Petrology and geochemistry of Charnockite patches and host Leptynites from Digapahandi area, EGB: Evidence for incipient growth of Charnockites

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ABSTRACT: Occurrences of the small, elongated, irregular shape of charnockite patches along the foliation planes of the leptynites in Digapahandi area, Ganjam district, Odisha of Eastern Ghats Belt (EGB) are reported. Petrography and mineral chemistry of charnockite patches and host leptynites suggest that both the rocks have analogues mineral assemblages, except the presence of ortho-pyroxene in charnockite patches. The mineral chemistry studies revealed that mineral phases common in both rocks are chemically identical. Based on whole rocks geochemistry it is evident that both charnockite patches and host leptynites are iso-chemical. The adamellite composition, per-aluminous nature with positive Europium anomaly of host leptynite and charnockite patches suggests their co-genetic relation. Higher values of (La/Yb)₉ and (Gd/Lu)₉ of leptynites indicate the highly fractionated HREE pattern of leptynites. High concentrations of HREE in charnockite patches are due to the influence of fluid phase in granulite facies metamorphism. The charnockite patches are characterized by higher K₂O content, higher HREE concentration, and less abundance of biotite indicating the in-situ growth of patchy charnockites.

Keywords: Incipient charnockite, Patchy charnockite, Incipient growth, Eastern Ghats Belt.

1. Introduction
The term *incipient charnockite* was first described by Pichamuthu (1960) [29] for the rocks from Dharwar Craton. Towards the end of the twentieth century, the presence of incipient charnockites in the Eastern Ghats Belt (EGB) as well as in the Southern Granulite terrain has been reported by several workers [1][5][17][41][42]. The term patchy charnockite, incipient charnockite, or arrested charnockites are generally used to designate the ortho-pyroxene bearing granitic assemblages, which occurs as patches and/or lenses within the quartzo-feldspathic assemblages. The processes of formation for patchy charnockite may be described in two major different ways. First, the development of charnockite within leucocratic gneiss through in-situ metamorphic transformation commonly referred to as ‘charnockitization process’ [1][9][15][17][24][27][42]. The second school of thought proposed the relict nature of pre-existing charnockite disseminated within the leptynite masses [5][6][18]. In the first case, the charnockitization process needs an open system environment [15][30][32][37][38] that allows foreign compounds to take part in the process. In the majority, these compounds are CO₂ and H₂O phases [25][30]. Hence it requires several channels within the pre-existing rock masses to migrate the above-mentioned compounds. Among these compounds, CO₂ is taken as an abundant phase by some authors [15][42] and some were preferred brine inclusion [3][44]. Migration of these phases might be...
taken as a prime responsible factor for charnockite development and localization. To resume the process, it needs to lower the water activity of the system, either through the presence of CO$_2$ [15][16][24][34][36] or the decrease in the fluid pressure [41]. As a major dehydrated phase, orthopyroxenes are hence formed from the breakdown of amphibole and/or biotite under dehydration conditions. This metamorphic change is generally described as prograde, and hence the charnockitization process has been described as a result of prograde metamorphism of upper amphibolites facies to granulite facies mineral assemblages.

The occurrences of charnockite patches within the host leptynites from EGB are either due to the late-stage development of charnockite [9] or as a remnant of previously formed charnockites [5][18]. Earlier studies on charnockite patches have proved the presence of both types of charnockite patches throughout the EGB.

The present paper deals with the detailed mineralogical and petrological studies of charnockite patches along with their host leptynites exposed near the Digapahandi area, Ganjam district, Odisha. The mineralogical and petrological studies are correlated with the geochemical nature of the rocks which throw light on their mode of origin.

2. Geological setup

The NE-SW trending Eastern Ghats Belt is a high-grade, polymetamorphic terrain along the East Coast of the Indian subcontinent, where principal rock types are charnockites, khondalites, and leptynites. The EGB is bounded by three Archean Cratons, namely; Singhbhum Craton in the north,
Bastar Craton in the west, and Eastern Dharwar Craton in the southwest. The EGB is dissected by two Gondwana Rifts; i.e., Mahanadi Rift at the north and Godavari Rift at the south end of the belt (Fig. 1a). Presences of charnockite patches within the belt have been reported by several authors. The marked locations are Adaba region of Ganjam district, Odisha [23], Angul sector [14], Chilka Lake region [5][6][9], Deobhog region [13], Jenapur area [18], Rengali sector [8] and Titilagarh area [20]. Among these charnockites, relict growth has been reported from the Jenapur and Chilka area whereas other areas are marked as charnockite development in gneiss through the breakdown of biotite and hornblende.

