New Insights On The Chronological Relation Between The Supracrustals And The Magmatic Rocks (Charnockite Massifs) In The Eastern Ghats Granulite Belt, India And The Question Of Basement To The Supracrustals

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ABSTRACT

In spite of voluminous research publications, the erstwhile model of charnockite petrogenesis: felsic magma subsequently metamorphosed, on the one hand, and intrusion of the felsic rocks into the khondalites on the other, are not corroborated by published geochronological data in the Eastern Ghats Belt. Our alternative petrogenetic model: deep-crustal anatexis coeval with granulite facies metamorphism is consistent with the geochronological data. Second, we demonstrated single granulite-cum-anatectic event involved melting in mafic and pelitic rocks in both the Eastern Ghats Province and the Ongole domain. We also propose deposition of supracrustals on mafic basement that formed the first continental crust-basaltic magma around 2.5 Ga.

Key Words: Crustal anatexis, Mafic basement, Cover sediments.

1.INTRODUCTION

High-grade crystalline terrains, such as the Proterozoic Eastern Ghats Province of the Indian Peninsula, record multiple deformation and complex metamorphic evolution [1] and hence original stratification of the sedimentary or volcanic protoliths are obliterated [2]. This complicates the relative chronological relation between different units or gneiss-components. Thus application of geochronological methods to reconstruct the history of the crystalline terrains is the urgent requirement.

The Eastern Ghats Granulite Belt along the east coast of India, a high-grade crystalline terrain, has been described as a polycyclic terrain [1]. Here two major lithology or gneiss components are the charnockite gneiss and the supracrustals, commonly described as khondalites. Chronological relation between them and the nature of the basement to the supracrustal rocks have not been described in the literature with any degree of certainty. Many of the workers considered the khondalites as the oldest component with unknown basement and the charnockite-protoliths as intrusive into the khondalites [(3),(4)]. On the other hand, some workers considered the charnockite-gneiss as metamorphosed igneous precursors [(5),(6)]. Although, these workers did not specify the nature or composition of the charnockite-protolith, no evidence of orthopyroxene formation during granulite facies metamorphism having been provided, would lead to the inevitable conclusion that charnockite-protoliths were of mafic composition. In this context, it is important to note that felsic/tonalitic rocks could not be directly derived from mantle peridotite [7]. Erstwhile published geochronological data do not corroborate either of these notions. Onset of khondalite sedimentation in the northern Eastern Ghats Belt, constrained by detrital zircon U-Pb data as around 1.3 Ga [8] and the charnockite-protolith emplacement, constrained by Nd-model ages as between 1.9 and 2.9 Ga [9]. We have pointed out in an earlier publication that these geochronological data could argue against the idea of intrusion of felsic magma (tonalite) into the khondalites [10].

In the present communiqué, we considered the alternative petrogenetic models for both the supracrustals and the charnockitic gneiss and in terms of geochronological data try to elucidate the chronological relations between the two. We also tried to identify the nature of the khondalite-basement.

2. GEOLOGICAL BACKGROUND

The Eastern Ghats Granulite Belt comprises several rock types that can be grouped into the following: a) supracrustals including metapelitic granulites, khondalites, quartzites and calcgranulites; b) charnockite-enderbite gneisses; c) mafic granulites; d) garnetiferous granite gneiss and leptynites; e) anorthosites and f) alkaline complexes (Figure I).

