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# Mafic granulite xenoliths in the Chilka Lake suite, Eastern Ghats Belt, India: evidence of deep-subduction of residual oceanic crust

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## Abstract

Granulite xenoliths preserve key geochemical and isotopic signatures of their mantle source regions. Mafic granulite and pyroxinite xenoliths within massif-type charnockitic rocks from the Eastern Ghats Belt have recently been reported by us. The mafic granulite xenoliths from the Chilka Lake granulite suite with abundant prograde biotite are geochemically akin to Oceanic Island Basalt (OIB). They can be distinguished from the hornblende-mafic granulite xenoliths with signatures of Arc-derived basalt occurring in the other suites of the Eastern Ghats Belt. These two groups of xenoliths in the Paleoproterozoic Eastern Ghats Province have quite distinct Nd-model ages- 1.9 Ga and 2.5 Ga respectively, which may be interpreted as their crustal residence ages. 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. Also low Yb and Sc contents and high $(La/Yb)_N$ ratios can be attributed to melting in the presence of residual garnet and hence at great depths (> 80 km). The variable enrichment in radiogenic $^{87}$Sr, between 0.70052 and 0.71092 at 1.9 Ga and less radiogenic $^{143}$Nd between $\varepsilon$-1.54 and 7.46 are similar to those of the OIBs compared to MORBs. As OIBs commonly contain some recycled oceanic crust in their sources, we suggest that the residue of the oceanic crust from a previous melting event (~ 2.5 Ga) that produced the Arc-derived basalts (protoliths of hornblende-mafic granulite xenoliths) could have subducted to great depths and mechanically mixed with the mantle peridotite. A subsequent re-melting event of this mixed source might have occurred at ca. 1.9 Ga as testified by the crustal residence ages of the biotite-mafic granulite xenoliths of the Chilka Lake granulite suite.





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## 1 Introduction

Lower crustal rocks commonly occur in large outcrops (granulite terrains) and as small fragments (xenoliths) brought to the surface by fast-erupting volcanics. However, granulite xenoliths differ from those of the exposed terrains in two important aspects. First, many granulite terrains are Archaean, whereas very few granulite xenolith localities are situated in the Archaean crust. Second, granulite terrains tend to be dominated by evolved compositions, whereas granulite xenoliths are clearly dominated by mafic lithologies (Rudnick, 1992).

Recently mafic granulite and pyroxinite xenoliths within massif-type charnockitic rocks have been described from the Eastern Ghats Granulite Belt, India (Bhattacharya et al., 2011). These mafic granulite xenoliths, both in the Paleoproterozoic (Eastern Ghats Province) and in the Archaean crustal domains (Dobmeier and Raith, 2003), are characterized by abundant prograde hornblende and geochemical signatures of Arc-derived basalts. In the Chilka Lake suite of the Eastern Ghats Province, the xenoliths are mineralogically distinct, namely with abundant prograde biotite, from those in other suites of the Eastern Ghats Province.

In this communiqué we describe geochemistry and Sr-Nd isotopic composition of the biotite- mafic granulite xenoliths along with geochemistry of the host charnockitic rocks from the Chilka Lake suite to reveal the nature and mantle-source of their protoliths (Condie, 2001). We also try to explain the different geochemical and isotopic signatures in them in relation to tectonic setting and mantle dynamics (Condie, 1998).

## 2 Geological setting

### 2.1 Eastern Ghats Belt

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





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events (Bhattacharya et al., 1994; Dasgupta et al., 1994; Sen et al., 1995; Bhattacharya, 1996; Dasgupta and Sengupta, 1998; Bhattacharya and Kar, 2002). Although generally considered as a Proterozoic terrain, some Archaean domains have been recognized and even Archaean granulite facies event recorded recently (Ramakrishnan et al., 1998; Rickers et al., 2001; Bhattacharya et al., 2001). The massif-type charnockite and associated granulites form an important component in this large granulite terrain with other exposed lithologies such as: metapelitic granulites, calc-granulites, per aluminous granitoids and migmatites (Fig. 1). Although contact between charnockite and other important granulite lithologies- metapelitic granulites and calc-granulites are not exposed, plutonic nature of the charnockite is evident from expansive bodies of continuously varying compositions, from enderbite through charno-enderbite to charnockite. Barring the cratonic margins in the north and west, the northern Eastern Ghats Belt, north of Godavari graben has been defined as the Eastern Ghats Province (Dobmeier and Raith, 2003). From this Paleoproterozoic Eastern Ghats Province we have described hornblende-mafic granulite xenoliths interpreted as basaltic melts with Arc – basalt signatures, the mafic magmatism occurring at ca. 2.5 Ga as indicated by $T_{DM}$ ages of the xenoliths (Bhattacharya et al., 2011). It was also reported earlier that hornblende-dehydration melting in the protolith of the hornblende-mafic granulites produced the charnockitic melts of tonalitic composition in the Jenapore suite of the Eastern Ghats Belt (Kar et al., 2003).

## 2.2 Chilka Lake area

The Chilka Lake area in the Eastern Ghats Province, however, have certain distinctive features: it exposes diverse assemblages, including patchy charnockite, massif-type charnockite, bands of enderbite within per aluminous granitoids and migmatites, patches of UHT pelitic granulites, khondalites-quartzites, calc-granulites and massif-type anorthosite (Bhattacharya et al., 1994). Geochronological record from the Chilka Lake area is also complicated and somewhat controversial, particularly in relation to granulite facies metamorphism and anorthosite magmatism. A genetic link between





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the anorthosite-massif and granulite association, viz., anorthosite intrusive cores acting as "exotic" heat sources for granulite facies metamorphism was proposed (Mukherjee, 1989). The Chilka Lake anorthosite was dated by Rb-Sr whole rock method as 1404 Ma (Sarkar et al., 1981). However, from detailed structural studies the anorthosite was described as post-$S_2$, while the granulite suites record a strong $S_2$ imprints, in the form of shear fabric and small scale shear zones, and hence the anorthosite could not have been the source of heat for the granulite facies metamorphism (Bhattacharya et al., 1994). Recently published isotopic data from Chilka Lake granulite suites indicate a strong Grenvillian imprint and post-Grenvillian transpression (Crowe et al., 2001; Bhattacharya et al., 2002; Dobmeier and Simmat, 2002). On the other hand, two recent publications have come up with U-Pb ages of the Chilka anorthosite (Krause et al., 2001; Chatterjee et al., 2008). While Krause et al. (2001), suggested an emplacement age of 793 Ma, and Chatterjee et al. (2008), suggested an emplacement age of 983 Ma for the Chilka Lake anorthosite. Krause et al. (2001) described the ferrodiorite as late stage differentiates of the anorthosite magma, while Chatterjee et al. (2008) argued that ferrodiorite (dated by Krause et al. 2001) occurs as late intrusive into the anorthosite-massif. Recently reported U-Pb monazite ages (1.2 Ga) in the Eastern Ghats Province, suggest that anorthosite intrusion is surely much younger and unrelated to granulite facies metamorphism (Simmat and Raith, 2008). Dobmeier and Simmat (2002) also reported post-Grenvillian fabric-defining transpression at 690–662 Ma and local resetting at 520–505 Ma.

