Grenvillian thermal event and remnant charnockite: Isotopic evidence from the Chilka Lake granulite-migmatite suite in the Eastern Ghats belt, India

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Spectacular exposures of granulite-migmatite occur in the Chilka Lake area of the Eastern Ghats belt. The garnetiferous granite gneiss of peraluminous granitic composition, often contains restitic metapelite inclusions and is demonstrably a product of biotite-dehydration melting in pelitic rocks. On the other hand, older layers and bands of charnockitic rocks frequently occur as dismembered patches within the peraluminous granite, thus imparting a measled appearance of the granite exposures.

The partial melting and emplacement of the peraluminous granite represent the Grenvillian thermal event, as evidenced by Rb-Sr whole rock and Pb-Pb zircon dating. On the other hand, minor patches of charnockite represent migmatized relict, as evidenced by some older zircons, in addition to those of Grenvillian age.

1. Introduction

The Eastern Ghats granulite belt along the east coast of India is characterised by polyphase deformation and complex, multi-stage metamorphic evolution (Lal *et al* 1987; Kamineni and Rao 1988; Sen *et al* 1995; Dasgupta *et al* 1995; Bhattacharya 1996; Mohan *et al* 1997; Shaw and Arima 1998). The dominant lithological varieties are metapelitic granulites including khondalites, quartzites and calc-granulites; mafic granulites; orthopyroxene-bearing quartzofeldspathic gneisses (charnockite–enderbite); orthopyroxene-free granitoids (leptynites) and some anorthosite and alkaline complexes.

Deformation structures and field relations suggest structural breaks marked by cross-cutting and often transposed foliations (Rao 1976; Halden *et al* 1982; Bhattacharya *et al* 1994) and different modes of formation and/or migmatisation of charnockites (Bhattacharya *et al* 1993; Bhattacharya 1996; Dobmeier and Raith 2000). Isotopic record on the granulite facies rocks of the Eastern Ghats belt is dominated by the Grenvillian thermal event (Mezger and Cosca 1999), although, Archaean, mid-Proterozoic and Pan-African dates were also reported (Vinogradov *et al* 1964; Paul *et al* 1990; Shaw *et al* 1997; Sarkar *et al* 1998; Dobmeier and Simmat 2002; Krause *et al* 2001). However, interpretation of these isotopic data in relation to deformation and petrologic processes have mostly been tentative. Only recently Bhattacharya *et al* (2001), documented a 3.0 Ga granulite facies event defined by partial melting in basic rocks and generation of a charnockite suite in the Eastern Ghats belt.

In this article we report isotopic data on peraluminous granite (leptynite) and patchy charnockite from the Chilka Lake granulite-migmatite suite and relate the Grenvillian thermal event to biotite-dehydration melting in pelitic rocks. Also,

the time-relation between leptynite and patchy charnockite, as evidenced by Pb-Pb zircon dating, corroborates the hypothesis of remnant charnockite (Bhattacharya *et al* 1993).

2. Geological setting

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). Also Chetty and Murthy (1998) proposed a regional tectonic framework and suggested dominant transpressional tectonics related to collisional processes.

In the Chilka Lake area of Orissa, the impress of three phases of folding and associated penetrative foliations are observed (Bhattacharya *et al* 1994). First generation folds, associated gneissic foliation with granulite mineral assemblage occur only as relict. Second generation folds and associated leptynitic foliation are regionally pervasive, determine the map pattern. Transposition of earlier structures and anatexis and migmatisation are dominant during the second phase of deformation. Third deformation is less intense on a regional scale, with no development of pervasive foliation. The earlier two episodes of deformation record a compressional tectonic setting while the third deformation structures, namely, fold-axis parallel stretching lineations and drag folds with axial plane parallel shear veins, indicate an extensional setting (Bhattacharya 1997).

The leptynites occur as small stock like bodies with a plattung structure, related to axial plane of second-generation folds in the pelitic granulites and pyroxene granulites (cf. figure 5 in Sen and Bhattacharya 1997). Besides the large bands, metapelites also occur as minor patches within the leptynites. In the Chilka Lake area leptynites are garnetiferous quartzofeldspathic gneisses, in terms of mineralogy and chemical composition they can be described as peraluminous granites or *s*-type granites and hence a likely product of crustal anatexis.

