Early Archaean continental crust in the Eastern Ghats granulite belt, India: isotopic evidence from a charnockite suite

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Abstract – The Eastern Ghats granulite belt of India has traditionally been described as a Proterozoic mobile belt, with probable Archaean protoliths. However, recent findings suggest that synkinematic development of granulites took place in a compressional tectonic regime and that granulite facies metamorphism resulted from crustal thickening. The field, petrological and geochemical studies of a charnockite massif of tonalitic to trondhjemitic composition, and associated rocks, document granulite facies metamorphism and dehydration partial melting of basic rocks at lower crustal depths, with garnet granulite residues exposed as cognate xenoliths within the charnockite massif. The melting and generation of the charnockite suite under granulite facies conditions have been dated *c.* 3.0 Ga by Sm–Nd and Rb–Sr whole rock systematics and Pb–Pb zircon dating. Sm–Nd model dates between 3.4 and 3.5 Ga and negative epsilon values provide evidence of early Archaean continental crust in this high-grade terrain.

1. Introduction

Most of the early Archaean (≥ 3.5 Ga) crustal components worldwide are represented by tonalite–trondjhemite–granite suites, for which it is difficult to constrain the depth of melting (Rudnick, 1995). Although Wolf & Wyllies' (1994) experiments on amphibolite suggest that melts of tonalitic to granitic compositions are produced at around 10 kbar pressure, absence of restitic assemblages in the Archaean tonalite–trondjhemite–granite suites makes it difficult to discern whether they were generated within the lower continental crust or at mantle depth. On the other hand, evidence for thick continental crust (at 3.5 Ga) has been reported from a number of high-grade terrains: the Napier Complex in Enderby Land, Antarctica (Black & McCulloch, 1987), West Greenland (Griffin *et al.* 1980), the Ancient Gneiss Complex of Swaziland (Kroner, Compston & Williams, 1989) and the Anabar Shield of Siberia (Rosen, Andreev & Belov, 1980). These high-grade terrains all record a 'normal' geothermal gradient of 30 °C to 35 °C km^{-1} (England & Bickle, 1984).

In the Indian Peninsula, crustal components as old as 3.5 Ga have been reported from several granite–greenstone terrains (Fig. 1): Dharwar (Nutman *et al.* 1992), Singhbhum (Goswami *et al.* 1995), Bastar (Sarkar *et al.* 1993) and Aravalli (Roy & Kroner, 1996). It is important to note that some of these isotopic data are derived from tonalite–trondjhemite–granite suites (Sengupta *et al.* 1996), but none of these suites have been linked to a high-grade terrain on mineralogical or petrological grounds. Also, recent zircon (Pb–Pb) data suggest that crust formation was initiated by 3.6 Ga ago in the Singhbhum region (Misra *et al.* 1999). In contrast, the granulite belts of the Eastern Ghats and southern India are considered to have been formed and accreted during younger events (Buhl, Grauert & Raith, 1983; Naqvi & Rogers, 1987; Harris, Santosh & Taylor, 1994; Hansen *et al.* 1997).

Isotopic data on the granulite facies rocks of the Eastern Ghats belt, of late Archaean to Pan-African age, have been uncovered in abundance recently, but despite this, the correlation of the isotopic data with polyphase deformation and multi-stage or multiple granulite facies metamorphism is still uncertain. The two most common age clusters are at *c.* 1.5 Ga (Rao, 1976; Shaw *et al.* 1997; Mezger & Cosca, 1999) and 1.0 Ga (Grew & Manton, 1986; Aftalion *et al.* 1988; Paul *et al.* 1990; Shaw *et al.* 1997; Mezger & Cosca, 1999). Some Archaean (2.6–2.8 Ga: Vinogradov *et al.* 1964; Paul *et al.* 1990; Shaw *et al.* 1997) and Pan-African ages (0.5 Ga: Shaw *et al.* 1997; Bindu, Yoshida & Santosh, 1998; Mezger & Cosca, 1999) have also been documented. The Archaean ages reported from the Eastern Ghats rocks up to now are either Sm–Nd model ages or U–Pb zircon ages, interpreted exclusively as protolith ages, and hence they have not been taken to imply the presence of an Archaean high-grade metamorphism in the Eastern Ghats. However, on the basis of structural and petrological observations, several workers have argued for the presence of an older, possibly Archaean granulite facies metamorphism in the Eastern Ghats belt that has been largely

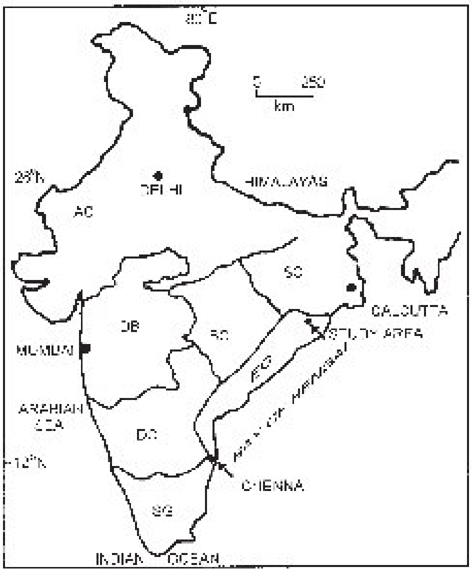

Figure 1. Map of India showing different crustal segments: AC – Aravalli Craton, SC – Singhbhum Craton, BC – Bastar Craton, DB – Deccan Basalt, DC – Dharwar Craton, EG – Eastern Ghats, SG – Southern Granulites.

