *minimum* temperatures of crystallisation of 713 ± 19°C (n = 5) based on the Ferry and Watson (2007) thermometer. U (1250 ± 300 ppm, 2σ) is uniformly high, and Th (22 ± 10 ppm, 2σ) low, yielding consistent but extremely low Th/U (0.018 ± 0.006, 2σ).

Zircon REE chemistry is presented normalised against chondrite values of Anders and Grevasse (1989) in Fig. 14. The REE patterns are characterised by very strong negative Eu anomalies (Eu/Eu* = 0.01-0.05) and negligible to weakly positive Ce (Ce/Ce* = 0.6-2.2) anomalies. HREE are flat (Yb_n/Tb_n = 1.0 ± 0.05) with a 'shoulder' dropping to lower Gd_n so that Yb_n/Gd_n is >1 (2.0 ± 0.3). Dy_n is generally in the range 450 ± 120. The low Yb coupled with the high U contents result in high U/Yb (20.7 ± 3.7, 1σ) that increases to 29 ± 5 when U is back-corrected to the age of zircon crystallisation (1.92 Ga, see below). Coupled with the low Th/U, this chemistry is unique for zircon reported from the Trivandrum Block (cf. Shabeer et al., 2005; Kröner et al, 2012, 2015; Harley and Nandakumar, 2014; Taylor et al., 2014; Whitehouse et al., 2014).

Zircon U-Pb zircon geochronology

Zircon U-Pb analyses have been carried out on spots adjacent to those sites analysed for REE. The U-Pb isotopic results are presented in Table 5 and the Tera-Wasserburg inverse Concordia diagram of Fig. 15. All 22 zircon analyses are strongly discordant, defining a single discordia with model 1 intercepts at 1923 ± 40 Ma and 528 ± 18 Ma (95% conf.; MSWD = 1.3, probability of fit 0.19). When 2 analyses with relatively high common Pb (f_{206} > 0.14%) are excluded the remaining 20 analyses yield essentially identical upper and lower intercepts of 1918 ± 51 Ma and 525 ± 23 Ma (95% conf., MSWD = 1.4, probability of fit 0.12).

DISCUSSION

Palaeoproterozoic High Grade Metamorphism in the Trivandrum Block

The ED10 leucosome at Kanjampara preserves unequivocal evidence for anatexis and zircon crystallisation at ca. 1.92 Ga, at minimum temperatures of 715°C required by the Ti contents of the zircon. The zircon grains are chemically distinct from igneous protolith zircon widely reported from the TB and NB (e.g. Whitehouse et al., 2014; Taylor et al., 2014; Kröner et al., 2012, 2015; Johnson et al., 2015; Clark et al., 2015) and hence do not share the same origin. The ED10 zircon grains have high U and low Th and hence distinctively low Th/U, preserve flat HREE patterns, and have high U/Yb (24-34) compared to all other Palaeoproterozoic zircon recorded from the TB and NB. These chemical features are compatible with zircon crystallisation in leucosome formed through the anatexis of garnet-bearing metasediment, and consistent with the presence of quartz, feldspars and, notably, sillimanite as inclusions in the zircon grains. The Palaeoproterozoic zircon age confirms the chemical age spectra obtained from monazite that on the basis of textural relationships formed along with or after the zircon. These chemically heterogeneous and variably zoned monazite grains locally preserve EPMA ages of up to ca. 1.8 Ga within otherwise 'younger' or reset domains (570-560 Ma) and hence initially formed in the Palaeoproterozoic HT anatectic episode.

Examination of previous monazite and zircon studies from the Trivandrum Block reveals potential evidence for a metamorphic event at or near 1.92 Ga. Braun et al. (1998) obtained

EPMA ages of ca. 1.97 Ga for cores of monazite grains and interpreted these to provide a minimum age for first monazite growth or complete homogenization. Several ca. 1.9 Ga U–Pb electron microprobe monazite ages reported by Santosh et al. (2003, 2005, 2006) also would be consistent with the KNJ data if re-interpreted as reflecting metamorphism at that time. Shabeer et al. (2005) reported ca. 1.95 Ga high-U, low Th/U zircon in their sample KPS30/1 that could be analogous to the zircon documented here from sample ED10.