Patchy charnockites, which occur within leptynites also record some older structures, indicating their remnant origin (Bhattacharya *et al* 1993). Also, mineralogical changes, namely, increase of *K*-feldspar concentrations in the marginal parts of these patches, indicate a strong migmatisation effect from the enclosing *K*-feldspar-dominant, peraluminous granite, the leptynite (Bhattacharya *et al* 1994; Sen and Bhattacharya 1997). Dobmeier

and Raith (2000), on the other hand, presented an alternative interpretation of the patchy charnockites of the Chilka Lake area as arrested growth.

Sen and Bhattacharya (1997) interpreted the leptynites of the Chilka area as products of mica-dehydration melting in pelitic and psammitic rocks. The sillimanite inclusion trails and more magnesian biotite-inclusions in some of the garnets of the leptynites are strong indicators of biotite-dehydration partial melting in pelitic rocks (with sillimanite) that produced the leptynites. In the common variety of metapelites absence of prograde biotite on the one hand and occasional occurrence of quartzofeldspathic pods in them on the other, indicate melting in the neighbourhood of 850°C. The geothermobarometric results on the common variety of metapelites indicate temperatures in the neighbourhood of 860°C at 8 kbar (Sen *et al* 1995).

3. Sample description

On the basis of the petrological and geochemical investigations (Sen *et al* 1995; Sen and Bhattacharya 1997) we have selected six leptynite and one restitic metapelite samples for whole rock isotopic study. Rb-Sr whole rock isotopic analyses were aimed at defining the partial melting event. Additionally, one patchy charnockite inclusion and host leptynite sample were selected for zircon analysis, to study the effects of migmatization and time relation between leptynite and patchy charnockite (figure 1).

The leptynite samples have the assemblage quartz-*K*-feldspar-plagioclase-garnet-opaque ± sillimanite; are corundum-normative (1 to 2%), with A/CNK values within a narrow range (1.0 to 1.4) and K_2O/Na_2O values range from 1.2 to 2.3. Lack of co-variation of Sr and Zr also suggests that very little fractionation occurred. A variety of metapelitic granulite occurs as minor patches within leptynites. These restitic patches have the assemblage garnet-cordierite-sillimanite-quartz-*K*-feldspar-plagioclase; garnets in them are more magnesian (X_{Mg} 0.36) than those of the common metapelites (X_{Mg} 0.15–0.27); CaO (> 1% wt.) and Sr (average 206 ppm) are also higher than those in the common metapelites (CaO $\sim$ 0.2%, Sr < 50 ppm). One sample of this patchy variety (T-5/1-P4) is also analysed.

Patchy charnockite sample has the assemblage quartz-*K*-feldspar-plagioclase-orthopyroxene-ilmenite ± garnet; contain apatite and zircon as accessory minerals. Because of their isolated occurrence within the leptynite, no meaningful results were expected in their whole rock isotopic compositions, hence only zircons from this sample were analysed.
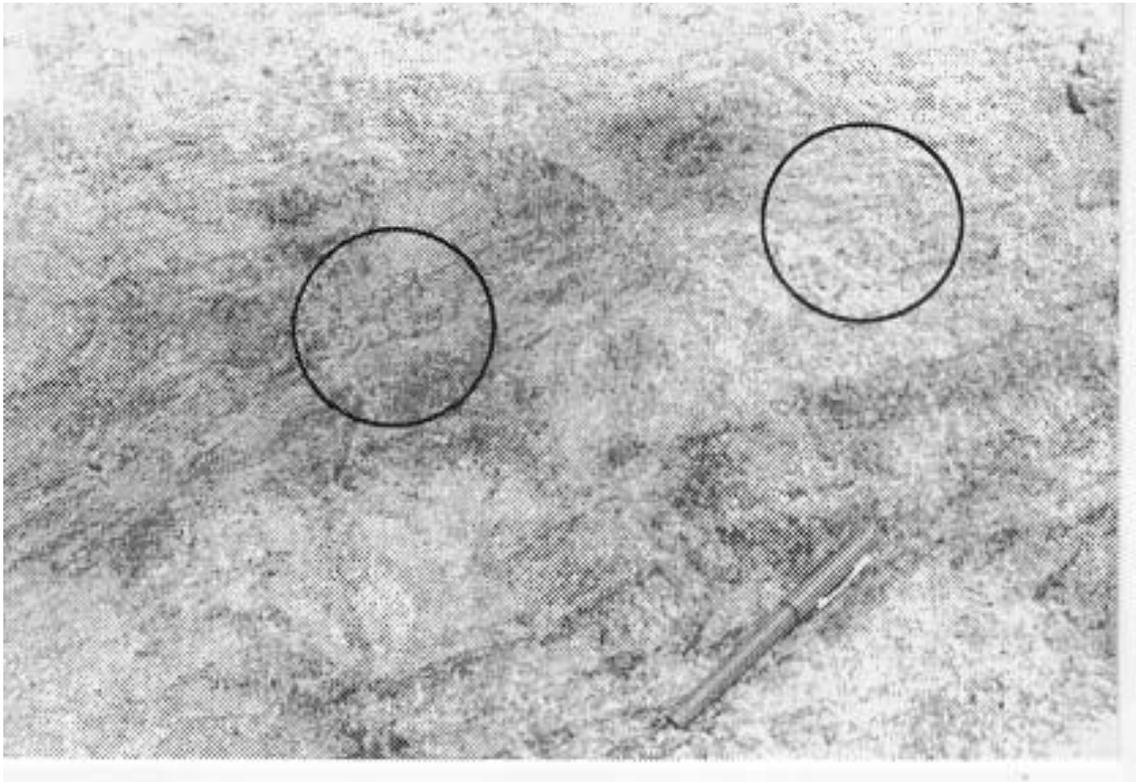
Figure 1. Field photograph showing a patchy charnockite within host leptynite. Analysed samples 10/93 (charnockite) and 11/93 (leptynite) are marked on the photograph.