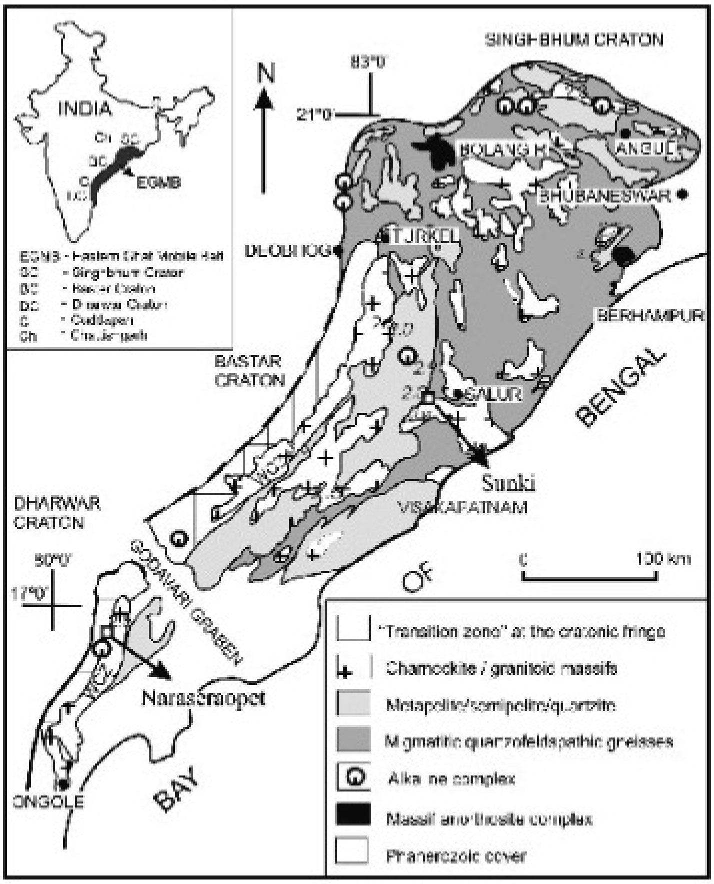

Figure I.

Figure I. Simplified geological map of the Eastern Ghats Belt, modified after Ramakrishnan et al. 1988.

Based on published geochronological data, northern Eastern Ghats belt, north of the Godavari rift, has been defined as the Eastern Ghats Province, while that to the south has been defined as the Ongole domain [11]. Several large-scale bodies of charnockitic rocks occur in both the aforesaid domain; while khondalites, the dominant supracrustal lithology, are also exposed in the two domains.

3. PETROGENETIC MODELS

Large-scale bodies of the charnockitic rocks could be described as charnockite massifs of variable composition- tonalite-granodiorite-granite. The hornblende-mafic granulites commonly occur as enclaves or inclusions in the host charnockite and petrographic and mineralogical features in these mafic granulite enclaves clearly demonstrate their restitic nature [(12)-(14)]. Furthermore, complimentary trace element distribution between the host charnockitic rocks and mafic granulite enclaves, demonstrate a melt-restite relation between them (opcit). Thus our favoured petrogenetic model for the charnockite massifs is of hornblende-dehydration melting in mafic rocks under granulite facies conditions. Unlike the model of mantle-derived tonalitic magma subsequently metamorphosed to enderbite [(5),(6)] our petrogenetic model indicates deep-crustal anatexis and granulite facies metamorphism as coeval. It is important to note that charnockitic rocks of TTG-like composition are most unlikely to be directly extracted from peridotitic mantle [7].

On the other hand, the intimate association of the pelitic granulites (khondalites) with garnetiferous granite gneisses on the one hand and high-Mg pelitic migmatites with melanosome and leucosome, suggest biotite-dehydration melting in pelitic precursors under granulite facies conditions, as described by us [(15),(16)].

4. GRANULITE-GRANITE CONNECTION

The pressure-temperature conditions in granulite facies metamorphism entails partial melting, particularly, dehydration partial-melting in most crustal lithologies [17]. Significant phase equilibrium and experimental studies have demonstrated: 1) biotite-dehydration melting in pelitic rocks at temperatures exceeding 750^{o} C [(18)-(21)] and 2) hornblende-dehydration melting in mafic rocks at temperatures exceeding 850^{o}C at mid crustal depths [(22)-(25)].

These have been amply demonstrated in the Eastern Ghats Granulite Belt [(13)-(16)]. Here we present a few field photographs to elucidate the aforesaid granulite-granite connections in the Eastern Ghats Granulite Belt.

Figure 2 shows mafic granulite enclaves within host charnockite gneiss in the Chilka Lake suite. Quartzofeldspathic films at hornblende-plagioclase contact in the Chilka Lake suite suggest in

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situ melting [26]. Thus the mafic granulite enclaves and the host charnockite could be interpreted as restite and melt respectively.

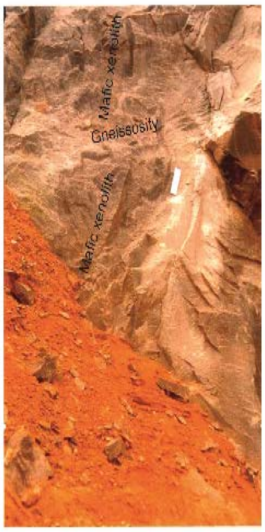

Figure II.

Figure II. Mafic granulite enclaves within host charnockite-gneiss in the Chilka Lake area. Some of the enclaves are also folded (near the scale); the gneissosity in the photograph is aligned E-W on a vertical section.

Figure 3 a) shows folded mafic granulite enclave within host charnockite gneiss, the gneissosity is axial planar to the rootless fold in the Sunki suite and b) several blocks and dismembered bands of mafic granulite enclaves in the Naraseraopet suite. In both of these suites, petrographic evidence in the enclaves indicate prograde hornblende breakdown to produce orthopyroxene and plagioclase, consistent with hornblende-dehydration melting in mafic rocks as the mode of origin of the charnockites [(12),(13)].