erased by later granulite facies overprints and reworking (Halden, Bowes & Dash, 1982; Grew & Manton, 1986; Bhattacharya, Sen & Acharyya, 1994; Sen, Bhattacharya & Acharyya, 1995). For example, Sarkar *et al.* (1998) reported 2.6–2.7 Ga Rb–Sr isochron ages for charnockites in the northern sector, but the relationship with deformation, metamorphism or tectonic setting for the origin of these charnockites was not discussed.

In this paper we present evidence of Archaean (*c.* 3.0 Ga) granulite facies metamorphism and partial melting in the Eastern Ghats belt, here represented by a charnockite massif and associated rocks. Coupled with the isotopic data, evidence is presented for synkinematic emplacement of the charnockite massif with compressional deformation.

2. Geological setting

2.a. Eastern Ghats belt

The Eastern Ghats granulite belt, along the east coast of India (Fig. 2, inset), has the impress of polyphase deformation and a complex metamorphic record. Detailed field studies in several sectors have revealed three phases of folding with development of pervasive foliations, often truncating and transposing earlier fabrics on different scales (Bhattacharya, Sen & Acharyya, 1994; Bhattacharya, 1996).

Structural studies in several sectors have established an early dominantly compressional setting; isoclinal and rootless F_1 folds with NE–SW-trending steep axial plane foliation S_1, and common structural repetitions suggest a regional NW–SE-directed compression and shortening during the development of first generation folds (Bhattacharya, 1997). Granulite facies metamorphism is attendant with S_1 foliation, as is evident from the most common P–T values given by the garnet–sillimanite–ilmenite–rutile assemblage in the metapelites and pyroxene–garnet–plagioclase–quartz assemblage in the charnockites and mafic granulites (Sen, Bhattacharya & Acharyya, 1995). Significant crustal thickening during the first deformation is also evident from the pressure record of 8 to 9 kbar in the exhumed metapelitic granulites (Bhattacharya, 1996).

2.a.1. *Charnockite massif*

Detailed structural, petrological and geochemical investigations have been carried out on the massif-type charnockite body (8000 m × 200 m) around Jenapore, Orissa, and its associated granulites (R. Kar, unpub. Ph.D. thesis, Univ. Calcutta, 1999) (Fig. 2). Here we

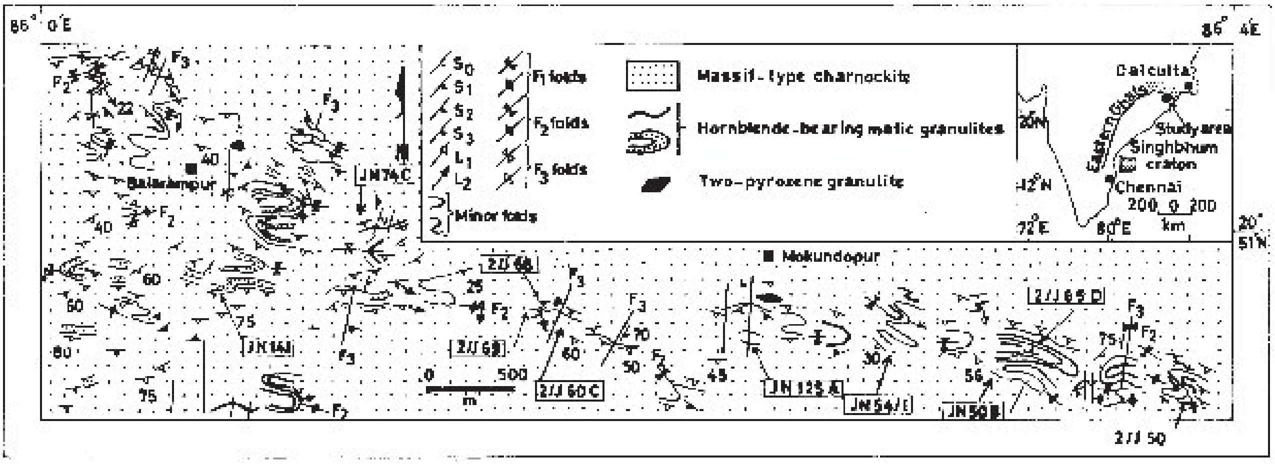

Figure 2. Simplified map, showing the field relations and structures of the charnockite massif and associated rocks, around Jenapore, Orissa, India. Inset shows location of the study area in the Eastern Ghats. Location of analysed samples are also shown in rectangular boxes.

present summarized results of this investigation. The charnockite massif and associated rocks are considered to be a charnockite suite with the following members: charnockite (*senso lato*) massif, enderbitic granulite, two-pyroxene mafic granulite and hornblende–pyroxene mafic granulite.