Zircons from one host leptynite were also analysed in order to verify the age relation between leptynite and patchy charnockite of the area.

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.

4. Analytical procedure

Rb-Sr analysis was performed at the Geochronological Research Center (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 have been corrected to the mean value of NBS-987 standard [$0.710254 \pm 22(2\sigma)$]. The measured $^{87}Sr/^{86}Sr$ 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.

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 and Srinivasan (1994). The analytical procedure and data assessment technique, with zircon standard (sample 83407) used are described in Wiedenback and Goswami (1994). Age of the sample is computed from radiogenic $^{207}Pb/^{206}Pb$ ratio. Radiogenic values are computed from measured $^{207}Pb/^{206}Pb$ ratios after necessary

5. Analytical data

The Rb-Sr whole rock isotopic data for six granite (leptynite) and one restitic metapelite from the Chilka Lake area are presented in table 1. Six granite and one restitic metapelite inclusion define a seven point isochron age of 913 ± 82 Ma (MSWD = 4.3) with an initial Sr ratio of 0.7405 ± 61 (figure 2).

The results of *in situ* Pb isotopic analysis of zircons from leptynite and patchy charnockite are presented in tables 2 and 3. Out of five recovered zircon grains from the leptynite sample, only two are euhedral, prismatic, transparent, with inclusions of apatite and opaques. Some grains have homogeneous growth rims (figure 3a). Some other analysed zircon grains from this sample have high common Pb correction ($\sim 10\%$) and hence excluded from age computation. The two zircon grains with error ratio ~ 1, indicate the presence of a single zircon age population, c. 1.0 Ga or the Grenvillian event. Nine selected zircon grains from the patchy charnockite sample, are euhedral

Table 1. *Rb-Sr isotopic data of metapelite-granitoid suite of Chilka Lake, Orissa, India.*

Ref. no.	Sample no.	Rb (ppm)	Error	Sr (ppm)	Error	$^{87}Sr/^{86}Sr$	Error (1σ)	$^{87}Rb/^{86}Sr$	Error (1σ)
L1.	CD/2L. Gran	176.7	3.5	125.2	2.5	0.78962	0.00007	4.118	0.116
L2.	TA/111. Gran	191.5	3.8	88.3	1.8	0.82332	0.00006	6.348	0.18
L3.	HD/2L. Gran	124.2	2.5	105.6	2.1	0.78639	0.0001	3.434	0.097
L4.	K/10. Gran	257.6	5.2	71.3	1.4	0.88155	0.00007	10.636	0.301
L5.	H/5. Gran	209.5	4.2	134.7	2.7	0.79664	0.00007	4.534	0.128
L6.	11/93. Gran	222.6	4.5	88.3	1.8	0.83973	0.00006	7.391	0.209
P1.	T/5-1. Pel.	71.7	2.1	273.0	4.6	0.75300	0.00008	0.764	0.022

