

## **Imprints of ancient recycled oceanic lithosphere in heterogeneous Indian Ocean mantle: Evidence from Petrogenesis of Carlsberg Ridge basalts from Northwest Indian Ocean**

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### **Abstract**

This paper reports new petrological, geochemical and isotopic data for Carlsberg Ridge Basalts (CRB) of northwest Indian Ocean and evaluates their petrogenetic aspects in the context of the geochemical and tectonic evolution of the Indian Ocean mantle. The CRB samples exhibit tholeiitic to transitional composition of precursor melts derived by high degree, shallow level partial melting of a spinel peridotite mantle source. CRB reflects distinct E-MORB affinity with selective enrichment in incompatible trace elements. Higher values of Zr/Hf (33.8-47.3) and Zr/Sm (24.9-36.4) in conjunction with lower Nb/Ta (1.7-7.3) ratio corroborate their origin from an enriched mantle source. Negative Nb anomalies with lower Nb/Y (0.04-0.11) and Zr/Y (2.5-3.5) conform to a non-plume origin of these basalts. Higher Zr/Nb (25.5-71.5) and Th/Nb(0.6-0.42) compared to OIB substantiate contributions from recycled subduction-processed components in the source mantle. Lower Nb/U (6.2-37.9) values with higher Ba/Nb (6.1-21.9), and Ba/Th (27.7-147.5), Zr/Nb (25.5-71.5) and Th/Nb(0.6-0.42) compared to OIB and N-MORB attest to role of a metasomatized oceanic lithosphere that recycled into the depleted upper mantle attributing to the source heterogeneity. Sr-Nd isotopic signatures ( $^{87}\text{Sr}/^{86}\text{Sr}$ : 0.702668 to 0.702841 and  $^{143}\text{Nd}/^{144}\text{Nd}$ : 0.512972 to 0.513068) of CRB suggest a HIMU source component preserved in the northwest Indian Ocean Mid Oceanic Ridge mantle. The compositional diversity of the Indian Ocean mantle can be translated in terms of periodic refertilization of depleted N-MORB type mantle through delamination and recycling of oceanic (HIMU component) and continental lithosphere (EM I component) concurrent with Neoproterozoic-Palaeozoic amalgamation and Jurassic dispersal of Gondwana Supercontinent respectively. This study complies with the derivation of CRB from a geochemically heterogeneous Indian Ocean mantle that experienced a protracted residence beneath the Gondwana Supercontinent prior to the opening of Indian Ocean and trapped recycled metasomatized oceanic lithosphere genetically linked with multiple stages of paleo-ocean closure and continental convergence during Gondwana assembly.

