**Late Palaeoproterozoic depositional age for khondalite protoliths
in southern India and tectonic implications**

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Abstract

SHRIMP dating of detrital zircons from garnet-sillimanite-cordierite paragneisses (khondalites) of the Trivandrum Block, southern India, revealed nanometer-scale Pb isotopic inhomogeneity in most grains that we ascribe to annealing processes during ultra-high-temperature metamorphism at ca. 570 Ma.

Our age data for zircons from six representative khondalite samples do not document any Neo- or Mesoproterozoic detrital grains, and we conclude from the concordant ages and discordant minimum $^{207}\text{Pb}/^{206}\text{Pb}$ ages that the khondalite precursor sediments were deposited more than 2.1 Ga ago and were subsequently intruded by granitoid rocks at ca. 1765-2100 Ma. Some detrital zircons in the khondalites contain late Palaeoproterozoic metamorphic domains, suggesting that these grains are derived from an unknown crustal source that most likely experienced late Palaeoproterozoic high-grade metamorphism. Both the metasedimentary assemblage and granitoids were severely ductilely deformed, metamorphosed and migmatized during the pervasive Pan-African event at ca. 550-580 Ma. This caused many detrital zircons in the khondalites to become variably recrystallized and to develop metamorphic rims. Proper interpretation of cathodoluminescence images and zircon morphology is important in interpreting detrital populations.

The southern Indian khondalites were part of an extensive Palaeoproterozoic metasedimentary assemblage that may have extended from southern Madagascar via the Trivandrum Block to the Highland Complex of Sri Lanka and seems to reflect a continental margin sequence that was deposited on an Archaean to early Palaeoproterozoic

continental terrane, possibly the southern margin of the Indian Dharwar craton. The tectonic history of this terrane remains obscure due to the pervasive overprint during the Pan-African event.

Key words: Khondalite; zircon geochronology; Pb isotopic inhomogeneity; Trivandrum Block; India

1. Introduction

Granulite-facies metapelites (locally named khondalites) are widespread together with granitoid-derived charnockites in the Trivandrum Block of southern India (Fig. 1). They have been the focus of several investigations concerning their composition, metamorphic evolution, age and tectonic significance (for reviews and literature see [Santosh et al., 2006](#); [Sato et al., 2011](#)). These cordierite-, sillimanite- and spinel-bearing metapelite assemblages have provided important clues on the pressure–temperature conditions and exhumation history of the region and also yielded critical geochronologic information on source characteristics, tectonothermal histories and timing of high grade metamorphism (for review and literature see [Santosh et al., 2006](#)).

Santosh et al. (2006) provided a comprehensive review of the mineral composition and P-T evolution of the khondalite suite and reported electron-probe (EPMA) $^{207}\text{Pb}/^{206}\text{Pb}$ ages for zircon and monazite from five key metapelite localities in the Trivandrum Block. From these data the above authors concluded that the khondalite sedimentary precursors were derived from Archaean to Proterozoic sources and were deposited after 569 Ma ago. This was deduced from what Santosh et al. (2006) interpreted as abraded grains that apparently underwent fluvial transportation prior to deposition. This interpretation led to widespread supposition of a late Neoproterozoic depositional age for the precursor sediments of khondalite suite (e.g., Collins et al., 2007; 2014; Santosh et al., 2009) and to tectonic models that interpreted the metapelitic assemblage as part of a Neoproterozoic (Pan-African) accretionary belt in a subduction environment (Santosh et al., 2009; Rajesh et al., 2013).

Fig. 1 about here

Doubt about a late Neoproterozoic depositional age for the khondalite precursors comes from rare intrusive contacts with adjacent and frequently interlayered charnockitic gneisses of granitoid origin, as documented by Whitehouse et al. (2014) and Kröner et al. (2015a) and for which magmatic emplacement ages between 1765 and ca. 2100 Ma were

determined. However, the above intrusive relationships are often difficult to establish and, at most localities, the khondalites and charnockites have parallel contacts due to intense ductile deformation which brought them into parallelism. Furthermore, detailed single zircon analysis combined with cathodoluminescence imaging revealed very complex crystallization-recrystallization phenomena and Pb-loss in the charnockites, probably caused by fluid-assisted high-grade metamorphism, metasomatism, and anatexis during ca. 550-580 Ma granulite-facies metamorphism and subsequent fluid-related retrogression (Whitehouse et al., 2014; Kröner et al., 2015a). Such processes have also been documented in high-grade rocks of Madagascar (Ashwal et al., 1999; Tucker et al., 2011). They are also likely to have affected the khondalite zircons, and the interpretation of well rounded grains to be of detrital origin may therefore be incorrect, and some of the young EPMA ages reported by Santosh et al. (2006) are likely to be the result of severe Pb-loss or may reflect high-grade metamorphism during the 550-580 Ma Pan-African event.

The purpose of this study was to re-investigate and date detrital zircons from typical khondalites of the Trivandrum Block, since a previous field-based survey has shown that these rocks were intruded by ca. 1765-2106 Ma old granitoids (Kröner et al., 2015a). We have therefore analyzed single zircons from six representative khondalite samples (Table 1), using a SHRIMP II high-resolution ion-microprobe, combined with cathodoluminescence imaging.

The sample localities are shown in Fig. 1, and a brief petrographic characterization of the samples is provided in Table 1.

Table 1 about here (GPS location, brief mineral composition)

Fig. 2 about here (field photos of khondalites).

2. Brief geological setting and petrological characterization and PT conditions of the dated samples

The Trivandrum Block (Fig. 1) consists predominantly of granulite-facies granitoid leucogneisses and garnetiferous metasediments (collectively referred to as leptynites and khondalites, respectively, in the literature), in association with minor charnockites and mafic granulites. Details on the regional geology and field relationships were recently summarized by Collins et al. (2014), Whitehouse et al. (2014) and Kröner et al. (2015a). Pelitic metasediments constitute a major part of the supracrustal sequences, and six samples were collected for zircon geochronology from six different quarries as summarized in Table 1, and representative field photographs are shown in Fig. 2. These

metasediments were intruded by light grey, fine- to medium-grained and equigranular granitoid leucogneisses, often termed leptynite, but the original intrusive contacts are now generally obliterated due to strong ductile deformation, bringing these rocks into parallelism (Kröner et al., 2015a). However, in low-strain zones such intrusive contact are occasionally preserved and were documented by Kröner et al. (2015a). Similar structural relationships between metasediments and granitoid gneisses were described from the high-grade terranes of Sri Lanka by Kehelpannala (2003). Calc-silicate rocks found as xenoliths (enclaves) in charnockite occur in the Nagercoil Block of southernmost India (see Kröner et al., 2015a for details).

The fine- to medium-grained khondalites have a gneissosity defined by cordierite-garnet-biotite-sillimanite±graphite bands ranging in width from 0.3 to 15 cm and alternating with quartzo-feldspathic layers of variable width. Cordierite-garnet-sillimanite-biotite-rich bands alternate with orthoclase-, plagioclase-, and quartz-rich layers, giving the rock a migmatitic appearance. Quartzo-feldspathic layers alternating with layers rich in sillimanite, cordierite and spinel are also common in strongly migmatized areas. A bluish colour imparted by cordierite-rich zones is a characteristic feature of the khondalites in many quarries. In general, sillimanite occurs in the form of needles and columnar prisms aligned parallel to the foliation and defining a lineation. Segregation of quartz in the form of pods and veins is also common. Biotite and sillimanite appear to wrap around these pods.

Strong migmatization is observed in many quarries, and migmatitic structures are well developed, with extensive disruption of the banded mesosome by a medium-grained leucosome, bordered locally by a thin biotite/cordierite-rich melanosome. A cordierite+garnet +quartz+feldspar+sillimanite assemblage is widely distributed in quarries of the khondalite belt and contains porphyroblasts of garnet and cordierite. The size of porphyroblasts ranges from 2 mm to 6 cm. Some eyeball-shaped garnets are rotated by more than 360°. The garnet porphyroblasts are partially wrapped into curved prisms of sillimanite and stretched cordierite grains. The proportion of sillimanite, garnet, spinel and cordierite varies in the matrix, and there are zones where sillimanite and garnet are more common than cordierite, whereas in other zones the amount of cordierite may be greater. Cordierite is slightly opaque in zones of pinitization.