Reference values used in calculations: $^{87}Sr/^{86}Sr$ ratios normalised to $^{88}Sr/^{86}Sr = 8.3752$.
Decay constant $\lambda = 1.42 \times 10^{-11} Y^{-1}$.
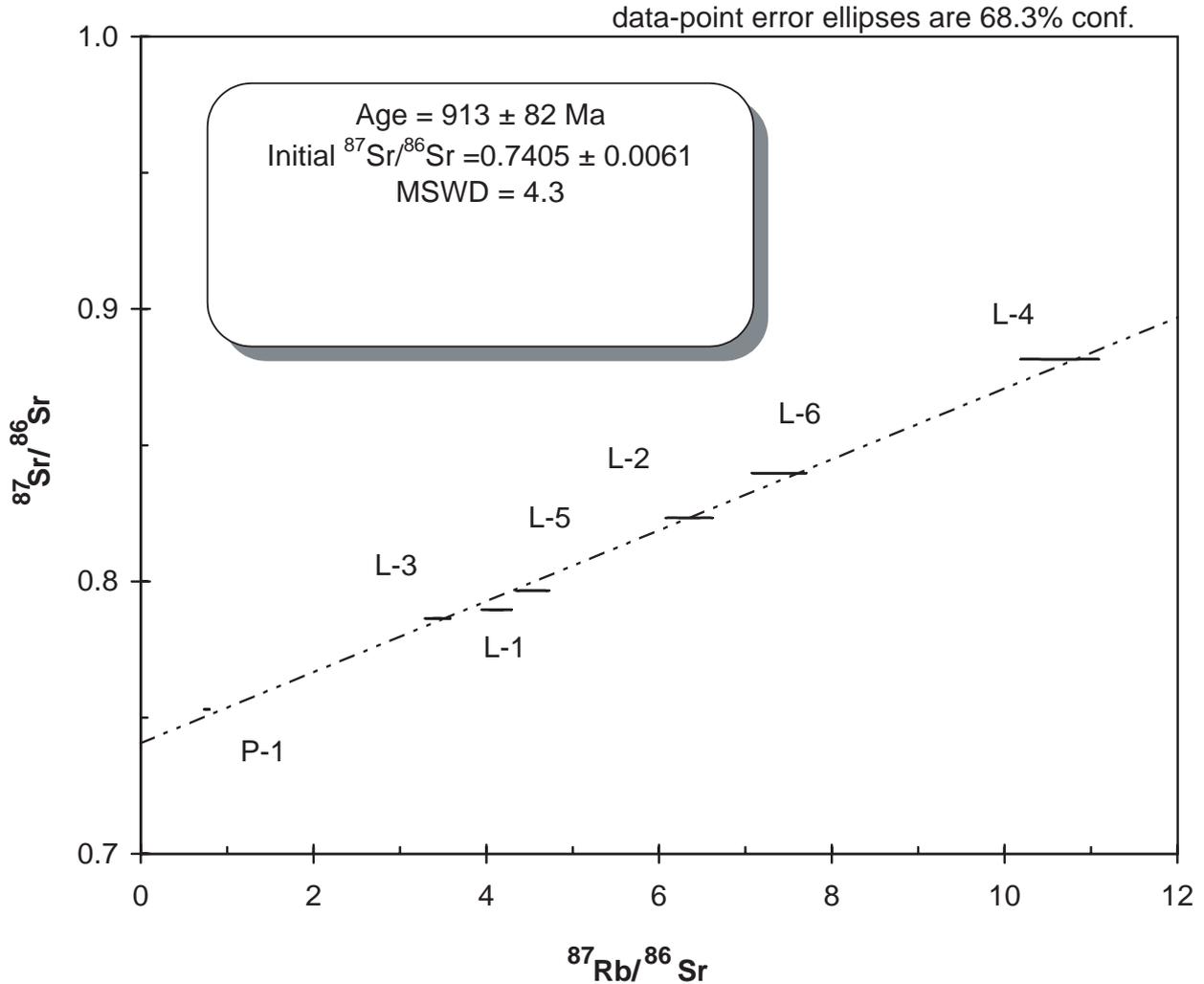

Figure 2. Seven-point Rb-Sr isochron for the granitoid (leptynite) — restite suite of the Chilka Lake area. Data given in table 1.