Bartlett et al. (1998) also noted the existence of a possible Palaeoproterozic metamorphic event, interpreting a zircon Pb-evaporation plateau age of 1802 ± 16 Ma to indicate new zircon growth under amphibolite facies conditions. This age is considerably younger than both the age of anatexis at Kanjampara and of the 1.89-1.85 Ga orthogneisses recently documented by Kröner et al. (2012) and Whitehouse et al. (2014) in the TB, and is not recorded in any of the gneisses examined in this and other recent studies.

The 1.92 Ga HT anatectic event recorded at Kanjampara is also distinct in age from the intrusive ages of older granitic orthogneisses and charnockites from the TB and NB (Kröner et al., 2015; Johnson et al., 2015), which as noted above are 2.1 Ga, 2.07 Ga and 2.0 Ga. Kröner et al. (2012) and Whitehouse et al. (2014) have also reported igneous protolith ages of 1.89 and 1.85 Ga from localities in the central TB to the north of Kanjampara. These granitoid intrusions are arguably younger than the high-grade metamorphic event recorded by the zircon in KNJ.

The age data of Kröner et al. (2015) imply that the metasediments that are interleaved and co-deformed with the granitic gneisses of the Trivandrum Block had to have been deposited before 1765 Ma (the age of a moderately-deformed garnet-bearing K-feldspar blastic granite gneiss) and most likely prior to 2.0 Ga, the age obtained from an unfoliated granodiorite at Kottavattom and from two well-foliated garnetiferous leucogneisses. A 2.1 Ga granitic leucosome formed in a metasedimentary enclave within the 2.07 Ga charnockitic gneiss at Kottaram in the Nagercoil Block provides an even older potential minimum age for the deposition of sedimentary precursors to the paragneiss, as well as implying high-grade metamorphism of at least some of the metasediments at or before 2.0-2.1 Ga (Kröner et al., 2015, Johnson et al., 2015). The zircon chemical and age data from Kanjampara record no evidence for this older event but instead demonstrate a high-T event at 1.92 Ga that, if present on a regional scale, might be recorded by accessory minerals in other metasedimentary gneisses and in the 2.1-2.0 Ga orthogneisses from both the Trivandrum Block and Nagercoil Block. Demonstration of a 1.92 Ga overprint on the orthogneisses would confirm that the orthogneiss precursors were either basement to the metasedimentary gneiss precursors or intrusive into them, and also the regional extent of the event, whereas the absence of such an overprint might indicate that, in general, tectonic interleaving of earlier-formed metasediments and orthogneisses occurred after 1.92 Ga.

Age and duration of the Neoproterozoic-Cambrian Tectonothermal Episode

The Palaeoproterozoic high-grade event documented from Kanjampara and sporadically preserved in the TB was extensively and thoroughly overprinted at ca. 580-520 Ma by the well-documented HT-UHT tectonothermal episodes recorded throughout the TB and adjacent blocks in southern India (Santosh et al., 2003, 2006, 2009; Braun and Kriegsman, 2003; Braun, 2006; Cenki and Kriesgman, 2005; Collins et al., 2007, 2014; Sato et al., 2011; Harley and Nandakumar, 2014; Taylor et al., 2014, 2015; Clark et al., 2015; Johnson et al., 2015).