The Koliakode quarry (sample TBK-3) preserves quartzite bands and metapelite without any melt patches. These features and the presence of sillimanite and cordierite are good

indicators of a sedimentary protolith for the khondalite. In the Kuttikonam quarry (sample KTKN) khondalite layers alternate with bands of granitoid leucogneiss (Fig. 2a).

The khondalites analyzed in this study are granulite-facies metapelites with a mineral assemblage (mineral abbreviations after Whitney and Evans, 2010) of garnet (Grt) + sillimanite (Sil) + biotite (Bt) + K-feldspar (Kfs) + plagioclase (Pl) + quartz (Qz) $\pm$ cordierite (Crd) $\pm$ spinel (Spl). The K-feldspar is often mesoperthitic showing coarse exsolution lamellae of plagioclase. Some of the retrogressed assemblages also contain graphite as disseminations along foliation planes. Magnetite (Mag), ilmenite (Ilm), zircon (Zrn) and monazite (Mnz) are ubiquitously present as accessories. The rocks exhibit various reaction textures including $Bt + Sil + Qz = Grt + Crd \pm Kfs$, $Grt + Sil + Qz = Crd$, $Grt + Crd + Sil = Spl + Qz$, $Spl + Qz = Crd$, and $Grt + Sil = Spl + Crd$.

Grt, Sil, Crd, Bt, Spl and Ilm occur as resititic aluminous bands alternating with leucocratic quartzofeldspathic layers in millimetre or decimetre scale. Garnet grains are porphyroblastic and carry poikilitic inclusions of Bt, Sil and Qz. Crd occurs as coarse crystals and as coronal rims around garnet. Crd + Qz symplectites are also common. Sil occurs as oriented elongate tabular grains or as small inclusions within garnet and K-feldspar. Based on textural studies of khondalites from the Trivandrum Block, Morimoto et al. (2004) noted that the early mineral assemblage is characterized by Bt, Sil and Qz which reacted to produce Grt and Crd. From thermometry of mesoperthites, they estimated peak temperatures of ca. 1000 °C. This estimate is also confirmed by the association of low Zn Spl with Qz in grain contact, suggesting 950 °C at 8 kbar. These estimates indicate that the khondalites have undergone ultrahigh-temperature metamorphism. The decompression reaction of Spl and Qtz to produce Crd is estimated at 900 °C. According to Morimoto et al. (2004) the Grt-Crd and Grt-Crd-Sil-Qtz assemblages trace an isothermal decompression path (Fig. 3).

Fig. 3 about here (P-T diagram)

Johnson et al. (2015) reported the pressure-temperature-time (P-T-t) evolution of khondalites in the Kottaram quarry of the Nagercoil Block, from the same metapelite horizon investigated in the present study (sample NGK-2). They inferred that the peak metamorphic assemblage is defined by $Grt + Kfs + Sil + Pl + Mt + Il + Spl + melt$, consistent with pressures of 6 to 8 kbar and temperatures in excess of 900 °C. High-temperature retrograde decompression is recorded by the growth of Crd and Bt at around 5 kbar and 800 °C. These authors also reported two phases of monazite growth; the first generation of REE-enriched monazite grew during partial melting along the prograde path

at around 570 Ma, and a second generation of REE-depleted rims with marked negative europium anomalies, formed during melt crystallization along the retrograde path at around 535 Ma.

3. Morphological modification of zircon during prograde metamorphism and effects of recrystallization and Pb-loss

The zircon populations in the granulite-facies metapelite samples dated in this study show evidence of morphological modification and complex recrystallization during high-grade metamorphism. Kröner et al. (2013, 2015b) documented the change in the morphology of magmatic zircon during progressive metamorphism in a series of high-magnification electron microscope photographs for grains from high-grade metamorphic rocks in Sri Lanka. The process of resorption and recrystallization may produce a variety of zircon morphologies, including egg-shaped grains that are particularly frequent in high-grade rocks at the amphibolite- to granulite-facies transition (see Figs. 11e, f in Kröner et al., 2015a). In extreme cases such grains may become ball-round and can then easily be mistaken for long-travelled detrital grains or for metamorphic zircon.

Metamorphic zircon can usually be recognized under a binocular microscope and is distinguished from apatite by its strong reflectivity, its “soccer-ball” shape (Vavra et al., 1996; Schaltegger et al., 1999; Kröner et al., 2000; 2015a), its multi-faceted surface, and its internal structure as revealed in CL images (see also Corfu et al., 2003; Fig. 13i, j in Kröner et al., 2015).

Zircon populations from rocks with long and multiphase tectono-metamorphic histories generally do not consist of homogeneous crystals but may contain multiple components such as old cores, surrounded by magmatic overgrowth and further surrounded by metamorphic overgrowth (e.g., Corfu, 2013). However, the robustness of zircon without radiation damage, even during ultra-high temperature metamorphism, and the insignificance of Pb-diffusion have been demonstrated in many studies, and careful CL- and trace element-assisted investigations make it possible to extract reliable age data from such grains (e.g., Möller et al., 2003; Kooijman et al., 2011; Kröner et al., 2015b, c). In contrast, fluid-induced alteration is common in zircon from high-grade metamorphic rocks (e.g., Geisler et al., 2007; Flowers et al., 2010; Wan et al., 2011; Dong et al., 2013; Ma et al., 2012; Kröner et al., 2015a), and recrystallization, combined with Pb-loss, will produce variable discordance in a zircon population, particularly in granulite-facies assemblages

(e.g., Ashwal et al., 1999; Tucker et al., 2011; Wan et al., 2011; Corfu, 2013; Kröner et al., 2013; 2015a, c).

More severely discordant data are generally the result of either Pb-loss or mixing of two different zircon phases. Pb loss by recrystallization and/or redistribution, particularly under fluid conditions, often leads to partial or even complete isotopic resetting, and no closed-system domains remain that can provide concordant ages. These cases are typical of high-grade metamorphic terranes where only discordant data can be extracted from many zircons (e.g., Corfu et al., 1994; Ashwal et al., 1999; Connelly, 2001; Moser et al., 2011). Fluid-assisted alteration and recrystallization may occur at small scales in zircon and lead to complex intergrowth of several phases with intricate shapes as shown in CL images (e.g., Wan et al., 2011; Kröner et al., 2015a, b). Even a narrow ion beam during SIMS analyses often fails to resolve these complexities and yields discordant isotopic ratios. Such severe partial resetting by recrystallization and associated new growth results in linear arrays of data points in the concordia diagram between the time of crystallization and that of secondary reworking and/or local new growth (Moser et al., 2009; Kröner et al., 2013; 2015a, b).

A further problem related to zircon discordance concerns the interpretation of data that are nearly, but not fully, concordant. In many cases a slight discordance is due to ancient Pb loss, and the ages can then be extrapolated by projecting a line through the data from lower-intercept ages corresponding to the time of the supposed Pb-loss event. In cases where the difference between the two concordia intercept ages is relatively small, the discordia line becomes subparallel to the concordia curve and, dependent on the magnitude of the uncertainty, is indistinguishable from it (e.g., Corfu et al., 1994; Corfu, 2007; Kröner et al., 2013, 2015c).

4. Analytical procedures

4.1 Zircon mounting and cathodoluminescence imaging

Heavy mineral concentrates were obtained from whole-rock samples after crushing and panning, and zircons were then handpicked and mounted in epoxy resin together with chips of the zircon standard TEMORA (Black et al., 2003) in the Beijing SHRIMP Centre, Chinese Academy of Geological Sciences. The mount was ground down and polished so that the zircon interiors were exposed, and zircons were photographed under cathodoluminescence (CL) to enable easy and best location on the mount during SHRIMP analysis. CL imaging was performed in the Beijing SHRIMP Centre, using a

Hitachi S-3000N scanning electron microscope (accelerating voltage 9 kV, beam current 109 nA, for high-resolution images of Figs. 4-6 a pixel time of 400 was used).