Table 2. *Ion-microprobe data of Zircons of sample 11/93(L-6) leptynite.*

Analysis no.	Grain no.	Measured $^{204}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	Total counts ^{206}Pb	^{206}Pb (ppm)	U (ppm)	$^{207}Pb/^{206}Pb$ Radiogenic	Error ratio	Age (Ma)
2	R3g9	0.00026	0.0762	13975	66	457	0.0725 ± 73	1.02	1000 ± 206
3	R6g2	0.0003	0.0759	45150	193	1375	0.0716 ± 33	1.01	975 ± 95

Table 3. *Ion-microprobe data of Zircons of sample 10/93A (patchy charnockite).*

| Analysis no.	Grain no.	Measured $^{204}Pb/^{206}Pb$	Measured $^{207}Pb/^{206}Pb$	Total counts ^{206}Pb	^{206}Pb (ppm)	U (ppm)	$^{207}Pb/^{206}Pb$ Radiogenic	Error ratio	Age (Ma)
1	R2g1	Nd	0.0682	35530	61	491	0.0681 ± 22	1.10	873 ± 67
2	R1g3A	Nd	0.0689	91205	169	1319	0.0689 ± 1	1.17	896 ± 29
3	R1g3B	Nd	0.072	20075	34	242	0.0719 ± 38	1.02	984 ± 107
4	R5g10	Nd	0.1054	19270	65	248	0.1054 ± 39	1.16	1722 ± 68
5	R5g3	Nd	0.1856	34685	64	143	0.1846 ± 24	2.36	2694 ± 22
6	R3g3	Nd	0.0672	35775	63	523	0.0672 ± 22	1.09	845 ± 68
7	R2g7	Nd	0.0694	17095	44	338	0.0694 ± 44	0.98	911 ± 132
8	R2g11B	Nd	0.0754	14380	57	366	0.0753 ± 52	1.17	1078 ± 139
9	R3g12	Nd	0.0728	38435	91	624	0.0728 ± 21	1.04	1008 ± 57

(a)
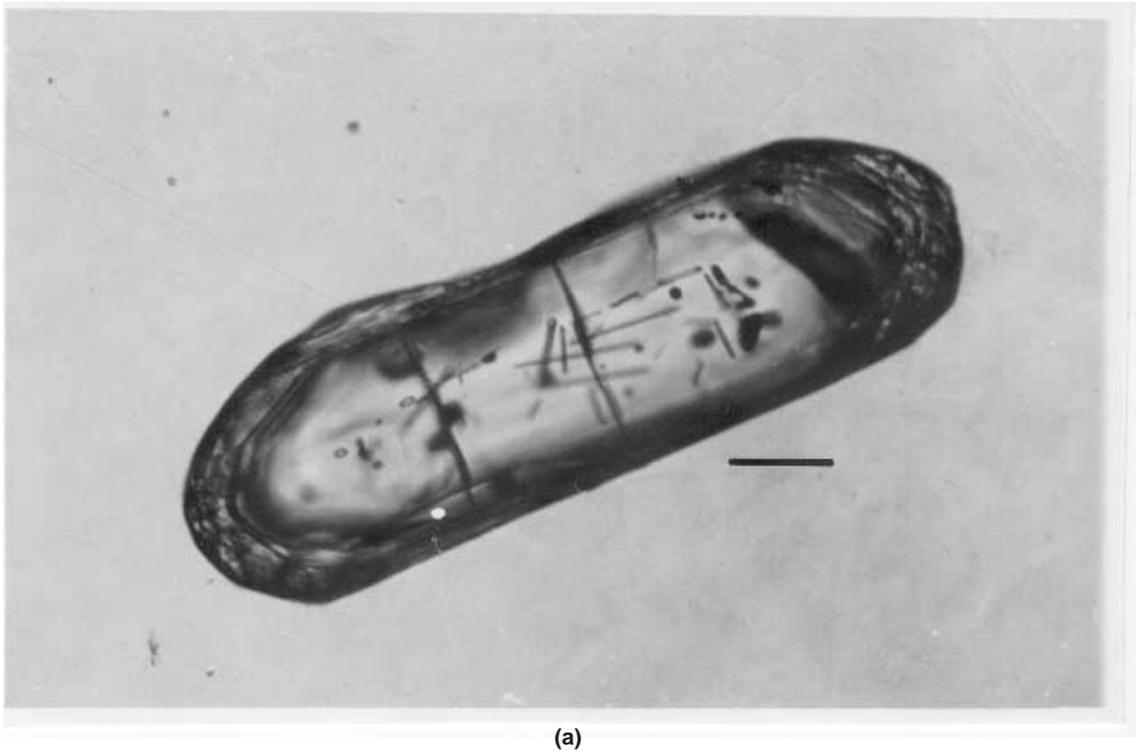
Figure 3. Transmitted light photomicrographs of representative zircons. Scale bar is 100 m in each case. **(a)** Prismatic zircon (r3g9) in leptynite, with homogeneous growth rims.