2.a.2. Structure

The charnockite massif is characterized by a streaky gneissic foliation, designated S_1, which is parallel to the axial planes of intrafolial folds represented by bands of hornblende-bearing mafic granulite (Fig. 2). The discordance between the hornblende-bearing mafic granulite and the S_1 gneissic foliation in the host charnockite indicates the prior existence of the mafic granulite protolith. The hornblende-bearing mafic granulite may thus represent cognate xenoliths. In contrast, enderbitic granulite and two-pyroxene mafic granulite occur as small lenticular patches concordant with the S_1 foliation.

The rootless, isoclinal F_1 folds with a strong near-vertical axial planar foliation S_1 is consistent with a major crustal shortening during the development of these structures in the Eastern Ghats belt. In metapelitic granulites and hornblende-bearing mafic granulites, S_1 is a typically penetrative foliation, not a layer-differentiated crenulation cleavage type commonly interpreted as a manifestation of extension (Rubenach, 1992). In the charnockite massif this S_1 foliation is defined by lenticular accumulation of orthopyroxene–plagioclase–Fe–Ti oxides ± garnet. Occasional development of directional myrmekitic intergrowth and the common occurrence of flame-perthite and mesoperthite are indicative of deformation induced intergrowth texture (Simpson & Wintsch, 1989). Additionally, a moat of fine-grained orthopyroxene along the margin of orthopyroxene porphyroblasts indicates high-temperature recrystallization (Passchier & Trouw, 1996).

These mesoscopic to microscopic fabrics and microstructures suggest that the emplacement of the charnockite massif was broadly syntectonic with F_1 deformation. Although a pre-F_1 emplacement cannot be ruled out at this point, zircon morphology suggests deformation during crystallization (see Section 3.b.2).

2.a.3. Petrology and geochemistry

In the hornblende-bearing mafic granulites many hornblende grains have embayed grain boundaries, with pyroxene and plagioclase in the embayed portions, indicating the primary nature of the hornblende. Ilmenite deposition along hornblende–pyroxene contact also confirms the primary nature of hornblende (Skjerlie & Johnston, 1992). On the other hand, zoning in plagioclase and exsolution lamellae in pyroxene in the charnockites suggest their magmatic origin.

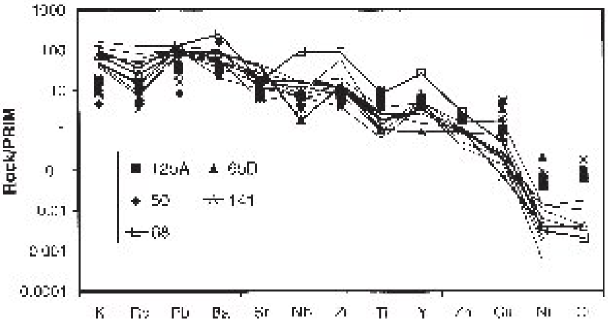

Figure 3. Primitive mantle (of Taylor & McLennan, 1985) normalized spidergram for charnockites and hornblende-bearing mafic granulites. Charnockites represented by open symbols (for analysed samples) and connecting lines, and mafic granulites represented by solid symbols (for analysed samples) and asterisks.

The charnockites (*sensu lato*) in the study area may be mineralogically referred to as enderbite or charno-enderbite, according to Streckeisen's nomenclature (1976). They are metaluminous to weakly peraluminous, and are of tonalitic to trondjhemitic composition. These rocks are geochemically similar to tonalite–trondjhemite–granite gneisses. But unlike the tonalite–trondjhemite–granite gneisses of Archaean cratons, these rocks occur in an undifferentiated massif-type intrusive body and are characterized by the presence of anhydrous orthopyroxene, presumably due to crystallization at depth (Kramers & Ridley, 1989). To emphasize the geological setting, namely that of a granulite terrain, these rocks are described as massif-type charnockites (*sensu lato*). Most charnockites have low Cr, Ni, Sc, V, Cu, Zn, Ti, Y, Th, U, Zr and Nb contents, whereas Sr, Pb and Ba are relatively high. The spidergram (Fig. 3) shows marked Y depletion, but little or no Sr depletion, relative to the restitic mafic granulites, consistent with melting involving little residual plagioclase, but major residual hornblende and/or garnet (Tarney *et al.* 1987).

The hornblende-bearing mafic granulites are of variable composition, but comparable to low-K tholeiitic basalt. The correlation between Mg no. (53 to 64) and normative olivine content (2 to 20%) is interpreted to have resulted from variable extraction of partial melts from the protolith of these mafic granulites. On the other hand, lack of correlation between Mg no. and Niggli value (*alk*) suggests that the chemical variation cannot be the result of a previous magmatic differentiation. These rocks are enriched in Ni, Cr, Sc, V, Zn and Ti and depleted in K, Rb, Pb and Ba, relative to the host charnockites (*sensu lato*). High Ti, transition element and base metal contents further support their restitic nature (Fig. 3).