**Key Words:** Carlsberg Ridge Basalts; HIMU source; Oceanic lithosphere; Indian Ocean mantle; Gondwana Supercontinent

## 1. Introduction

The convection driven homogenization process contemporaneous with geochemically heterogeneous domains preserved over a considerable period of geological time represent the physical and chemical dichotomy of the Earth's mantle. Mantle derived basaltic magmas in oceanic realms are devoid of crustal assimilation and thus provide a first-order estimation of the geochemical and isotopic signatures of the source. Mid oceanic ridge-rift (MOR) systems or oceanic spreading centres posit a fundamental link between the earth's mantle and extracted juvenile crustal components. Thus, the thermo-tectonic evolution of global mid oceanic ridge rift systems squares with the geochemical changes in the mantle over the geological history in terms of periodic melt extraction, refertilization, fluid-melt infiltration and crustal recycling (Mahoney et al., 1989; 1998; Jackson and Dasgupta, 2008; Fuentes et al., 2019). The global network of mid-oceanic ridge-rift (MOR) systems stretching over 60,000km across the world's oceans represent potential sites for 75% of terrestrial volcanism and two-third of juvenile oceanic crust generation (Dyment, 1998; Gale et al., 2013). Mid-Oceanic Ridge Basalts (MORBs), generated by partial melting of refractory upper mantle owing to oceanic plate divergence, adiabatic upwelling and decompression, present best geochemical sampling of sub-ridge asthenospheric mantle thereby underpinning the thermal and chemical characteristics of globally extensive crustal and mantle reservoirs. MORBs including normal mid-oceanic ridge basalts (N-MORB), enriched mid-oceanic ridge basalts (E-MORB) and plume-type mid-oceanic ridge basalts (P-MORB) are characterized by a non-uniform, depleted to enriched compositional spectrum in terms of incompatible trace element abundances and radiogenic isotopic signatures attributing to the ubiquitous chemical heterogeneity of mantle. Regional and global compositional variations for MORBs are inherited from anhydrous to hydrous, depleted to fertile mantle sources collectively complying with diverse elemental and radiogenic isotopic signatures of the mantle reservoirs (Eiler et al., 2000; Liu and Liang, 2020). This leads to the consensus of a double-layered mantle of contrasting viscosities. The upper mantle represents a well-mixed reservoir depleted of incompatible trace elements that contributed to the formation of the earth's crust whereas, the lower mantle undergoes a sluggish convection retaining the elemental and isotopic anomalies delivered through melt extraction, recycling, metasomatism and convective mantle stirring (Elliott et al., 2006; Barry et al., 2017). The geochemical deviation of oceanic crust from standard upper mantle composition (N-MORB) can be translated in terms of influxes of buoyant plumes from lower mantle or incorporation/induction of shallow lithospheric components. Geochemical signatures of basaltic magmas in oceanic realms, owing to minimal effects of contamination during ascent, record imprints of crustal recycling from paleotectonic events and

hence provide a natural archive to probe into the compositional diversity of the melting domains within the mantle accounting for the heterogeneity. Oceanic crust produced at subduction-related ocean-ocean and ocean-continent convergent margin settings preserves geochemical signatures coherent with various stages of ocean basin closure and arc-continent collisions, while that generated in subduction-unrelated settings like oceanic plateau and mid-oceanic ridges can be tectonically correlated with continental break-up and ocean basin formation events (Dilek and Furnes, 2011). Besides, mantle-derived crust emplaced at modern subduction-related and subduction-unrelated oceanic environments preserves distinct tectono-thermal fingerprints of ancient Wilson Cycle events including opening and closure of ocean basins synchronized with assembly and dispersal of super continents. Geochemical data compiled for MORB from 771 ridge segments across the globe suggest an inhomogeneous upper mantle source carrying both enriched and depleted components (Gale et al., 2013) that in turn contributed to the compositional diversity in MORB.

The morphological and structural attributes of the Indian Ocean floor predominantly comprise the Indian Ocean Ridge System (IORS) along with several fracture systems trending N-S, hotspots, seamounts, a seismic ridges and convergent plate margins. The Carlsberg Ridge (CR), Central Indian Ridge (CIR), Southeast (SEIR) and Southwest (SWIR) Indian Ridges collectively constitute the Indian Ocean Ridge System. At the Rodriguez Triple Junction (RTJ; 25°30'S, 70°E) the IORS bifurcates into SWIR and SEIR forming an inverted Y shape, while the entire ridge-rift system is intermittently traversed by multiple transform faults and fracture zones with an overall NNE-SSW trend. The north-south disposition of some discernible fracture zones across the CIR is delineated by Owen, Mahabiss, Sealark, Vityaz, Vema, Argo, Marie Celeste, Egeria and Gemino which altogether govern the melt dynamics and petro-tectonic style of the Indian Ocean floor (Langmuir et al., 1986; Klein and Langmuir, 1987; Gregg et al., 2009; Chatterjee et al., 2013; Ray et al., 2013; Chen et al., 2017). The northern portion of Indian Ocean Ridge is segmented into the Gulf of Aden spreading centre, the Carlsberg Ridge (CR), Northern Central Indian Ridge (NCIR) and Southern Central Indian Ridge (SCIR) from north to south (Mahoney et al., 1989, 1992; Ray et al., 2013; Chen et al., 2017). Unlike the Pacific and Atlantic Oceans, the Indian Ocean represents varied types of spreading centres from the ultra-slow SWIR to the slow CR to the intermediate SEIR. Likewise, the variable spreading rates in conjunction with capricious modes of generation, transport, accumulation of melts and dynamicity of source regions yield vital controls on the composition of Indian Ocean MORB. It has been envisaged that the detachment faults associated with asymmetric spreading of slow to ultra-slow mid-oceanic ridge-rift systems serve as the pathways for exhumation of lower crustal gabbros and peridotitic mantle sections as oceanic core complexes (OCC) that provide *prima facie* record of