or subhedral prismatic, colourless and transparent. Most of the grains are homogeneous, with occasional growth rims (figure 3b, c). In rare cases overgrowths on elongate prismatic core are seen, where growth boundaries are parallel to the margin (figure 3d, e). Seven analysed grains belong to a single population (analysis nos. 1, 2, 3, 6, 7, 8, 9), give a mean radiogenic $^{207}Pb/^{206}Pb$ ratio of $0.07051 \pm 0.00028(1\sigma)$ corresponding to a minimum age of 943 ± 85 Ma. The observed/expected error ratios for most of the analyses vary between 0.98 and 1.17, indicating that the analysed domains experienced minimum or no Pb loss. Two analyses (4 and 5) represent older populations. It is important to note that these zircon grains show overgrowth on prismatic core (figure 3d, e). The analysis number 4 is associated with an error

ratio of 1.16 and the radiogenic $^{207}Pb/^{206}Pb$ ratio of 0.1054 ± 39 corresponds to an age of 1722 ± 68 Ma. For the grain R5g3 (analysis no. 5) the error ratio is much higher (2.36) indicating Pb loss. This zircon age (2694 ± 22 Ma) is not precise, but definitely belongs to an Archaean population.

6. Discussion

The overwhelmingly dominant Pb-Pb zircon ages around 0.9 Ga from patchy charnockite inclusion and leptynite (peraluminous granitoid) and the Rb-Sr whole rock isochron of ca. 0.9 Ga from granitoid-restite suite of the Chilka Lake area imply a strong Grenvillian thermal event in the
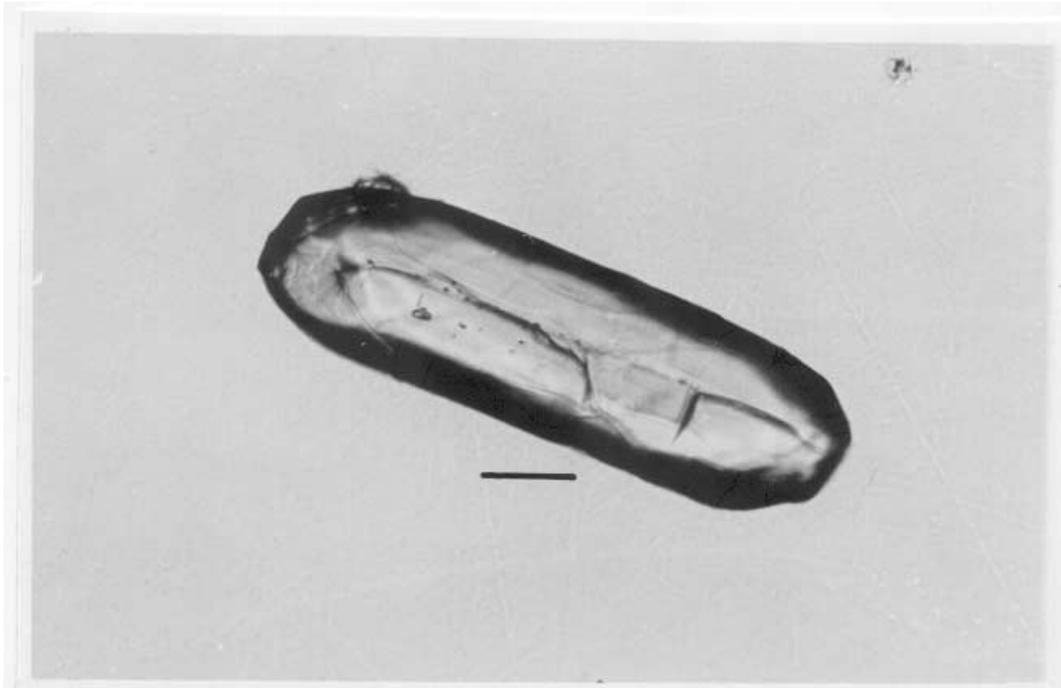
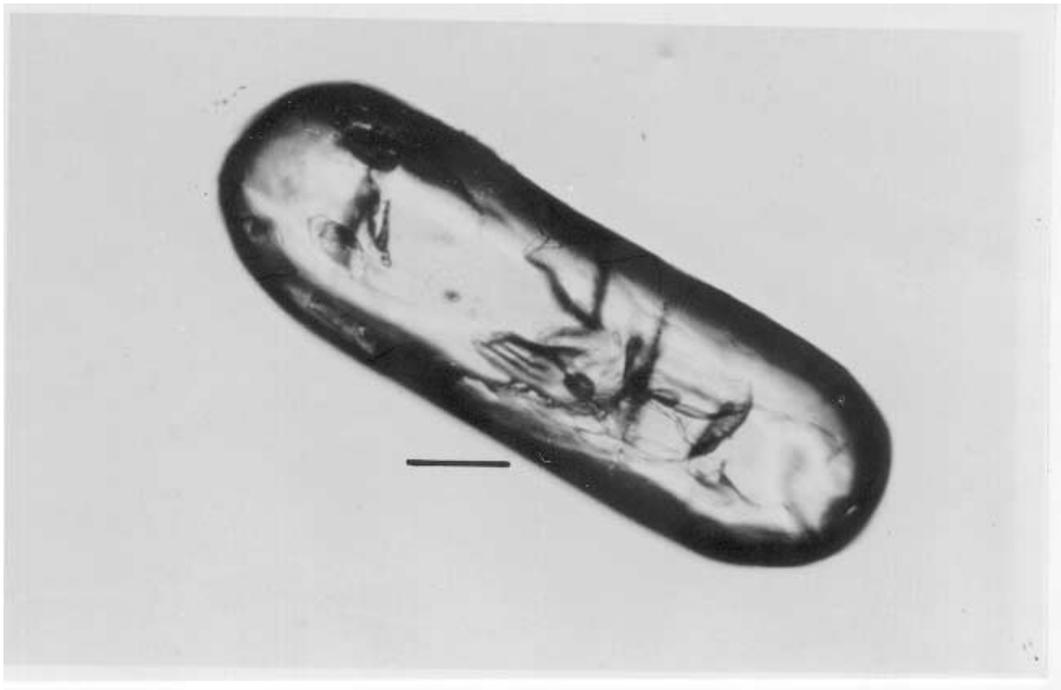Figure 3(b).   Slender prismatic zircon (r2g7) in charnockite, with growth rims.

Figure 3(c).   Prismatic zircon (r2g11) in charnockite, with rounded terminations.

Eastern Ghats belt. This ca. 0.9 Ga age is interpreted as the age of partial melting of pelitic rocks under granulite facies conditions synkinematic with F_2 folding, which also resulted in migmatisation of older rocks. Although, a strong Grenvillian thermal event was recorded from several areas in the Eastern Ghats belt, the nature of this thermal event or the tectonic-cum-petrological consequences have not been deciphered so far (Mezger and Cosca 1999).