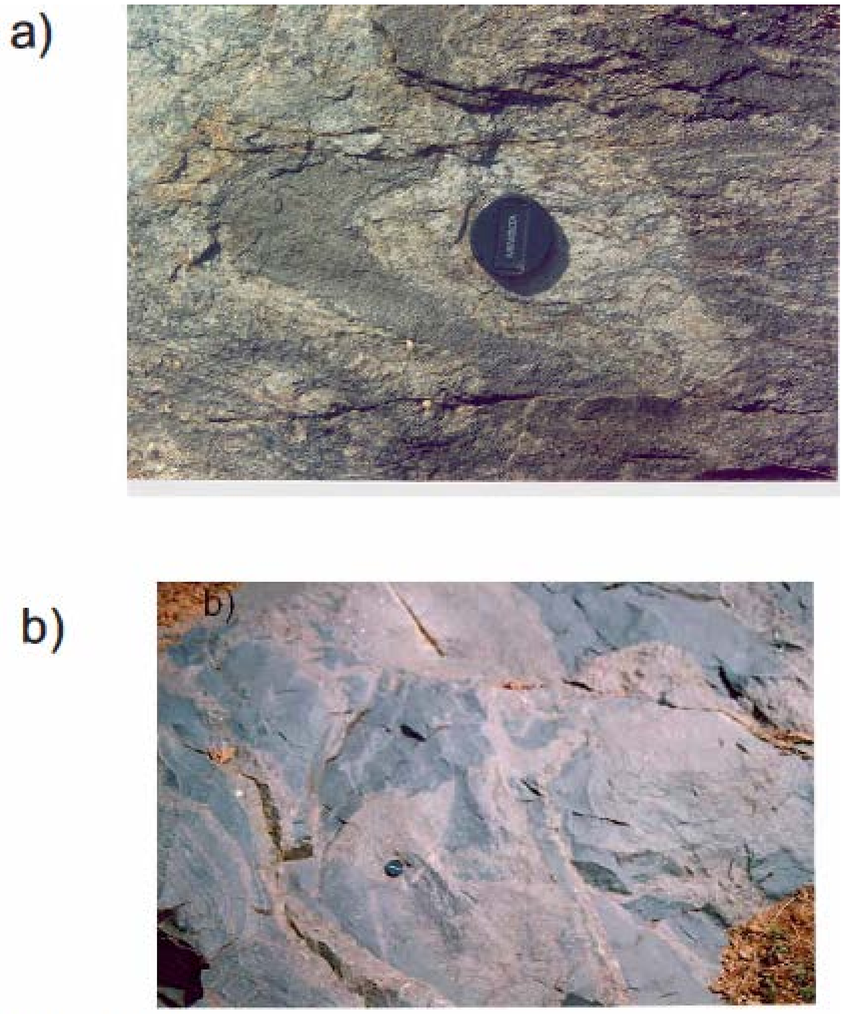

Figure III

Figure IIIa. Folded mafic granulite enclave within host charnockite-gneiss at Sunki. On the sub-horizontal plane, the E-W aligned gneissosity is axial planar to the fold.

Figure IIIb. Blocks and dismembered bands of mafic granulite enclaves within host charnockite in the Naraseraopet suite.

Figure 4 shows pelitic migmatite with folded leucosomes and melanosomes, indicating melting in pelitic precursors, near Naraseraopet, Ongole domain.

Figure IV

Figure IV. Pelitic migmatite with folded melanosome and leucosome, near Naraseraopet of the Ongole domain.

Figure 5 shows garnetiferous granite gneisses; the gneissosity folded with small patches of pelitic granulites as inclusions, near Salur, Andhra Pradesh. Incidentally, these inclusions contain high-Mg minerals, like orthopyroxene, cordierite and occasionally sapphirine [27] and hence could be considered as restites.

Figure V

Figure V. Garnetiferous granite gneiss near Salur, Andhra Pradesh. Gneissosity folded with small patches of pelitic granulites as inclusions (arrow head).

5. PHASE EQUILIBRIA MODELLING

In view of the limitations of traditional thermobarometry and petrogenetic grids, used in our previous publications, we intend to update the P-T equilibrations in the two suites of Jenapore and Paderu, by phase equilibria modelling. While selecting samples of the Restites for these modelling, we tried to avoid, as far as possible, mixed assemblages. It is important to note, however, that in dehydration melting, incongruous melting, some solid phases (peritectic) are produced along with the melt, resulting in disequilibrium, as manifested in the trace element concentrations [(14),(15)]. Isochemical phase diagrams (pseudosections) were constructed using Perplex version 6.6.8 [28] and later modified [29] Solution models of Holland & Powell [30] for orthopyroxene & clinopyroxene; Dale et al. [31] for amphibole; Newton et al. [32] for plagioclase; Holland & Powell [30] for garnet; Holland & Powell [33] and White et al. [34] for melt; Powell & Holland [35] and White et al [36] for biotite were used. Thermochemical parameters of sapphirine, phengite and cordierite are taken from Thermocalc program of Holland & Powell [33], using the internally consistent data base of Holland & Powell [33].