The principal population of chemically heterogeneous and variably zoned monazite in the ED10 leucosome at Kanjampara recrystallized at 560 ± 6 Ma. Whilst similar in age to the peak metamorphic monazite reported by Braun et al. (1998), the timing of this monazite reconstitution at Kanjampara is some 10-15 Ma later than monazite crystallisation at Kottavattom (Taylor et al., 2014) and 15-20 million years earlier than the 535 ± 6 Ma timing of monazite formation at Kulappara (Harley and Nandakumar, 2014). This confirms the long-lived character of the Neoproterozoic-Cambrian HT-UHT metamorphism in the Trivandrum Block, with monazite development or recrystallization occurring at various times from 585 ± 10 Ma to 535 ± 10 Ma, depending on locality, lithology and structural context of the monazite-bearing sample. A similar range in monazite ages has been reported from the adjacent Nagercoil Block (Johnson et al., 2015).

Late-stage higher-ThO_2 cuspate rim domains on monazite grains at Kanjampara (517 ± 15 Ma), attributed to coupled dissolution / re-precipitation (Seydoux-Guillaume et al., 2002), were produced at a similar time to that recorded in other Trivandrum Block samples (e.g. Santosh et al., 2006; Collins et al., 2007; Harley and Nandakumar, 2014; Clark et al., 2014; Taylor et al., 2014).Whilst the lower age intercept obtained from the zircon discordia (528 ± 18 Ma) is consistent with the age of late-stage monazite re-equilibration, the extent of extrapolation required from the group of discordant zircon grains in ED10 means that this lower intercept age should be treated with caution in the absence of concordant new zircon rims or grain of similar age. Nevertheless, the lower intercept age is similar to those reported in other recent studies of zircon from leucogranites from the TB (Whitehouse et al., 2014; Kröner et al., 2012, 2015) and to the ages of concordant metamorphic zircon grains reported by Shabeer et al. (2005) (ca. 530-525 Ma), documented in garnet-biotite gneiss from Kottavattom (Taylor et al., 2014: 523 ± 7 Ma), and recorded from a number of gneisses from the NB (Johnson et al., 2015).

Granulite Facies Metamorphic Conditions: Neoproterozoic or Palaeoproterozoic?

Conditions of the granulite facies metamorphism and partial melting recorded in the KLP gneisses are constrained to be 0.6-0.65 GPa and >820-860ºC based on thermodynamic phase diagram modelling, broadly consistent with the results of regional thermobarometry in the central TB (Chacko et al., 1987; Nandakumar and Harley, 2000) and detailed P-T studies from nearby localities (e.g. Harley and Nandakumar, 2014). These conditions lie at the lower P-T end of the range of UHT-HT conditions inferred by Morimoto et al. (2004) and Tadokoro et al. (2008) for the area, but do not preclude higher temperatures being present prior to melt crystallisation in the migmatites. However, the evidence preserved in the ED10 zircon for earlier, Palaeoproterozoic, anatexis under conditions in which sillimanite (included in zircon) and garnet (zircon flat HREE pattern) were present complicates the interpretation of the phase diagram modelling. The highly discordant zircon isotopic data coupled with the largely reset monazite ages is indicative of polymetamorphism (e.g. Schaltegger et al., 1999), and whilst the major element homogenisation in garnet suggests the retrieved P-T conditions reflect the 570-530 Ma event, strong REE zoning in the garnet indicates that this assumption requires further consideration.

Garnet REE zoning

The style of zoning observed in the inner (core) garnet domain can be interpreted as simple growth zoning governed by Rayleigh fractionation, in which the heaviest of the REE are partitioned most strongly into the earliest garnet and so decrease in concentration outwards (the HREE from Dy through to Lu all show this decrease). However, the increases in Sm, Gd, Tb, Dy, Ho and (to a lesser extent) Er and Lu, and resultant migration of the MREE-HREE ‘hump’ in the garnet REE pattern for the outer garnet domain is not consistent with continued growth of garnet from the same chemical environment as the inner domain i.e. it is not consistent with simple growth zoning. The enhanced MREE in particular either imply garnet growth accompanied by the breakdown of a competitor mineral into which these REE are preferentially partitioned (e.g. monazite), or renewed garnet growth in a chemical environment that had become enriched in MREE by other means, such as the introduction of melt (Spear and Kohn, 1996). This requires a two-stage formation history with intragranular diffusion within garnet causing the REE compositional gradient between the core and outer/rim domains. The critical question then is: does the first stage correspond to the time of the crystallisation of the flat-HREE zircon (i.e. at 1.92 Ga) or is all garnet growth post-zircon and hence most likely related to the Neoproterozoic-Cambrian event? This question can be addressed through an examination of the distribution of MREE-HREE between garnet and included zircon, which occurs in both the core and outer garnet compositional domains (Fig. 5).