the magmatic events and successive stages in the evolution of oceanic lithosphere (Balestro, et al., 2019; Festa, 2020). The morphotectonic features of the Western Alpine Ophiolite in north-west Italy represent a fossil OCC comprising exhumed and serpentized mantle peridotites and gabbros that collectively reverberate the magmatic and tectonic evolution of the Alpine Tethyan ocean basin in Jurassic (Balestro et al., 2020). In the present scenario, the asymmetric spreading along the northern and southern flanks of SWIR has resulted in detachment faulting and consequent emplacement of OCC (Liang et al., 2013). The source regions of Indian Ocean MORB are characterized by lithologically and chemically heterogeneous mantle domains which upon partial melting gives rise to basaltic magmas with diverse elemental and isotopic abundances (Liu and Liang, 2020). This paper reports new petrological, geochemical and radiogenic (Rb-Sr, Sm-Nd) isotope data for basalt samples dredged from the Carlsberg Ridge of Northwest Indian Ocean (NWIO) and evaluates (i) the mantle source characteristics, melt generation processes and petrogenetic implications of Carlsberg Ridge basalts (CRB) and (ii) their coherence with the thermal, chemical and tectonic evolution of Indian Ocean MOR mantle in the context of Gondwanaland reconfiguration.

## **2. Geological Background**

Slow spreading MOR systems represent 80% of the total length of the global system of diverging oceanic plates. The structure and morphology of slow-spreading mid-oceanic ridges are predominantly controlled by spreading rate, segmentation and crustal accretion pattern, ridge depth, rate of mantle melting beneath the ridge, melt transportation and supply to the crust (Murton and Rona, 2015). The Indian Ocean floor is traversed by a complex and dynamic system of three active spreading ridges that disintegrated the super continental fragments of Gondwana viz. Africa (Somalia), India, Antarctica and Australia. The northern branch of the IORS initiates in the Gulf of Aden separating Africa from Arabia and propagates along the Carlsberg Ridge. The slow-spreading Carlsberg Ridge of IOR retains a typical and anomalous mantle domain beneath. Global bathymetric and ship-board multibeam echo-sounder data have collectively suggested that the Carlsberg Ridge spreading at 26mm/yr is segmented by non-transform, second-order discontinuities and lacks major transform faults.

Mudholkar et al. (2002) provided the first multibeam swath bathymetric map over a ~120km long segment of the Carlsberg Ridge and described the fine-scale segmentation pattern. In 2007, CSIR-NIO carried out a combined seafloor mapping and plume investigations onboard RV Sonne, over a 440km long segment of the CR rift valley between 62°20'E and 66°20'E. The multibeam bathymetry and magnetic data acquired under this initiative provided the first high-resolution seafloor image over this part of the Carlsberg Ridge (Kamesh Raju et al., 2008). During the above