Digapahandi and the adjacent area belong to the Central Migmatite zone of the EGB, situated at about 200 km south-west of Bhubaneswar, Odisha (Figure. 1a and 1b). Different lithologies exposed in and around the Digapahandi area are leptynites, khondalites, charnockites, and mafic granulites. The detailed geological map of the study area is present in figure.1c. Charnockites of the study area can be grouped into two categories; such as Massif charnockite and patchy Charnockite. Massif charnockites are compositional ranges from charnockite to enderbite concerning their feldspar content. The charnockite patches are present in host leptynites and gneisses. The development of charnockite patches in the host leptynites is found to restrict along the foliation planes of the leptynites (Figure. 2a). These charnockite patches have diffused margins with the host leptynites (Figure. 2b). Both charnockites and leptynites are separated through a thin layer of biotite matrix. The khondalites of the study area are present in association with the large leptynite bodies. The general trends of the khondalites are almost in the North-South direction. The mafic granulite bodies are present as dykes stretching along the NE-SW direction. These rocks occur in the vicinity of leptynites and charnockites. Mafic granulites are showing dark color, coarse to medium grain, porphyritic texture characterized by the presence of orthopyroxene, clinopyroxene, and hornblende.

Figure 2. (a) Charnockite patches developed along the foliation plane of host leptynite. (b) Diffused margin around the charnockite patches where biotite present as rim in between host leptynites and charnockite patches.

3. Petrography

(a) Leptynite Host

Host leptynites are characterized by the presence of abundant plagioclase and alkali feldspar that to be of equal proportion. Myrmekitic intergrowth of quartz and feldspars are common. Other minerals like biotite, garnet, and ilmenite are also present in leptynite. Biotite is arbitrarily distributed throughout the rock. Small ilmenite inclusions are also common in biotite. The granoblastic texture is a common phenomenon in leptynites. At places, small patches of pelitic assemblages (sillimanite – biotite – garnet
– feldspar – quartz + ilmenite) are present as xenoliths within the leptynite (Figure 3a). Sen and Bhattacharya [39] suggested that these leptynites are the product of partial melting of khondalites during granulite facies metamorphic conditions. The presences of relict pelitic assemblages within leptynites also advocate that the khondalites were the protolith for leptynites.

**(b) Charnockite Patches**

Overall, the charnockite patches show granoblastic texture. Mineral assembly of charnockite patches is ortho-pyroxene, plagioclase, orthoclase, garnet, biotite and apatite. Orthoclase contents are moreover the plagioclase. Ilmenite is an important opaque mineral phase that is present in charnockite patches. Ortho-pyroxene grains are mostly euhedral to subhedral and have sharp contact with each other (Figure 3b). Garnet and biotites proportion in charnockites are comparatively less than the host leptynites. Small inclusions of ilmenite and biotite are also present in some ortho-pyroxene grains of charnockite (Figure 3c) suggesting the formation of ortho-pyroxene through biotite dehydration. Biotite inclusions in garnet are also common in charnockites which indicate the development of garnet by the biotite breakdown reaction. Biotite proportion in charnockite patches is quite low as compared to the host leptynite. It is probably due to the consumption of biotite to form ortho-pyroxene through dehydration melting. However, the proportions of mafic phases are comparatively higher in charnockite than leptynites. At a few places, ortho-pyroxene seems to be growing within the biotite grains (Figure 3d), which also favours the generation of ortho-pyroxene through the biotite-dehydration process.

![Figure 3](image-url)

**Figure 3.** (a) Xenoliths of restite pelitic assemblages present within the leptynites. (b) Euhedral grains of orthopyroxene are present along with the ilmenite and biotite in charnockite. (c) Biotite and ilmenite are present as inclusion in pyroxene grains. (d) Growth of orthopyroxene within biotite. Mineral abbreviations are from Whitney and Evans [45].
4. Mineral chemistry
To determine mineral chemistry, the Electron Micro Probe Analyses (EPMA) was carried out at Electron Probe Laboratory in IIT Bombay (India) by using Cameca SX Five electron microprobe, operating at 15 keV accelerating voltage and 20na beam current. The beam size of the instrument is 1 µm and the dwell time for each analysis is around three minutes. EPMA data are represented by the weight percentage of major oxides. Ferric proportions were calculated by using the stoichiometric method [10] where ever necessary. The representative mineral phases from both leptynite (host) and charnockite (patches) were analyzed and presented in table 1.