## 3 Chilka suite

Field relation and petrography. The Chilka Lake suite occurs in the northeastern part of the Eastern Ghats Province. The biotite-mafic granulites mostly occur as irregular and discordant blocks within massif-type charnockite (Fig. 2). In the Chilka Lake suite the mafic granulite xenoliths contain abundant prograde biotite and the massif-type charnockite in this suite is of granitic to granodioritic compostion, with the assemblage: quartz-Alkali-feldspar-plagioclase-orthopyroxene-Fe-Ti oxides. Mafic granulite xenoliths selected for analysis in this suite have the dominant assemblage: biotite-orthopyroxene-plagioclase-Fe-Ti oxides ± hornblende. Biotite has embayed grain boundaries against K-feldspar, and orthopyroxene, indicating prograde or restitic nature of the biotite in these mafic granulite xenoliths (Fig. 3).

## 4 Analytical procedures

Bulk chemical analysis was carried out by X-Ray Flourescence Spectrometry, at National Geophysical Research Institute, Hyderabad. Trace elements including rare earth elements were analyzed by Inductively Coupled Plasma Mass Spectrometer, at Institute Instrumentation Center (I. I. C), Indian Institute of Technology, Roorkee. Isotopic analysis was carried out with Thermal Ionization Mass Spectrometer (TRITON), at I. I. C, Indian Institute of Technology, Roorkee.

Operating condition for XRF machine was 20/40 KV for Major oxides and 50/60 KV for trace elements. Nominal analysis time was 300 s for all major oxides and 100 s for each trace element. For the XRF analysis the overall accuracy (% relative standard deviation) for major and minor oxides are less than 5 % and that for trace elements is less than 12 %. The average precision is reported as better than 1.5 %.

For determination of concentrations of trace and rare earth elements, about 20 mg of each of the samples were weighed in a screw capped Teflon (Savillex) vial and digested in the conventional way by adding HF and $HNO_3$ mixture. The dissolved samples were diluted to 100 g of the sample solution in 2N $HNO_3$. All measurements were done on a Perkin-Elmer Sciex ELAN DRC 6000 ICP-MS at I. I. C, Indian Institute of Technology, Roorkee. For calibrating the instrument two USGS rock standards, GSP-2 and AGVO-2 were used. In general the RSD for all the elements is much less than 4 %. Individually they are less than 2.5 % for alkali and alkaline earth metals, less than 2 % for the transition elements, within 3 % for LREE and within 4 % for HREE.





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For isotope dilution and isotopic composition, Rb, Sr and REE fractions were separated from the rock solutions using Bio-Rad AG50 X 8 ion exchange resin in silica glass columns. Sm and Nd were separated from REE fractions using pre-packed LN Spec Resins (bought from Eichron Technologies INC, Dorien, Illinois, USA). The total procedure blank in the laboratory was less than 8 ng of Sr and ~1 ng of Nd during the period of analysis. Rb, Sr, Sm and Nd abundances were determined by isotope dilution method. The isotope ratios were measured on a Thermo Fisher TRITON T1 fully automatic variable multi collector mass spectrometer at I. I. C, Indian Institute of Technology, Roorkee, based on 2$\sigma$ error statistics. Measured ratios for isotopic composition were normalized to $^{86}Sr/^{88}Sr = 0.1194$ for Sr and $^{146}Nd/^{144}Nd = 0.7219$ for Nd. The long term average for measured ratio of 87Sr/86Sr for NIST-987 Sr Standard was 0.710248 ± 10 (2$\sigma$) and that of 143Nd / 144Nd for Ames Nd Standard was 0.512138 ± 4 (2$\sigma$).

## 5 Geochemistry

### 5.1 Bulk composition

The mafic granulites of the Chilka Lake suite comprise abundant prograde biotite. This is reflected in the relatively lower values of CN / CNK between 0.89 and 0.94 (Table 1). Broadly their composition can be described as tholeiite, but compositional variation is noted in normative olivine between 8.65 and 22; and Mg# between 51.14 and 68.95. A distinctive chemical feature is that these biotite-mafic granulites have relatively low normative Di and low normative Olv and no normative Ne in them, in contrast to the hornblende-mafic granulites of the other suites in the Eastern Ghats Province, which have high normative Di, Olv and Ne (Bhattacharya et al., 2011). Additionally, some heterogeneity in the source rock compositions can be inferred from lack of correlation between Mg# and CN / CNK values. With these constraints, the near co-variation between Mg# and normative Olv contents can be interpreted as resulting from variable extraction of partial melts from them; or in other words, these mafic granulites are restitic in nature. On the other hand, this chemical variation can not be assigned to a previously differentiated suite, which is apparent from the lack of correlation between Mg# and Niggli *alk*. Mg# versus $SiO_2$ / $Al_2O_3$ diagram shows that inspite of the effect of granulite facies metamorphism and partial melting, the biotite mafic granulites are akin to primary basaltic melt composition: four samples plotted in the field of primary melt and two samples represent evolved alkaline melt (Fig. 4). It is important to note that mafic granulite xenoliths from western Hungary have been argued, on similar ground, as being solidified melts rather than mafic cumulates (Kempton and Harnon, 1992).

The host Charnockitic rocks are somewhat variable in composition between granodiorite and granite, with normative Or between 14.49 and 27.2 (Table 1).

## 5.2 Trace element composition

Trace elements, including REE, composition of the biotite-mafic granulite xenoliths and the host charnockites is presented in Table 2.

Comparative K, between charnockite and mafic granulite xenolith appears problematic; however, it is important to note here that the xenoliths with abundant biotite could be responsible for the lack of K-enrichment in the charnockitic melts. Rb, Ba enrichment, but marginal Sr depletion in charnockite relative to biotite mafic granulite xenoliths is consistent with biotite-melting and coexisting with charnockitic melt of granitic composition (Table 2). Significant Y depletion in the charnockite on the other hand, is compatible with plagioclase-poor melt composition and significant depletion of Ti and Zr suggest poor melt-restite interaction (Fig. 5).

Variation of trace elements Sr, Ce, Ni and Zr in the mafic granulites are not related to variation in Mg# and this further attests to the fact that the chemical variability in these mafic granulite xenoliths are not the result of a previous magmatic differentiation and/or fractional crystallization of minerals. Also compared to the hornblende-mafic granulite xenoliths (Bhattacharya et al., 2011) the biotite-mafic granulite xenoliths are poorer in V, Sc, Cr and Ni, averaging 187, 5.21, 144 and 32.23 ppm respectively, as against 316,





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21, 987 and 69 ppm respectively. These are also compatible with the mineralogical contrasts, namely biotite against hornblende in these xenoliths. Trace element distribution relative to Primitive Mantle (Fig. 6) shows a conspicuous peak in Rb (Ba spike in hornblende-mafic xenoliths); no negative Nb anomaly and most of the trace element contents are on the higher side. The pattern of incompatible element enrichments in the mafic xenoliths are similar to those in OIBs as well as those in high-Ti continental flood basalts; however, strong positive Nb anomalies, much low Yb (average 2.22 ppm) and Sc (average 5.5 ppm) contents and low La / Nb ratios are distinct from those in continental flood basalts. Also these xenoliths are distinctive in having high values of Nb / U (average 33.04), compared to the hornblende-mafic granulite xenoliths (average 22.8) from the Eastern Ghats Province described earlier (Bhattacharya et al., 2011). La / Nb values are also low (average 0.85) compared to those in the hornblende-mafic granulite xenoliths (average 2.6).