These complementary chemical features are consistent with a genetic connection between charnockite and hornblende-bearing mafic granulite through partial melting. Some experimental observations suggest that

Table 1. Modal mineralogy of charnockite and mafic granulite samples used for isotopic study

Sample no.	Quartz	Alk-felds	Plag	Opx	Cpx	Gart	Hbl	Bio	Opq	Accessory
JN 141 (c)	30.8	19.2	43.5	5.2	–	–	–	0.7	0.4	0.2 (Zr)
2J 68 (c)	17.6	13.6	38.4	7.6	–	6.8	7.2	1.2	7.6	trace (Zr)
2J 69 (c)	23.2	13.6	54.6	3.4	–	–	3	–	2	0.2(Zr)
JN125A (M)	3.8	–	16.2	8.8	14	11.6	42	–	2.8	0.4(Cc)
2J 65D (M)	3.8	–	19.8	9.6	11.4	9	40	–	6.2	0.2(Cc)
2J 50 (M)	5	–	25.1	–	22.1	23.5	23.3	–	0.3	0.7(Sp)
JN 50B (c)	21.6	39.6	34.8	2.8	–	–	–	–	0.8	0.4(Zr)
2. J 60C (c)	17.6	39.2	34.4	2.4	–	3.6	1.6	0.4	0.4	0.4(Zr)
JN 54/1 (c)	18	21.2	46.8	12	–	0.4	–	–	1.6	–
JN 74C (c)	28.6	21.2	44	1.6	–	–	2.6	–	2	–

(c) denotes charnockite samples and (M) denotes restitic mafic granulite samples. Hbl – hornblende, Bio – biotite, Gart – garnet, Opx – orthopyroxene, Cpx – clinopyroxene, Opq – opaque, Plag – plagioclase, Alk-felds – alkali-feldspar, Cc – calcite, Zr – zircon, Sp – sphene.

hornblende-dehydration melting leads to a lower CN/CNK value in the restite (Patino Douce & Beard, 1995; Skjerlie & Patino Douce, 1995). Such a trend can be observed in the hornblende-bearing mafic granulites, varying between 0.94 and 0.98.

Some mineral–chemical features are also consistent with the purported genesis by hornblende-dehydration melting. For example, variable hornblende compositions (X_{Mg} 0.62–0.69) and magnesium enrichment in the hornblende rims (X_{Mg} 0.62 core, 0.63 rim; 0.64 core, 0.65 rim) suggest the restitic nature of hornblende. Less calcic plagioclase (An_{19-21}) and less magnesian orthopyroxene (X_{Mg} 0.61–0.62) in the charnockite compared to those of the hornblende-bearing mafic granulite (An_{30-36} and X_{Mg} 0.67–0.69 respectively) are consistent with experimental results of hornblende-dehydration melting (Patino Douce & Beard, 1995; Springer & Seck, 1997).

In spite of the mineralogical and chemical evidence of hornblende-dehydration melting producing the charnockite massif and associated rocks, the chemical heterogeneity in the source rocks is evident in some trace element characteristics of the charnockites. The high Zr in some charnockite samples (some also with high Th; Zr: 337, 434, 485 ppm; Th: 1, 4, 6 ppm) seems to suggest entrainment of (presumably) restitic zircon. Mafic rocks are generally poor in zircon, however (Black *et al.* 1991), and thus the extensive source terranes may well have more felsic components; the hornblende-bearing mafic granulites (or more precisely their protolith) may represent only the more mafic end-member of the source rocks.

3. Isotopic studies

3.a. Sm–Nd systematics

3.a.1. *Sample selection*

On the basis of our structural and petrological investigations, five samples were selected for Sm–Nd whole rock isotopic study. Selected samples exhibit only the S_1 gneissic foliation. Sm–Nd isotopic analysis is more suitable for relatively mafic rocks, but in view of the melt–restite relationship, we selected three samples of hornblende-bearing mafic granulite and two samples of charnockite (Table 1) for analysis. These were considered to represent restites and melts, respectively, of a hornblende-dehydration melting, synkinematic with F_1–S_1 deformation. In selecting these samples, we also considered both their Sm and Nd contents, to give sufficient spread in their Sm/Nd ratios: 0.26, 0.32, 0.33 for the restites and 0.14, 0.20 for the melts.

3.a.2. *Analytical procedure*

Sm–Nd whole rock analyses were carried out using the two column technique, as described by Richard, Shimizu & Allegre (1976), with the addition of some improvements. In the CPGeo (Centre of Research in Geochronology) of Sao Paulo University, an ion exchange resin was used for primary separation of the REE, followed by a second HDEHP-coated Teflon powder column for separation of Sm and Nd. The Sm and Nd abundances were determined by the isotope dilution method. The isotope ratios were measured based on 2σ error statistics on the VG 354 multi-collector mass spectrometer. The measured ratio of $^{143}Nd/^{144}Nd$ obtained for La Jolla standard was 0.511857 ± 0.000046 (2σ). The laboratory blanks for the chemical procedure during the period of analysis yielded maximum values of 0.4 ng for Nd and 0.7 ng for Sm.