4.2 SHRIMP II U-Pb zircon analysis

Zircon isotopic analyses were performed on a SHRIMP II sensitive high-resolution ion-microprobe of the Beijing SHRIMP Centre, and the analytical procedures are detailed in Kröner et al. (2012) and references therein. The reduced $^{206}\text{Pb}/^{238}\text{U}$ ratios were normalized to the adopted age of 417 Ma for standard TEMORA (Black et al., 2003). U concentrations were calibrated using standard M257 (U = 840 ppm, Nasdala et al., 2008). For data collection, five scans through the critical mass range were made. Primary beam intensity was about 3.0 nA, and a Köhler aperture of 100 μm diameter was used, giving a slightly elliptical spot size of about 30 μm . Peak resolution at 1 % peak height was ca. 4800, enabling clear separation of the ^{208}Pb -peak from the HfO peak. Sensitivity was ca. 15 cps/ppm/nA Pb on the standard. Analyses of samples and standards were alternated to allow assessment of Pb^+/U^+ discrimination. The 1-sigma error of the $^{206}\text{Pb}/^{238}\text{U}$ ratio during analysis of all standard zircons during this study was 3.05 %. Raw data reduction and error assessment followed the method described by Nelson (1997), using the Macintosh software programs Prawn 6.4, WALLEAD 2.7 and Plonk 4.3. Common-Pb corrections were applied using the ^{204}Pb -correction method, and because of very low counts on ^{204}Pb in most samples it was assumed that common lead is surface-related (Kinny, 1986). Therefore, the isotopic composition of Broken Hill lead was used for correction. Analyses with ^{204}Pb counts more than 3 times background were corrected using the Cumming and Richards (1975) values. Errors of individual analyses in Table 2 are given at the 1-sigma level and are based on counting statistics and include the uncertainty in the U/Pb age of the standard, added in quadrature (Nelson, 1997). Errors of pooled analyses in the text and in the Concordia diagrams of Figs. 8-10 are reported at the 2-sigma confidence interval.

5. Zircon morphology and internal structure

The zircons recovered from five khondalite samples are quite variable in their morphologies and CL images (Figs. 4-6), and there are basically two populations in each sample. One zircon population is represented by oblong to well rounded varieties of clearly magmatic origin because some grains preserved their long-prismatic shape although the pyramidal terminations are now well rounded due to metamorphic corrosion (e.g., Figs. 4a,

e). The internal CL-patterns of some grains of igneous origin are complicated and reflect multiple phases of recrystallization. Examples of such grains from charnockitic gneisses interlayered with the khondalites were presented by Kröner et al. (2015a), and such zircons were avoided during the present survey. Many igneous grains are oscillatory or broadly zoned (Figs. 4a, b, 6a, f), and some also display striped zoning (Fig. 4e). However, most grains show evidence of recrystallization, presumably during the late Neoproterozoic (ca. 550-580 Ma) granulite-facies event, and these recrystallized domains are mostly homogeneous in CL and can be seen to have replaced the igneous domains (Figs. 4b, 5a, f, 6b, d). This may result in “ghost structures” where relicts of primary magmatic textures are preserved but are cut and surrounded by mostly homogeneous, newly grown domains. Hoskin and Black (2000) interpreted such textures to represent recrystallization in the solid-state.

Figs. 4-6 about here (typical CL images)

The second zircon population is clearly of metamorphic origin and consists of relatively small (ca. 50 μm or less in diameter) ball-round, multifaceted to rectangular or ovoid grains that are either homogeneously grey and unzoned in CL images or show the typical faint sector or fir-tree zoning that often characterizes metamorphic zircon (e.g., Figs. 5b, c; see also Fig. 7 in Corfu et al., 2003; Kröner et al., 2000; 2015c). Further details will be discussed below individually for each sample in combination with their zircon ages.

6. Nanometer-scale Pb-heterogeneity in zircon

For many zircons in this study the raw data of the SHRIMP analyses were highly variable, and it was impossible to obtain flat-top peaks for the relevant Pb-isotopes during analysis (i.e., ^{206}Pb , ^{207}Pb , ^{208}Pb). In contrast, flat-top peaks were obtained for all Pb-isotopes on the standard zircon (TEMORA) as well as for UO, ZrO_2 , Th and U. This phenomenon resulted in unusually large errors in U/Pb and Pb/Pb ratios and corresponding ages and is most likely due to an unusual sputtering behaviour, caused by stable emission of the radioactive parent isotopes of U and Th and accompanied by unstable emission of radiogenic daughter Pb-isotopes (Williams et al. 1984 ; Black et al. 1986; Whitehouse et al., 2014). Kuziak et al. (2013; 2015), using a SIMS-based scanning ion imaging technique, documented an uneven distribution of radiogenic Pb in zircon from ultra-high temperature granulites in Antarctica and found Pb-enriched domains at a spatial resolution of ca. 2 nm. At the scale of such heterogeneities, apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages obtained from a typical ca. 20 μm SIMS analysis can be inaccurate by several tens or even hundreds of

Ma (Kuziak et al., 2013).

Whitehouse et al. (2014) undertook a similar study on zircon crystals of a patchily charnockitized Palaeoproterozoic granite-gneiss from a quarry at Elavattom, southwest of Ponmudi, and in the centre of our study area in the Trivandrum Block of southern India. These authors employed high-spatial resolution secondary ion mass spectrometry analysis together with scanning ion imaging and scanning ion tomography (depth-profiled ion imaging). These analytical techniques revealed a patchy distribution of radiogenic Pb throughout the zircon cores, and the results of depth-profiling of the scanning ion tomography image stack showed that the Pb-rich domains range in size from <5 nm to several 10 nm. Whitehouse et al. (2014) concluded from their study that radiogenic Pb redistribution is not a rare phenomenon but may be a common feature of zircon that has experienced UHT metamorphism. These authors also argued that annealing processes during the UHT metamorphism at ca. 570 Ma in their Indian zircons likely arrested the movement of radiogenic Pb through the zircon crystals at a relatively advanced stage. Thus, large-scale heterogeneity of radiogenic and unsupported Pb as well as some quantitative Pb-loss have resulted.

Fig. 7 about here

We have overcome the Pb isotopic heterogeneity during SHRIMP analysis by “smoothing” the irregular peaks obtained for ^{206}Pb , ^{207}Pb and ^{208}Pb (Fig. 7a) by using the data reduction routine Prawn 6.6.0 developed in the Research School of Earth Sciences, Australian National University. This resulted in artificial flat-top peaks that were used for the calculation of isotopic ratios and corresponding ages, and the procedure yielded surprisingly accurate data which are listed in Table 2. The Concordia diagram of Fig. 7b shows an extreme example of this manipulation for zircon grain 2 of sample TBK-1. The original data calculated using the program SQUID 1.02 (Ludwig, 2001) resulted in large errors in all isotopic ratios, whereas the ratios changed significantly and the errors improved after peak “smoothing”.

7. Zircon geochronology

Sample KTKN is a khondlite collected at the Kuttikonam quarry (Fig. 1, Table 1) where it is in structural parallelism with granitoid orthogneiss (leptynite) (Fig. 2a). An intrusive relationship cannot be observed because of high strain. The zircons are predominantly long-prismatic with well rounded terminations due to metamorphic corrosion (Fig. 4a), but oval-shape and even ball-round morphologies due to mechanical transport are also present.

Most grains display simple concentric oscillatory zoning of magmatic origin, but striped zoning also occurs. Some grains exhibit evidence of complex recrystallization (Fig. 4b). There are also many grains with very narrow black (high-U) rims in CL images, but these are too narrow for SHRIMP analysis. No metamorphic grains were seen in this zircon population, but some grains contain metamorphic overgrowth rims

Thirteen grains were dated from this sample (Table 2), and most analyses are discordant, whereas the four most concordant results indicate ages between 2.0 and 2.27 Ga (Figs. 4a, 8a). Three grossly discordant data points (Fig. 8a, inset) come from metamorphic rims and seem to suggest that the analyzed zircons grew during ca. 550 Ma metamorphism but subsequently lost Pb during a Recent event. In summary, the near-concordant analyses suggest derivation of the detrital zircon population from a ca. 2 Ga or slightly older Palaeoproterozoic source.

