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Charnockite Massifs: Key to Tectonic Evolution of the Eastern Ghats Belt, India, and Its Columbia Connection

S. Bhattacharya[a],* ; M. Basei[b]; R. Kar[c]

[a] Indian Statistical Institute, Kolkata.
[b]Institute of Geosciences, Sao Paulo University, Brazil.
[c] J. K. College, Purulia,
*Corresponding author.

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Abstract

The Eastern Ghats Granulite Belt, India, with two major lithological associations: charnockites and meta sedimentary granulites, is characterized by polyphase deformation and complex, possibly multiple granulite events. Barring the cratonic margins in the north and west, two distinct crustal domains have been identified: the Eastern Ghats Province (EGP) and Ongole domain, separated by the Godavari graben. These domains also have distinct geochronological record of granulite event: in the EGP the first granulite event has been recorded as between 1.2 and 0.9 Ga; while in the Ongole domain the granulite event is recorded as 1.6 - 1.7 Ga. However, charnockite-massifs in both the domains, interpreted as product of deep crustal anatexis under granulite facies conditions, could provide a link in tectonic evolution of the EGB as a whole. LA-ICP-MS analysis of zircon spot ages of two charnockite massifs reveals vestiges of the1.6 Ga charnockite magmatism in the EGP as identical to that in the Ongole domain. Another charnockite massif in the EGP records concordant zircon spot age of 940 Ma, but single spot age of 990 Ma could indicate a prolonged UHT event. Thus magmatic charnockites of intracrustal melting origin could represent two granulite events, at ca. 1.6 and 1.0 Ga in the Eastern Ghats Belt. Also, accretionary orogenic processes of the Supercontinent Columbia might have encompassed the Eastern Ghats Belt with Australia, Antarctica and Laurentia.

Key words: Columbian connection, Zircon spot ages, Charnockite massifs, Eastern Ghats belt.

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INTRODUCTION

The Eastern Ghats Granulite belt along the east coast of India has the impress of polyphase deformation and a complex, possibly multiple granulite facies metamorphic events (Bhattacharya et al., 1994; Dasgupta et al., 1994; Sen et al., 1995; Bhattacharya, 1996; Dasgupta & Sengupta, 1998; Bhattacharya & Kar, 2002). Barring the cratonic margins in the north and west, the northern Eastern Ghats Belt, has been defined as the Eastern Ghats Province, while south of Godavari graben is defined as the Ongole domain (Dobmeier & Raith, 2003). Based on Nd-mapping different crustal domains with unconnected pre-metamorphic history has been identified in the Eastern Ghats granulite belt (Bhattacharya et al., 2001; Rickers et al., 2001; Dobmeier & Raith, 2003).

The Ongole domain bears Archaean protolith signatures (Rickers et al., 2001; Bhattacharya et al., 2011). It was also shown that rock suites in this domain have distinct imprints of Paleo-Mesoproterozoic thermal events, while the Meso-Neoproterozoic tectonothermal imprints are largely missing (Mezger & Cosca, 1999; Bose et al., 2011). However, 1181 Ma thermal event was reported from the eastern flank of the Ongole domain (Simmat & Raith, 2008). On the other hand, protolith ages in the Eastern Ghats Province range between 1.8 and 2.5 Ga (Rickers et al., 2001), while dominant tectonothermal events belong to the Meso-Neoproterozoic times. Although, based on field relations of cross-cutting veins, pre-Grenvillian thermal event was argued by Grew and Manton (1986) and some early work indicated 1.5 Ga ages from Rayagada, with whole-rock Sm-Nd isochrones

(Shaw et al., 1997), with precise geochronological work undertaken in recent times, Paleo-Mesoproterozoic thermal events have not been recorded from the Eastern Ghats Province so far (Simmat & Raith, 2008; Bose et al., 2011). However, Bose et al. (2011) and Das et al. (2011) reported oscillatory-zoned zircon cores with near concordant $^{207}Pb/^{206}Pb$ ages: 1.78-1.70 Ga, in metapelite from the EGP and interpreted to record magmatic events in the source of these detrital grains. A reasonable question that might be asked at this point is whether that magmatic event could be related to charnockite massifs. Thus, there remains the possibility that vestiges of Paleo-Mesoproterozoic thermal events could be present in the EGP; while minor impact of Meso-Neoproterozoic thermal event is present in the Ongole domain.

With the significant record of 1760-1600 Ma events in the Ongole domain, Bose et al. (2011) argued that the accretionary orogenic processes in the super continent Columbia encompassed Australia, Antarctica, Laurentia and parts of India (specifically the Ongole domain).

Although, many workers have described the meta-sedimentary granulites of the EGP, as the oldest component and intruded by magmatic rocks, enderbites and charnockites (Rickers et al., 2001; Mezger & Cosca, 1999; Simmat & Raith, 2008), published geochronological data do not corroborate this relation between meta- sedimentary granulites and enderbites-charnockites. Rickers et al's data (2001), on the other hand would indicate older crustal rocks (magmatic precursors of enderbites-charnockites, given by Nd-model ages, between 1.8 & 2.5 Ga) as basement on which precursor khondalite sediments might have been deposited around 1.37 Ga, constrained by detrital zircon U-Pb ages (Upadhyay et al., 2009). It is also important to note that the metasediments in the Ongole domain were evidently older than 1.7 Ga (Bhui et al., 2007; Simmat & Raith, 2008; Bose et al., 2011) than those of the EGP.