Table 1A. Representative mineral chemistry of analysed phases from Patchy charnockites

| Mineral | SiO₂ | Al₂O₃ | Fe₂+ | Fe³+ | MgO | MnO | CaO | Na₂O | K₂O |
|---------|------|-------|------|------|-----|-----|-----|------|-----|
| Biotite | 36.75 36.38 | 14.61 | 0.11 | 20.70 | 10.15 | 0.02 | 0.03 | 0.13 | 9.69 |
| Garnet | 35.64 | 19.62 | 0.12 | 0.00 | 10.30 | 0.02 | 0.00 | 0.19 | 13.50 |
| Plagioclase | 36.77 | 19.82 | 0.00 | 0.00 | 10.50 | 0.00 | 0.00 | 0.00 | 11.60 |
| (O) Basis | 24 | 12 | 8 |
| Si | 5.79 | 2.71 | 0.00 | 2.73 | 2.38 | 0.00 | 0.04 | 1.95 | 16.20 |
| Ti | 0.62 | 0.64 | 0.00 | 0.71 | 0.62 | 0.00 | 0.04 | 0.90 | 16.10 |
| Al | 0.66 | 2.75 | 0.00 | 2.67 | 2.41 | 0.00 | 0.01 | 1.10 | 16.20 |
| Cr | 0.00 | 1.94 | 0.00 | 2.11 | 2.41 | 0.00 | 0.04 | 1.50 | 16.20 |
| Fe₂⁺ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 16.20 |
| Fe³⁺ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mg | 0.40 | 2.35 | 0.00 | 0.15 | 0.40 | 0.00 | 0.04 | 0.04 | 8.00 |
| Mn | 0.33 | 0.37 | 0.00 | 0.17 | 0.33 | 0.00 | 0.01 | 0.01 | 8.00 |
| Ca | 0.35 | 0.40 | 0.00 | 0.16 | 0.35 | 0.00 | 0.01 | 0.01 | 8.00 |
| Na | 0.04 | 0.04 | 0.00 | 0.00 | 0.04 | 0.00 | 0.04 | 0.04 | 8.00 |
| K | 0.06 | 0.12 | 0.00 | 0.06 | 0.06 | 0.00 | 0.06 | 0.06 | 8.00 |
| Σ Cations | 35.40 | 35.50 | 34.40 | 34.50 | 35.50 | 34.40 | 34.50 | 34.50 | 34.50 |

Almandine | Grossular | Pyrope | Spessartine

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| SiO$_2$        | 49.32       | 48.32     |
| TiO$_2$        | 0.02        | 0.07      |
| Al$_2$O$_3$    | 0.73        | 0.79      |
| Cr$_2$O$_3$    | 0.03        | 0.02      |
| FeO (T)        | 33.69       | 37.30     |
| MgO            | 13.91       | 11.24     |
| MnO            | 0.68        | 1.17      |
| CaO            | 0.39        | 0.37      |
| Na$_2$O        | 0.01        | 0.01      |
| K$_2$O         | 0.00        | 0.00      |
| (O) Basis      | 6           | 6         |
| Si              | 1.964       | 1.964     |
| Ti              | 0.001       | 0.002     |
| Al              | 0.035       | 0.037     |
| Cr              | 0.001       | 0.001     |
| Fe$^{3+}$      | 1.098       | 1.232     |
| Fe$^{2+}$      | 0.027       | 0.027     |
| Mg              | 0.828       | 0.673     |
| Mn              | 0.023       | 0.038     |
| Ca              | 0.017       | 0.016     |
| Na              | 0.001       | 0.000     |
| K               | 0.000       | 0.000     |
| Σ Cations      | 4.0         | 4.0       |
| Ferrosilite    | 56.5        | 64.6      |
| Enstatite      | 42.6        | 34.6      |
| Wollastonite   | 0.9         | 0.8       |
| X$_{Mg}$       | 0.43        | 0.36      |
| X$_{Fe}$       | 0.57        | 0.64      |