The MREE-HREE composition of zircon is uniform, whether present in core garnet, outer domain garnet or in the matrix exterior to garnet (Fig. 14). Hence, we have used this zircon composition to predict the MREE-HREE composition of the garnet with which it would be in equilibrium at 900ºC according to the 0.5 GPa experimental data of Taylor et al. (2015) for Fe-Mg garnet and 2 GPa experimental data of Rubatto and Hermann (2007) for Ca-bearing Fe-Mg garnet. The REE pattern of this predicted garnet is compared with those of the core and outer domain garnet compositions in Fig. 16.

The core garnet MREE-HREE (especially MREE) are strongly depleted relative to zircon for the experimental calibration of Taylor et al. (2015). The garnet rims approach or attain MREE equilibrium (for Gd, Tb, Dy), and based on the Rubatto and Hermann (2007) model these rims could be argued, in the absence of the textural observations on zircon location, to be in equilibrium with zircon. Critically, for either experimental calibration the predicted model garnet has much higher Eu than the observed garnet, whether core or rim: D_{Eu}(Zrc/Grt) is anomalously high (4.7) in comparison to the experimental values.

The zircon-garnet REE distribution analysis indicates that the core garnet which encloses Palaeoproterozoic zircon in Kanjampara sample ED10 is *not* in REE equilibrium with that zircon. The garnet grew from a chemical environment relatively depleted in most MREE-HREE and especially in Eu compared with the zircon. The relative depletion in Eu suggests that significantly more feldspar had crystallised in the bulk composition from which the garnet cores and outer domains formed than that accessed by the 1.92 Ga zircon during its growth.

Based on this reasoning we conclude that the zoned garnet formed in the Neoproterozoic-Cambrian tectonothermal event subsequent to the crystallisation of most of the feldspar in the rock, in a chemical environment replenished in MREE during the time of garnet growth. Dissolution-reprecipitation of monazite (e.g. Buick et al., 2010) at or after ca. 530 Ma may have facilitated the increase in MREE observed in garnet rims compared with cores, as the younger Th-rich monazite rinds and cuspate rims are lower in REE than most of the main monazite phase (Fig. 9). Although the garnet has Zr contents (25-30 ppm) that are consistent with zirconium saturation at 800-900ºC (Kelsey et al., 2008b; Kelsey and Powell, 2011), mass balance calculations show that the saturation of a 1 cm diameter garnet in Zr (to 30 ppm) only requires the dissolution of one 35 micron diameter zircon, or resorption of only 1 micron of a rim of a zircon initially 100 microns in diameter. Hence, the breakdown of trivial amounts of 1.92 Ga zircon at 565-525 Ma could account for the Zr present in the garnet. The final garnet-bearing metamorphic mineral assemblage in ED10 is therefore attributed to the Neoproterozoic-Cambrian granulite facies tectonothermal event recorded throughout the Trivandrum Block and the Palaeoproterozoic metamorphic record, essentially obliterated, is only hinted at by the inclusions (Sil, Bt, Qz-feldspar, apatite) preserved in the 1.92 Ga anatectic zircon that formed at > 715ºC.