Charnockite massifs with mafic granulite inclusions form a distinct litho-unit in the Eastern Ghats Belt. These are clearly plutonic bodies of magmatic origin (Kar et al., 2003; Frost & Frost, 2008; Bhattacharya & Chaudhary, 2010; Korhonen et al., 2013), unlike small bands/patches of enderbite/charnockite, that were ascribed to metamorphic transformation/arrested charnockite formation by some workers (Halden et al., 1982; Dobmeier & Raith, 2000;). Kar et al. (2003) described the Jenapur charnockite pluton as product of deep-crustal anatexis (hornblende-dehydration melting) and Frost and Frost (2008) referred to this, as to have been formed by dry crustal anatexis. Summarising the tectonic environment of formation of magmatic charnockites, Frost and Frost (2008) suggested that deep crustal melting related to granulite metamorphism or emplacement of hot ferroan magmas as one of the four tectonic environments. Thus, UHT metamorphism and charnockite magmatism could be concomitant. And most recently, Korhonen et al (2013) argued that petrogenesis of charnockites-enderbites is consistent with emplacement of magmas into hot supra-solidus crust at the peak of UHT metamorphism. Referring to the charnockite plutons in the Eastern Ghats Belt, Bhattacharya and Chaudhary (2010), geochemically differientated the Proterozoic and Archean charnockites as intracrustal melting at relatively shallow and greater depths respectively. Proterozoic charnockites of Naraseraopet (Ongole domain at ca. 1.6 Ga), Paderu (EGP at ca. 1.0 Ga) and Sunki (EGP at 0.9 Ga) with high Rb/Sr ratios and significant negative Eu anomalies indicate residual plagioclase, and hence intracrustal melting might have occurred at shallow depth, in the stability field of plagioclase. In contrast, low Rb/Sr ratios and lack of Eu-anomalies in the Archean charnockites (Jenapur, at ca. 3.0 Ga and Jaypur at ca. 2.8 Ga) are indicative of intracrustal melting at greater depths in the stability field of garnet or amphibole (Bhattacharya & Chaudhary, 2010). Our work on several charnockite-massifs in the Eastern Ghats Belt, show that these are product of deep crustal anatexis, dehydration melting, under granulite facies conditions, the restitic mafic granulites being commonly observed as enclaves/inclusions within these charnockite-massifs (Kar et al., 2003; Bhattacharya et al., 2010; Bhattacharya & Chaudhary, 2010; Bhattacharya et al., 2011). With such a premise, we attempted this precise age dating, by LA-ICP-MS of zircons from the several charnockite-massifs, which could resolve the problem of a unique tectonic model for the Eastern Ghats Belt, hitherto said to be unfeasible (Dasgupta et al., 2012). Moreover, these age data could indicate whether accretionary orogenic processes in the Supercontinent Columbia encompassed the Eastern Ghats Province also.

1. GEOLOGICAL BACKGROUND

Several charnockite massifs occur as large-scale bodies of variable composition in the Eastern Ghats Belt and commonly contain restitic mafic granulite inclusions. The four charnockite-massifs selected for the present study occur across the discontinuity, defined by the Godavari graben (Figure 1). The charnockite massifs are characterized by a gneissic foliation, S_1, often depicting an axial planar character to rootless folds, defined by mafic granulite inclusions. Also the gneissic foliation, S_1 is commonly folded on mesoscopic scales. Based on the field relations and petrology-geochemistry, these massifs have been described as product of deep-crustal anatexis under granulite facies conditions (Kar et al., 2003; Bhattacharya, 2003; Bhattacharya et al., 2010; Bhattacharya et al., 2011). Herewith, we describe some critical field features of the four such massifs, which are being taken up for precise age dating. In the Chilka massif dismembered and folded mafic granulite inclusions are commonly observed (Figure. 2a).In the Naraseraopet massif dismembered bands and irregular blocks of mafic

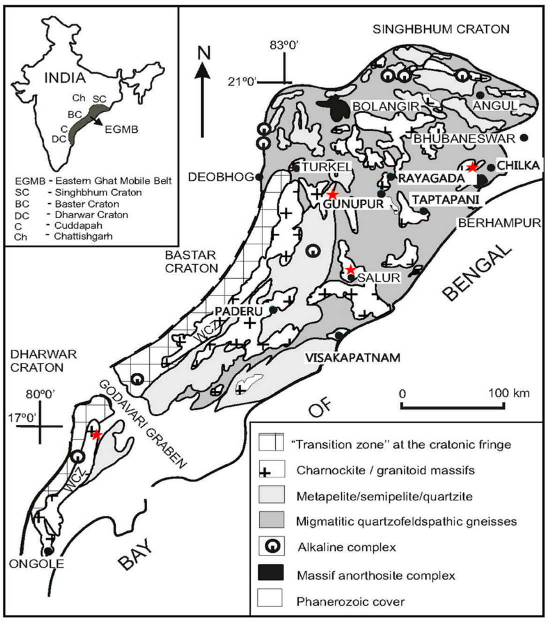

Figure 1
Generalized Geological Map of the Eastern Ghats Belt, India, Showing Sample Locations, Marked With Asteric. The Inset Shows Position of the Eastern Ghats Belt in Peninsular India

granulite inclusions indicate prior existence of mafic protolith before the development of gneissosity in the charnockite massif (Figure 2b). In the Sunki massif, folded mafic granulite inclusion, gneissic foliation parallel to the axial plane of the fold, is commonly observed (Figure 2c). In the Gunupur massif, deformed mafic granulite layers could also represent solidified peritectic assemblage (Figure 2d); and pods and apophyses of granite within the Gunupur massif, suggests an older status of the massif with respect to granite, which are common in the Eastern Ghats Province (Figure 2e). The charnockite massifs of variable composition are commonly associated with folded layers & blocks of hornblende-mafic granulite and also patches of two-pyroxene mafic granulites (Kar et al., 2003, Bhattacharya et al., 2011). It is also important to note that charnockite massifs with the anhydrous assemblage do not record significant effect of later metamorphic events. In fact, we could find some new mineral growth, namely clinopyroxene at the expense of plagioclase and orthopyroxene in the Gunupur massif and myrmekite and quartzofeldspathic films on plagioclase in the Chilka massif (Figure 3). The selected samples have the assemblage: alkfls-qz-pl-opx-opq±bio and zircon & apatite as common accessories (3CKG-Chilka); qz-pl-alkfls-opx±bio±opq and with zircon as common accessory (12CKG-Naraseraopet); pl-alkfls-opx-qz±cpx±bio, with zircon and apatite as common accessories (8CKG-Sunki) and alkfls-qz-pl-opx-opq, and zircon & apatite as common accessories (7CKG-Gunupur), respectively.