expedition onboard RV Sonne, the deep water of 600 m above the valley floor was scanned using an array of Miniature Autonomous Plume Recorders (MAPRs) and vertical Conductivity-Temperature-Depth (CTD) casts. The data recorded in the MAPRs and CTDs delineated a hydrothermal plume extending from 63°39'E to 63°46'E, between 2900 m and 3300 m. Subsequently, during 2009, a series of MAPR hydrocasts concentrating on the locations of maximum optical backscatter anomalies were conducted onboard *MV Akademik Boris Petrov*, where we found robust optical backscatter and distinct or subtle oxidation reduction potential (E) anomalies, centered between 3100 and 3400 m (upper plume) and between 2930 m and 3120 m (lower plume). The results of the 2007 and 2009 expeditions on the Carlsberg Ridge including optical backscatter and potential temperature anomalies along with chemical signatures in the water column (<sup>3</sup>He, Mn) collectively demarcated consistent hydrothermal plumes from unidentified vents active near 3°41.5'N, 63°50'E and 3°42'N, 63°40'E (Ray et al., 2012). The studied basalt samples from Carlsberg Ridge (Fig. 1) were collected during Sagar Kanya cruise (SK 114 and SK 154) covering five locations in the axial valley (Table S1). On the basis of bottom topography and morphology, dredging was carried out at five locations.

### **3. Analytical Techniques**

#### **3.1 Mineral chemistry**

The chemical composition of the olivine clinopyroxene and plagioclase grains were determined with CAMECA SX Five Electron Probe Micro Analyser at CSIR-National Institute of Oceanography (NIO), Goa, India. The analyses were performed with a voltage of 15 kV and a sample beam of 10 nA. Natural mineral standards were used for calibration. The precision of the analysis is better than 1% for major element oxides from the repeated analysis of standards. Representative mineral chemical data are given in the supplementary tables.

#### **3.2 Major, trace and rare earth elements**

Representative twenty four samples of CRB were finely powdered and used for preparation of fused beads for the major element analyses. Major elements were analysed by Philips MAGIX PRO X-ray fluorescence spectrometer. Fused beads were prepared using Merck's Spectromelt A12 flux mixing with the finely powdered rock, heated in a platinum crucible to ~1100<sup>0</sup>C using conducting furnace (Minifuse2 of PANalytical). Accuracy and precession were better than %5 RSD for all major element analyses. Trace element including rare earth elements (REE) have been analyzed at CSIR-National Geophysical Research Institute, Hyderabad, India by using Inductively Coupled Plasma Mass Spectrometry (ICP-MS; Perkin Elmer SCIEX ELAN DRC II). Method suggested by Balaram and Rao, 2003 have been followed. The trace and REE concentrations were

determined by using closed digestion method. For trace and REE analyses, international standards JB-2 (Geological Survey of Japan), BCR-2, BHVO-1 (United States Geological Survey) were used as certified reference materials and the accuracy and precision were found to be better than %8 RSD for all trace elements.  $^{103}\text{Rh}$  was used as an internal standard for performing the analysis.

### 3.3 Sr and Nd Isotopes

Sr and Nd isotopic analyses of twelve samples were conducted using Multi Collector-Inductively Coupled Plasma Mass Spectrometer (MC-ICP MS) of model NU Plasma 3 at the Centralized Analytical Facilities of CSIR-National Institute of Oceanography, Goa, India. 50 mg powders of 12 selected representative samples from the Carlsberg Ridge, procedural blank and 50 mg samples of 3 Certified Reference Materials were digested in tight Savillex beakers using a supra-pure acid mixture of HF:HNO<sub>3</sub> (7:3) for 72 hours at 110°C on a hot plate. After acid evaporation, samples were treated with 1 ml of 2N HCl (to convert the solution to HCl medium) to obtain a clear solution. Sr element extraction was performed using EICHROM Sr Resin (50-100 μm mesh) with 2N HCl and REEs were collected as a group with 6N HCl using the same resin. The eluted REEs were dried and then dissolved in 1 ml of 0.16 N HCl. Nd was separated from the REE group using EICHROM LN Resin (50-100 μm mesh) with 0.27 N HCl as eluent. Certified Reference Materials BCR-2, BIR-1 and JB-2 (Govindaraju, 1994) were used in order to validate the results obtained here. Procedural blanks were below detection limits. During the course of these analyses Sr isotope internal standard SRM987 and Nd isotope internal standard JNd<sub>i</sub> were run repeatedly. The mean value obtained on 4 analyses of SRM987 for  $^{87}\text{Sr}/^{86}\text{Sr}$  is  $0.710272 \pm 0.000006$ ; and, the mean  $^{143}\text{Nd}/^{144}\text{Nd}$  value obtained on 4 analyses of JNd<sub>i</sub> is  $0.512102 \pm 0.000003$  (values for SRM 987  $^{87}\text{Sr}/^{86}\text{Sr} = 0.710230 - 0.710280$  and JNd<sub>i</sub>  $^{143}\text{Nd}/^{144}\text{Nd} = 0.512080 - 0.512141$ ). Error quoted as  $2\sigma$  errors of the mean.