Fig. 8 about here (Concordia diagrams KTKN & NGK-2)

Sample NGK-2 is a typical khondalite from the Kottaram quarry near Kanya Kumari village (Fig. 1, Table 1) where it occurs as a large xenolith within charnockitic gneiss of the Nagercoil massif (Fig. 2b) whose precursor was emplaced at ca. 2070 Ma (Kröner et al., 2015a). Most zircons are spectacularly well rounded (Fig. 4c), many are ball-round to oval (Fig. 4d), and only a few have long-prismatic habits with well-rounded terminations and display concentric oscillatory as well as striped zoning (Fig. 4e). Fig. 4c shows a grain with an ancient core (2312 ± 6 Ma), surrounded by homogeneous, high-U metamorphic overgrowth (551 ± 13 Ma). Similarly, in Fig. 4d a small undated ancient core is enclosed by a broad rim of faintly zoned metamorphic zircon (566 ± 32 Ma). Other grains exhibit complex internal structures under CL, and some are entirely metamorphic with fir-tree zoning, whereas others, also ball-round, show no evidence of metamorphic growth or recrystallization in their CL images.

We have dated 16 grains from this sample, and the data are shown in Table 2 and Fig. 8b. The oldest detrital grains are concordant at 3351 ± 6 , 2640 ± 7 , 2456 ± 5 Ma (Fig. 4e), and 2291 ± 18 Ma, whereas all younger grains are discordant but have minimum $^{207}\text{Pb}/^{206}\text{Pb}$ ages of ca. 2 Ga. (Table 2, Fig. 8b). Only one of eight metamorphic grains or metamorphic rims on detrital grains yielded a concordant analysis at 546 ± 18 Ma (grain 5, Table 2, Fig. 8b, inset) whereas the remaining data are variably discordant but well aligned in the concordia diagram (Fig. 8b, inset), suggesting a crystallization age at ca. 550 Ma and Recent Pb-loss.

Sample TBK-1 is another typical khondalite from Eranikonam, a large active quarry located north of Koliakodu and south of Kakkodu (Fig. 1, Table 1), where the major rock types are granitoid leucogneiss and khondalite. Incipient charnockite patches occur within the leucogneiss portion but are absent in the khondalite layers. The dark layers of khondalite are composed of cordierite, sillimanite, garnet and spinel, and large flakes of graphite occur locally. Compositional bands are often distorted due to migmatization.

The zircons are predominantly long-prismatic with well rounded terminations to oval, and very round, but ball-shaped varieties are rare. Most grains show well-preserved internal zonation of magmatic origin in CL images (e.g., Fig. 4f), and some have narrow to wide metamorphic rims (e.g., Figs. 5a). We found no purely metamorphic zircon in this sample. Eighteen grains were analyzed and, as in previous samples, some data are concordant, but there are also many discordant results (Table 2, Fig. 9a). The analyses of the oldest grains are concordant at 2664 ± 10 and 2573 ± 5 Ma, and there are two discordant results indicating minimum ages of ca. 2500 Ma. Two further concordant data are at 2222 ± 5 and 2124 ± 12 Ma (Table 2, Fig. 9a). The analyses of six metamorphic rims provide a similar pattern as in sample NGK-2, namely there is one near-concordant result at 565 ± 14 Ma (Fig. 5a), and the other data are slightly discordant, but have similar $^{207}\text{Pb}/^{206}\text{Pb}$ ratios, therefore suggesting Recent Pb-loss (Fig. 9a, inset).

Fig. 9 about here (Concordia diagrams of TBK1 & TBK2)

Sample TBK2 is also typical of the khondalite lithologies in the Trivandrum Block and comes from the Kakodu quarry where it is tectonically interlayered with granitoid leucogneiss (Fig. 2c). The rock is migmatitic and contains large garnet porphyroblasts (Fig. 2d). The heavy mineral population is dominated by titanite, and there were only few well-rounded zircons in this sample with most of these displaying metamorphic features (Figs. 5b-d). We found only one long-prismatic, typical igneous grain.

The analyses of 14 grains are dominated by late Neoproterozoic (Pan-African) ages, and there are only two discordant results suggesting Palaeoproterozoic crystallization (Table 2, Fig. 9b). The metamorphic grains or rims provided a similar pattern of their isotopic ratios as in the two previous samples, i.e. there is one near-concordant analysis at 566 ± 13 Ma (grain TBK2-3, see Fig. 5c), whereas all others are variable discordant but well aligned in the concordia diagram with similar $^{207}\text{Pb}/^{206}\text{Pb}$ ratios and compatible with Recent Pb-loss (Fig. 9b, inset).

TBK-3 is another typical khondalite and comes from the Koliakode quarry just north of Trivandrum (Table 1, Fig. 1) where it is interlayered with meta-psammitic lithologies and

contains porphyroblasts of cordierite and garnet (Fig. 2e). The zircons are all well-rounded with oval shapes predominating, but ball-shaped and long-prismatic types also occur. The CL images show grains with simple magmatic oscillatory growth (e.g., Fig. 6a) but also many complex features ranging from severe metamictization (e.g., Fig. 5e) to multiphase recrystallization (e.g., Fig. 5f).

As in the previous samples, there are 12 concordant but also several severely discordant zircon analyses, but for all detrital grains these suggest crystallization at ca. 2 Ga or earlier (Table 2, Fig. 10a). The data for 5 metamorphic grains are variably discordant, suggesting Recent Pb-loss as seen in other samples and crystallization during high-grade metamorphism at ca. 550 Ma (Fig. 10a, inset).

Fig. 10 about here (Concordia diagrams TBK3 & TBK4)

Lastly, TBK4 is a typical khondalite with a cordierite-sillimanite-spinel-garnet assemblage (Fig. 2f) from the Nedumpara quarry east of Trivandrum (Table 1, Fig. 1). The zircons are highly variable in their morphologies and internal structures, but all show significant rounding. Surprisingly, there are many long-prismatic grains with high length/width ratios up to 5, suggesting that these were not derived from a distant source. Some of these grains also show excellent concentric oscillatory zoning. Other grains are oval or ball-round or have irregular shapes (e.g., Fig. 6c). The CL images also show significant variations, and there are simple, zoned grains (Fig. 6f) as well as those with variably recrystallized domains (e.g., Fig. 6b-e).

Fourteen grains were analyzed, and all analyses on detrital zircons are older than 2 Ga although only 3 are concordant at 2872 ± 5 , 2724 ± 8 and 2294 ± 8 Ma (Table 2, Fig. 10b). Two metamorphic zircon domains reflect the same features as in the previously discussed samples, namely one concordant result at 560 Ma and one discordant analysis suggesting Recent Pb-loss (Fig. 10b, inset).

8. Evidence for a Palaeoproterozoic high-grade event

Several detrital grains analyzed in this study provide clear evidence via their cathodoluminescence images that they experienced high-grade metamorphism prior to the late Neoproterozoic. For example, grain 1 from TBK4 (Fig. 6b) exhibits several recrystallized domains with the dark grey area in the upper left part providing a discordant minimum $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1842 ± 6 Ma. Similarly, the top of grain 5 from TBK4 (Fig. 6d) shows recrystallization typical of high-grade metamorphism, but the result is also discordant and provides a minimum age of 1814 ± 8 Ma. Lastly, grain 4 from TBK4 is

thoroughly recrystallized with no primary igneous zonation preserved, and yielded a minimum age of 2097 ± 2 Ma (Fig. 6c). These and other grains show that at least some of the detrital zircons in the khondalites are derived from a crustal source that most likely experienced late Palaeoproterozoic high-grade metamorphism, probably some time prior to 1.8 Ga.