#### 5.2.1 Th / Ta – La / Yb relationships

Th / Ta and La / Yb ratios in basalts are particularly sensitive to mantle source composition and to mixing processes (Condie, 2001). In the Chilka xenoliths these ratios range between La/Yb (8 and 15), Th / Ta (0.2 and 2.4) and these are consistent with those in most of the OIBs (wide range of La / Yb: 3–25; moderate range of Th / Ta: 0.7–2). Th / Ta-La / Yb relationships in Fig. 7 further indicate presence of HIMU and or enriched components in the source of these xenoliths.

### 5.3 Rare earth element composition

These mafic granulite xenoliths are LREE enriched $(La/Yb)_N = 5.9–10.4$; while LREE fractionation $(La/Sm)_N = 2.8–3.4$ is more than HREE fractionation $(Gd/Lu)_N = 1.3–2.9$. The chondrite normalized plot shows both negative and positive Eu anomaly, $Eu/Eu^*$ between 0.88 and 1.08 (Fig. 8). Negative Eu anomaly and LREE enrichment are also characteristics of the plagioclase-rich garnet granulite xenoliths from



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the Northern Baltic shield (Kempton et al., 2001). However, Baltic shield xenoliths with garnet, are more enriched in LREE $(La/Yb)_N = 10.5–23.8$. On the other hand marginal positive Eu anomaly could imply no plagioclase in the residue. LREE-enrichment and flat to depleted HREE patterns are comparable to those in OIBs.

## 6 Sr-Nd isotopic composition

The whole rock Rb-Sr and Sm-Nd isotopic compositions of the biotite mafic granulites and the host charnockites is given in Table 3. Whole rock Rb-Sr and Sm-Nd isotopic data could not be used for precise age determination of the granulite facies event due to poor spread or co linearity of the isotopic data.. In this section of the EGB, our main interest is to find the age of the protolith or the age of mafic magmatism, which can be best represented by Nd-model ages. The Nd-model age or $T_{DM}$ has been calculated with reference to CHUR values of $^{143}Nd/^{144}Nd$ as 0.513151 and $^{147}Sm/^{144}Nd$ as 0.222 and decay constant $\lambda$ as $6.54 \times 10^{-12}\,yr^{-1}$ (DePaolo, 1988). The average crustal residence time for biotite-mafic granulite xenoliths and host charnockites is 1.9 Ga, which is interpreted as the age of mafic magmatism in this area. The initial $^{87}Sr/^{86}Sr$ ratios calculated at 1.9 Ga, range between 0.70052 and 0.71092; while $\varepsilon$ values calculated at 1.9 Ga range between 7.46 and −1.54.

## 7 Discussion

### 7.1 Geochemistry

In a previous study, it was reported that the bulk composition of the Charnockitic rocks of the Chilka Lake area show a relic magmatic trend, comparable to the Antarctic charnockites described by Sheraton and Collerson (1984) (Bhattacharya, 1996). In the context of the igneous precursors of the biotite-mafic granulites occurring as enclaves



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within the host massif-type charnockites, it is reasonable to assume a genetic link between them via partial melting in the precursors of the mafic granulites. Complementary trace element signatures between charnockite and biotite-mafic granulite are compatible with the melt-restite relation between them and hence the biotite-mafic granulites could be interpreted as cognate xenoliths. Most of the incompatible elements in the Chilka biotite-mafic xenoliths are more enriched than those in either MORB or Arc-basalts. Rb-spike, lack of positive Sr-anomaly and consistently positive Nb-anomalies are similar to those of the Oceanic Island Basalt (McCulloch, 1993). Low values of La / Nb are also compatible with those of the Oceanic Island Basalt (Rudnick, 1995; Condie, 1999). Strongly positive Nb anomaly together with relatively high Nb / U values (average 33.04) in these xenoliths, unlike those in the hornblende-mafic granulite xenoliths, are comparable although a little less than those in the OIB, indicating no recycled continental crust in their mantle source. The high $(La/Yb)_N$ ratios (average 7.87) can be attributed to melting in the presence of residual garnet, and hence at depths below the spinel to garnet transition in mantle peridotite (Thirlwall et al., 1994). LREE enrichment and a strongly fractionated REE pattern are also akin to OIBs.

The wide range in La / Yb, yet small range in Th / Ta in Iceland and Ascension basalts could have resulted from varying degrees of melting, leaving garnet in the residue (Condie, 2001); and a similar explanation for the Chilka xenoliths seems likely, as indicated by low Yb and Sc contents in them. The high incompatible – element enrichments coupled with low abundances of Yb and Sc, most likely caused by persistence of garnet in the melt residue, are stable in peridotites at depths greater than 80 km (Hofmann, 2004). Particularly important is the strong positive Nb anomalies, indicating the presence of a relatively Nb-rich component, such as subducted oceanic crust in the mantle source of this xenolith suite (Fitton, 2007). In view of the Arc volcanism at ca. 2.5 Ga, represented by the hornblende-mafic granulite xenoliths in the Eastern Ghats Province (Bhattacharya et al., 2011), the residue of oceanic crust remaining from this process could have subducted further to great depths (> 300 km), where it may ultimately be mechanically mixed with mantle material (Allegre and Turcotte, 1986). On





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the other hand, the geochemistry of Oceanic Island Basalts is widely believed to contain some recycled oceanic crust in their sources (Dixon et al., 2002). Oceanic Island Basalt type geochemical signatures in the biotite-mafic granulite xenoliths of the Chilka Lake suite may be viewed as remelting of this mixed source (Peridotite + Residue) at greater depths, sometime later (< 2.5 Ga). It is interesting to note that the Chipman mafic dyke swarm was suggested to have been derived from a predominantly depleted lithospheric or asthenospheric mantle source with assimilation of older subduction related intrusive during emplacement (Flowers et al., 2006).

### 7.2 Isotopic compositions

The average crustal residence age of these xenoliths, given by $T_{DM}$, is 1.9 Ga and this may be interpreted as the age of mafic magmatism in the Chilka Lake area in the Eastern Ghats Province. This is definitely younger than the 2.5 Ga mafic magmatism, recorded from the hornblende-mafic granulite xenoliths in the Eastern Ghats Province (Bhattacharya et al., 2011). It is important to note that older zircons in the Chilka charnockite, namely 1722 Ma and 2694 Ma was reported earlier and interpreted as pre-Grenvillian magmatism (Bhattacharya et al., 2002). Also some recently analyzed zircons from the Chilka charnockite, by LA-ICP-MS (unpublished data with the present authors) show concordant zircons between 2.1 and 1.9 Ga. The variable enrichment in radiogenic $^{87}$Sr, between 0.70052 and 0.71092 at 1.9 Ga and less radiogenic $^{143}$Nd between $\varepsilon$-1.54 and 7.46 are similar to those of the OIBs compared to MORBs (Hofmann, 2004) and this suggests subducted oceanic crust in their mantle source. The coupled enrichment in both Sm and Rb, with positive $\varepsilon$ values at 1.9 Ga, being contrary to the geochemical properties of these elements, could also indicate subducted oceanic crust in their mantle source. Nd-Sr isotope relationships in these xenoliths may also be viewed in terms of mantle source components. Figure 9 shows the majority clustered around HIMU; and as in the Th / Ta-La / Yb relationship a HIMU dominated source can be envisaged.