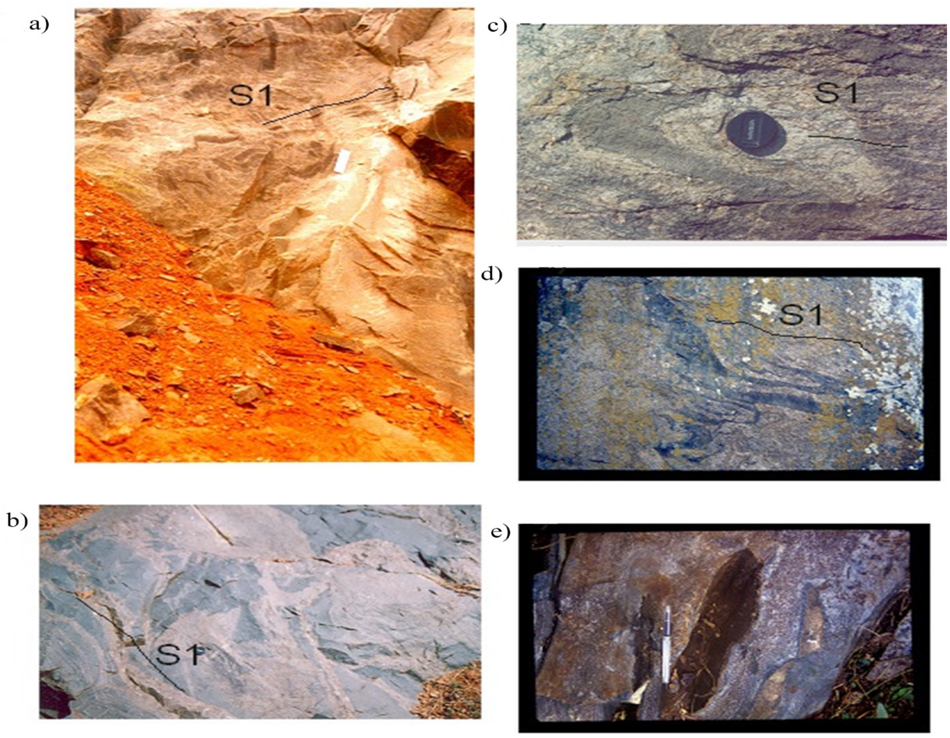

Figure 2
Field Photographs: (a) Folded and Dismembered Mafic Granulite Inclusions in the Chilka Charnockite Massif, (b) Irregular and Dismembered Bands of Mafic Granulite Inclusions in the Naraseraopet Charnockite Massif. Width of Photograph:10 Feet, (c) Folded Mafic Granulite Inclusion in the Sunki Charnockite Massif; Gneissosity Axial Planar to the Fold, (d) Intrafolial Folds Defined by Mafic Granulite Bands Within Gunupur Charnockite Massif. Width of Photograph: 7.5 Feet, (e) Granite Apophyses and Rods in the Gunupur Charnockite Massif

a)

b)

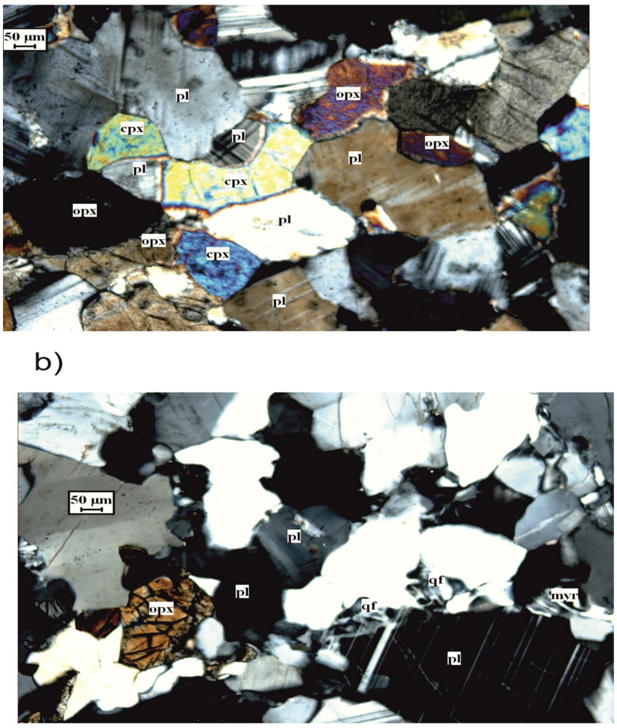

Figure 3
Photomicrographs: (a) Late Growth of Clinopyroxene at the Expense of Orthopyroxene and Plagioclase in Charnockite of the Gunupur Massif, (b) Late Growth of Myrmekite and Quartzofeldspathic Film on Plagioclase in Charnockite of the Chilka Massif

2. GEOCHRONOLOGICAL RECORD IN THE CHARNOCKITE-MASSIFS

The three massifs at Chilka, Gunupur and Sunki belong to the Eastern Ghats Province, while the Naraseraopet massif belongs to the Ongole domain. Nd-model ages of the mafic granulite enclaves in several charnockite-massifs, including that at Naraseraopet in the Ongole domain, define a mafic magmatism around 2.5 Ga (Bhattacharya et al., 2011). Although, first granulite facies metamorphism were dated as between 1.2 and 0.9 Ga in the Eastern Ghats Province and 1.6 Ga in the Ongole domain respectively, most of these data were reported from UHT metapelites (Mezger & Cosca, 1999; Simmat & Raith, 2008; Korhonen et al., 2011; Bose et al., 2011). The only U-Pb zircon (TIMS) age of 1.6 Ga was reported by us from the Naraseraopet massif of the Ongole domain (Bhattacharya et al., 2010). Here we report more precise U-Pb zircon spot ages from the four charnockite massifs.

3. ANALYTICAL PROCEDURE

After the jaw crusher the sample was sieved and the fraction between 100 and 250 mesh was passed on the Wiffley table for heavy mineral concentration. Final fraction preparation was achieved by hand-picking the impurities under a binocular microscope. When the interest of the analysis was to define the provenance of the crystals, care was taken that all populations were represented. The zircon grains were placed on epoxy mounts, polished and cleaned. Prior to analysis, cathodoluminescence (CL) and transmitted and reflected images were obtained so that sites for analysis could be chosen. Following the CL images the samples were vacuum-coated with high-purity gold.

The U-Pb analysis was performed on zircon grains using a Thermo-Fisher Neptune laser-ablation multicollector inductively coupled plasma mass spectrometer equipped with a 193 Photon laser system. The operating conditions and instrument settings of NEPTUNE and laser ablation system during analytical sessions are described in Sato et al. (2010).

The U-Pb analyses on zircon grains were carried out using the standard-sample bracketing method (Albarède et al., 2004) using the GJ-1 reference zircon in order to control the fractionation. The U-Pb analysis were obtained in sheets composed of 2 measures of blanks, 3 GJ 1 analysis, 13 unknown zircon spots, followed by analysis of 2 more blanks and 2 GJ 1. The raw data were processed on-line and reduced using an Excel worksheet (Sato et al, 2009, 2010).

U-Pb analyses were performed using spot size of 29 µm and laser induced fractionation of the $^{206}Pb/^{238}U$ ratio was corrected using the linear regression method (Kosler et al., 2002). In all analysed zircon grains the common Pb was monitored by the 202 Hg content

4. RESULTS

The U-Pb analytical data are presented in Tables 1-4.