For the Jenapore sample of hornblende-mafic granulite, (JN95B), the calculations were undertaken in the chemical system: Na_2O-CaO-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2 (NCFMASHTO). K_2O not considered, because of the absence of K-feldspar in the mafic granulite and also because the charnockitic melt of tonalitic composition with very little K_2O in them. 0.5% water added for hydrous mineral hornblende. The compositional data are taken from Kar et al. [14]. The residual solid assemblage equilibrated with charnockitic (tonalitic) melt. P-T conditions of equilibration derived in this pseudosection: 930^{o}C; 9.2 Kbar is given as box (Figure VI). The X_{Mg} of the melt in the stability field varies between 0.46 and 0.47; while the X_{Mg} of the charnockitic melt in the area varies between 0.33 and 0.49 and this is consistent with the envisaged melt-to -restite relation. Although, pressure appears to have been somewhat overestimated in Kar et al. [14], the temperatures of equilibration just below 950^{o}C in Kar et al. [14] is confirmed in this modelling

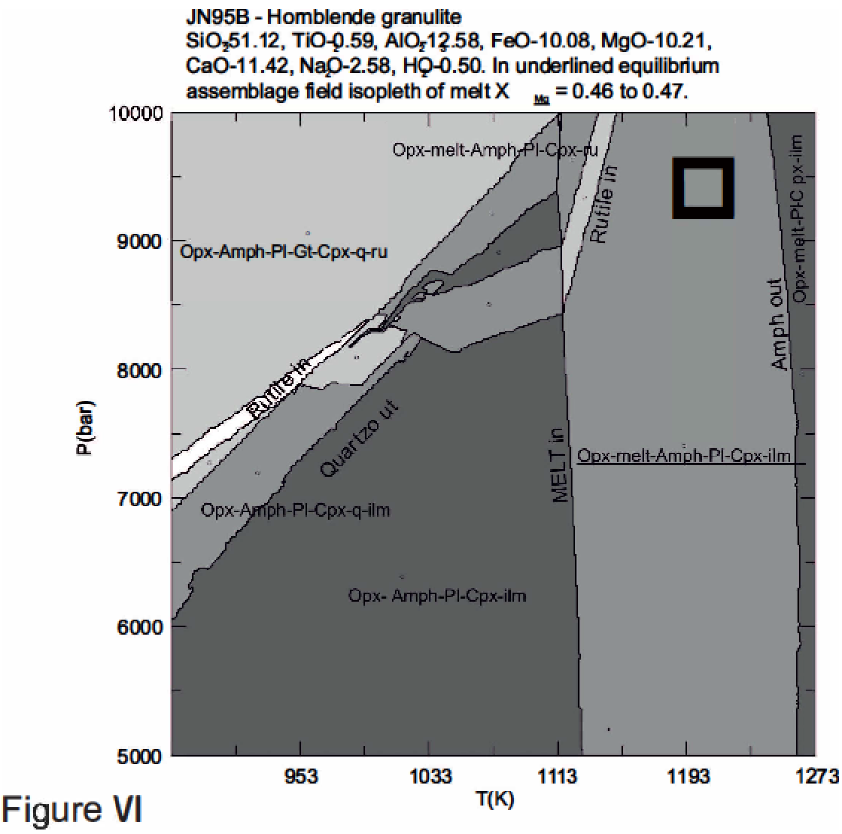

Figure VI. Calculated P-T pseudosection for mafic granulite sample JN95B of the Jenapore suite.

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For the Paderu sample of sapphirine granulite (97/31b), the calculations were undertaken in the chemical system: K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2 (KFMASHTO). In view of significant hydrous minerals, like, biotite and cordierite, 0.5% water was added. The compositional data are taken from Bhattacharya and Kar [15]. The residual solid assemblage equilibrated with granitic melt. The P-T conditions derived from this pseudosection: >900^{o}C, 8.6 Kbar, is given as box (Figure VII). X_{Mg} of the melt in the stability field is 0.68; while that varies between 0.40 and 0.51 in a group of granitoids. At this point it will be interesting to note that one quartzofeldspathic layer (95/15C) of granite-migmatite with cordierite-orthopyroxene-sillimanite as peritectic phases, has X_{Mg} of 0.69. And in view of the X_{Mg} 0.68 of melt in the stability field, the particular pair of 97/31b & 95/15C could represent restite & melt respectively. It is important to note that Bhattacharya and Kar [15] had argued that high-sanidine/anorthoclase having been observed in the granitoids, could reflect relatively higher temperatures of equilibration or crystallization. Recently Korhonen et al. [37] also reported temperatures in excess of 900^{o}C (cf. Figure 9 in 37).