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## 7.3 Mantle-source and model melting

Although, recycled oceanic crust is generally believed to be present in OIB sources (Dixon et al., 2002; Fitton, 2007), some alternative models were also proposed (Niu and O'Hara, 2003; Sobolev et al., 2005, 2007). Niu and O'Hara suggested that metasomatized and recycled deep portions of oceanic lithosphere are the most likely candidates for OIB source in terms of petrology, geochemistry and mineral physics (Metasomatic model). Sobolev et al. (2005) proposed the "pyroxenitic" source model. They argued that high Ni and $SiO_2$ in the Hawaiian tholeiites do not permit equilibrium with an olivine bearing source. But Fitton (2007) argued that although EM OIBs tend to have the lowest Δ Nb values, most still have $\Delta Nb > 0$, suggesting that a relatively Nb-rich component (probably subducted oceanic crust) is present in all OIB sources. Given that the Chilka xenoliths are poor in Ni (average 32.23 ppm), the pyroxenitic model seems inappropriate here. On the other hand, the evidence of oceanic crustal residue in the form of Nb-enrichment in the xenoliths suite and a previous subduction event in the Eastern Ghats Province, India (Bhattacharya et al., 2011) is consistent with a mixed source for the OIB-type magma, as represented by the biotite-mafic granulite xenoliths of the Chilka suite.

The residue of the 15 % melting of a source (70 % peridotite + 30 % GLOSS) (Bhattacharya et al., 2011) is considered here to have been mixed with peridotite, as the source composition for the remelting and generation of the melts with OIB signatures. This source is considered as mechanical mixture of 30 % of residue from previous melting and 70 % of the peridotite. Batch melting calculations have been performed using NEWPET computer programme (selected results given in Table 4), which indicates 7 % melting for the best match (Fig. 10).

## 7.4 Deep-subduction and 1.9 Ga superevent connection?

Some Nb-rich component in the source of the xenoliths suite, arguably the oceanic crustal residue from a previous subduction around 2.5 Ga, might have subducted to



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great depths (> 300 km) and mechanically mixed with the mantle peridotite (Allegre and Turcotte, 1986). On the other hand, the 1.9 Ga mafic magmatism representing juvenile crust (with positive epsilon values), could be related to the 1.9 Ga superevent (Condie, 1995).

In terms of models of mantle dynamics, layered convection in the earth catastrophically changes to whole mantle convection during short-lived episodes that could represent the three superevents: 2.7, 1.9 and 1.2 Ga (Condie, 1998). As argued by Condie (1998), after the formation of the Late Archean supercontinent, mantle returns to layered convection and some fragments of descending slabs may subduct further and again begin to accumulate at the 660-km discontinuity.

Evidence of deep-subduction of oceanic crustal residue and 1.9 Ga juvenile crust formation in this xenoliths suite are consistent with the models of catastrophic superevents.

## 8 Concluding remarks

Mafic magmatism with Oceanic Island Basalt signatures in the Chilka Lake area, at 1.9 Ga, following an earlier magmatism at 2.5 Ga in the Paleoproterozoic Eastern Ghats Province, could be attributed to re-melting at greater depths in the mantle.

The source of this xenoliths suite includes deeply subducted oceanic crustal residue from the previous melting and arc-related mafic magmatism at 2.5 Ga.

1.9 Ga mafic magmatism with HIMU dominated source related to the ~1.9 Ga superevent?

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**Table 1.** Bulk compositional data of the biotite-mafic granulites and host charnockites of the Chilka Lake suite, Eastern Ghats Belt, India.

| Bulk composition of Chilka Lake Suite | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Biotite-mafic granulite xenoliths | | | | | | Charnockite | | |
| Oxides Wt % | CK 3/2 | CK 4/2 | CK 5/2 | D1/01 | *CK 3/1 | CK 5/1 | CK 2/4 | D4/01 | D7/01 |
| $SiO_2$ | 49.71 | 48.88 | 47.93 | 48.64 | 46.91 | 46.9 | 68.03 | 64.94 | 72.31 |
| $Al_2O_3$ | 15.95 | 14.7 | 15.58 | 16.58 | 14 | 14.28 | 15.19 | 14.59 | 14.3 |
| $TiO_2$ | 2.19 | 1.45 | 2.47 | 2.66 | 1.92 | 1.99 | 0.36 | 0.4 | 0.05 |
| $Fe_2O_3$ | 12.38 | 13.96 | 14.93 | 14.55 | 12.95 | 12.84 | 3.95 | 4.69 | 1.24 |
| MnO | 0.19 | 0.21 | 0.23 | 0.22 | 0.17 | 0.18 | 0.05 | 0.06 | 0.02 |
| MgO | 6.46 | 7.83 | 4.82 | 4.5 | 7.68 | 7.81 | 1.2 | 1.75 | 0.56 |
| CaO | 5.39 | 5.69 | 6.12 | 5.85 | 9.17 | 9.13 | 3.87 | 4.42 | 2.64 |
| $Na_2O$ | 3.69 | 2.36 | 3.51 | 4.2 | 2.91 | 2.77 | 3.61 | 3 | 3.08 |
| $K_2O$ | 1.87 | 1.52 | 1.05 | 1 | 1.46 | 1.31 | 3.17 | 2.35 | 4.54 |
| $P_2O_5$ | 0.4 | 0.24 | 0.48 | 0.52 | 0.24 | 0.24 | 0.22 | 0.11 | 0.02 |
| Total | 98.23 | 96.85 | 97.12 | 98.73 | 97.41 | 97.44 | 99.65 | 96.32 | 98.74 |
| CN/CNK | 0.89 | 0.9 | 0.94 | 0.94 | 0.93 | 0.94 | 0.93 | 0.94 | 0.97 |
| Mg. No. | 67.39 | 68.95 | 56.11 | 55.05 | 51.14 | 51.77 | 34.91 | 39.71 | 44.36 |
| Normative composition | | | | | | | | | |
| Q | 0 | 0 | 0 | 0 | 0 | 0 | 23.32 | 24.92 | 30.35 |
| C | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Or | 11.39 | 9.41 | 6.49 | 6.08 | 8.98 | 8.05 | 18.88 | 14.49 | 27.2 |
| Ab | 32.19 | 20.92 | 31.05 | 36.53 | 21.17 | 22.67 | 30.77 | 26.48 | 26.42 |
| An | 22.1 | 26.22 | 24.74 | 24.1 | 21.67 | 23.57 | 16 | 20.25 | 11.95 |
| Ne | 0 | 0 | 0 | 0 | 2.41 | 0.92 | 0 | 0 | 0 |
| Di | 2.3 | 1.42 | 3.14 | 1.89 | 19.85 | 18.07 | 1.6 | 1.58 | 1 |
| Hy | 9.02 | 29.7 | 15.74 | 6.93 | 0 | 0 | 8.17 | 11.14 | 2.91 |
| Olv | 17.57 | 8.65 | 12.64 | 17.82 | 21.36 | 22.02 | 0 | 0 | 0 |
| Mt | 0.19 | 0.21 | 0.23 | 0.22 | 0.2 | 0.19 | 0.06 | 0.07 | 0.02 |
| Il | 4.29 | 2.88 | 4.9 | 5.19 | 3.79 | 3.93 | 0.69 | 0.79 | 0.1 |
| Ap | 0.98 | 0.6 | 1.19 | 1.27 | 0.59 | 0.59 | 0.52 | 0.27 | 0.05 |
| Total | 100.02 | 100.01 | 100.03 | 100.03 | 100.01 | 100.01 | 100.01 | 100.01 | 100 |