CONCLUSIONS

In-situ zircon U-Pb isotopic ages obtained on a garnet + cordierite bearing leucosome in migmatitic paragneiss at Kanjampara in the Trivandrum Block, demonstrate zircon crystallisation from melt at 1.92 ± 0.04 Ga. The unique trace element chemistry of the zircon, including high U/Yb, low Th/U, and flat MREE-HREE patterns with pronounced negative Eu anomalies, coupled with the presence of inclusions of sillimanite, apatite, quartz, feldspar and rare biotite in the zircon, confirms its formation as a result of anatexis associated with a high-T metamorphism at 1.92 Ga. This conclusion is supported by the local preservation of Palaeoproterozoic chemical age domains (<1.8 Ga) within monazite grains that enclose and are texturally associated with the zircon grains.

The main Neoproterozoic-Cambrian (570-520 Ma) granulite facies tectonism at Kanjampara involved the formation of garnet + cordierite -bearing assemblages in the presence of significant partial melt at 0.65 GPa and >820-860ºC, consistent with *P-T* estimates obtained for this tectonothermal event from nearby localities in the Trivandrum Block (Nandakumar and Harley, 2000; Harley and Nandakumar, 2014). The strongly REE-P zoned garnet present in the Kanjampara leucosome, which is demonstrated to not be in HREE or Eu equilibrium with the 1.92 Ga zircon, formed as a result of anatexis and melt interaction during this Neoproterozoic-Cambrian tectonothermal event. Th-U-Pb chemical age data indicates that monazite was either formed or extensively recrystallized at during this anatexis at 565 ± 6 Ma, undergoing further modification to form high-Th cuspate rims at 517 ± 15 Ma. The age of the final monazite chemical modification is equivalent to the lower intercept age of 528 ±

18 Ma for extensive Pb-loss from the highly discordant but otherwise well-preserved Palaeoproterozoic (1.92 Ga) zircon.

The growth or recrystallisation of monazite at ca. 565 Ma and its further modification at ca. 520 Ma indicates that the high-T metamorphism in the Pan-African was long-lived, with a duration of at least 45 Myr. This adds further weight to recent proposals, based on zircon-monazite isotopic studies from other localities in the Trivandrum Block, that the region formed the mid- to deep-crust of a long-lived collisional hot orogenic belt that welded Gondwana from ca. 580-510 Ma. (e.g. Jamieson et al., 2004; Vanderhaeghe, 2009; Jamieson and Beaumont, 2011; Clark et al., 2011).

Our new age-event results from Kanjampara confirm that at least some of the metasedimentary paragneisses in the Trivandrum Block are polymetamorphic, initially metamorphosed in the Palaeoproterozoic in an event older than the 1.89-1.85 Ga granitic orthogneisses recognised from the region. The nature of the relationship between these >1.92 Ga paragneisses and the 2.0-2.1 Ga granitic and charnockitic orthogneisses of the Trivandrum and Nagercoil Blocks, in particular whether they share the same Palaeoproterozoic history or were interleaved after 1.92 Ga, requires further investigation focussed on the presence or absence of the isotopic imprint of this event in both rock suites throughout the region.

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Figure captions

Fig. 1: Simplified geological map of the Kerala Khondalite Belt (KKB) region, southern India, showing the location of the Kanjampara quarry (KNJ) within the Trivandrum Block (TB). The Kulappara site studied in detail by Harley and Nandakumar (2014) is also shown. Inset is the location of the KKB region in relation to other domains of south India. Abbreviations are: BSZ – Bhavani Shear Zone; K-CHM – Kodiakanal-Cardamom Hills and Massif; NH – Nilgiri Hills; PCSZ – Palghat-Cauvery Shear Zone. Key to shaded areas in inset map: 1 – Archaean Dharwar Craton north of orthopyroxene-in isograd; 2 – Archaean charnockite massifs; 3 – Madurai Block and other dominantly Proterozoic crust; 4 – Kerala Khondalite Belt (including Trivandrum and Nagercoil blocks); 5 – recent sediments.