3.a.3. *Isotopic results*

The results of Sm–Nd isotopic analyses are given in Table 2. Two of the restite samples, 2J/50 and 2J/65D, have Nd evolution lines subparallel to CHUR (Fig. 4). Their $^{147}Sm/^{144}Nd$ values are close to that of present-day CHUR, and this implies that the restites were derived from sources which were modified or hybridized. One restite (JN125A) and two melts (JN/141 and 2J/68) have negative epsilon values between 16 and 48, indicating their derivation from old crustal rocks.

Table 2. Sm–Nd isotopic data from mafic granuite–charnockite suite of Jenapore, Orissa, India

Sample no.	Sm (ppm)	Error	Nd (ppm)	Error	^{147}Sm/^{144}Nd	Error (1σ)	^{143}Nd/^{144}Nd	Error (1σ)	T_{DM} (Ga)	fSm/Nd	$\varepsilon_0^{\mathrm{Nd}}$	ε(3.0 Ga)Nd
2J/50	2.065	0.006	6.290	0.016	0.1996	0.0001	0.512603	0.000008	–	0.01	–0.68	–1.7
2J/65D	2.940	0.008	9.108	0.019	0.1952	0.0007	0.512545	0.000008	–	–0.01	–1.81	
JN/125A	2.726	0.009	10.388	0.025	0.1587	0.0007	0.511798	0.000009	3.57	–0.19	–16.39	
JN/141	1.279	0.004	9.198	0.019	0.0841	0.003	0.510135	0.00001	3.47	–0.57	–48.43	
2J/68	19.278	0.053	95.513	0.351	0.1217	0.0006	0.511046	0.000015	3.37	–0.38	–31.06	

Reference values used in calculations: CHUR(0) ^{143}Nd/^{144}Nd = 0.512638; DM(0) ^{143}Nd/^{144}Nd = 0.513114; CHUR(0) ^{147}Sm/^{144}Nd = 0.1967; DM(0) ^{147}Sm/^{144}Nd = 0.222; decay constant $\lambda = 6.54 \times 10^{-12}$ a^{-1}.

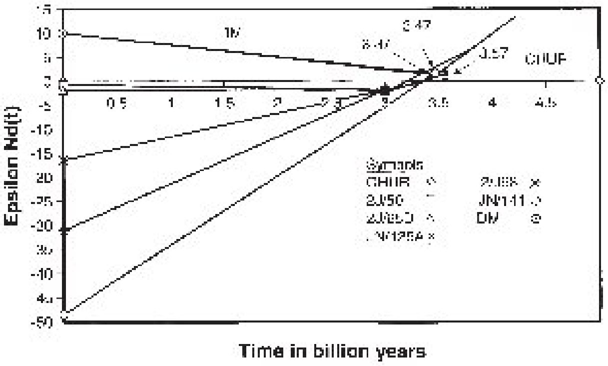

Figure 4. Nd evolution diagram for the five analysed samples (data and reference values are given in Table 2).

The three restites and two melts have higher (0.26, 0.32, 0.33) and lower (0.14, 0.20) Sm/Nd ratios respectively, consistent with relative fractionation of felsic and mafic chemistry. Also, no mixing line is indicated in a 1/Nd vs. Sm plot. The five-point isochron (MSWD = 12.2) of 3.0 Ga could then represent the melting event. However, samples JN/141 and 2J/68 do not intersect on the evolution diagram (Fig. 4), except at positive epsilon values and hence cannot be taken as comagmatic. Excluding the sample JN/141, four samples intersect at 3.0 Ga with –1.7 epsilon value in the evolution diagram and hence can be considered for age computation. Considering all the field-structural, petrographic and chemical features, there is no reason to think that sample JN/141 is not comagmatic. In view of the low Nd content in sample JN/141, and as the melting involved some more felsic components, the source of this sample must have been different. For deriving the age of partial melting, sample JN/141 is excluded from the isochron calculation. The four-point isochron age of 3.03 ± 0.2 Ga with MSWD of 5.96 and initial ^{143}Nd/^{144}Nd ratio of 0.508618 ± 55 (Fig. 5) suggest that the partial melting could indeed be 3.0 Ga old.

Additionally, three samples give model ages of approximately 3.5 Ga and negative epsilon $^{\varepsilon}$Nd (0) values between 16 and 48 (Table 2). The epsilon value corresponding to the isochron age of 3.0 Ga is –1.7. This negative epsilon value implies that the charnockite massif and restitic mafic granulites were derived from older crustal precursors.