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**Table 2.** Trace element data of the biotite-mafic granulites and charnockites of the Chilka Lake suite in the Eastern Ghats Belt, India.

| Trace element composition in ppm of Biotite-mafic granulite and Charnockite of Chilka Lake suite | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Biotite-mafic granulite | | | | | | | | | | Charnockite | | |
| Sample | CK 3/2 | CK 4/2 | CK 5/2 | D1/01 | CK 3/1 | CK 5/1 | Average | | | | CK 2/4 | D4/01 | D7/01 |
| Ni | 31.74 | 71.25 | 16.26 | 14.8 | 30.01 | 29.32 | 32.23 | | | Ni | 16.52 | 16.12 | 6.84 |
| Cr | 122.17 | 622.54 | 18.99 | 17.85 | 42.47 | 45.2 | 144.1 | | | Cr | 93.4 | 83.81 | 29.2 |
| V | 155.21 | 253.82 | 189.92 | 198.13 | 235.07 | 245.93 | 187.2 | | | V | 76.26 | 101.66 | 21.9 |
| Sc | 3.88 | 6.32 | 4.4 | 4.63 | 5.77 | 6.23 | 5.21 | | | Sc | 1.59 | 2.11 | 0.54 |
| Co | 52.14 | 66.64 | 39.47 | 50.18 | 51.56 | 55.79 | | | | Co | 80.44 | 51.73 | 76.9 |
| Cu | 39.83 | 4.71 | 60.62 | 60.08 | 67.34 | 68.69 | | | | Cu | 16.21 | 16.94 | 1.61 |
| Zn | 108.82 | 100.91 | 138.58 | 136.03 | 105.36 | 78.33 | | | | Zn | 50.92 | 46.38 | 13.2 |
| Th | 0.86 | 3.85 | 2.80 | 2.20 | 2.46 | 2.94 | | | | Th | na | na | na |
| U | 0.6 | 1.97 | 0.99 | 1.42 | 1.08 | 1.80 | | | | U | na | na | na |
| Sr | 447.28 | 215.66 | 425.64 | 403.57 | 437.5 | 393.72 | | | | Sr | 182.06 | 156.13 | 183 |
| Rb | 146.42 | 81.01 | 76.76 | 25 | 53.23 | 45.35 | | | | Rb | 78.88 | 56.87 | 90.3 |
| Ba | 751.46 | 315.45 | 893.42 | 954.97 | 550.42 | 571.11 | | | | Ba | 764.82 | 616.69 | 433 |
| Zr | 116.36 | 31.68 | 55.78 | 83.94 | 55.73 | 97.82 | | | | Zr | 25.91 | 48.7 | 19.1 |
| Nb | 46.15 | 18.29 | 44.57 | 46.76 | 22.42 | 24.38 | | | | Nb | 5.85 | 6.82 | 0.21 |
| Y | 20.43 | 19.91 | 28.3 | 31.43 | 26.16 | 28.81 | | | | Y | 5.6 | 10.41 | 1.29 |
| La | 28.63 | 13.91 | 34.52 | 38.95 | 23.8 | 25.46 | | | | La | 23.77 | 17.14 | 8.63 |
| Ta | 3.94 | 1.61 | 2.64 | 2.99 | 1.47 | 1.68 | | | | Ta | 1.44 | 0.5 | 0.08 |
| Ce | 52.58 | 25.49 | 63.72 | 71.76 | 44.07 | 47.04 | | | | Ce | 43.41 | 31.18 | 15.9 |
| Pr | 6.52 | 3.28 | 8.1 | 9.07 | 5.7 | 6.19 | | | | Pr | 5 | 3.4 | 1.49 |
| Nd | 24.14 | 12.52 | 29.64 | 33.72 | 21.55 | 23.47 | | | | Nd | 17.59 | 11.94 | 4.91 |
| Sm | 5.3 | 3.08 | 6.35 | 7.64 | 4.96 | 5.51 | | | | Sm | 3.54 | 2.57 | 0.78 |
| Eu | 1.73 | 1.14 | 2.01 | 2.49 | 1.8 | 1.66 | | | | Eu | 1.27 | 0.81 | 0.36 |
| Gd | 5.97 | 3.33 | 7.74 | 8.64 | 5.55 | 5.98 | | | | Gd | 4.4 | 3.69 | 1.95 |
| Tb | 0.79 | 0.51 | 0.98 | 1.15 | 0.81 | 0.9 | | | | Tb | 0.32 | 0.36 | 0.09 |
| Dy | 4.05 | 3.3 | 5.25 | 6.03 | 4.72 | 5.29 | | | | Dy | 1.24 | 1.89 | 0.3 |
| Ho | 0.71 | 0.73 | 1.05 | 1.13 | 0.96 | 1.06 | | | | Ho | 0.21 | 0.41 | 0.06 |
| Er | 1.87 | 1.98 | 2.72 | 2.86 | 2.52 | 2.76 | | | | Er | 0.45 | 1.01 | 0.12 |
| Tm | 0.27 | 0.29 | 0.42 | 0.45 | 0.39 | 0.44 | | | | Tm | 0.07 | 0.16 | 0.02 |
| Yb | 1.87 | 1.58 | 3.18 | 3.42 | 1.7 | 2.68 | | | | Yb | 0.4 | 0.88 | 0 |
| Lu | 0.26 | 0.32 | 0.37 | 0.42 | 0.39 | 0.39 | | | | Lu | 0.08 | 0.14 | 0.04 |
| | | | | | | | | OIB | MORB | | | | |
| La/Nb | 0.62 | 0.76 | 0.77 | 0.83 | 1.06 | 1.04 | 0.85 | 0.77 | 1.07 | | | | |
| Nb/U | 76.92 | 9.28 | 44.99 | 32.83 | 20.67 | 13.57 | 33.04 | 52 ± 15 | 47 ± 11 | | | | |
| Nb/Ta | 11.71 | 11.36 | 16.88 | 15.64 | 15.25 | 14.51 | 14.23 | 16.0 ± 0.5 | 14.5 ± 1.5 | | | | |
| Ba/Nb | 16.28 | 17.25 | 20.05 | 20.42 | 24.55 | 23.43 | 20.33 | 7.3 | 2.7 | | | | |
| Nb/Y | 2.26 | 0.92 | 1.57 | 1.49 | 0.86 | 0.85 | 1.32 | 1.66 | 0.08 | | | | |
| Rb/Y | 7.17 | 4.07 | 2.71 | 0.80 | 2.03 | 1.57 | 3.06 | 1.1 | 0.02 | | | | |
| Rb/Sr | 0.33 | 0.38 | 0.18 | 0.06 | 0.12 | 0.12 | 0.20 | 0.05 | 0.01 | | | | |
| La/Yb | 15.31 | 8.80 | 10.86 | 11.39 | 14.00 | 9.50 | 11.64 | 17.1 | 0.82 | | | | |
| $(La/Yb)_N$ | 10.35 | 5.95 | 7.34 | 7.70 | 9.46 | 6.42 | 7.87 | | | | | | |
| $(La/Sm)_N$ | 3.40 | 2.84 | 3.42 | 3.21 | 3.02 | 2.91 | 3.13 | | | | | | |
| $(Gd/Lu_N)$ | 2.86 | 1.30 | 2.60 | 2.56 | 1.77 | 1.91 | 2.17 | | | | | | |
| $Eu/Eu^*$ | 0.94 | 1.08 | 0.88 | 0.93 | 1.04 | 0.88 | | | | | | | |
| $(La/Sm)_N$ | 3.40 | 2.84 | 3.42 | 3.21 | 3.02 | 2.91 | 3.13 | | | | | | |
| $(Gd/Lu_N)$ | 2.86 | 1.30 | 2.60 | 2.56 | 1.77 | 1.91 | 2.17 | | | | | | |
| $Eu/Eu^*$ | 0.94 | 1.08 | 0.88 | 0.93 | 1.04 | 0.88 | | | | | | | |