Fig. 2:

a) Kanjampara Quarry (KNJ): Field view of a 20 cm width garnet-bearing leucogranite / leucogneiss sheet (L) within Grt + Sil + Crd migmatitic gneiss (M). The near-vertical fabric is defined by gneissic layering comprising Grt + Sil + Crd + Ilm mesosomes, 1-2 cm width concordant to sub-concordant leucosome veins and lenses, and 1 cm width cordierite horizons. 12 cm length pen for scale.

b) Kanjampara Quarry (KNJ): Field view the margin of one Grt-Crd bearing leucogranitic gneiss (L) showing coarse subhedral porphyrobalsts and cumuloblasts of garnet and schlieren or lenses of cordierite within the leucogneiss, and braidly alternating garnet- and cordierite-rich layering in the adjacent mesosome (M). 12 cm length pen for scale.

Fig. 3. Photomicrographs and back-scattered electron (BSE) images of typical mineral textures in KLP leucogranitic sample ED10.

a) Subhedral garnet (Grt) containing an inclusion of zircon (Zrc), embayed and resorbed by cordierite (Crd). This cordierite also partially encloses the garnet. Numbers on the garnet (e.g. 27) and cordierite (e.g. 67) refer to their measured X_{Mg} (100*(Mg/(Mg+Fe)). Crossed polars.

b) Euhedral twinned cordierite (Crd) within the quartzo-feldspathic groundmass remote from the garnet porphyroblast of (a). The cordierite contains inclusions of sillimanite (Sill), quartz (Qz) and plagioclase. Crossed polars.

c) Leocosome texture involving Qz and perthitic K-feldspar (Pth), with myrmekite (Myr) appearing to replace the pethitic K-feldspar. BSE image.

d) Typical leucosome texture adjacent to the garnet porphyroblast in ED10. Antiperthitic plagioclase (Plag) and interstitial quartz are separated by grain boundary rinds of K-feldspar (Kfs) that lacks perthitic lamellae. BSE image.

e) Zircon and monazite hosted in feldspars (Plagioclase / Antiperthite (Apth) and K-feldspar) in the leucosome. Monazite appears to overgrow or envelope the zircon. Crossed polars.

f) Leucosome texture of plagioclase and minor quartz (Qz) with isolated subhedral zircon (Zrc), and euhedral monazite (Mnz). Crossed polars.

Fig. 4. Calculated Pressure-Temperature phase diagram (pseudosection) for migmatitic mesosome sample KNJ2 with 0.5 wt% H_2O in the system NCKFMASHTO, with all Fe assumed to be in the divalent state. Calculated using theriak-domino (de Capitanti and Petrakakis (2010) updated software version 03-01-2012, applying the THERMOCALC (Holland and Powell, 1998) dataset version tcdb55c2d. The wt% oxide bulk rock composition of KNJ2, recast in terms of cations given at the top of the diagram, is: SiO_2 61.94, TiO_2 0.73, Al_2O_3 18.67, Fe_2O_3 7.43, MnO 0.08, MgO 2.12, CaO 1.14, Na_2O 2.39, K_2O 3.53, P_2O_5 0.07 (sum = 98.11 wt%). Calculated mineral compositional isopleths are as follows: green dashed lines - mol X_{Grs} in garnet; red dashed lines - X_{Mg} in garnet; blue short dashed lines - X_{Mg} in cordierite. The elliptical field denotes the minimum *P-T* conditions required by the mineral assemblage in ED10 (Grt + Crd + Sil + Ilm + Plag + Kfs + Qz + L) based on the measured core garnet and cordierite compositions reported by Nandakumar and Harley (2000), modelled as a closed system.

Fig. 5. Spatial variations in the trace element compositional features of the large garnet porphyroblast in ED10. (a) Line tracing of garnet texture and petrographic context based on merged photomicrographs and BSE images. Garnet (pink) is partially embayed and surrounded by cordierite, as shown in more detail in Fig. 3(a) [position shown by the smaller outlined box]. Note distribution of zircon grains within and outside of the garnet. The dark blue numbers on the garnet are its chondrite-normalised Yb(n)/Gd(n) ratio at the analysed point. The dashed circle shows the limit of the higher Yb(n)/Gd(n) core domain (>1.5).