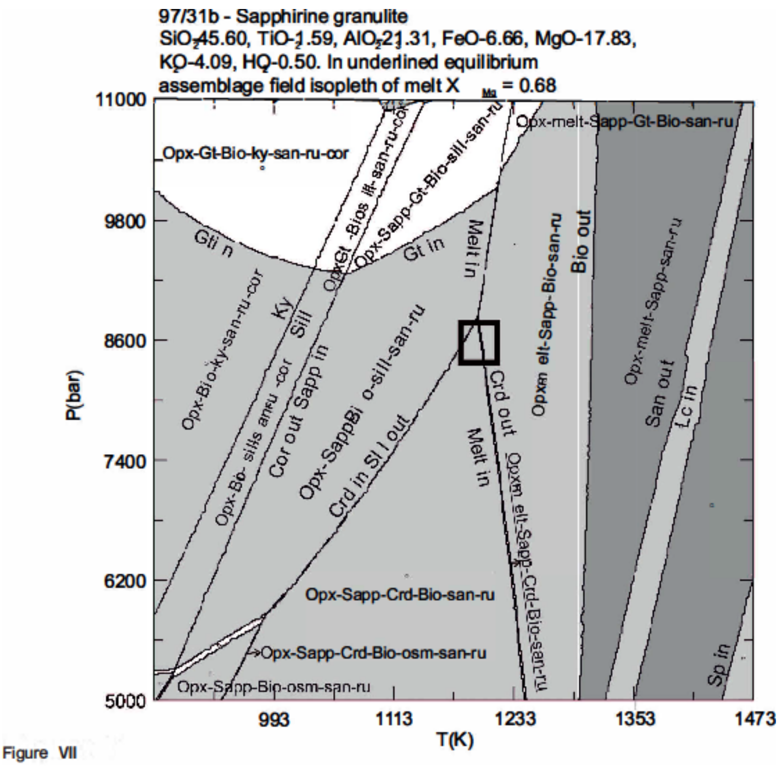

Figure VII. Calculated pseudosection for high-Mg pelitic granulite sample 97/31b of the Paderu suite.

6.GEOCHRONOLOGICAL CONSTRAINTS

Geochronological data could provide important constraints on the evolutionary scenario in the complex, polycyclic terrain of the Eastern Ghats Granulite Belt. However, for a proper and sound interpretation of the geochronological data, even the most precise data, such as U-Pb in zircon by SHRIMP or LA-ICPMS; we need valid petrogenetic models for the rock suites investigated.

For the pelitic granulite-granite-migmatite suites, we have described a petrogenetic model of biotite-dehydration melting in the deep crust under granulite facies conditions [(15),(16)]. For the Chilka suite, our geochronological data confirmed the melt-restite relations between the garnetiferous granite and metapelitic granulite: Whole rock Rb-Sr data for six granite (leptynite) and one restitic metapelite from the Chilka Lake area gave a seven point isochron age of 913±82 Ma (MSWD=4.3) and *in situ* Pb isotopes in zircon from leptynite gave an age of 975±95 Ma [38]. We have also recorded U-Pb isotopic data in zircon and monazite from the Paderu suite (Andhra Pradesh): a metamorphic peak at 988 Ma and subsequent cooling till 900 Ma [39]. It is important to note that this age is also replicated by U-Pb SHRIMP data in zircon and monazite from several pelitic migmatite suites in the central part of the Eastern Ghats Province. For the Sunki suite, $^{207}Pb/^{235}U$ in monazite range between 1014 and 959 Ma [40]. Also from several suites in the central Eastern Ghats Province U-Pb in zircon and monazite, it was concluded that "For the residual granulites and migmatites, weighted mean ages between 970 and 930 Ma…are interpreted to record the timing of crystallization of melt..." [41].

For several charnockite-mafic granulite suites in the Eastern Ghats Belt, we have described a petrogenetic model of hornblende-dehydration melting in the deep crust under granulite facies conditions [(12),(13),(14)]. For the Jenapore suite, Sm-Nd whole rock data for the mafic granulite-charnockite gave a four point isochron age of 3.03±0.2 Ga (MSWD=5.96) and this confirmed the melt-restite relation between charnockite and mafic granulite enclave. *In situ* Pb isotopes in zircon from charnockite gave an age of 2930±42 Ma [42]. Also, charnockite protolith age constrained by Sm-Nd isotopic data of five samples, including two charnockite and three mafic granulite samples, gave 3.5 Ga as average crustal residence age, which reflected the age of the mantle-derived basaltic magma, the precursors of the restitic mafic granulites [42].