## 4. Petrography and Mineral Chemistry

Basalts from the Carlsberg ridge were studied and it was observed that most of the studied samples showed development of phenocrysts along with crystal and volcanic glass in groundmass depicting porphyritic texture. Phenocrysts of plagioclase, (Fig.2A) clinopyroxene (Fig. 2B) and occasional olivine (Fig. 2C) are embedded in a groundmass of clinopyroxene granules, tiny plagioclase laths (microlites) and volcanic glasses (Fig. 2C). Fine grained nature of minerals indicating rapid crystallisation at or near the surface. Majority of the minerals lacked crystal faces while few exhibited partially developed crystal faces (plagioclase), and hence are subhedral to anhedral crystals respectively. Plagioclase is the most abundant phenocrystal phases in Carlsberg

Ridge basalts, followed by clinopyroxenes (cpx) and occasionally olivine grains. Most of the mega plagioclase grains are resorbed (Fig.2A).

The plagioclase phenocryst (lath shaped) showed a compositional variation between bytownite-labradorite ( $An_{62}$  to  $An_{82}$ ; based on plagioclase symmetrical extinction angle). In some places, plagioclase crystals are partially enclosed by clinopyroxene grains depicting subophitic texture (Fig. 2D). Typical intergranular and intersertal textures are observed in the groundmass where clinopyroxene and volcanic glass respectively fill up triangular interspaces formed by plagioclase microlites (Fig. 2E). In few places, plagioclase microlites show a radiating nature due to rapid cooling of high temperature magma and magma-seawater interaction depicting variolitic texture. In the groundmass evidences of devitrification of volcanic glass is also noted (Fig. 2F)

Olivine represents a significant phenocrystal phase in the studied basalts from Carlsberg Ridge, NWIO. Forty-seven Electron microprobe analyses of olivine phenocrysts from the studied basalts are presented in Table S2. The Fo (forsterite) content of olivines ranges from  $Fo_{77}$ –  $Fo_{88}$  indicating a restricted compositional variation. The compositional spectrum of phenocrystal olivines corroborates a stable crystallization condition in the prevailing magmatic environment. The high MgO contents of the analysed olivine phenocrysts varying between 39 and 46 wt.% indicate negligible effects of crustal contamination (Table S2). Mineral chemical compositions (Table S3) obtained from forty-two pyroxene analyses represents both phenocrystal and groundmass compositions from respective CRB samples. Based on ‘Q’ and ‘J’ relations (where  $Q=Ca+Mg+Fe$  and  $J=2Na$ ) (expressed in terms of a.p.f.u), the pyroxenes are designated as ‘QUAD’ pyroxenes (Morimoto et al., 1988; Morimoto 1989).The phenocrystal clinopyroxene grains are Ca-rich, while their groundmass counterparts show Ca-poor chemistry (Table S3). In the Wo–En–Fs triangular diagram (Morimoto 1989; Fig. 3A) the Ca-rich phenocrystal pyroxenes correspond to hedenbergite and augite compositions, whereas the groundmass pyroxenes with decreasing Ca content correspond to augite, pigeonite and clinoenstatite respectively. Pyroxene chemistry serves as an effective proxy to constrain the tectonic setting (Letterrier et al.,1982). Plots of Ti vs Ca for constituent clinopyroxene phase chemistry (Fig. 3B) straddle subduction-unrelated and subduction related orogenic fields (Rogers et al., 1995, Nelson and McCulloch, 1989) thereby implying a subduction related regime controlled by protoplate convergence. The plagioclase phenocryst compositions obtained from thirty-two chemical analyses (Table S4) are projected into Or–Ab–An triangular diagram (Fig. 3C) where the data-plots reflect a uniform labradorite-bytownite compositional spectrum. The anorthite component of plagioclase of the investigated basalts varies from  $An_{57}$  to  $An_{85}$ .