Interestingly, Harley and Nandakumar (2016) recently investigated a leucosome sample from a typical migmatitic khondalite sequence containing garnet, K-feldspar, plagioclase, quartz, ilmanite sillimanite and cordierite and exposed in a quarry at Kanjampara, very close to our sample TBK-3 (Fig. 1). The mineral paragenesis in this leucosome sample suggests a peak metamorphic temperature of ca. 840 ± 20 °C and pressures of 0.62-0.66 GPa. Large porphyroblastic garnet in this sample contains inclusions of zircon in its core regions, but abundant zircon also occurs in the groundmass (Harley and Nandakumar, 2016). Apparently these zircons define a single population with CL images revealing weak oscillatory, sector and sector-planar zoning, with the latter being dominant in most grains (Harley and Nandakumar (2016). U-Pb spot analyses on 22 zircons from this sample by SIMS (Cameca-1270) yielded strongly discordant results that are well aligned in a concordia diagram (MSWD = 1.3, probability of fit 0.19) and define an upper concordia intercept age of 1923 ± 40 Ma and a lower intercept at 528 ± 18 Ma (Harley and Nandakumar, 2016). The Cambrian lower intercept age was interpreted to reflect the widespread granulite-facies event characteristic of almost all high-grade gneisses in the Trivandrum Block, whereas the Palaeoproterozoic upper intercept age was interpreted as reflecting migmatization and zircon crystallization during an earlier high-grade metamorphic event at ca. 1.92 Ga, mainly based on the observation that these old zircons are distinct from igneous protolith zircon widely reported from the Trivandrum Block (Harley and Nandakumar (2016).

The above first evidence for Palaeoproterozoic high-grade metamorphism in rocks of the Trivandrum Block may imply that the detrital grains of metamorphic origin in samples TBK4 may be derived from a local source, but it is also possible that they reflect a more distant source such as the Dharwar craton (see discussion in Tucker et al., 2011, and references cited therein).

9. Discussion: Implications of the depositional age for the khondalite precursors and regional correlations

Our zircon age data, in combination with a detailed study of cathodoluminescence images, unambiguously shows that all undoubted grains of magmatic origin are of late Palaeoproterozoic and older ages. A few strongly discordant results with $^{207}\text{Pb}/^{206}\text{Pb}$ ratios suggesting “ages” less than 2 Ga are due to Pb-loss during the high-grade metamorphic event at ca. 550-580 Ma, and these data lie on trajectories in the concordia diagram between ca. 550 Ma and an imprecisely determined Palaeoproterozoic crystallization age. Many grains are strongly rounded due to metamorphic corrosion and not due to mechanical rounding during sedimentary transport as suggested in previous studies. There are numerous ball-round detrital grains with old cores, surrounded by ca. 550-580 metamorphic overgrowth, and there are also newly-grown metamorphic grains as indicated by their CL images and late Neoproterozoic ages. None of these grains are exclusively detrital, and their ages cannot therefore be used to constrain the depositional age of the khondalite precursor sediments. We consider the single monazite grain dated by Santosh et al. (2006) at 569 Ma to be of metamorphic, not detrital, origin.

Our ages for truly detrital zircons range between ca. 2000 and 3351 Ma. Bindu et al. (1998), Braun et al. (1998) and Santosh et al. (2005; 2006) also observed similar Palaeoproterozoic monazite and zircon ages. The oldest zircon core identified by Santosh et al. (2006) from a metapelite yielded a single grain age of ca. 3193 Ma, whereas our sample NGK-2 contained a detrital grain with a concordant age of 3351 Ma. The large zircon population investigated by Santosh et al. (2006) defines a prominent age peak at ca. 680 Ma, including core ages from some round grains erroneously interpreted as detrital, and this led to the speculation of a late Neoproterozoic depositional age for the khondalite precursor sediments (Santosh et al., 2005; 2006). From this Santosh et al. (2005) proposed that the metasedimentary belts in southern India may have formed part of an extensive late Neoproterozoic sedimentary basin during the final amalgamation of the Gondwana supercontinent. However, our data show that this basin likely was Palaeoproterozoic in age.

A Palaeoproterozoic age for the southern Indian khondalites suggests correlation with similar-age rocks in southern Madagascar and Sri Lanka. The Malagasy rocks south of the Tranomaro high strain zone (Fig. 11) consists predominantly of garnet-cordierite metapelites of the Tranomaro Group and leucogneisses mapped as leptynites (probably granitoid gneisses as in India) of the Tolanaro Group, both previously known as Ft. Dauphin Group of the Androyan System (Besairie, 1973) and now part of the Anoyesen Domain (Tucker et al., 2011; 2012; 2014). The leptynites were described as fine-grained

leucogneisses derived from volcanoclastic or rhyolitic protoliths (Paquette et al., 1994) and are strikingly similar to the leptynites of the Trivandrum Block in southern India, recently shown to represent high-grade leucogranitic gneisses with protolith ages of 1765-2106 Ma (Rimša et al., 2007; Kröner et al., 2015a). Müller (2000) dated abraded single zircons from a Tolanaro leptynite sample, using the TIMS method, and only obtained discordant results most likely reflecting variable recrystallization during the pervasive Pan-African event at ca. 550 Ma. However, the upper concordia intercept age of 1840 ± 5 Ma derived from near-perfect alignment of 8 discordant analyses most likely reflects the emplacement age of this rock and is compatible with the age range established for the Indian leptynites (leucogneisses). Other Palaeoproterozoic rocks in the Tolanaro Group of Madagascar include granitoid orthogneisses and coarse-grained gabbro from which zircons were dated at 1793 and 1908 Ma (Tucker et al., 2011). Thus the Tranomaro Shear Zone (TSZ) of Ishwar-Kumar et al. (2016) probably continues into southern India, most likely joining the Achankovil Shear Zone (ASZ) (Fig. 11).

Fig. 11 about here

The leucogneisses in southern India, as well as their apparent counterparts in southern Madagascar, were strongly deformed and metamorphosed together with tectonically interlayered metapelites (khondalites) during the Pan-African high-grade event, and Rimša et al. (2007) and Kröner et al. (2015a) described rare intrusive contacts showing at least some of the leucogneisses to be younger than the khondalite precursor metasediments, consistent with our age data reported above. We follow Tucker et al. (2014) who suggested that the garnet-cordierite paragneisses of the Tolanaro Group in southern Madagascar are Palaeoproterozoic in age and were intruded by leptynites (granitoid leucogneisses) for which Müller (2000) reported a minimum emplacement age of 1840 Ma. Kröner et al. (1996) obtained strongly discordant U-Pb zircon ages (vapour digestion TIMS method) for 6 zircon fractions from a cordierite-sillimanite gneiss of the large Ihosy quarry exposing migmatitic paragneisses of the Tolanaro Group (Fig. 11). These data are well aligned in the Concordia diagram with an imprecise upper intercept age of $2143 \pm 179/-160$ Ma, suggesting a Palaeoproterozoic age of its protolith deposition. Similarly, Collins et al. (2012) dated detrital zircons from high-grade metasediments of the Tolanaro Group (their Androyen Series), with one sample collected just east of Ihosy, and their data define discordia lines with upper concordia intercept ages of 1844 ± 16 and 1920 ± 15 Ma. Thus these metasediments likely correspond to the khondalites of the Trivandrum Block. Tucker et al. (2011; 2014) have provided additional evidence for the

widespread presence of Palaeoproterozoic crust in southern Madagascar.

Correlation of the Indian khondalites with metapelites and associated metaquartzites and marbles of the Highland Group in Sri Lanka (Fig. 12) is also supported by similar lithologies and age data. Kröner et al. (1987) dated detrital zircons from a metaquartzite of the Highland Group, and although many analyses are discordant the data suggest a depositional age >2120 Ma. A metapelitic migmatitic gneiss, also from the Highland Group, yielded abundant concordant and discordant $^{207}\text{Pb}/^{206}\text{Pb}$ ages around 2 Ga, also suggesting a Palaeoproterozoic depositional age for the metapelite protolith. Furthermore, Hölzl et al. (1994) and Baur et al. (1991) reported U-Pb zircon crystallization ages between 1851 ± 28 and 1942 ± 8 Ma for granitoid rocks intruding the Highland metasedimentary assemblage, thus confirming their Palaeoproterozoic deposition, most likely in a continental margin basin (Kehelpannala, 1997; 2003; Kröner and Brown, 2005).