Table 1
U-Pb Isotopic Data For Zircons

Gunupur massif charnockite		Ratios and errors											Ages and errors				Conc.
		207/235	1sigma	206/238	1 sigma	erro corr.	238/206	1 sigma	207/206	1 sigma	208/206	1 sigma	T206/238 Ga	1 sigma	T207/206 Ga	1 sigma	206/238 207/206 (%)
7CKG	1.1	1.82073	0.03084	0.17722	0.00208	0.694	5.64267	0.06634	0.07448	0.00065	125.68402	200.73700	1.052	0.011	1.056	0.018	100
7CKG	10.1	4.11951	0.06459	0.30345	0.00323	0.679	3.29542	0.03509	0.09878	0.00083	7.84398	48.63271	1.708	0.016	1.607	0.015	106
7CKG	3.2	4.14567	0.06510	0.30272	0.00324	0.682	3.30337	0.03536	0.09965	0.00084	27.32257	54.71599	1.705	0.016	1.623	0.015	105

To be continued

continued

Gunupur massif charnockite	Ratios and errors											Ages and errors				Conc.
	207/235	1sigma	206/238	1 sigma	erro corr.	238/206	1 sigma	207/206	1 sigma	208/206	1 sigma	T206/238 Ga	1 sigma	T207/206 Ga	1 sigma	206/238 207/206 (%)
7CKG 4.1	4.15412	0.06535	0.30206	0.00325	0.684	3.31059	0.03562	0.09914	0.00083	23.81444	52.09954	1.702	0.016	1.613	0.015	105
7CKG 20.1	4.10900	0.04598	0.30045	0.00212	0.630	3.32836	0.02346	0.10077	0.00189	1.38144	4.43614	1.694	0.010	1.643	0.034	103
7CKG 8.1	4.15060	0.06600	0.29932	0.00333	0.699	3.34089	0.03713	0.10029	0.00084	22.00145	89.50809	1.688	0.016	1.635	0.015	103
7CKG 4.2	4.25385	0.08005	0.29916	0.00478	0.848	3.34272	0.05336	0.10278	0.00094	23.51168	56.67731	1.687	0.024	1.680	0.017	100
7CKG 21.1	4.06358	0.04785	0.29785	0.00243	0.693	3.35735	0.02739	0.09979	0.00187	1.30546	4.87170	1.681	0.012	1.625	0.034	103
7CKG 19.1	4.10287	0.04516	0.29676	0.00202	0.619	3.36975	0.02297	0.10052	0.00189	2.01023	5.66495	1.675	0.010	1.639	0.034	102
7CKG 3.1	4.09046	0.06620	0.29590	0.00337	0.703	3.37953	0.03846	0.10007	0.00084	41.73523	77.05767	1.671	0.017	1.631	0.015	102
7CKG 9.1	4.06184	0.06407	0.29590	0.00321	0.688	3.37956	0.03666	0.09933	0.00083	11.86192	58.27632	1.671	0.016	1.617	0.015	103
7CKG 5.1	4.08829	0.06431	0.29545	0.00319	0.686	3.38470	0.03654	0.09995	0.00084	42.85073	113.22745	1.669	0.016	1.628	0.015	102
7CKG 11.1	4.05279	0.06412	0.29071	0.00317	0.690	3.43991	0.03753	0.09956	0.00086	8.35791	70.21605	1.645	0.016	1.621	0.016	101
7CKG 12.1	4.00588	0.04545	0.28782	0.00207	0.634	3.47444	0.02498	0.09999	0.00191	5.69681	8.64532	1.631	0.010	1.629	0.035	100
7CKG 13.1	4.03499	0.04748	0.29350	0.00217	0.629	3.40714	0.02523	0.09968	0.00191	2.70173	4.38948	1.659	0.011	1.623	0.035	102
7CKG 14.1	3.98201	0.05104	0.28943	0.00203	0.547	3.45506	0.02424	0.10051	0.00201	2.05620	3.59435	1.639	0.010	1.639	0.036	100
7CKG 15.1	3.97800	0.04581	0.28835	0.00221	0.665	3.46799	0.02657	0.10042	0.00190	1.54485	2.92240	1.633	0.011	1.637	0.034	100
7CKG 16.1	4.04046	0.04434	0.29416	0.00199	0.618	3.39954	0.02305	0.09977	0.00189	1.90408	3.92450	1.662	0.010	1.625	0.034	102
7CKG 17.1	4.02524	0.04414	0.29334	0.00197	0.612	3.40896	0.02287	0.10033	0.00189	2.71976	6.15693	1.658	0.010	1.635	0.034	101
7CKG 18.1	3.92986	0.04601	0.28990	0.00229	0.675	3.44948	0.02726	0.10094	0.00196	1.79851	4.44812	1.641	0.011	1.647	0.035	100
7CKG 22.1	4.03088	0.04664	0.29192	0.00202	0.599	3.42554	0.02373	0.10151	0.00194	1.03386	4.60457	1.651	0.010	1.657	0.035	100
7CKG 23.1	4.02895	0.04381	0.29132	0.00199	0.627	3.43263	0.02339	0.10144	0.00189	0.86965	4.80241	1.648	0.010	1.656	0.034	100
7CKG 24.1	3.99697	0.04384	0.28986	0.00199	0.625	3.44999	0.02366	0.10032	0.00187	0.54647	3.97020	1.641	0.010	1.635	0.034	100
7CKG 2.1	4.02514	0.06385	0.28853	0.00322	0.703	3.46585	0.03865	0.09953	0.00084	69.61176	119.22504	1.634	0.016	1.621	0.016	101
7CKG 6.1	3.97700	0.06244	0.28753	0.00310	0.686	3.47792	0.03747	0.09959	0.00084	34.70528	105.06519	1.629	0.016	1.622	0.016	100
7CKG 7.1	3.95662	0.06248	0.28713	0.00310	0.684	3.48274	0.03763	0.09959	0.00084	31.11358	108.00990	1.627	0.016	1.622	0.015	100

Table 2
U-Pb Isotopic Data For Zircons

Naraseraopet massif charnockite	Ratios and errors											Ages and errors				Conc.
	207/235	1sigma	206/238	1 sigma	erro corr.	238/206	1 sigma	207/206	1 sigma	208/206	1 sigma	T206/238 Ga	1 sigma	T207/206 Ga	1 sigma	206/238 207/206 (%)
12 CKG 1.1	4.0231	0.0583	0.2934	0.0031	0.72	3.4080	0.0356	0.1001	0.0011	0.4181	0.2274	1.659	0.015	1.631	0.020	102
12 CKG 1.2	4.0033	0.0591	0.2914	0.0031	0.72	3.4313	0.0364	0.0998	0.0011	0.4966	0.2561	1.649	0.015	1.625	0.020	101
12 CKG 2.1	4.0553	0.0587	0.2953	0.0031	0.72	3.3858	0.0354	0.1003	0.0011	0.6096	0.2989	1.668	0.015	1.635	0.019	102
12 CKG 2.2	3.9324	0.0589	0.2891	0.0031	0.72	3.4589	0.0376	0.0996	0.0011	0.6212	0.2903	1.637	0.016	1.621	0.020	101
12 CKG 3.1	4.0573	0.0587	0.2946	0.0031	0.72	3.3944	0.0355	0.1006	0.0011	0.5367	0.2396	1.665	0.015	1.640	0.019	101
12 CKG 4.1	3.9929	0.0578	0.2909	0.0030	0.72	3.4373	0.0360	0.1005	0.0011	0.5170	0.2209	1.646	0.015	1.639	0.019	100
12 CKG 4.2	3.8877	0.0571	0.2870	0.0031	0.74	3.4849	0.0379	0.0996	0.0011	0.7654	0.3153	1.626	0.016	1.621	0.020	100
12 CKG 5.1	3.9241	0.0570	0.2879	0.0030	0.72	3.4733	0.0364	0.0998	0.0011	0.7426	0.2922	1.631	0.015	1.625	0.020	100
12 CKG 6.1	4.0337	0.0584	0.2912	0.0031	0.73	3.4345	0.0361	0.1014	0.0011	0.6715	0.2542	1.647	0.015	1.655	0.019	100
12 CKG 8.1	3.9256	0.0569	0.2841	0.0030	0.73	3.5193	0.0372	0.1012	0.0011	0.7790	0.2740	1.612	0.015	1.652	0.019	98
12 CKG 9.1	3.9727	0.0571	0.2883	0.0030	0.73	3.4689	0.0363	0.1006	0.0011	0.7351	0.2498	1.633	0.015	1.641	0.019	100
12 CKG 10.1	3.8899	0.0574	0.2850	0.0031	0.74	3.5085	0.0385	0.0997	0.0011	0.7933	0.2606	1.617	0.016	1.623	0.019	100
12 CKG 7.1	3.7147	0.0536	0.2721	0.0029	0.73	3.6745	0.0386	0.1000	0.0011	0.6205	0.2263	1.552	0.014	1.629	0.019	95