Figure 4. Compositional diagrams of minerals (a) Pyroxene composition range [22] from core and margin part of charnockite patches, (b) Garnet compositional diagram [7], (c) Biotite compositional diagram [19], (d) Plagioclase compositional diagram.
(a) Orthopyroxene
Orthopyroxene is an essential mafic phase present in the charnockite patches and compositionally marked as hypersthene (Figure. 4a) as per the orthopyroxene classification proposed by Morimoto [22]. In general, ortho-pyroxene grains (from the core part of the charnockite patch) have an $X_{Mg}$ value of 0.35 to 0.36, whereas ortho-pyroxene grains are present near the margin of charnockite patches have $X_{Mg}$ value 0.43 – 0.45. Comparative study of both pyroxenes indicates that the pyroxenes at the margin of charnockite patches have lower FeO and higher MgO. The compositional variations among orthopyroxene grains are due to the migration of the basic components (FeO, Al$_2$O$_3$, and MnO) from the marginal part towards the core during the metamorphic process under the influence of the fluid phase. The distance of migration depends upon the intensity of the fluid-rocks interaction [28].

(b) Garnet
Compositionally the garnets are Fe rich with a subordinate concentration of Mg, Mn, and Ca. The almandine composition of garnets in charnockite patches is higher as compared to leptynites whereas the other end members of garnet i.e., pyrope, spessartine, and grossularite proportion are almost similar. Compositions of garnet are plotted in the garnet mineral classification diagram (Figure. 4b) after Coleman et al. [7]. The core parts of garnet have higher MgO content than their rim counterpart. Such variations in garnets are common among the rocks which have suffered progressive regional metamorphism. The compositional variation of garnets, among both the rock types is mainly controlled by the bulk rock composition as well as the diversity in the mineral assemblage.

(c) Biotite
Biotite is a common phase in both charnockite patches as well as leptynite hosts. The compositions of biotite from both portions are quite similar. The TiO$_2$ and Na$_2$O content of biotite are slightly higher in the charnockite portion as compared to host leptynite. Similarly, the MnO content of biotite is higher in leptynite. The $X_{Fe}$ values for all the biotites are almost constant and range from 0.65-0.68. The $X_{Fe}$ values are plotted in $X_{Fe}$-Al$_{IV}$ compositional diagram (Figure. 4c) after Lalonde and Bernard [19] to mark the compositional differences. The fluorine content of biotite is more in host leptynites than charnockite patches. Tropper et al. [44] observed that there is an increase in the modal abundance of the F-apatite in granulite facies rocks when compared to their amphibolite facies precursors. The lower fluorine content in biotite from charnockite patches might be due to the mobility of fluorine from biotite to apatite during the granulite facies metamorphism under the fluid dominant environment.
(d) Plagioclase

Another mineral phase that is commonly present in both charnockite patches and host leptynite is plagioclase with andesine composition (Figure 4d). The albite content of plagioclase from charnockite patches is $Ab_{63.1-64.8}$. Whereas in the leptynite portion it is $Ab_{65.2-67.7}$. Plagioclases from leptynites have higher CaO (6.53 – 7.31%) and Na2O content (7.47 – 7.90%) than the plagioclases from charnockites, where the CaO and Na2O content varies from 6.81 – 7.48% and 6.44 – 7.78% respectively.

Table 1B. Representative mineral chemistry of analysed phases from Leptynites.

|                | Biotite | Garnet | Plagioclase |
|----------------|---------|--------|-------------|
| SiO2           | 36.56   | 36.64  | 36.38       |
| TiO2           | 4.88    | 3.74   | 4.35        |
| Al2O3          | 15.12   | 15.11  | 13.94       |
| Cr2O3          | 0.00    | 0.00   | 0.00        |
| FeO(T)         | 20.78   | 20.69  | 20.75       |
| MgO            | 10.26   | 10.36  | 10.55       |
| MnO            | 0.01    | 0.08   | 0.10        |
| CaO            | 0.05    | 0.13   | 0.14        |
| Na2O           | 0.04    | 0.07   | 0.10        |
| K2O            | 9.52    | 9.44   | 8.82        |
| (O) Basis      | 7.48    | 6.81   | 7.48        |
| Si              | 5.76    | 5.77   | 5.86        |
| Ti              | 0.58    | 0.44   | 0.53        |
| Al              | 2.80    | 2.88   | 2.65        |
| Cr              | 0.00    | 0.00   | 0.00        |
| Fe2+           | 0.64    | 0.67   | 0.31        |
| Fe3+           | 0.00    | 0.00   | 0.00        |
| Mg              | 2.41    | 2.55   | 2.49        |
| Mn              | 0.00    | 0.01   | 0.01        |
| Ca              | 0.01    | 0.01   | 0.01        |
| Na              | 0.01    | 0.02   | 0.03        |
| K               | 1.91    | 1.90   | 1.81        |
| Σ Cations      | 67.60   | 67.70  | 67.30       |
| Almandine       | 68.80   | 69.90  | 69.60       |
| Grossular       | 11.90   | 10.50  | 10.40       |
| Pyrope          | 13.90   | 13.80  | 14.50       |
| Spessartine     | 5.40    | 5.90   | 5.60        |
| Xas            | 5.40    | 5.90   | 5.60        |
| Xao             | 65.60   | 65.20  | 65.50       |
| Xav             | 1.20    | 1.30   | 1.00        |
| Xas             | 0.33    | 0.34   | 0.33        |
| Xao             | 0.67    | 0.66   | 0.67        |