Most Gondwana reconstructions place Sri Lanka in the position next to India as shown in Fig. 11 (e.g., Veevers et al., 2009; 2012). However, this is incompatible with the major tectonic contacts and structural trend lines that are oriented NW-SE in the Trivandrum Block and broadly N-S in Sri Lanka (Fig. 11). Therefore, anticlockwise rotation of Sri Lanka, as already envisaged by Tucker et al. (2011), would bring the structural grains in line between both crustal blocks (Fig. 12). The Wannai Complex has been compared with similar rocks in northern Mozambique and southern Tanzania (Kröner et al., 2003), whereas we have no plausible model for correlation of the ca. 1000-1100 Ma Vijayan magmatic arc terrane in eastern Sri Lanka (Kröner et al., 2013) with any terrane in India, Antarctica, or East Africa.

Fig. 12 about here

In summary, the above correlations support the suggestion of Tucker et al. (2011) for the existence of a regionally extensive Palaeoproterozoic sedimentary basin on a pre-Gondwana continental domain that included southernmost India, southern Madagascar and what is now the Highland Complex of Sri Lanka. The presence of shallow-water passive margin assemblages, including quartzite and marble, in Sri Lanka and the predominance of pelitic sequences in southern India and southern Madagascar suggest that this basin was close to an ancient continental margin. The presence of Archaean detrital zircons up to ~ 3170 Ma in age in the Sri Lankan metaquartzite (Kröner et al., 1987) may support this interpretation. However, the location of the original Archaean hinterland of the Highland metasediments remains unknown although it is possible that in an Indian-Sri Lankan connection the Archaean detrital grains may be derived from the Dharwar craton.

10. Conclusions

SHRIMP dating of detrital zircons from garnet-sillimanite-cordierite paragneisses (khondalites) of the Trivandrum Block revealed nanometer-scale Pb isotopic inhomogeneity in most grains. Following Whitehouse et al. (2014), we ascribe this to annealing processes during ultra-high-temperature metamorphism at ca. 570 Ma that arrested the movement of radiogenic Pb through the zircon crystal at a relatively advanced stage. Thus, larger-scale heterogeneity of radiogenic and unsupported Pb as well as some quantitative Pb-loss has resulted.

Our age data for zircons from six representative khondalite samples do not document any Neo- or Mesoproterozoic detrital grains, and we conclude from the concordant ages and discordant minimum $^{207}\text{Pb}/^{206}\text{Pb}$ ages that the khondalite precursor sediments in southern India and southern Madagascar were deposited more than 2.1 Ga ago and were subsequently intruded by granitoid rocks at ca. 1765-2100 Ma (Tucker et al., 2011; Kröner et al., 2015). Some detrital zircons in the khondalites contain late Palaeoproterozoic metamorphic domains, suggesting that these grains are derived from an unknown crustal source that most likely experienced late Palaeoproterozoic high-grade metamorphism. Both the metasedimentary assemblage and granitoids were severely ductilely deformed, metamorphosed and migmatized during the pervasive Pan-African event at ca. 550-580 Ma. This caused many detrital zircons in the khondalites to become variably recrystallized and to develop metamorphic rims.

The southern Indian khondalites were likely part of an extensive Palaeoproterozoic metasedimentary assemblage that extended from southern Madagascar via the Trivandrum Block to the Highland Complex of Sri Lanka and seems to reflect a continental margin sequence that was deposited on an Archaean to early Palaeoproterozoic continental terrane whose palaeogeographic context remains unknown. We are unable to reconstruct the tectonic history of this terrane due to the pervasive overprint during the Pan-African event.

There has been significant discussion in the literature on the age of the southern Indian khondalites, and it is therefore not inappropriate to conclude with a quotation from James Hutton: “While man has to learn, mankind must have different opinions; these, indeed, are often, commonly I may say, erroneous; but are commonly corrected, and it is thus that truth in general is made to appear“ (Theory of the Earth, vol. I, 1795, p. 250).

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Figure and table captions

Fig. 1. Simplified geological map of the southern part of Kerala and Tamil Nadu, showing the various Proterozoic granulite blocks and rock types as well as sample localities of khondalites dated in this study (compiled after Geological Survey of India 1995; modified from Kröner et al., 2015a).

Fig. 2. Representative field photographs of khondalite relationships in quarries of the Trivandrum Block. (a) Strongly ductilely deformed bands of khondalite (dark) and granitoid leucogneiss (light grey) in a quarry at Kuttikonam (sample KTKN). Contacts are everywhere parallel due to high strain. (b) Large xenolith of interlayered khondalite and granitoid leucogneiss (inclined pink band) within massive charnockitic gneiss (brown) in large quarry at Kottaram (from Kröner et al., 2015a). (c) Alternating bands of khondalite (dark) and granitoid leucogneiss (light) in a quarry at Kakodu (sample TBK-2). Note buckling in leucogneiss due to viscosity contrast between the two rock types. (d) Khondalite with clusters of porphyroblasts of cordierite and garnet in a quarry at Koliakode (TBK-3). (e) Migmatitic khondalite with leucosome and restite porphyroblasts of garnet, cordierite, and sillimanite in a quarry at Koliakode (TBK-3). (f) Khondalite with cordierite-sillimanite-spinel-garnet assemblage in a quarry at Nedumpara (sample TBK-4).

Fig. 3. Pressure-temperature (P-T) diagram showing the metamorphic evolution of khondalites in the Trivandrum Block. (a) P-T conditions from various mineral

assemblages in khondalites as estimated by Morimoto et al. (2004), compared with regional P-T conditions in different domains of the Trivandrum Block. (b) Photomicrograph (crossed nicols) showing the representative mineralogy of khondalites. All studies suggest a clockwise P-T path with decompression following peak metamorphism.

Fig. 4. Representative cathodoluminescence (CL) images of detrital and metamorphic zircon grains from dated samples of this study. (a-b) sample KTKN; (c-e) sample NGK2. (f) sample TBK1. Ellipses indicate spots for SHRIMP II analyses and corresponding ages (Table 2). Last number for each sample denotes grain number in Table 2.

Fig. 5. Representative cathodoluminescence (CL) images of detrital and metamorphic zircon grains from dated samples of this study. (a) sample TBK1; (b-d) sample TBK2; (e-f) sample TBK3. Explanation as in Fig. 4.

Fig. 6. Representative cathodoluminescence (CL) images of detrital and metamorphic zircon grains from dated samples of this study. (a) sample TBK3; (b-f) sample TBK4. Explanation as in Fig. 4.

Fig. 7. (a) SHRIMP II scan of mass ^{206}Pb for zircon of khondalite sample TBK-1, showing irregular peak top with “smoothing line” indicated in red. (b) Concordia diagram showing original data for grain 2 of sample TBK1 and result after “peak smoothing”.

Fig. 8. Concordia diagrams showing analytical data for detrital zircons from khondalite samples KTKN (a) and NGK2 (b). Insets show data for metamorphic grains or overgrowth. Data boxes for each analysis are defined by 1-sigma errors in $^{207}\text{Pb}/^{235}\text{U}$, $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{206}\text{Pb}$. For analytical data see Table 2.

Fig. 9. Concordia diagrams showing analytical data for detrital zircons from khondalite samples TBK1 (a) and TBK2 (b). Insets show data for metamorphic grains or overgrowth. Data boxes as in Fig. 8.

Fig. 10. Concordia diagrams showing analytical data for detrital zircons from khondalite samples TBK3 (a) and TBK4 (b). Insets show data for metamorphic grains or

overgrowth. Data boxes as in Fig. 8.

Fig. 11. Southern India-southern Madagascar-Sri Lanka fit before rifting of Gondwana (India-Madagascar after graphical abstract in Ishwar-Kumar et al., 2016; India-Sri Lanka after Veevers, 2009). Acronyms in the southern parts of Madagascar, India and Sri Lanka are as follows: RSZ - Ranotsara Shear Zone, TSZ - Tranomaro Shear Zone, BeSZ - Betroka Shear Zone, AmSZ - Amphanihy Shear Zone, PCSZ - Palghat-Cauvery Shear Zone, MB - Madurai Block, ASZ - Achankovil Shear Zone, TB - Trivandrum Block, WC - Wanni Complex, HC – Highland Complex, VC – Vijayan Complex.