More recently, we have reported precise U-Pb isotopic data in zircons by LA-ICPMS, for several charnockite suites in the Eastern Ghats Belt [26].

For the Sunki suite U-Pb zircon spot ages indicated a Concordia age of 939.3±1.8 Ma (MSWD=0.86). This would imply a single granulite-cum anatectic event in the central sector of the Eastern Ghats Province. It is important to note that from this central sector, Korhonen et al [37] argued "Regionally extensive enderbite and charnockite magmas were emplaced into the hot suprasolidus crust around the time of peak metamorphism". Charnockite protolith, as represented by the mafic granulite enclaves at Sunki, is dated as 2.5 Ga, the Nd-model (T_{DM}) age [42].

For the Chilka suite we have recorded prismatic and oscillatory zoned core spot ages: 2116±63, 2227±64 and 2150±61 Ma; while oscillatory zoned rim spot ages: 1666±81, 1695±77 and 1773±73 Ma. The core spot ages could represent a magmatic event around 2.1 Ga and rim spot ages could represent a magmatic/anatectic event [26]. The 2.1 Ga magmatism could be interpreted as mantle-derived basaltic magma, the precursor of the mafic granulite enclaves. This is confirmed by the Sm-Nd whole rock isotopic data: though not so precise, T_{DM} varying between 2.36 and 1.86 Ga [44]). On the other hand, rim spot ages could be interpreted as the granulite-cum-anatectic event around 1.6 Ga.

For the Naraseraopet suite in the Ongole domain, we have recorded a 16300.9±3.5 Ma Concordia age, with MSWD=12, representing the granulite-cum-anatectic event [41]. The protolith of this charnockite suite, the basaltic magma, was derived from the mantle around 2.5 Ga, given by T_{DM} [26]. Here it is important to note that the ca. 1.7 Ga granulite event was also reported from metapelite-migmatite suite of Kondapalle in the Ongole domain [45]. This again should imply a single granulite-cum anatectic event around 1.6 Ga in the Ongole domain. In other words, around this time deep crustal anatexis under granulite facies conditions occurred in both mafic and pelitic rocks.

7. IDENTIFYING SUPRACRUSTALS' BASEMENT

As for the question of basement for the supracrustal rocks, the khondalites, the fact that granulite-cum-anatectic event around 1.0 Ga in the Eastern Ghats Province and around 1.6 Ga in the Ongole domain, both involved melting in mafic and pelitic rocks, would suggest a basement-cover relationship between the mafic rocks and the khondalites. In the Eastern Ghats Province, the khondalites deposited around 1.3 Ga, on the mafic rocks, which represented the first continental crust, the basaltic magma formed around 2.5 Ga [43]. In the Ongole domain, though khondalite deposition is not yet constrained, it must have been earlier to the 1.6 Ga granulite-cum anatectic event. The early continental crust, the basaltic magma in the Ongole domain also formed around 2.5 Ga [43]. This scenario is also consistent with experimental studies on layered crustal protoliths [46].

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REFERENCES:

[1] Mukhopadhyay, D. and Basak, K.2009. *The Eastern Ghats Belt- A polycyclic granulite terrain*. Journal Geological Society of India, 73, 489-518

[2] Rey, J and Galotti,S.(Eds) 2008. *Stratigraphy: terminology and practice*. Editions Technip, Paris

[3] Mezger,K. and Cosca,M. 1999.*The thermal history of the Eastern Ghats Belt (India) as revealed by U-Pb and 40Ar/39Ar dating of metamorphic and magmatic minerals: Implications for the SWEAT correlation*. Precambrian Research, 94, 251-271

[4] Simmat,R. and Raith,M.M. 2008.*U-Th-Pb monazite geochronometry of the Eastern Ghats Belt, India and spatial disposition of polymetamorphism*. Precambrian Research, 162, 16-39

[5] Subba Rao,M.V. and Divakara Rao, V. 1988.*Chemical constraints on the origin of the charnockites in the Eastern Ghats Mobile Belt, India.* Chemical Geology, 69, 37-48

[6] Bhui,U.K., Sengupta,P and Sengupta, P. 2007.*Phase relations in mafic dykes and their host rocks from Kondapalle, Andhra Pradesh, India: Implications for the time-depth trajectory of the Paleoproterozoic (Late Archaean?) Granulites from Southern Eastern Ghats Belt*. Precambrian Research, 156, 153-174

[7] Kemp,A.I.S. and Hawkesworth, C.J. 2004.*Granitic perspectives on the generation and secular evolution of the continental crust.* Treatise on Geochemistry, 3, 349-411