5. Geochemistry

The major oxide analyses of the samples were done by X-ray Fluorescence at National Centre for Earth Science Studies (NCESS), Trivandrum, India. The rare earth and trace element concentrations were analyzed by HR-ICP-MS available at National Geophysical Research Institute (NGRI), Hyderabad, India. Details of the ICP-MS analysis procedure and operating parameters are described by Balaram and Rao [4]. The major oxide geochemical data and their normative mineralogical calculations are presented in table 2. The trace and REE concentration data are presented in table 3.
As per major oxide analysis, the SiO$_2$ content in leptynites (76.19 – 76.30%) is more than charnockite patches (72.97 – 73.92%) whereas the MgO, FeO$^T$, K$_2$O, and TiO$_2$ contents are higher in charnockite patches. Overall, the major oxide data for both charnockite patches and host leptynites are analogous.

Feldspar composition diagram of O’Connor [26] shows that both charnockite patches and host leptynites belong to adamellite composition (Figure 5). As per the normative mineral composition, orthoclase and hypersthene proportions in charnockite patches are higher than the host leptynites whereas quartz proportion is higher in leptynites. Except for hypersthene, there is no compositional difference of minerals existing between host leptynite and charnockite patches. Based on the alumina saturation index [40] both leptynite and charnockite patches belong to peraluminous (Figure 6). The charnockite shows I-type affinity while leptynites fall within the S-type field of Maniar and Piccoli [21]. Similarly, as per the alkali lime index [12] host leptynites belong to calcic whereas charnockite patches represent calc-alkali nature (Figure 7). It is mainly due to increasing K$_2$O content in the charnockite portion during the granulite facies metamorphism. The K$_2$O content of charnockite is slightly higher than leptynite. Endo et al. [11] mentioned that there is a slight increase in K$_2$O from garnet-biotite gneiss (leptynite) to charnockite, as ortho-pyroxene becomes more stable with increasing K$_2$O content.

**Figure 5.** Or-Ab-An normative proportion [26] of charnockite patches and their host leptynites of Digapahandi area, EGB.

**Figure 6.** Discrimination diagram of Alumina saturation index [40] with the relative source of rocks [21] showing peraluminous nature for charnockite patches as well as host leptynites.

**Figure 7.** Alkali – lime index diagram [12] for charnockite patches and host leptynites.
### Table 2. Major oxide data of Patchy charnockite and host leptynites along with their norm calculation

| Sample no | Rock type | Charnockite | Leptynite |
|-----------|-----------|-------------|-----------|
|           | SiO₂      | SM 208     | SM 208 ii |
|           | TiO₂      | 0.21        | 0.2        |
|           | Al₂O₃     | 14.72       | 13.67      |
|           | MnO       | 0.02        | 0.03       |
|           | Fe₂O₃     | 1.48        | 1.82       |
|           | CaO       | 1.81        | 1.61       |
|           | MgO       | 0.21        | 0.43       |
|           | Na₂O      | 2.46        | 2.14       |
|           | K₂O       | 5.48        | 5.58       |
|           | Fe₂O₃     | 0.04        | 0.05       |
|           | Total     | 99.4        | 99.45      |