Fig. 12. Southern India-Sri Lanka correlation of Precambrian rocks with Sri Lanka rotated anticlockwise to bring it in line with the structural grain in southern India.

Table 1. Summary of sample localities, mineral compositions, and types of zircon ages for pelitic metasediments (kondalites) in the Trivandrum Block, southern India. For locations see Fig. 1.

Table 2. SHRIMP II analytical data for spot analyses of zircons from khondalite metasediments of southernmost India.

Table 1

Table 1. Summary of sample localities, mineral compositions, and types of zircon ages for pelitic metasediments (kondalites) in the Trivandrum Block, southern India. For locations see Fig. 1.

Sample	GPS location	Locality	Main mineral association	Zircon ages
KTKN	76° 52' 31" E 09° 00' 52" N	Quarry at Kuttikonam	Garnet+sillimanite+K-feldspar ±cordierite	Detrital Metamorphic
NGK-2	77° 30' 58" E 08° 07' 49" N	Kottaram quarry near Kanya Kumari village	Garnet+sillimanite+K-feldspar ±cordierite	Detrital Metamorphic
TBK-1	76° 47' 32" E 08° 45' 27" N	Eranikonam quarry	Garnet+sillimanite+K-feldspar ±cordierite	Detrital Metamorphic
TBK-2	76° 49' 07" E 08° 45' 53" N	Kakodu quarry	Garnet+sillimanite+K-feldspar +cordierite+spinel	Detrital Metamorphic
TBK-3	76° 53' 27" E 08° 38' 21" N	Koliakode quarry	Garnet+sillimanite+K-feldspar +cordierite+spinel	Detrital Metamorphic
TBK-4	76° 58' 48" E 08° 33' 47" N	Nedumpara quarry	Garnet+sillimanite+K-feldspar +cordierite+spinel	Detrital Metamorphic

Table 2

Table 2. SHRIMP II analytical data for spot analyses of zircons from khondalite metasediments of southernmost India.

Samle No.	U ppm	Th ppm	Th/U	²⁰⁶ Pb 204Pb	²⁰⁷ Pb 206Pb	²⁰⁶ Pb 238U	²⁰⁷ Pb 235U	206/238 age ± 1σ	207/235 age ± 1σ	207/206 age ± 1σ
KTKN-1	219	74	0.338	400000	0.1433± 5	0.4220±48	8.339±103	2270±22	2269±11	2267± 6
KTKN-2	241	28	0.116	27397	0.1016± 7	0.2292±26	3.211± 44	1330±14	1460±11	1654±12
KTKN-3.1	347	85	0.244	8150	0.1234± 6	0.2751±31	4.682± 60	1566±16	1764±11	2007± 8
KTKN-3.2	3211	212	0.066	575	0.0596±18	0.0210± 2	0.173± 6	134± 1	162± 5	589±64
KTKN-4	185	97	0.524	169492	0.1232± 5	0.3392±39	5.761± 74	1883±19	1941±11	2003± 8
KTKN-5	278	142	0.511	243902	0.1237± 4	0.3678±42	6.273± 77	2019±20	2015±11	2010± 6
KTKN-6	234	72	0.309	69444	0.1260± 7	0.2149±24	3.734± 49	1255±13	1579±10	2043± 9
KTKN-7	375	153	0.407	238095	0.1296± 4	0.3664±41	6.550± 78	2013±19	2053±11	2093± 5
KTKN-9	416	176	0.423	769231	0.1327± 4	0.2907±33	5.318± 64	1645±16	1872±10	2134± 5
KTKN-10	227	74	0.324	555556	0.1328± 5	0.3648±42	6.680± 83	2005±20	2070±11	2135± 6
KTKN-11	3846	443	0.115	989	0.0594±15	0.0171± 2	0.140± 40	109± 1	133± 4	580±54
KTKN-12	283	155	0.549	232558	0.1254± 4	0.3740±43	6.468± 80	2048±20	2042±11	2035± 6
KTKN-13	267	120	0.449	2776	0.1256± 7	0.3761±43	6.513± 87	2058±20	2048±12	2037±10
KTKN-14	4506	327	0.073	505	0.8612±19	0.0153± 2	0.129± 45	98± 1	123± 4	647±68
NGK2-1	372	169	0.453	416667	0.1473± 4	0.4297±48	8.726±103	2305±22	2310±	2314± 4
NGK2-2	83	71	0.864	112360	0.2779±10	0.16854±85	26.259±350	3365±32	3356±13	3351± 6
NGK2-3.1	176	60	0.343	123457	0.1470± 5	0.4368±51	8.854±112	2336±23	2323±12	2312± 6
NGK2-3.2	1134	69	0.061	153846	0.0586± 4	0.0775± 9	0.626± 8	481± 5	493± 5	551±13
NGK2-4	39	16	0.409	38314	0.1453±15	0.3601±48	7.212±129	1983±23	2138±16	2291±18
NGK2-5	507	31	0.061	142857	0.0584± 5	0.0892±10	0.719± 11	551± 6	550± 6	546±18
NGK2-6	1228	122	0.099	256410	0.0591± 3	0.0823± 9	0.671± 9	510± 5	521± 5	571±11
NGK2-7	351	49	0.139	128205	0.1247± 4	0.2978±34	5.121± 63	1681±17	1840±10	2025± 6
NGK2-8	325	8	0.025	57143	0.0590± 9	0.0833± 9	0.677± 13	516± 6	525± 8	566±32
NGK2-9	261	160	0.611	500000	0.1601± 5	0.4641±53	10.241±124	2457±23	2457±11	2456± 5
NGK2-10	930	229	0.246	416667	0.1260± 3	0.2716±30	4.718± 54	1549±15	1771±10	2043± 4
NGK2-11	302	38	0.126	136986	0.1130± 5	0.2335±26	3.638± 46	1353±14	1558±10	1848± 8
NGK2-12	415	39	0.093	263158	0.0587± 5	0.0803± 9	0.650± 9	498± 5	509± 6	557±18
NGK2-13	1413	86	0.061	769231	0.0585± 2	0.0776± 9	0.626± 8	482± 5	494± 5	548± 9
NGK2-14	105	49	0.467	75188	0.1786± 7	0.5083±61	12.521±165	2650±26	2644±12	2640± 7
NGK2-15	53	35	0.652	1547	0.0971±35	0.1279±16	1.712± 67	776± 9	1013±25	1568±67
NGK2-16	608	20	0.034	119048	0.0586± 5	0.0836± 9	0.676± 10	518± 6	524± 6	553±17
TBK1-1	702	7	0.010	239234	0.1055± 3	0.1750±19	2.547± 30	1040±11	1286± 9	1724± 5
TBK1-2	42	23	0.548	43898	0.1813±11	0.5103±65	12.753±188	2658±28	2662±14	2664±10
TBK1-3.1	289	69	0.240	163934	0.1613± 4	0.3939±44	8.758±104	2141±21	2313±11	2469± 4
TBK1-3.2	540	8	0.015	300300	0.1048± 3	0.1976±22	2.855± 34	1162±12	1370± 9	1711± 8
TBK1-4	679	11	0.017	167224	0.0863± 4	0.1176±13	1.398± 18	716± 8	888± 7	1344± 9
TBK1-5.1	177	151	0.855	64977	0.1637± 6	0.4501±52	10.158±127	2396±23	2449±12	2494± 6
TBK1-5.2	534	3	0.006	133511	0.0586± 5	0.0813± 9	0.657± 9	504± 5	513± 6	552±17
TBK1-6	262	76	0.289	277778	0.1380± 5	0.3222±37	6.131± 75	1800±18	1995±11	2202± 6
TBK1-7	166	39	0.236	156006	0.1114± 7	0.2194±25	3.371± 46	1279±13	1498±11	1823±11
TBK1-8	407	20	0.050	204918	0.1005± 6	0.1252±14	1.735± 23	760± 8	1022± 8	1634±11
TBK1-9	413	44	0.107	95877	0.0586± 6	0.0894±10	0.722± 11	552± 6	552± 7	552±21
TBK1-10	381	153	0.402	6398	0.0590± 9	0.0869±10	0.708± 14	537± 6	543± 8	569±32
TBK1-11	587	10	0.018	135685	0.0587± 6	0.0814± 9	0.659± 9	504± 5	514± 6	558±17
TBK1-12	73	44	0.597	78064	0.1319± 9	0.3902±48	7.099±106	2124±22	2124±13	2124±12
TBK1-13	514	50	0.097	2631579	0.0589± 4	0.0813± 9	0.661± 9	504± 5	515± 5	565±14
TBK1-14.1	470	9	0.019	190840	0.1107± 4	0.1812±20	2.765± 34	1073±11	1346± 9	1811± 7
TBK1-14.2	300	106	0.352	25132	0.0591± 9	0.0844± 9	0.688± 14	523± 6	532± 8	572±34
TBK1-15	163	32	0.199	61087	0.1321±10	0.2604±30	4.742± 70	1492±16	1775±12	2126±13
TBK1-16	555	5	0.009	358423	0.0704± 4	0.1215±13	1.179± 15	739± 8	791± 7	940±10
TBK1-17	252	148	0.588	255754	0.1716± 5	0.4899±56	11.589±141	2570±24	2572±11	2573± 5
TBK1-18	376	240	0.638239	228311	0.1396± 4	0.4100±46	7.891± 94	2215±21	2219±11	2222± 5
TBK2-1	957	97	0.102	65789	0.0589± 4	0.0826± 9	0.671± 9	511± 5	521± 5	565±13
TBK2-2	1635	10	0.006	120482	0.0596± 2	0.0838± 9	0.688± 8	519± 5	532± 5	589± 9
TBK2-3	890	22	0.025	33445	0.0585± 4	0.0897±10	0.724± 10	554± 6	553± 6	549±13
TBK2-4	671	3	0.005	303030	0.0590± 4	0.0875±10	0.712± 10	541± 6	546± 6	566±13
TBK2-5	470	7	0.015	19011	0.0896± 6	0.1027±11	1.269± 17	630± 7	832± 8	1416±12
TBK2-6.1	345	2	0.007	12690	0.0591± 9	0.0861±10	0.702± 14	532± 6	540± 8	572±33
TBK2-6.2	690	95	0.138	15723	0.0587± 6	0.0880±10	0.713± 11	544± 6	546± 7	557±22
TBK2-7.1	1023	92	0.090	6281	0.0589± 6	0.0754± 8	0.612± 10	468± 5	485± 6	565±22
TBK2-7.2	201	41	0.204	68966	0.0592± 8	0.0853±10	0.696± 13	528± 6	536± 8	575±29
TBK2-8	594	8	0.013	9891	0.0593± 6	0.0828± 9	0.676± 11	513± 5	525± 6	577±22
TBK2-9	1152	13	0.011	370370	0.0582± 3	0.0798± 9	0.641± 8	495± 5	503± 5	538±11
TBK2-10	1086	46	0.043	95238	0.0590± 3	0.0871±10	0.708± 9	538± 6	544± 5	565±11