[8] Upadhyay,D., Gerdes,A. and Raith, M.M. 2009.*Unravelling sedimentary Provenance and tectonothermal history of the high temperature metapelites using zircon and monazite chemistry: A case study from the Eastern Ghats Belt, India*. Journal of Geology, 117, 665-683

[9] K.Rickers , K. Mezger and M.M. Raith. *Evolution of the continental crust in the Proterozoic Eastern Ghats Belt, India and new constraints for Rodinia reconstruction: Implications from Sm-Nd, Rb-Sr and Pb-Pb isotopes*. Precambrian Research, vol. 112, No.3-4, 2001, pp.183-210

[10] S. Bhattacharya, R. Kar, A.K. Saw and P.Das, *Relative chronology in high-grade crystalline Terrain of the Eastern Ghats, India:New insights*. International Journal of Geosciences, vol.2, 2011, pp. 398-405

[11] Dobmeier, C. and Raith, M.M. 2003 *Crustal architecture and Evolution of the Eastern Ghats Belt and adjoining regions of India*. Geological Society, London, Special Publication. 206, 145-168

[12] Bhattacharya, S. *Dehydration melting in mafic rocks in the Eastern Ghats Belt, India: Implications for variable composition of charnockitic melt and heterogeneity of source rocks*. Memoir Geological Society of India. 52, 133-144

[13] Bhattacharya, S., Saw, A.K. and Chaudhary, A.K. 2016.*Proterozoic charnockites at 1.6 and 1.0 Ga in the Eastern Ghats Belt mirror secular evolution of the Continental crust in the Proterozoic era.* Advances in Natural Science, 9, 2, 1-9

[14] Kar, R., Bhattacharya, S. and Sheraton, J.W. 2003.*Hornblende-dehydration melting in mafic rocks and the link between massif-type charnockite and associated granulites, Eastern Ghats Granulite Belt, India*. *Contributions to Mineralogy & Petrology*, 145,707-729

[15] Bhattacharya, S. and Kar, R. 2002. *High temperature dehydration melting and decompressive P-T path in a granulite complex from the Eastern Ghats, India*. Contributions to Mineralogy and Petrology, 143, 175-191

[16] Sen,S.K. and Bhattacharya,1997. *Dehydration melting of micas in the Chilka Lake khondalites: the link between the metapelites and granitoids*. Proceedings Indian Academy of Sciences (Earth & Planetary Science), 106, 277-297

[17] Clemens, J.D. *The granulite-granite connection*. 1990. In: Vielzeuf & Vidal, (eds), Granulites and Crustal evolution, 25-36

[18] Le Breton,W. and Thompson, A.B. 1988.*Fluid-absent (dehydration) melting in metapelites in the early stages of crustal anatexis*. Contributions to Mineralogy & Petrology, 199, 226-237

[19] Patino Douce,A.E. and Johnston, A.D. 1991.*Phase equilibrium and melt productivity in the pelitic system: Implications for the origin of peraluminous granitoids and aluminous granulites*. Contributions to Mineralogy & Petrology, 107, 2202-2218

[20] Vielzeuf, D. and Holloway, A. 1988.*Experimental determination of the fluid-absent melting reactions in the pelitic system.* Contributions to Mineralogy & Petrology, 98, 257-276

[21] Vielzeuf, D. and Montel, J.M. 1994.*Partial melting of metagreywackes. Part I. Fluid-absent experiments and phase relationships*. Contributions to Mineralogy & Petrology, 117, 375-393

[22] Thompson,A.B. and Ellis,D.J. 1994. *$CaO+MgO+Al_2O_3+H_2O$ to 35 Kbar: amphibole, talc and zoisite dehydration and melting reactions in the silica excess part of the system and their possible significance in subduction zones, amphibolite melting and magma fractionation*. American Mineralogist, 294, 1229-1289

[23] Wolf, M.B. and Wyllie, P.J. 1994.*Dehydration melting of amphibolite at 10 Kbar: Effects of temperature and time.* Contributions to Mineralogy & Petrology, , 115, 369-383

[24] Patino Douce, A.E. and Beard, J.S. 1995.*Dehydration melting of biotite gneiss and quartz amphibolite from 3 to 15 Kbar*. Journal of Petrology, 36, 707-738

[25] Springer,W. and Seck, H.A. 1997.*Partial fusion of basic granulites at 5 to 15 Kbar: implications for the origin of TTG magmas.* Contributions to Mineralogy & Petrology, 127, 30-45

[26] Bhattacharya,S., Basei,M and Kar,R. 2014.*Charnockite massifs: key to tectonic evolution of the Eastern Ghats Belt, India, and its Columbia connection*. Advances in Natural Science, 7, 1-11