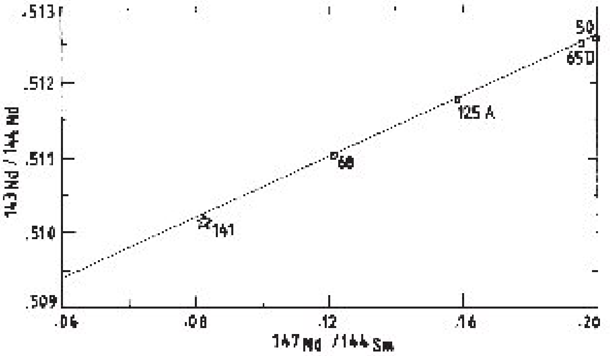

Figure 5. Sm–Nd whole rock isochron for mafic granulite–charnockite suite of Jenapore, Orissa, India. Sample JN/141 is excluded from isochron calculation (see text for explanation). Four point model 1 isochron age is 3.03 ± 0.2 Ga; MSWD = 5.96; initial ^{143}Nd/^{144}Nd ratio = 0.508618 ± 0.000055.

3.b. Pb–Pb zircon

3.b.1. Analytical procedure

The *in situ* Pb isotopic analyses of zircons were carried out at the Physical Research Laboratory, Ahmedabad, India. The small ion-microprobe machine, Cameca ims 4f, used in this study is described in Goswami & Srinivasan (1994). The analytical procedure and data assessment technique, with zircon standard (sample 83407) used are described in Wiedenback & Goswami (1994). In brief, a 7nA focused ^{16}O primary beam is used to sputter a ~20 μm domain in individual zircons. The secondary beam thus generated is first energy filtered and then mass analysed at a high mass resolution of M/ΔM = 4500. The fundamental unit of an analysis is a cycle where the magnet scans and measures ^{204}(Zr$_2$O), ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{176}HfO$_2$ and ^{208}Pb in peak jumping sequence. Time schedules for measuring each mass are 1, 5, 10, 30, 1 and 1 second respectively. At the beginning of each fresh cycle the magnet is automatically recalibrated at the mass ^{204}(Zr$_2$O). Five cycles constitute a block and fifteen such quasi-independent blocks constitute an analysis.

Age of the sample is computed from the radiogenic ^{207}Pb/^{206}Pb ratio. Radiogenic values are computed from measured ^{207}Pb/^{206}Pb ratios after necessary common Pb corrections. If the correction is low (< 5%), the data are considered for age computation. Analyses belonging to the same age group constitute a population. Block level radiogenic ^{207}Pb/^{206}Pb ratios of those analyses are then pooled and tested for outliers at 3σ level. A grand weighted mean of these radiogenic ratios is then computed. As we did not measure U–Pb isotopic pairs in our analysis, we do not know the Pb-loss history of the analysed zircons. Therefore, the date corresponding to the grand weighted mean of radiogenic ^{207}Pb/^{206}Pb ratio (at 1σ level) is considered as the 'minimum age' of the sample. Errors associated with the mean ^{207}Pb/^{206}Pb ratios are of two types, observed (based on standard deviation) and expected (based on ion-counting statistics). An error ratio close to unity is acceptable.

3.b.2. Sample description

Zircons for analysis were separated from one sample of the massif-type charnockite with the assemblage: plagioclase–quartz–alkali-feldspar–orthopyroxene ± hornblende ± Fe–Ti oxides (Table 1).

Selected zircon grains are subhedral, prismatic and homogeneous, but contain needles and stout prisms of apatite as inclusions (Fig. 6a,b,c). None of the zircons show zoning or core-overgrowth morphology, but rounding of prism faces is common and might have resulted from deformation during crystallization. Interestingly, deformation-induced intergrowth textures are common in the charnockites in this area, as described in Section 2.a.2. Only those grains containing a minimum number of inclusions were selected for analysis, so that sufficient space was available to hit the sample with a ^{16}O beam of diameter 20 µm during analysis.

3.b.3. Analytical data

Six zircon grains were analysed and the analytical data are presented in Table 3. Except for the analysis no. 2/1/1, which has a relatively high common Pb correction, the zircons belong to a single population. Grand weighted mean of the radiogenic ^{207}Pb/^{206}Pb ratios of the five zircons is 0.2134 ± 52 and this corresponds to an age of 2930 ± 42 Ma.

3.c. Rb–Sr systematics

3.c.1. Sample selection

Charnockitic (tonalite–trondjhemite–granite) melts of tonalitic to granodioritic composition, with plagioclase : alkali-feldspar ratios between 0.88 and 2.2 (Table 1) are also suitable for Rb–Sr isotopic analysis because they contain sufficient concentrations of these elements, and the four samples selected (Table 1) for analysis have enough spread in their Rb/Sr ratios: 0.004, 0.006, 0.24 and 0.33.