Table 3
U-Pb Isotopic Data of Zircons

Sample 8 CKG sunki massif		Ratios and errors											Ages and errors				Conc. %
		207/235	1sigma	206/238	1 sigma	erro corr.	238/206	1 sigma	207/206	1 sigma	208/206	1 sigma	T206/238 Ga	1 sigma	T207/206 Ga	1 sigma	206/238 207/206
8 CKG	4.1	1.5332	0.0091	0.1578	0.0008	0.82	6.3389	0.0308	0.0707	0.0002	0.7422	0.2555	0.944	0.004	0.948	0.007	100
8 CKG	5.1	1.5115	0.0082	0.1566	0.0007	0.85	6.3843	0.0293	0.0705	0.0002	0.5591	0.1965	0.938	0.004	0.942	0.006	100
8 CKG	8.1	1.4989	0.0109	0.1548	0.0009	0.76	6.4608	0.0358	0.0711	0.0003	1.1784	0.4386	0.928	0.005	0.958	0.008	97
8 CKG	9.1	1.5443	0.0081	0.1592	0.0008	0.91	6.2810	0.0301	0.0714	0.0002	1.1972	0.4548	0.952	0.004	0.968	0.005	98
8 CKG	10.1	1.5293	0.0576	0.1580	0.0046	0.77	6.3301	0.1838	0.0708	0.0006	1.5019	0.5881	0.946	0.025	0.950	0.018	100
8 CKG	10.2	1.5440	0.0580	0.1582	0.0046	0.77	6.3218	0.1833	0.0715	0.0006	1.4888	0.5991	0.947	0.025	0.970	0.017	98
8 CKG	11.1	1.5228	0.0569	0.1547	0.0044	0.76	6.4658	0.1847	0.0718	0.0006	1.0713	0.4436	0.927	0.025	0.980	0.017	95
8 CKG	13.1	1.5157	0.0557	0.1572	0.0044	0.77	6.3617	0.1799	0.0706	0.0006	0.7209	0.3172	0.941	0.025	0.946	0.016	100
8 CKG	14.1	1.4967	0.0549	0.1536	0.0043	0.77	6.5115	0.1836	0.0706	0.0006	0.7164	0.3249	0.921	0.024	0.944	0.016	98
8 CKG	15.1	1.5460	0.0569	0.1594	0.0045	0.77	6.2751	0.1779	0.0708	0.0006	0.9331	0.4350	0.953	0.025	0.952	0.018	100
8 CKG	19.1	1.5219	0.0549	0.1577	0.0044	0.77	6.3425	0.1770	0.0707	0.0006	0.6051	0.3261	0.944	0.024	0.947	0.017	100
8 CKG	20.1	1.5464	0.0557	0.1563	0.0043	0.77	6.3968	0.1779	0.0722	0.0006	0.8626	0.4833	0.936	0.024	0.991	0.016	95
8 CKG	21.1	1.4926	0.0536	0.1522	0.0042	0.77	6.5689	0.1825	0.0716	0.0006	0.6012	0.3509	0.913	0.024	0.976	0.017	94
8 CKG	16.1	1.4600	0.0532	0.1501	0.0042	0.77	6.6634	0.1874	0.0713	0.0006	1.4610	0.7076	0.901	0.024	0.964	0.017	94
8 CKG	17.1	1.5827	0.0575	0.1612	0.0045	0.77	6.2029	0.1735	0.0708	0.0006	0.6830	0.3427	0.964	0.025	0.951	0.017	101
8 CKG	12.1	1.5962	0.0590	0.1629	0.0046	0.77	6.1379	0.1741	0.0716	0.0006	1.5002	0.6397	0.973	0.026	0.973	0.017	100
8 CKG	6.1	1.3855	0.0070	0.1458	0.0007	0.89	6.8598	0.0307	0.0693	0.0001	0.5257	0.1880	0.877	0.004	0.907	0.004	97
8 CKG	7.1	1.5801	0.0088	0.1614	0.0008	0.86	6.1942	0.0297	0.0714	0.0002	0.9868	0.3590	0.965	0.004	0.969	0.006	100
8 CKG	1.1	1.6191	0.0099	0.1655	0.0008	0.81	6.0424	0.0299	0.0722	0.0002	0.8390	0.2734	0.987	0.005	0.990	0.005	100
8 CKG	2.1	1.4258	0.0080	0.1482	0.0007	0.85	6.7494	0.0321	0.0705	0.0002	0.9755	0.3237	0.891	0.004	0.941	0.006	95
8 CKG	3.1	1.4200	0.0092	0.1489	0.0008	0.78	6.7165	0.0340	0.0697	0.0002	0.6567	0.2219	0.895	0.004	0.917	0.006	98
8 CKG	18.1	1.6617	0.0604	0.1685	0.0047	0.77	5.9341	0.1662	0.0722	0.0006	0.7372	0.3829	1.004	0.026	0.992	0.017	101