Fig. 6: REE zoning in KNJ/ED10 garnet, showing changes in selected REE (normalised) and REE (normalised) ratios at distances away from a reference point adjacent to zircon Z3 (Fig. 5a). See text for discussion.

Fig. 7. REE patterns for (a) garnet core and (b) rims based on the analysis positions shown in Fig 5a. Chondrite values from Anders and Grevasse (1989). Note consistent position of Eu at or below 1 times chondrite, and marked increases in Sm, Gd, Tb and Dy, and decreases in Tm and Yb in rims compared with garnet cores.

Fig. 8. Back scattered electron (BSE) images of monazite grains in ED10. Scales shown by horizontal bars (in microns). Monazite labels are as used in the text; analyses for each are provided in Table 2 and. Three-digit labels (e.g. 539) are the Th-U-Pb chemical age for each analysis point (typical errors ± 13-18 Ma). Zircon grains shown in c) are superimposed from CL images of the same area. Image f) is a detail of the area of monazite Mnz9 shown by the outlined box in e), showing presence of micropores as well as ovoid and irregular areas of high- and low-BSE response.

Fig. 9: Chemical systematics of ED10 monazite. Th+U+Si versus REE+Y+P monazite compositional diagram illustrating the extents of covariation in monazite chemistry in terms of Th+U compared with REE+Y, and how these relate to the principal Brabantite (Ca(Th,U)REE_{-2}) and Huttonite ((Th,U)Si$REE_{-1}P_{-1}$) substitutions. Dark filled circles are analyses carried out on the SX100 electron microprobe; filled diamonds are analyses carried out earlier on the Camebax microprobe. Light shaded field shows the range in chemistry of monazite from Kulappara (Harley and Nandakumar, 2014) for comparison. Representative analysis points are annotated with their Th-U-Pb chemical age; there is no clear trend of the bulk Th vs REE chemistry with chemical age.

Fig. 10: Chondrite-normalised REE diagram showing the compositions of ED10 monazite grains. Grey shaded field depicts the REE obtained by EPMA analysis using both the SX100 and Camebax electron microprobes and with Y plotted as a proxy for Ho. The blue points show the normalised REE obtained for monazite using SIMS, which can allow determination of both Eu and the HREE. Note the marked negative Eu anomaly and the consistent drop-off in HREE in the monazite. Dispersion to low Tm and Yb in the SIMS analyses reflects uncertainties in corrections for isobaric interferences of MREE-oxides on the HREE. Chondrite values from Anders and Grevasse (1989).

Fig. 11: Relations between monazite chemistry and age for the main Neoproterozoic age group in ED10, plotted as oxide ratios Ce_2O_3/Y_2O_3 and ThO_2/UO_2 versus chemical age. The chemical ratios for monazite domains with chemical ages > 1250 Ma are shown by the shaded boxes. The two oxide ratios are broadly correlated, with younger (< 540 Ma) monazite domains having slightly elevated Ce_2O_3/Y_2O_3 and ThO_2/UO_2 compared with most 610-540 Ma domains.

Fig. 12: (a) Relative Probability diagram for all ED10 monazite analyses in the main age population of Fig. 11, based on analyses from both the SX100 and Camebax electron microprobes. The mean age obtained is 558.3 Ma with a standard error of the mean of 6.0 Ma based on 49 analyses. (b) Weighted age distribution diagram for ED10 main age population monazite analyses excluding high-Th (younger rinds) and older (>590 Ma) outliers from the full group shown in (a) (39 analyses). Shaded band represents the best-fit weighted age and its associated error (2σ confidence; 559.5 ± 5.4 Ma). Age errors on the individual analyses are shown by the vertical bars. Both plots in (a) and (b) calculated using Ludwig (2003).