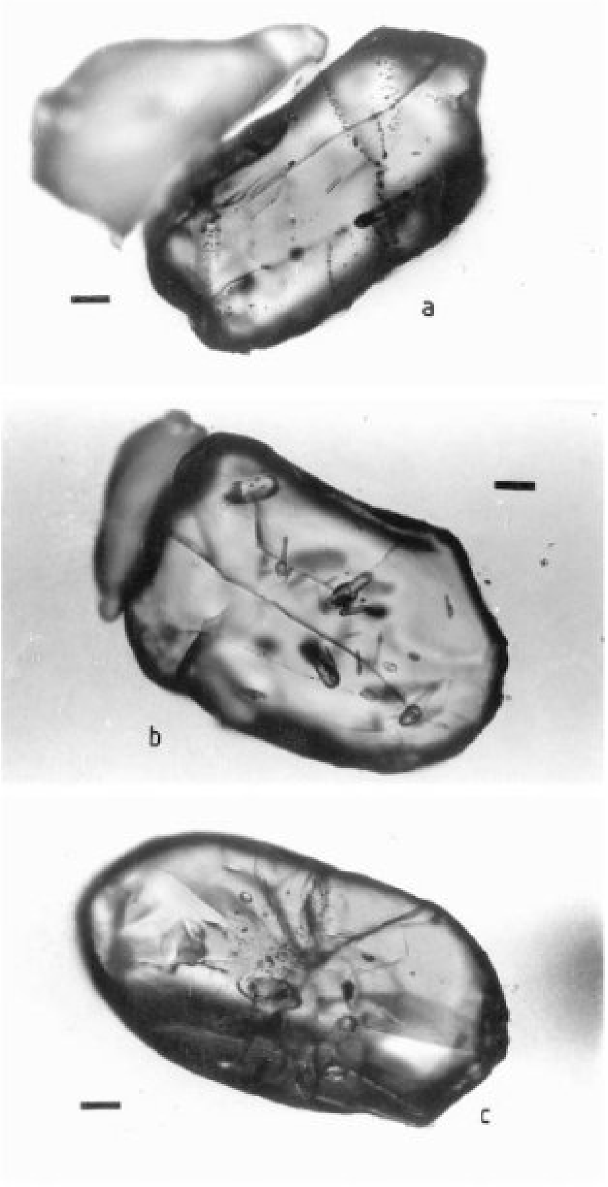

Figure 6. Photomicrographs (transmitted light) of selected zircon grains: (a) subhedral, prismatic, with fine needles of apatite as inclusions; (b) subhedral, prismatic, with prominent rounding of prism faces; (c) subhedral, prismatic, with tabular apatite inclusions, also with rounding of prism faces. Scale bar is 50 µm in each case.

3.c.2. Analytical procedure

Rb–Sr analysis was performed at the Geochronological Research Centre (CPGeo) of the University of Sao Paulo (Brazil). The ^{87}Sr/^{86}Sr ratios were measured in the VG 354 multi-collector and single collector mass spectrometers using the isotopic dilution method with absolute errors (2σ), and were corrected to the mean value of NBS-987 standard (0.710254 ± 22 (2σ)). The measured ^{87}Sr/^{86}Sr ratios were normalized to ^{86}Sr/^{88} Sr value of 0.1194. The overall blank for the chemical procedure at the CPGeo was 4 ng for Sr.

Table 3. Zircons from sample no. J-69 from the charnockite massif

Analysis no.	Measured $^{204}Pb/^{206}Pb$	Measured $^{207}Pb/^{206}Pb$	Total ^{206}Pb counts	^{206}Pb (ppm)	U (ppm)	Common Pb corrections (%)	$^{207}Pb/^{206}Pb$	Error ratio	Age (Ma)
1/2/1	0	0.2173	9245	42	84	0	0.2173 ± 73	0.98	2961 ± 54
2/1/1	0.00101	0.2218	8173	33	67	5.4	0.2099 ± 181	1.01	2905 ± 140
2/3/1	0	0.1985	21690	96	205	0	0.1985 ± 39	1.07	2814 ± 31
4/2/1	0	0.2288	19280	84	162	0	0.2288 ± 41	1.04	3044 ± 28
5/6a/1	0	0.2049	10625	79	165	0	0.2048 ± 67	1.04	2865 ± 53
5/7/1	0.00011	0.219	31048	114	226	0.6	0.2177 ± 40	0.93	2964 ± 30

3.c.3. Isotopic results

Results of isotopic analyses are given in Table 4. The four samples define an isochron age of 3236 ± 206 Ma (MSWD = 2.21) with an initial $^{87}Sr/^{86}Sr$ ratio of 0.701675 ± 0.000119 (Fig. 7). The low initial $^{87}Sr/^{86}Sr$ ratio, implying short crustal residence, is comparable to Archaean tonalitic xenoliths in the Singhbhum granite batholith (Saha, 1994).