TBK2-11	284	24	0.084	951	0.0587±23	0.0830±10	0.672± 28	514± 6	522±17	555±84
TBK2-12	1101	17	0.015	169492	0.0585± 3	0.0822± 9	0.663± 8	509± 5	516± 5	547±10
TBK2-13	328	34	0.104	59524	0.0586± 8	0.0923±10	0.746± 14	569± 6	566± 8	551±31
TBK2-14	1001	382	0.382	142857	0.1239± 2	0.3097±34	5.291± 61	1739±17	1867±10	2013± 3
TBK3-1	1204	56	0.046	31250	0.0825± 3	0.1146±13	1.303± 16	699± 7	847± 7	1257± 7
TBK3-2	404	141	0.350	68027	0.0588± 7	0.0847± 9	0.687± 12	524± 6	531± 7	560±25
TBK3-3	343	107	0.312	83333	0.1337± 4	0.3949±45	7.280± 88	2145±21	2146±11	2147± 5
TBK3-4	166	85	0.513	140845	0.1271± 6	0.3717±43	6.517± 85	2038±20	2048±12	2059± 8
TBK3-5.1	47	48	1.035	16420	0.1428±13	0.4185±55	8.238±138	2254±25	2058±15	2261±15
TBK3-5.2	1196	53	0.044	322581	0.0833± 3	0.1440±16	1.653± 20	867± 9	991± 8	1275± 7
TBK3-6.1	170	18	0.103	60976	0.1076± 8	0.2066±24	3.065± 45	1210±13	1424±11	1759±14
TBK3-6.2	569	15	0.026	114943	0.0586± 5	0.0824± 9	0.666± 10	511± 5	518± 6	552±17
TBK3-7	437	194	0.443	370370	0.1293± 4	0.3048±34	5.435± 65	1715±17	1890±10	2088± 5
TBK3-8	705	13	0.019	109890	0.0590± 5	0.0792± 9	0.645± 9	491± 5	505± 6	568±17
TBK3-9	211	140	0.662	163934	0.1384± 6	0.3369±39	6.427± 82	1872±19	2036±11	2207± 7
TBK3-10	1147	59	0.052	153846	0.0588± 4	0.0772± 9	0.626± 8	480± 5	493± 5	558±14
TBK3-11	256	150	0.583	185185	0.1238± 5	0.3599±41	6.143± 77	1982±19	1996±11	2011± 7
TBK3-12	164	42	0.258	12837	0.0941±10	0.1664±19	2.158± 36	992±10	1168±12	1509±21
TBK4-1	463	21	0.045	578035	0.1126± 3	0.2791±31	4.333± 52	1587±16	1700±10	1842± 6
TBK4-2	187	79	0.422	113636	0.2057± 6	0.5643±65	16.004±197	2884±27	2877±12	2872± 5
TBK4-4	1665	66	0.040	500000	0.1300± 2	0.3636±40	6.515± 74	1999±19	2048±10	2097± 2
TBK4-5	274	37	0.136	625000	0.1109± 5	0.2556±29	3.907± 49	1467±15	1615±10	1814± 8
TBK4-6	92	85	0.927	77519	0.1879± 9	0.5303±65	13.739±188	2743±27	2732±13	2724± 8
TBK4-7.1	126	35	0.278	29940	0.1664± 8	0.4014±47	9.209±122	2175±22	2359±12	2522± 8
TBK4-7.2	420	4	0.011	77519	0.0593± 6	0.0831± 9	0.680± 11	514± 5	527± 7	580±23
TBK4-8	128	67	0.523	63024	0.1455± 7	0.4260±50	8.546±113	2288±23	2291±12	2294± 8
TBK4-9	376	34	0.089	714286	0.1623± 4	0.3546±40	7.932± 95	1956±19	2223±11	2479± 5
TBK4-10	55	30	0.554	34722	0.2056±12	0.5601±73	15.877±236	2867±30	2869±14	2871± 9
TBK4-11	237	120	0.504	204082	0.1428± 5	0.3748±43	7.377± 91	2052±20	2158±11	2261± 6
TBK4-12	282	87	0.310	99010	0.1250± 4	0.3566±41	6.144± 76	1966±19	1997±11	2028± 6
TBK4-13	80	40	0.492	23585	0.1458±11	0.3168±39	6.366± 96	1774±19	2028±13	2297±13
TBK4-14	803	56	0.070	4730	0.0590± 7	0.0907±10	0.7379± 13	560± 6	561± 7	567±26

KTKN-1.1 is spot 1 on grain 1, KTKN-1.2 is spot 2 on grain 21 etc.

Figure 1

Liu et al., Fig. 1

Figure 2

Liu et al., Fig. 2

Figure 3

Figure 4

Fig. 4

Figure 5

Fig. 5

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Fig. 10

Figure 11

Fig. 11, Liu et al.

Figure 12

Liu et al., Fig. 12