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**Table 3.** Whole rock Rb-Sr and Sm-Nd isotopic data of biotite-mafic granulites and charnockites of the Chilka Lake suite in the Eastern Ghats Belt, India.

| Sr-Nd isotopic composition of biotite-mafic xenoliths, and host charnockite, Chilka Lake suite | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | Rb ppm | Sr ppm | $^{87}Rb/^{86}Sr$ | $^{87}Sr/^{86}Sr$ | Sm ppm | Nd ppm | $^{143}Nd/^{144}Nd$ | $^{147}Sm/^{144}Nd$ | $T_{DM}$ | $\varepsilon_{TDM(1.9)}$ | $Sr^{i(1.9)}$ |
| Biotite-mafic granulite xenoliths | | | | | | | | | | | |
| CK-4/2 | 76 | 188.6 | 1.172 ± 86 | 0.743032 ± 372 | 5.3 | 15.3 | 0.511522 ± 51 | 0.092 ± 92 | 1.91 | 3.68 | 0.71092 |
| CK-3/2 | 141 | 432 | 0.879 ± 44 | 0.723681 ± 362 | 5.3 | 24.1 | 0.512183 ± 51 | 0.1318 ± 132 | 1.6 | 7.02 | 0.69964 |
| CK3/1 | 33.7 | 319.2 | 0.3060 ± 153 | 0.712062 ± 356 | 6.1 | 26.4 | 0.512263 ± 51 | 0.1387 ± 139 | 1.79 | 6.89 | 0.70369 |
| D-1/01 | 18 | 303 | 0.172 ± 8 | 0.71031 ± 36 | 4.85 | 22.15 | 0.512051 ± 51 | 0.1325 ± 127 | 1.86 | 4.27 | 0.70561 |
| CK5/2 | 67 | 378 | 0.514 ± 25 | 0.71458 ± 36 | 4.55 | 23.62 | 0.512112 ± 51 | 0.1242 ± 131 | 1.59 | 7.46 | 0.70052 |
| CK5/1 | 31.1 | 326 | 0.276 ± 13 | 0.7119 ± 356 | 4.3 | 18.2 | 0.512021 ± 51 | 0.1429 ± 71 | 2.2 | −1.54 | 0.70435 |
| Host charnockites | | | | | | | | | | | |
| D-4 /01 | 48 | 137 | 1.016 ± 51 | 0.75237 ± 38 | 1.28 | 11.5 | 0.511258 ± 58 | 0.0673 ± 53 | 1.86 | 4.77 | 0.72459 |
| CK2/4 | 73.66 | 208.21 | 1.028 ± 16 | 0.752727 ± 35 | 5.29 | 24.15 | 0.51127 ± 51 | 0.1039 ± 138 | 2.33 | −3.96 | 0.72461 |
| D7/01 | 63 | 141 | 1.203 ± 60 | 0.74974 ± 38 | 0.46 | 3.65 | 0.511281 ± 81 | 0.0762 ± 62 | 1.96 | 3.04 | 0.71684 |
| Reference values used in calculations. CHUR(0) 143Nd/144Nd = 0.512638; DM(0) 143Nd/144Nd = 0.513114; | | | | | | | | | | | |
| CHUR(0) | 147Sm/144Nd = 0.1967; DM(0) 147Sm/144Nd = 0.222; decay constant $\lambda = 6.54 \times 10^{-12}\ a^{-1}$ | | | | | | $\lambda = 6.54 \times 10^{-12}\ a^{-1}$ | | | | |

**Table 4.** Model parameters and partial melting results.

| Mineralogy | Source modal, Residue from previous melting (Bhattacharya et al., 2011) | Wt. fraction in melt | Elements | Source = 70 % Peridotite + 30 % Residue from previous melting | 7 % melt |
|---|---|---|---|---|---|
| Olivine | 58.24 | 30 | La | 1.73 | 19.7 |
| | | | Ce | 3.4 | 39.75 |
| Orthopyroxene | 4.12 | 0 | Nd | 1.55 | 17.24 |
| | | | Sm | 0.38 | 3.68 |
| Clinopyroxene | 11.77 | 10 | Eu | 0.13 | 0.94 |
| | | | Gd | 0.43 | 3.54 |
| Garnet | 17.35 | 60 | Yb | 0.47 | 0.74 |
| | | | Lu | 0.07 | 0.07 |
| Plagioclase | 8.53 | 0 | | | |

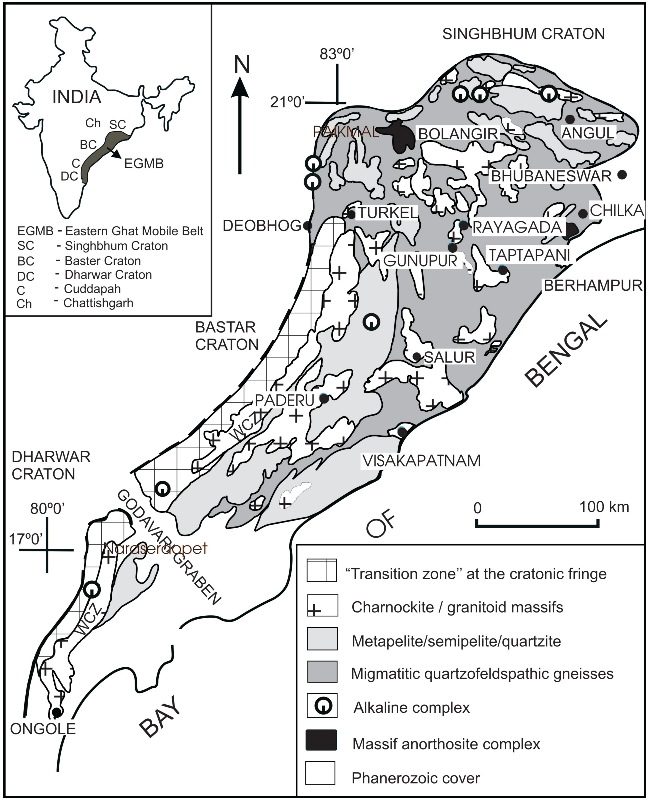


**Fig. 1.** Generalized geological map of the Eastern Ghats Belt, India, after Ramakrishnan et al., 1998.





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**Fig. 2.** Biotite-mafic granulite xenolith within massif-type charnockitic rocks of the Chilka Lake suite. Note one folded mafic granulite xenolith near the scale.