#### Norm Calculation

| Rock type | Sample no | SM 208 | SM 208 ii |
|-----------|-----------|--------|-----------|
| Quartz    | 33.16     | 35.52  | 39.62     |
| Corundum  | 1.55      | 1.31   | 1.78      |
| Orthoclase| 32.62     | 33.21  | 29.43     |
| Albite    | 20.97     | 18.23  | 20.43     |
| Anorthite | 8.78      | 7.71   | 7.94      |
| Hypersthene| 2.04     | 3.06   | 0.39      |
| Ilmenite  | 0.4       | 0.38   | 0.19      |
| Magnetite | 0.38      | 0.45   | 0.11      |
| Apatite   | 0.09      | 0.11   | 0.09      |
| Total     | 99.99     | 99.98  | 99.98     |

### Table 3. Trace and REE data of Charnockite patches and host leptynites.

| Sample no | Rock type | Charnockite | Leptynite |
|-----------|-----------|-------------|-----------|
|           | Sc        | 16.954      | 24.192    |
|           | V         | 84.005      | 88.314    |
|           | Cr        | 14.815      | 17.966    |
|           | Co        | 7.754       | 9.27      |
|           | Ni        | 1.094       | 1.165     |
|           | Cu        | 60.42       | 58.585    |
|           | Zn        | 15.272      | 19.38     |
|           | Ga        | 13.516      | 13.322    |
|           | Rb        | 8.647       | 10.731    |
|           | Sr        | 76.812      | 110.683   |
|           | Y         | 3.042       | 4.475     |
|           | Zr        | 19.555      | 21.274    |
|           | Nb        | 0.836       | 0.398     |
|           | Cs        | 0.04        | 0.05      |
|           | Ba        | 193.167     | 257.658   |
|           | Hf        | 0.478       | 0.536     |
|           | Ta        | 0.067       | 0.035     |
|           | Pb        | 6.77        | 8.104     |
|           | Th        | 0.142       | 0.216     |
|           | U         | 0.014       | 0.019     |
|           | La        | 4.826       | 5.669     |
|           | Ce        | 9.811       | 10.668    |
|           | Pr        | 1.111       | 1.241     |
|           | Nd        | 4.449       | 4.943     |
|           | Sm        | 1.059       | 1.165     |
|           | Eu        | 1.312       | 1.553     |
|           | Gd        | 0.967       | 1.144     |
|           | Tb        | 0.126       | 0.154     |
|           | Dy        | 0.633       | 0.779     |
|           | Ho        | 0.138       | 0.176     |
|           | Er        | 0.368       | 0.488     |
|           | Tm        | 0.056       | 0.083     |
|           | Yb        | 0.414       | 0.617     |
|           | Lu        | 0.065       | 0.098     |
|           | (La/Yb)N | 7.922       | 6.239     |
|           | (La/Sm)N | 2.845       | 3.04      |
|           | (Gd/La)N | 1.827       | 1.438     |
|           | Eu/Eu*   | 3.952       | 4.1       |
|           | Ba/Rb    | 22.338      | 24.011    |
|           | Ba/Sr    | 2.515       | 2.328     |
|           | Sr/Y     | 25.253      | 24.732    |
|           | LREE     | 21.257      | 23.686    |
|           | HREE     | 2.767       | 3.54      |
|           | LREE/HREE| 7.682       | 6.691     |
|           | K/Rb     | 5260.54     | 4316.474  |
|           | Rb/Sr    | 0.113       | 0.097     |
The trace element concentrations of both the rock types are almost comparable. The Sc, V, Co, Zn, Ga, and Y concentrations are higher in charnockite patches as compared to host leptynite. The Rb/Sr ratios for both the rock types are low and almost similar (0.09 – 0.12). Similarly, low to moderate Ba/Sr ratios (2.16 – 2.60) of both the rocks suggest the fractionation of plagioclase through the dehydration melting of the crustal source material [35]. The primitive mantle normalized spider plot [43] shows the depleted nature of Cr, Ni, Zn, Rb, and Y content whereas enrichment in Ba and Sr contents (Figure 8a). Strongly depleted Rb in rocks is due to the increasing metamorphic grade [2]. When it reaches the anatectic point, the Rb gets partitioned into the melt phase.