Table 4
U-Pb Data for Zircons

Chilka massif 3CKG		Ratios and errors											Ages and errors				Conc.
		207/235	1sigma	206/238	1 sigma	Erro corr.	238/206	1 sigma	207/206	1 sigma	208/206	1 sigma	T206/238 Ga	1 sigma	T207/206 Ga	1 sigma	206/238 207/206 (%)
3-CKG	1.1	1.6246	0.0793	0.1688	0.0020	0.24	5.9251	0.0691	0.0697	0.0029	0.0337	0.0098	1.005	0.011	0.918	0.085	110
3-CKG	2.1	1.0715	0.0482	0.1210	0.0014	0.26	8.2616	0.0953	0.0641	0.0024	0.3358	0.0965	0.737	0.008	0.739	0.078	100
3-CKG	3.1	1.1911	0.0532	0.1308	0.0015	0.25	7.6440	0.0869	0.0662	0.0024	0.1493	0.0426	0.793	0.008	0.808	0.077	98
3-CKG	4.1	0.9918	0.0442	0.1133	0.0013	0.26	8.8298	0.1018	0.0634	0.0023	0.3735	0.1057	0.692	0.008	0.716	0.077	97

To be continued

Chilka massif 3CKG	Ratios and errors											Ages and errors				Conc.
	207/235	1sigma	206/238	1 sigma	Erro corr.	238/206	1 sigma	207/206	1 sigma	208/206	1 sigma	T206/238 Ga	1 sigma	T207/206 Ga	1 sigma	206/238 207/206 (%)
3-CKG 5.1	3.5884	0.1802	0.2671	0.0035	0.26	3.7437	0.0484	0.1001	0.0040	0.1052	0.0299	1.526	0.018	1.632	0.072	94
3-CKG 5.2	1.7527	0.0773	0.1717	0.0020	0.26	5.8258	0.0667	0.0740	0.0027	0.0290	0.0081	1.021	0.011	1.043	0.073	98
3-CKG 6.1	1.5863	0.0743	0.1651	0.0019	0.25	6.0564	0.0709	0.0695	0.0027	0.0500	0.0139	0.985	0.011	0.912	0.080	108
3-CKG 8.1	3.6077	0.2037	0.2669	0.0034	0.22	3.7462	0.0471	0.1020	0.0047	0.0431	0.0118	1.525	0.017	1.666	0.081	92
3-CKG 9.1	7.3394	0.3304	0.4030	0.0066	0.37	2.4811	0.0408	0.1316	0.0049	0.5054	0.1370	2.183	0.030	2.116	0.063	103
3-CKG 9.2	3.8793	0.2031	0.2857	0.0036	0.24	3.4996	0.0436	0.1036	0.0045	0.2139	0.0575	1.620	0.018	1.695	0.077	96
3-CKG 10.1	1.3864	0.0596	0.1469	0.0017	0.27	6.8087	0.0780	0.0683	0.0024	0.0436	0.0116	0.883	0.009	0.874	0.073	101
3-CKG 12.1	1.0760	0.0417	0.1212	0.0011	0.23	8.2524	0.0750	0.0640	0.0024	0.5102	0.1338	0.737	0.006	0.738	0.078	100
3-CKG 13.1	1.2912	0.0506	0.1402	0.0014	0.25	7.1337	0.0701	0.0673	0.0025	0.0402	0.0107	0.846	0.008	0.844	0.077	100
3-CKG 14.1	1.2639	0.0516	0.1381	0.0013	0.23	7.2404	0.0675	0.0671	0.0026	0.0401	0.0109	0.834	0.007	0.838	0.081	100
3-CKG 15.1	7.6975	0.3255	0.3914	0.0037	0.22	2.5549	0.0243	0.1465	0.0057	0.2201	0.0615	2.129	0.017	2.301	0.066	93
3-CKG 16.1	1.7196	0.0783	0.1673	0.0020	0.26	5.9756	0.0711	0.0764	0.0030	0.0018	0.0023	0.997	0.011	1.109	0.079	90
3-CKG 17.1	1.5742	0.0615	0.1605	0.0015	0.24	6.2306	0.0578	0.0711	0.0027	0.0403	0.0115	0.960	0.008	0.960	0.076	100
3-CKG 19.1	1.7481	0.0728	0.1749	0.0023	0.32	5.7180	0.0755	0.0741	0.0028	0.0341	0.0172	1.039	0.013	1.046	0.075	99
3-CKG 20.1	7.4268	0.3068	0.4013	0.0045	0.27	2.4918	0.0279	0.1403	0.0054	0.0622	0.0206	2.175	0.021	2.227	0.064	98
3-CKG 20.2	6.2260	0.2371	0.3495	0.0044	0.33	2.8608	0.0362	0.1342	0.0049	0.1634	0.0506	1.932	0.021	2.150	0.061	90
3-CKG 23.1	6.3969	0.1329	0.3698	0.0024	0.31	2.7043	0.0177	0.1249	0.0030	0.2242	0.0971	2.028	0.011	2.026	0.041	100
3-CKG 28.1	1.2516	0.0269	0.1369	0.0010	0.34	7.3027	0.0533	0.0669	0.0016	0.0932	0.0338	0.827	0.006	0.831	0.049	100
3-CKG 30.1	1.1607	0.0244	0.1300	0.0012	0.44	7.6903	0.0717	0.0655	0.0015	0.3871	0.1320	0.788	0.007	0.786	0.048	100
3-CKG 31.1	1.6440	0.0352	0.1667	0.0015	0.43	6.0003	0.0551	0.0721	0.0017	0.0265	0.0088	0.994	0.008	0.989	0.047	100
3-CKG 32.1	1.2377	0.0235	0.1364	0.0008	0.33	7.3315	0.0455	0.0656	0.0015	0.1128	0.0362	0.824	0.005	0.790	0.047	104
3-CKG 33.1	3.7371	0.1035	0.2684	0.0019	0.26	3.7261	0.0270	0.1014	0.0031	0.0171	0.0053	1.533	0.010	1.655	0.054	93
3-CKG 34.1	2.2353	0.0423	0.2105	0.0013	0.33	4.7495	0.0293	0.0773	0.0017	0.0065	0.0020	1.232	0.007	1.131	0.045	109

4.1 Gunupur Massif: Sample 7CKG: 19°4'42"N; 83°48'24"E

Many of the zircon grains in the Gunupur sample (7 CKG) have oscillatory zonation without a distinct core (3, 4 & 16) and a few have more luminous core but show no zonation (11). The spot analyses from different parts of zonation and core of unzoned grain (average 1630 Ma), could define a 1.63 Ga magmatic event (Figure 4). It is important to note that all the zircons are concordant in the U-Pb Concordia diagram (Figure 5). Only one concordant zircon age of 1.0 Ga could reflect the Grenvillian metamorphic overprint. Here it is important to note that the Gunupur massif shows some new mineral growth (Figure 3a) and granitic pods within the massif (Figure 2e). Hence, new zircon may have formed by dissolution and re-precipitation.