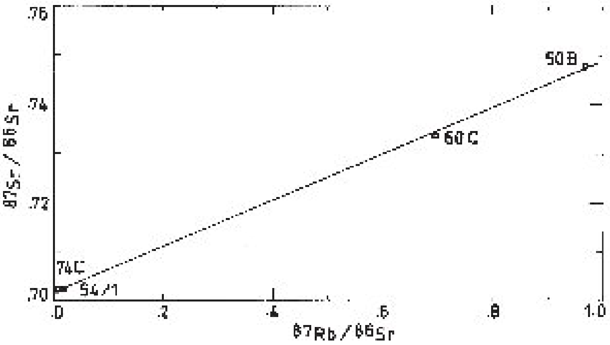

Figure 7. Rb–Sr whole rock isochron for the charnockite massif of Jenapore, Orissa, India. Model 1 (York, 1969) isochron age is 3.2 ± 0.2 Ga; MSWD = 2.21; initial $^{87}Sr/^{86}Sr$ ratio = 0.701675 ± 0.000119.

4. Discussion

The Sm–Nd whole rock isochron age of 3.03 ± 0.2 Ga of the charnockite–mafic granulite suite is interpreted to represent the hornblende-dehydration melting in basic rocks, and further equated to the time of the granulite facies event. The 2.9 Ga $^{207}Pb/^{206}Pb$ age of zircons from the massif-type charnockite is interpreted to be the minimum age of crystallization of charnockitic melt. The 3.2 ± 0.2 Ga Rb–Sr isochron for the charnockite–massif gives an older age relative to the Sm–Nd and Pb–Pb ages, possibly due to incomplete Sr remobilization on a whole-rock scale, as a result of fluid migration commonly recorded in synkinematic intrusions (Thoni, 1988). Considering all the isotopic results, a *c.* 2.9–3.0 Ga granulite facies event that produced the massif-type charnockite and associated rocks is evident. Thus, this is the first unequivocal evidence of an Archaean granulite facies event in the Eastern Ghats belt. It is also important to note that this is one of the rare occasions when a petrological event like granulite facies metamorphism and partial melting could be correlated to a deformation episode (F_1) in a terrain with polyphase deformation impress.

A number of lines of evidence suggest development of granulites in a compressional setting. First, the early deformation structures indicate extensive horizontal shortening (Bhattacharya, 1996, 1997). Second, until the late 1980s, prograde metamorphic reactions were thought to be post-kinematic with respect to crustal thickening, and this was the logic behind tectonic modelling of instantaneous thickening (England & Thompson, 1984). However, Patino Douce, Humphreys & Johnston (1990) demonstrated through tectonic modelling of crustal thickening that partial melting may indeed be synkinematic. Here we document a natural case of synkinematic partial melting that produced the charnockite–mafic granulite suite. Moreover, the granulite facies metamorphism under such a compressional setting would require the prior existence of a near normal thickness crust (Harley, 1989). This idea is consistent with the existence of older continental crust in the Eastern Ghats belt, as evidenced by the T_{DM} ages of ca. 3.5 Ga. The corresponding negative epsilon values indicate a depleted magma source for this early Archaean continental crust.

In the Gondwanaland reconstruction, the Eastern Ghats belt was contiguous with MacRobertson Land and Mawson station of East Antarctica (Grew & Manton, 1986). Although Archaean isotopic data have not yet been reported from these Antarctic areas, Clarke (1988) provided structural evidence of Proterozoic reworking of possibly Archaean crust. It

Table 4. Rb-Sr isotopic data for massif-type charnockites of Jenapore, Orissa

Sample no.	Rb (ppm)	Error	Sr (ppm)	Error	$^{87}Rb/^{86}Sr$	Error (1σ)	$^{87}Sr/^{86}Sr$	Error (1σ)
JN 50B	70.8	2	212.4	2	0.969	0.027	0.74787	0.00007
2.J 60C	59.1	2	246.0	2	0.697	0.020	0.73389	0.00009
JN 54/1	3.41	0.013	532.67	2	0.0185	0.0001	0.70259	0.00005
JN 74C	3.12	0.011	818.88	2	0.0099	0.0002	0.70213	0.00006

is interesting to note that the Eastern Ghats belt, with a predominant Proterozoic isotopic record, has similar structural and metamorphic evidence of reworking (Sen, Bhattacharya & Acharyya, 1995; Dasgupta & Sengupta, 1998). The isotopic data presented here confirm the hypothesis of Proterozoic reworking of Archaean crust at least in some parts of the Eastern Ghats belt.

5. Concluding remarks

The highlights of the present report are:

(1) An earlier proposal or suggestion of Archaean granulite facies event in the Eastern Ghats belt is demonstrated here with isotopic data.

(2) The granulite facies metamorphism and partial melting, dated *c.* 3.0 Ga, is correlated to F_1 deformation episode in a compressional setting.

(3) The 3.5 Ga model dates and negative epsilon values collectively indicate the existence of a normal thickness (≈35 km) continental crust prior to high-grade metamorphism (*c.* 3.0 Ga).This is consistent with the idea that continental crust could have been thick enough to permit granulite facies metamorphism during horizontal shortening (Mayers & Kroner, 1994).

(4) The oldest crustal components in the Indian Peninsula, *c.* 3.5–3.6 Ga, are not exclusive, as previously believed, to the granite–greenstone terrains.

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