The 1.7 Ga Pb-Pb age of zircon in the charnockite inclusion could represent a previous (pre-F_2) high-grade event or alternatively charnockitic magmatism. Incidentally, Dobmeier and Raith (2000)
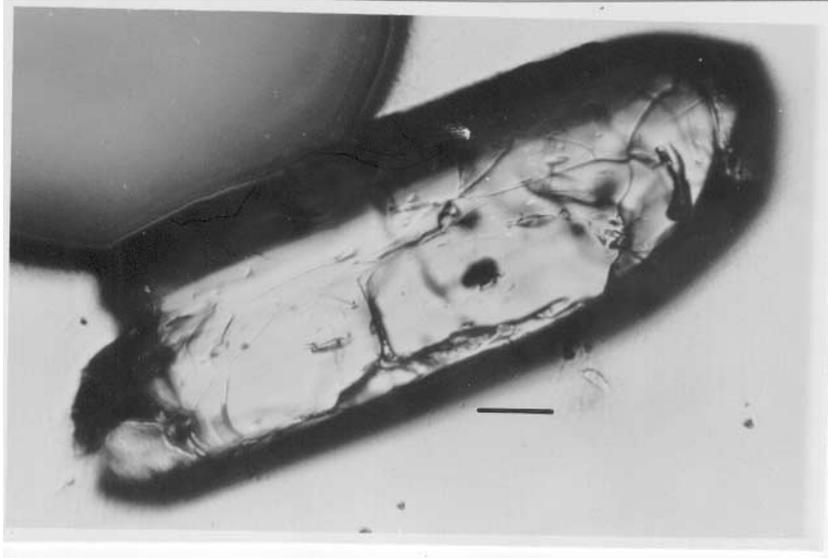
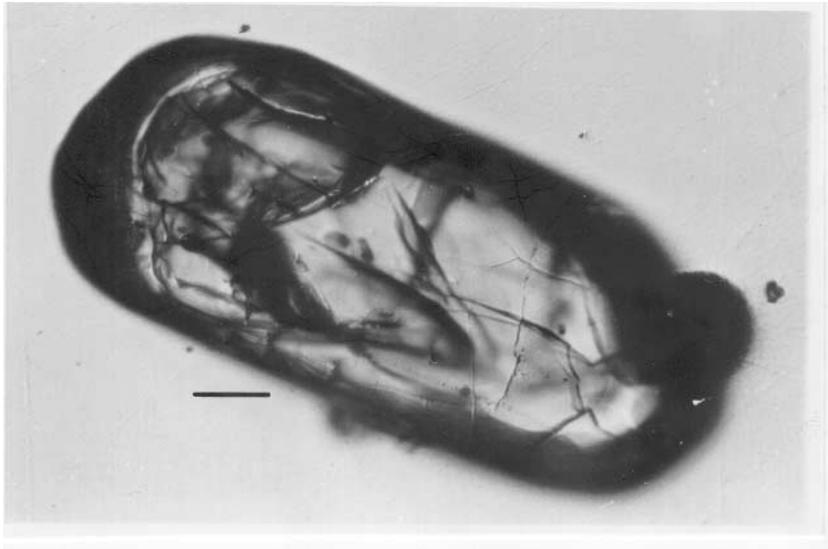Figure 3(d). Robust prismatic zircon (r5g10) in charnockite, with overgrowth.

Figure 3(e). Robust prismatic and homogeneous zircon (r5g3) in charnockite.

observed that "since the enderbitic and metasedimentary rocks have identical structural histories, the emplacement (of enderbitic/tonalitic magma) happened prior to the discernible deformation...." in the Chilka Lake area. It is significant that the relatively older status of the patchy charnockites than the host leptynites of the Chilka area was proposed on structural and petrological grounds by Bhattacharya *et al* 1993 and the isotopic evidence presented in this article confirms the older status of the patchy charnockites of the Chilka area. It is also important to note that from another area (Jenapore, south of Brahmani river, in the northern sector) in the Eastern Ghats belt, Kar (2002), concluded that source rocks of leptynites and patchy charnockites must have been different:

leptynites with low Rb/Sr ratios (0.18, 0.35) from a biotite-bearing source; while patchy charnockites with high Rb/Sr ratios (1.17, 1.45) from a hornblende-bearing source.

The ca. 2.7 Ga Pb-Pb age of zircon from the charnockite inclusion can only represent xenocrystic component. It is noteworthy that 2.6 Ga old zircon was also recovered from metapelite (khondalite) of the Chilka Lake area by Vinogradov *et al* 1964.

7. Implications

In the Eastern Ghats granulite belt some structural and petrological evidence have been advanced

favoring the hypothesis of reworking: transposition and obliteration of earlier fabrics, and occurrence of older lithological entities as minor inclusions (Bhattacharya *et al* 1994; Bhattacharya 1997); IBC at two different pressures (Sen *et al* 1995); post-IBC decompressive path, taken to indicate re-working of an isobarically cooled deep continental crust (Dasgupta and Sengupta 1998). The presence of 1.7 Ga high-grade or magmatic event in the largely Grenvillian partial melting-cum-migmatisation event are strong isotopic evidence of reworking, at least in parts of the Eastern Ghats belt.

Acknowledgements

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