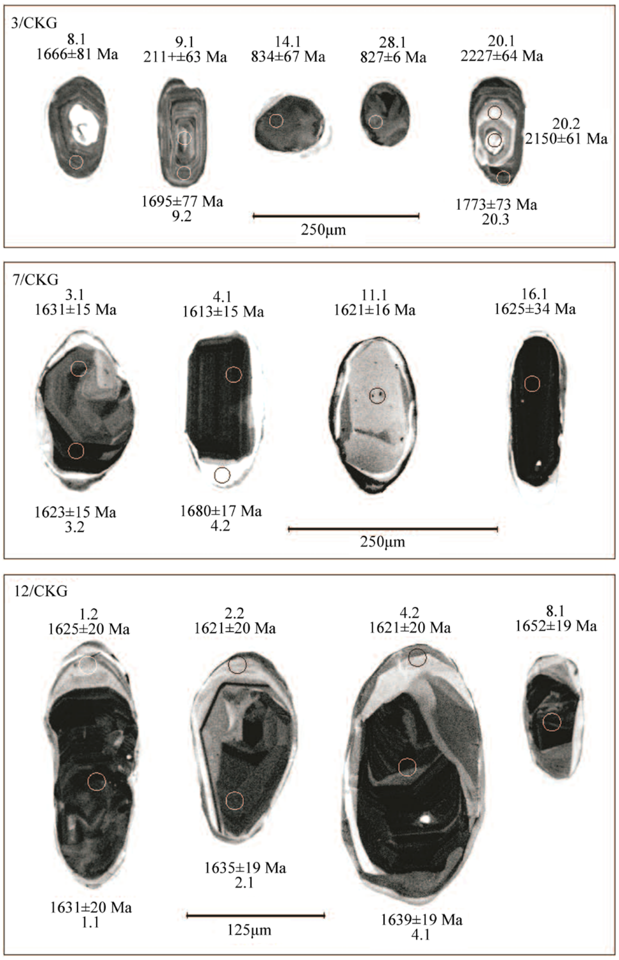

Figure 4
Cathodoluminiscence Images of Selected Zircons From the Three Charnockite Massifs

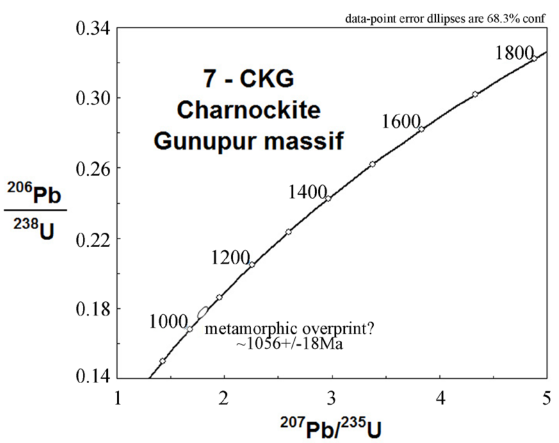

Figure 5
U-Pb Concordia Diagram for Zircons in the Gunupur Massif

4.2 Naraseraopet Massif: Sample 12 CKG: 16°8'55"N; 80°2'56"E

Many of the zircon grains have internal zonation and some have zoned cores (4.1), truncated by zoned rims (4.2). However, no significant difference in spot ages could be found and the concordant age is 1.63 Ga (Figure 6).

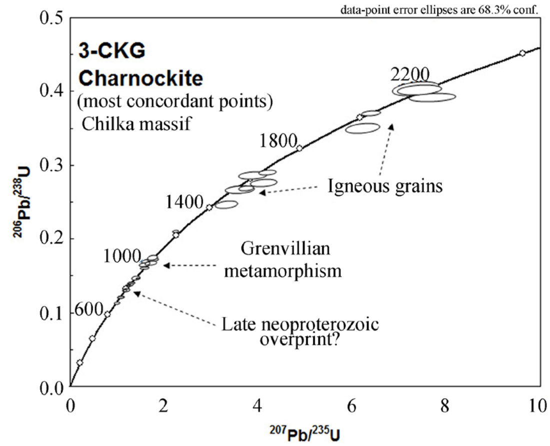

Figure 6
U-Pb Concordia Diagram for Zircons in the Naraseraopet Massif

4.3 Chilka Massif: Sample 3CKG: 20°10' N; 86°30' E

Many of the zircon grains have luminous rims and cores, showing both internal zonation (9.1, 9.2 and 20.1, 20.3). Characteristic oscillatory zoning in the rims (20.3) and cores (9.1 & 20.2) are notable features in many zircon grains. Prismatic and oscillatory zoned cores spot ages, 2116 ± 63 (9.1); 2227± 64 (20.1) and 2150 ± 61 Ma (20.2) could represent a magmatic event around 2.1 Ga. Prismatic and oscillatory zoned rims spot ages, 1666 ± 81 (8.1), 1695 ±77 (9.2) and 1773 ±73 Ma (20.3) should represent a second magmatic event around 1.7 Ga. The 2.1 Ga zircons could have been derived from the mafic granulite enclaves and hence of xenocrystic status, but the crystalline prismatic morphology would suggest their magmatic origin. This will be further discussed in a later section. A group of zircon grains are rounded or oval without any core or rim structure (14, 28). The spot ages of 834 ± 67 and 827± 6 Ma, should represent a metamorphic overprint. A significant number of concordant zircons could represent the dominant and pervasive Grenvillian metamorphism of the Eastern Ghats Province (Figure 7). Here it is important to

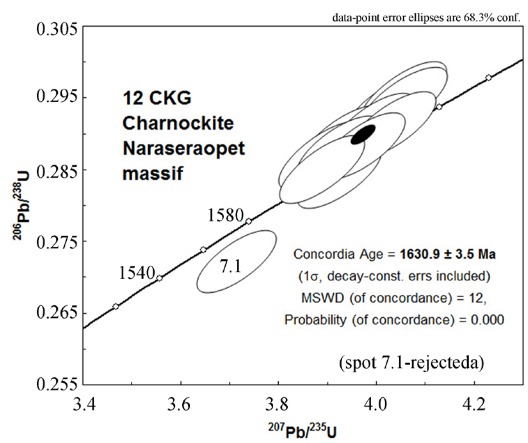

Figure 7
U-Pb Concordia Diagram For Zircons in the Chilka Massif

note that later metamorphic impact on the magmatic charnockite in the Chilka massif, though, rarely observed (Figure 4b) could have produced the neoblastic zircons during the Meso-Neoproterozoic thermal event in the EGP.

4. 4 Sunki Massif: Sample 8 CKG: 18°15'N; 82°55' E

All the zircon spot ages define a concordia age of 939.8± 1.8 Ma (Figure 8); however, oldest concordant spot $^{207}Pb/^{206}Pb$ age of 990 Ma (1.1 in Table 4) could imply a prolonged high temperature event. This is further discussed in the next section.