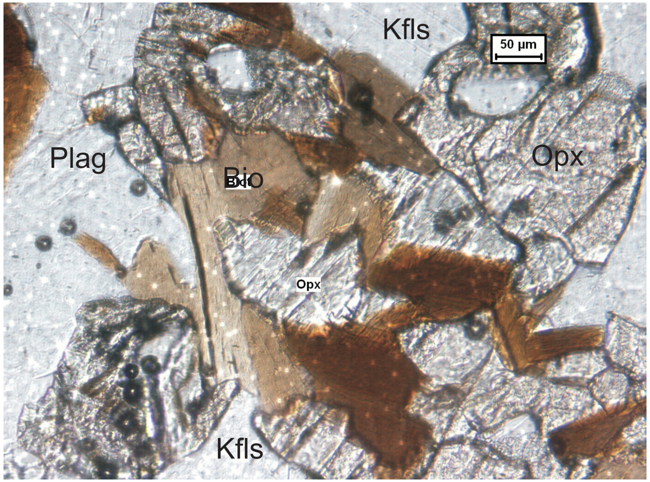


**Fig. 3.** Orthopyroxene and K-feldspar at embayed margin of biotite, indicating prograde nature of biotite.





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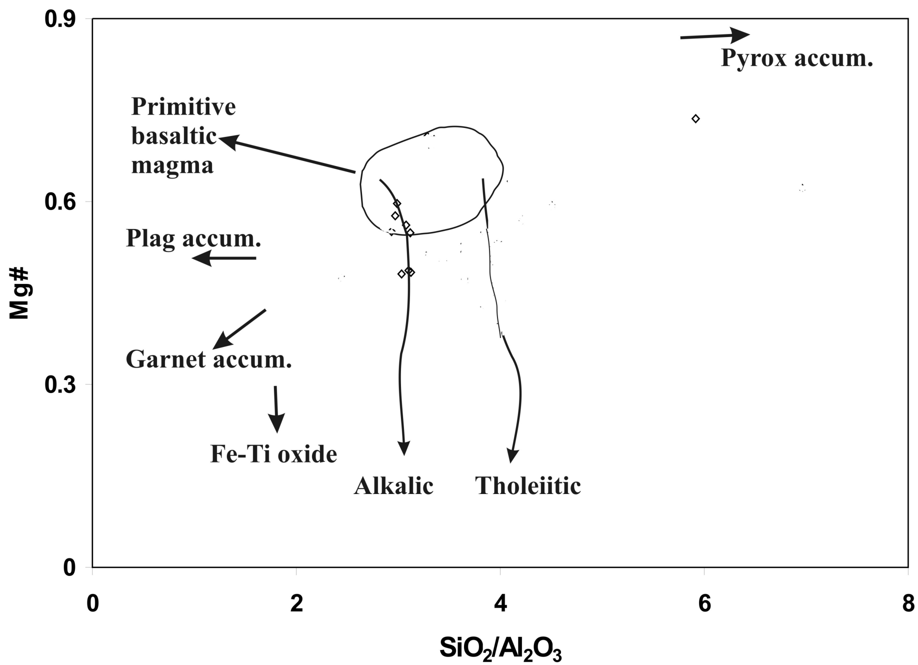


**Fig. 4.** Mg# versus $SiO_2/Al_2O_3$ diagram for the mafic granulites; field of primitive basaltic magma after Kempton and Harnon (1992).



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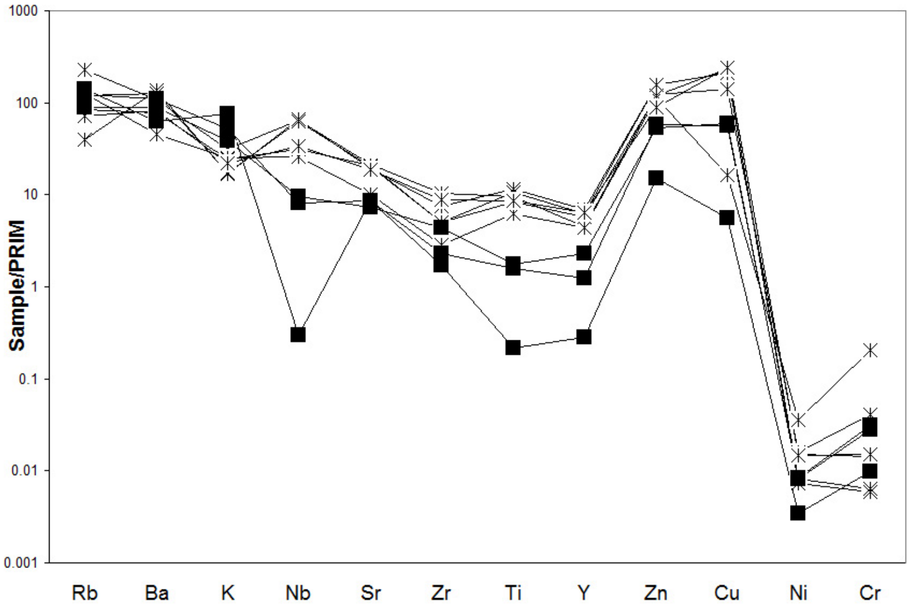


**Fig. 5.** Primitive mantle normalized spider plot of the biotite-mafic granulite xenoliths and host charnockites of the Chilka Lake suite. Normalizing values from Taylor and McLennan (1995). Symbols: Asterix = mafic xenoliths; Solid square = charnockites.



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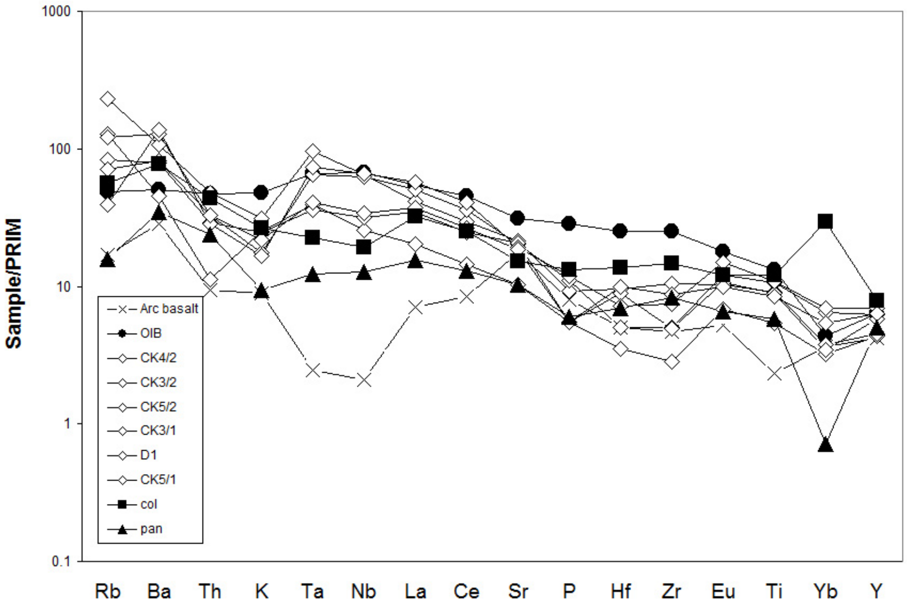


**Fig. 6.** Primitive mantle normalized spider plot of the biotite-mafic xenoliths, compared with basalts of different settings: CFB (Columbia and Parana; Hooper and Hawkesworth, 1993 and Peate, 1997, respectively), OIB (McDonough and Sun, 1995), Arc (Taylor and McLennan, 1995). Symbols: Open diamond = mafic xenoliths; Cross = Arc basalt; Solid circle = OIB; Solid triangle = Parana high-Ti basalt; Solid square = Columbia River basalt.