[27] Korhonen, F.J., Brown,M., Clark, C. and Bhattacharya, S. 2013.*Osumillite-melt interactions in ultrahigh temperature granulites: phase equilibria modelling and implications for the P-T-t evolution of the Eastern Ghats Province, India.* Journal of Metamorphic Geology, 31, 881-907

[28] Conolly,J.A.D. and Kerric, D.M. 1987. *An algorithm and computer program for calculating composition phase diagrams*. CALPHAD, 11, 1-55

[29] Conolly, J.A.D. 2009. *The geodynamic equation of state: what and how*. Geochemistry, Geophysics, Geodynamics, 10, Q10014

[30] Holland, T. and Powell, R. 1996. *Thermodynamics of order-disorder in minerals. 2. Symmetric formalism applied to solid solutions*. American Mineralogist, 81, 1425-1437

[31] Dale, J., Holland,T and Powell, R.2000. *Hornblende-garnet-plagioclase thermobarometry: a natural assemblage calibration of the thermodynamics of hornblende.* Contributions to Mineralogy & Petrology, 140, 353-362

[32] Newton,R.C., Charlu, T.V. and Kleppa, O.J. 1980.*Thermochemistry of the high structural plagioclases*. Geochemica Cosmochemica Acta, 44, 933-941

[33] Holland, T.J.B. and Powell, R.1988. *An internally consistent thermodynamic data set with uncertainties and correlations. 3 applications, methods, worked examples and a computer program.* Journal of Metamorphic Geology, 6, 173-204

[34] Holland, T.J.B. and Powell, R.2001. *Calculation of phase relations involving happlogranitic melts using an internally consistent thermodynamic data set*. Journal of Petrology, 42, 673-683

[35] White,R.W., Powell, R. and Holland, T.J.B, 2001.*Calculation of partial melting equilibria in the system* Na_2O-CaO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O *(NCKFMASH).* Journal of Metamorphic Geology,, 19, 139-153

[36] Powell, R. and Holland, T.J.B. 1998. An internally consistent thermodynamic data set for phases of petrological interest. *Journal of Metamorphic Geology*, 16, 309-343

[37] Bhattacharya, S., Demurer, M..P. and Teixeira, W. 2002. *Grenvillian thermal event and remnant charnockite: Isotopic evidence from the Chilka Lake granulite-migmatite suite in the*

Eastern Ghats belt, India. Proceedings Indian Academy of Sciences (Earth & Planetary Science), 111, 391-399

[38] S.Bhattacharya, R.Kar, W.Teixeira and M.Basei, 2003. *High-temperature crustal anatexis in a clockwise P-T Path: Isotopic evidence from a granulite-granitoid suite in the Eastern Ghats Belt, India*. Journal of Geological Society, 160, 39-46.

[39] Korhonen,F.J., Saw,A.K., Clark, C., Brown,M and Bhattacharya,S. 2011.*New constraints on UHT metamorphism in the Eastern Ghats Province through the application of phase equilibria modelling and in situ geochronology*. Gondwana Research, 20, 764-781

[40] F.J.Korhonen, C.Clark, M.Brown, S.Bhattacharya and R. Taylor, 2011. *How long-lived is ultrahigh temperature (UHT) metamorphism? Constraints from zircon and monazite geochronology in the Eastern Ghats orogenic belt, India* Precambrian Research, 234, 322-350

[41] Bhattacharya, S., Kar, R., Misra, S. and Teixeira, W. 2001. *Early Archaean continental crust in the Eastern Ghats Granulite belt, India: Isotopic evidence from a charnockite suite*. Geological Magazine, 138, 609-618

[42] Bhattacharya, S., Chaudhary, A.K., Saw,A.K and Das, P. 2011. *Mafic granulite xenoliths from the East Indian Shield: Evidence for recycled continental crust in the Archaean Mantle*. Lithosphere, 3, 155-169

[43] Bhattacharya,S., Chaudhary,A.K., Saw,A.K., Das, P. and Chatterjee,D. 2013.*Mafic granulite xenoliths in the Chilka Lake suite, Eastern Ghats Belt, India: Evidence of deep-subduction of residual oceanic crust*. Indian Journal of Geology, 85, 95-110

[44] Bose, S., Dunkley,D.J., Dasgupta, S. Das,K. and Arima,M. 2011. *India-Antarctica-Australia-Laurentia connection revisited: Evidence from new zircon U-Pb and monazite chemical age data from the Eastern Ghats Belt, India*. Bulletin Geological Society of America, 122, 2031-2049

[45] Skjerlie,K.P., Patino Douce,A.E. and Johnston,A.D. 1993.*Fluid-absent melting of layered crustal protoliths: Implications for the generation of anatectic granites*. Contributions to Mineralogy & Petrology, 114, 365-378