Fig. 13: CL images of ED10 zircon grains referred to in the text and listed in Table 4, with scales given by the horizontal scale bars. Bold numbers in white are the $^{206}Pb/^{238}U$ ages determined at the underlying points; numbers in brackets beneath these are the % concordance. Yellow numbers -Yb_n/Gd_n; blue numbers - U/Yb ratio. The image for zircon Z6 is a composite CL and BSE image with the BSE features of monazite superimposed on the CL features of the zircon grains it partially encloses along with ilmenite.

Fig. 14: REE patterns for ED10 zircon. Note the strong depletions in Eu (Eu/Eu* << 1) and low LREE with no Ce anomaly in all but two analyses. The two analyses with higher LREE and Eu are contaminated, based on elevated Ba and Ca (Table 4). All zircon grains have similar flat HREE from Dy to Lu. Chondrite values for normalisation are from Anders and Grevasse (1989).

Fig. 15: U-Pb geochronological data for ED10 zircon, presented as ^{204}Pb-corrected Tera-Wasserburg Concordia diagrams ($^{207}Pb/^{206}Pb$ versus $^{238}U/^{206}Pb$), with data ellipses corresponding to 1 sigma analytical uncertainties. The strongly discordant data array define a well-fitted discordia with an upper intercept age of 1923 ± 40 Ma and lower

intercept extrapolated to 528 ± 18 Ma, using all analyses. Exclusion of two analyses with slightly higher ^{204}Pb (yellow ellipses) does not affect the resultant age estimates.

Fig 16: Observed KNJ-ED10 REE patterns for garnet core (pink shaded field) and rim / outer domain (yellow shaded field) compared with modelled garnet REE compositions predicted from the measured ED10 zircon REE patterns using experimentally determined zircon-garnet REE distribution data, D_{REE}(Zrc/Grt), from Taylor et al. (2015) [red symbols] and Rubatto and Hermann (2007) [blue symbols]. Note that both garnet types are depleted in MREE-HREE relative to that predicted from the Taylor et al. (2015) model at 900-1000ºC, whereas observed garnet *rims* match the predictions of the Rubatto and Hermann (2007) model for MREE-HREE at 900ºC but are depleted on Eu in all cases. See text for discussion.

Supplementary Figure 1: Calculated Pressure-Temperature phase diagrams (pseudosections) for migmatitic leucosome sample KNJ1 with 0.5 and 1.0 wt% H_2O, in the system NCKFMASHTO, with the simplification that all Fe is assumed to be in the divalent state. Calculated using theriak-domino (de Capitanti and Petrakakis (2010) updated software version 03-01-2012, applying the THERMOCALC (Holland and Powell, 1998) dataset version tcdb55c2d. The wt% oxide bulk rock composition of KNJ1, recast in terms of cations given at the top of the diagram, is: SiO_2 74.45, TiO_2 0.02, Al_2O_3 14.80, Fe_2O_3 0.59, MnO 0.01, MgO 0.14, CaO 0.79, Na_2O 2.84, K_2O 5.76, P_2O_5 0.10 (sum = 99.49 wt%). Calculated mineral compositional isopleths are as follows: green dashed lines - mol X_{Grs} in garnet; red dashed lines - X_{Mg} in garnet; blue short dashed lines - X_{Mg} in cordierite. The yellow elliptical field denotes the *P-T* conditions required by the mineral assemblage in KNJ2 (ED10) as shown in Figure 4 of the paper.

Supplementary Figure 2: (a) Line tracing of garnet texture and petrographic context based on merged photomicrographs and BSE images, as per Figure 5. Garnet (pink) is partially embayed and surrounded by cordierite. (b) Selected elemental X-ray maps [position shown by the larger outlined box in (a)] of trace elements P, Y, Dy and Er in garnet and adjacent phases (see text for analytical details). Note differences in P, Y and Er contents of zircon and garnet, and the similarity in Dy for each phase. P in garnet is slightly higher in the core than the rim, whilst Y in garnet increases in a thin rim area adjacent to Crd and Qz.