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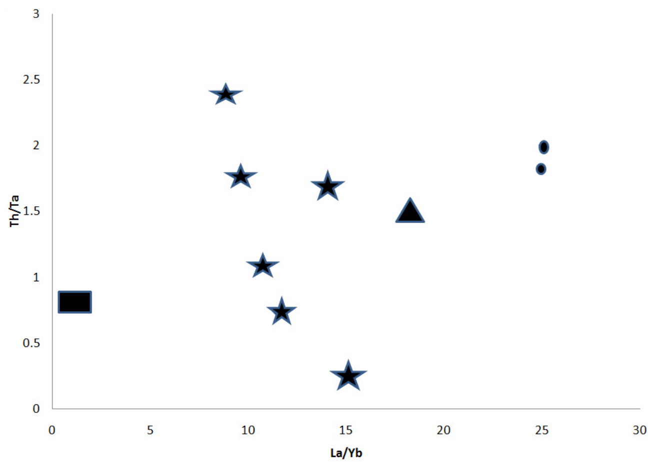


**Fig. 7.** Th / Ta and La / Yb relationships in the xenoliths and different mantle domains. Symbols: Star = xenoliths; Rectangle = DM; Triangle = HIMU; Oval = EM1 and 2.





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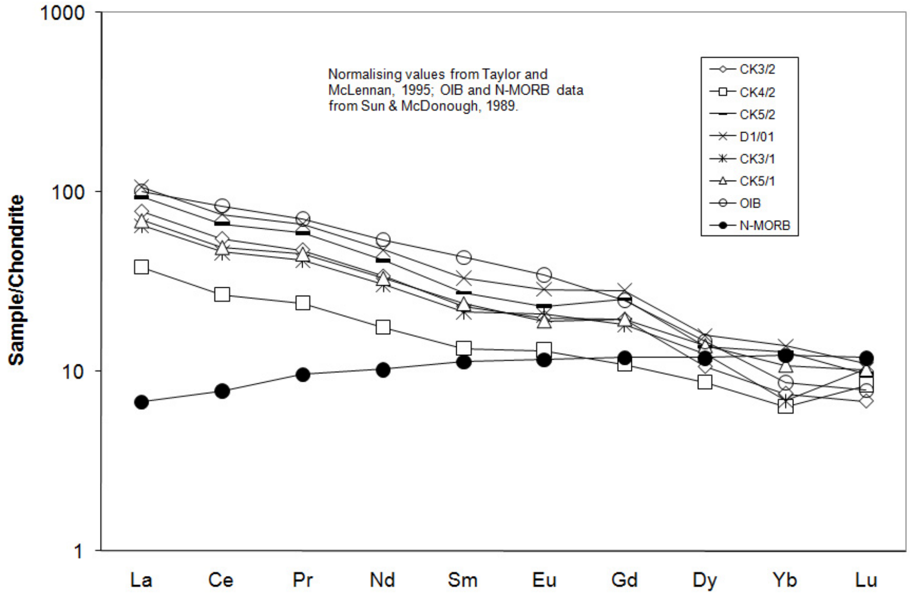


**Fig. 8.** Chondrite normalized REE plot of the biotite-mafic xenoliths.



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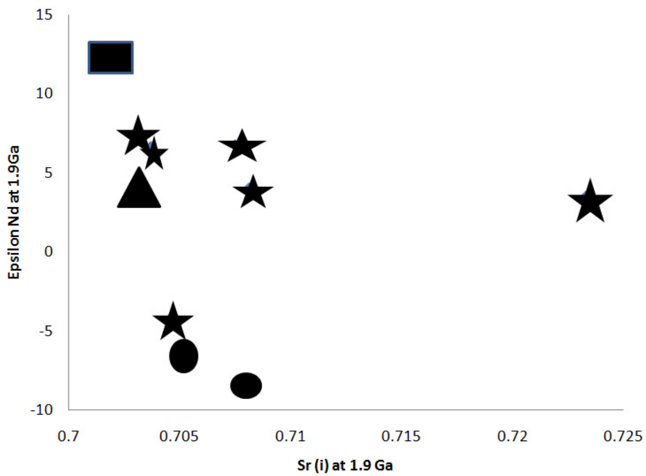


**Fig. 9.** Sr-Nd correlation diagram for the biotite mafic xenoliths and the same in the different mantle domains. Symbols as in Fig. 7.





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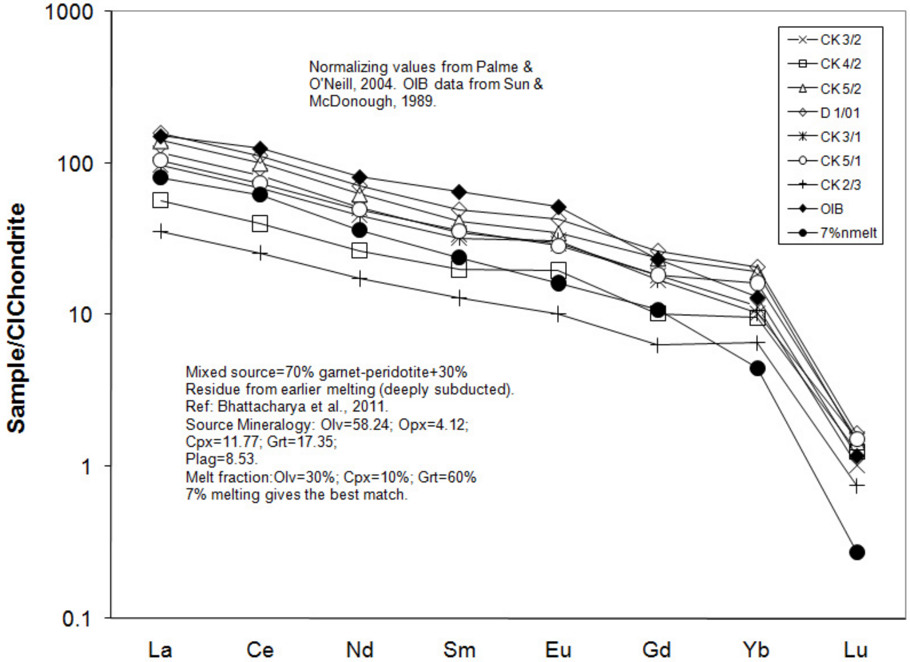


**Fig. 10.** Primitive mantle normalized spider plot of model melts compared with the mafic Xenoliths.





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