The chondrite normalized REE plot for all investigated samples is represented in figure 8b. The REE pattern for both host leptynites and charnockite patches is quite similar with a strong positive Eu anomaly, due to the incorporation of plagioclase in the rocks. The Eu/Eu* ratio varies from 2.67 – 4.14 and is almost constant for both the rocks. This is also supported by the abundance of plagioclase in rocks and is evidenced through petrography. These samples show LREE enrichment with depleted HREE (Figure 8b). Chondrite normalized [43] REE plot for both the rock types, show relatively steeper
LREE pattern as well as slightly steeper to nearly flat HREE pattern for both leptynite and charnockite respectively. The LREE/HREE ratio for charnockite patches (6.69 – 7.68) is lower than the leptynites (10.04 – 10.88). The charnockite patches show more HREE enrichment than host leptynite. The (La/Yb)_N ratio for charnockite patches is low (6.24 – 7.92) as compared to host leptynites (20.43 – 20.76). This pattern indicates that the host leptynites are highly fractionated compared to charnockite patches. The higher (Gd/Lu)_N ratio of leptynites is evident for HREE fractionation rather than LREE.

6. Discussion

The origin of patchy charnockites in different parts of EGB was proposed by different authors [5][8][9][13][18][23]. It is unanimously accepted that the charnockite patches are commonly present in host felsic gneisses and leptynites. The earlier views on the formation of charnockite patches are quite distinct. Bhattacharya et al. [5] and Kar [18] described the patchy charnockites as ‘relict charnockites’ based upon the diverse geochemical signatures as well as structural characteristics. Dobmeier and Raith [9] describe these charnockites as ‘arrested type of charnockites’, which probably originated through in-situ dehydration process within the leptynite and were presumably formed due to the localized syn-kinematic fluid migration through structurally controlled sites. About these two types of formation, nature of the studied patchy charnockites is described here.

As the major oxide and trace element concentrations are almost similar, it suggests that both the rocks are co-genetic in origin. The higher K/Rb ratio for both the rocks advocates the dehydration process. The Al_2O_3 versus SiO_2 (Figure. 9a) as well as Sr versus SiO_2 plots (Figure. 9b) after Rajesh et al. [32] for both the rocks of the study area also favours the dehydration process. The occurrence of small irregular-shaped elongated charnockite patches along the foliation planes within leucocratic leptynite host at Digapahandi area of EGB appears to be structurally controlled as manifested from field relationships which commonly exhibit diffuse margin. The presence of ortho-pyroxene in the charnockite portion makes it different from the host leptynite, otherwise, the rest of the mineral phases are common and compositionally analogues, as reflected by the mineral chemistry. As per the bulk rock geochemistry, both host leptynites and charnockite patches show iso-chemical nature. They are adamellite in composition with per-aluminous nature. The charnockite patches were developed within

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**Figure 9.** Compositional range of dehydration zone [15][16][32] applied for charnockite patches and host leptynites from Digapahandi area, EGB. (a) SiO_2-Al_2O_3 graph and (b) SiO_2-Sr graph showing the dehydration zone for charnockite patches.
the leptynite host through the biotite-dehydration melting process at structurally controlled sites, through the interaction of the fluid phase.

According to Tropper et al. [44], the solubility of HREE appears to be much more than LREE in the fluorine-bearing fluids during granulite facies metamorphism. The relatively higher HREE concentration within the charnockite patches as compared to the host leptynite seems to be due to the presence of a fluid phase. However, the fluid inclusion study was not performed in the present study but the biotites of charnockite patches having fluorine content compared to leptynite indicates the activity of CO₂ rich fluid phase in the formation of these charnockite patches. The detailed fluid inclusion studies on these rocks will certainly elucidate the role of fluid phases in their origin.

7. Conclusion
Charnockites occur as small patches within the host leptynites and granitic gneisses throughout the EGB. These charnockite patches have been described as ‘relict charnockite’ as well as ‘arrested or incipient charnockite’ based upon the structural and geochemical studies. Based on detailed petrography, minerals chemistry and geochemical studies carried out on the charnockite patches occurring within the leptynite host at Digaphandi area of EGB may be classified as incipient charnockite. The host leptynites are believed to be the product of anatectic melt generated through the partial melting of the khondalite during an early stage of evolution. The incipient charnockites were developed within the host leptynites, along the foliation planes, through biotite-dehydration melting under the influence of fluid phase, at a later stage of the evolutionary history. The mineral chemistry and whole-rock geochemistry data suggest both the charnockite patches and the host leptynites are isochemical. Hence the causative factor for the incipient growth of charnockite patches within-host leptynite is supposed to be the iso-chemical transformation of leptynites into charnockites under the high-grade granulite facies metamorphic condition.

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