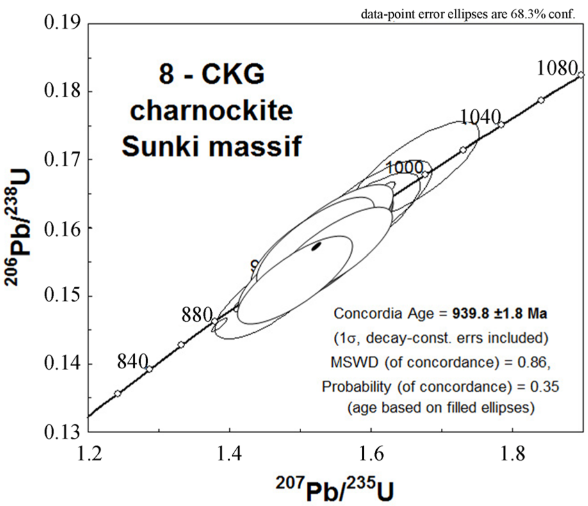

Figure 8
U-Pb Concordia Diagram for Zircons in the Sunki Massif

5. DISCUSSION

5.1 Magmatic charnockite of Different Ages in the Eastern Ghats Granulite Belt

Two episodes of charnockite magmatism could be clearly identified in the Eastern Ghats Belt. The ca. 1.6 Ga charnockite magmatism in the Ongole domain confirms the earlier reports (Bhui et al., 2007; Bhattacharya et al., 2010). But this episode of charnockite magmatism could be recognized in the Chilka and Gunupur massifs of the Eastern Ghats Province. On the other hand, the ca. 1.0 Ga charnockite magmatism is recorded from the Sunki massif in the Eastern Ghats Province. It is important to note that from Sunki area, it has been reported that the Eastern Ghats Province sustained UHT conditions (T >900 ◦C) for ~50 My, and perhaps for as long as 200 Ma from ca 1130 to 930 Ma, during a single CCW tectono-metamorphic event (Korhonen et al., 2013). These authors also described emplacement of charnockite-enderbite magma at the peak of this high-temperature metamorphic event. Our U-Pb concordant zircons between 990 and 940 Ma from the Sunki massif could represent the Meso-Neoproterozoic charnockitic magmatism in the EGP.

5.2 Tectonic Environment of Charnockites in the Eastern Ghats Belt

Based on field relation, petrology and geochemistry several such massifs have been described as product of dehydration melting in mafic rocks under granulite facies conditions (Kar et al., 2003; Bhattacharya et al., 2010; Bhattacharya et al., 2011). Some of these massifs in the Eastern Ghats Province, for example that at Sunki, were related to the Grenvillian granulite event (Paul et al., 1988; Aftalion et al., 1988; Bhattacharya et al., 2010; Korhonen et al., 2011, p.13; this study). This further confirms the relation between granulite metamorphism and charnockite magmatism, as envisioned by Frost and Frost (2008). In the Ongole domain, at Naraseraopet, charnockite magmatism at ca. 1.63 Ga could also be linked with the UHT metamorphism around 1.7-1.6 Ga (Simmat & Raith, 2008; Bose et al., 2011). In view of the 1.6-1.7 Ga charnockite magmatism recorded from the Chilka and Gunupur massifs and mafic granulite enclaves within these massifs would suggest a similar mode of genesis, namely, partial melting in mafic rocks under granulite facies conditions. The mafic rocks in question might have been generated in a previous subduction event during the Paleoproterozoic times around 2.1-2.5 Ga (2.1-2.2 Ga magmatism at Chilka described here; and 2.5 Ga mafic within the Naraseraopet massif, previously described by Bhattacharya et al., 2011). From the Chilka Lake area we have described the magmatic signatures in the mafic enclaves within the charnockite massif (Bhattacharya et al., 2013, in press). Strong positive Nb anomalies, indicating subducted oceanic crust in the source, LREE enrichment and strongly fractionated REE pattern are key geochemical signatures attesting to their origin as OIB-type magma. Low Yb and Sc contents and high $(La/Yb)_N$ ratio can be attributed to melting in the presence of residual garnet and hence at great depths (>80 km). Also Nd-model dates ~1.9 Ga was interpreted as the mantle-derivation age of the mafic magma. The 2.1 Ga magmatic event recorded here from the Chilka massif could be the precise age of this mafic magmatism.

5.3 Eastern Ghats Belt & its Columbia Connection

Recent synthesis indicated that Columbia assembled at ca. 2.1-1.8 Ga and grew by long-lived accretionary orogenesis before disintegration and re-assembly as Rodinia at ca. 1.0-0.9 Ga (Zhao et al., 2004; Li et al., 2008). Erstwhile models for the EGB (Ramesh et al., 2010; Vijay Kumar et al., 2010; Dharma Rao et al., 2012) in relation to the aforesaid history of Columbia and Rodinia were based on geological and geochronological investigations on the south-western end of EGB only. Dasgupta et al., (2012) pointed out that geological histories in the southern part are significantly different from that in the northern part; as they belong to different isotopic provinces. It is also important to note that the Paleo-proterozoic Provenance for the khondalite sediments (in the northern part in particular) could be identified in the Bastar craton magmatic rocks (Bhattacharya et al., 2012). With the record of 1760-1600 Ma events in the Ongole domain, Bose et al. (2011) indicated that accretionary orogenic processes in the supercontinent Columbia encompassed Australia, Antarctica, Laurentia and parts of India (specifically the Ongole domain).

The discovery of the ca. 1.6 Ga charnockitic magmatism in the Eastern Ghats Province, lead us to suggest that vestiges of a high-temperature event, in the form of charnockitic magmatism, are present in the EGP also. An alternative interpretation for the Gunupur charnockite massif may be that the Ongole domain extends further north across the Godavari graben and in that case UHT metamorphism around 1.7-1.6 Ga might also have occurred, as described from Kondapalli area of the Ongole domain (Bhui et al., 2007). However, in view of the 1.6 Ga record of charnockitic magmatism also in the Chilka massif, extension of the Ongole domain appears untenable and our preferred interpretation is that of two UHT-cum charnockitic magmatic events in the Eastern Ghats Province. It may be mentioned here that large-tract of the Eastern Ghats Province remains unexplored, being heavily forested and not easily accessible. Along with the mafic magmatism around 2.1 Ga, as represented by the mafic enclaves within the Chilka massif may provide evidence of the Columbia connection for the Eastern Ghats Province also.

6. CONCLUDING REMARKS

Two episodes of charnockite magmatism around 1.6 Ga and 1.0 Ga are recorded from the Eastern Ghats Province and in view of the demonstrated link between UHT metamorphism and charnockitic magmatism, Paleo-Mesoproterozoic UHT metamorphic event could have affected the Eastern Ghats Province also.

The vestiges of the 1.6 Ga charnockitic magmatism, along with the evidence of ca. 2.1 Ga mafic magmatism in the Eastern Ghats Province, would suggest that accretionary orogenic processes in the Supercontinent Columbia encompassed the Eastern Ghats Province also.

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