## 5. Whole Rock Geochemistry

### 5.1 Major elements

Major and trace element compositions of twenty four submarine volcanic rock samples dredged from Carlsberg Ridge are presented in Table 1. The studied samples are characterized by a restricted range of SiO<sub>2</sub> contents (45.76-52.25 wt.%), low to moderate TiO<sub>2</sub> (1.04-2.13wt.%), moderate concentrations of Fe<sub>2</sub>O<sub>3</sub><sup>(T)</sup> (9.31-11.52 wt.%) with moderate to elevated abundances of Al<sub>2</sub>O<sub>3</sub> (13.17-18.48 wt.%), MgO (5.82-10.05wt.%) and CaO (9.64-13.29 wt.%). These rocks show relatively higher Na<sub>2</sub>O (2.37-3.10 wt. %) content than K<sub>2</sub>O (0.07-0.74 wt.%). The Mg# values for the samples range from 32.46 to 44.99 thereby indicating an evolved nature of precursor melts. The studied samples plot in the field of basalts in the total alkali vs. silica (TAS) diagram (Fig. 4A; after Cox et al., 1979 and adapted from Wilson, 1989). This observation is in accordance with the distinct tholeiitic nature of the studied samples on AFM ternary plot (Fig. 4B) of Irvine and Baragar (1971). The Carlsberg Ridge basalts (CRB) clearly correspond to the tholeiite to transitional composition on Zr vs. Y plot (Fig. 4C).

### 5.2 Trace and rare earth elements

The transitional compatible trace element chemistry for the studied samples is marked by depleted Ni (36.03-127.81ppm), Cr (169.70-354.11 ppm) and Co (34.86-162.49ppm) concentrations (Table 1) with respect to primitive mantle values (Ni: 1890ppm Cr: 2940ppm, Co: 110ppm; Sun and Mc Donough, 1989). Chondrite-normalized REE patterns (Fig. 5A) for the CRB show a comparable LREE abundance with respect to E-MORB, moderate enrichment in LREE with respect to that of N-MORB, but a depleted LREE trend with respect to OIB. Chondrite-normalized MREE and HREE profile reflects elevated abundances with respect to N-MORB and E-MORB. The (La/Sm)<sub>CN</sub>: 0.17-0.85, (Ce/Yb)<sub>CN</sub>: 0.72-1.1, (Gd/Yb)<sub>CN</sub>: 1.08-1.28 and (Sm/Yb)<sub>CN</sub>: 0.93-1.12 collectively suggest feeble to discernible LREE/MREE, LREE/HREE and MREE/HREE fractionation patterns marked by depletion to moderate enrichment of LREE and MREE over HREE. Primitive mantle-normalized trace element abundance patterns (Fig. 5B) show distinct negative anomalies for Th, Nb, Hf with positive spikes at Ba, Nd, Zr and Y. Primitive mantle-normalized trace element patterns for CRB deviate from typical N-MORB trend conforming to distinct enrichment in LILE and LREE.

### 5.3 Radiogenic Sr-Nd isotope systematics

Sr and Nd isotopic compositions and related parent-daughter element concentrations of representative samples of CRB are given in Table 2. Initial Sr and Nd isotopic ratios along with epsilon values were calculated assuming an emplacement age of 0Ma for South West Indian Ridge



(SWIR) (after Mahoney et al., 1998). Epsilon values are calculated using present-day ratios of  $^{87}\text{Sr}/^{86}\text{Sr}=0.7045$  (DePaolo, 1988) and  $^{87}\text{Rb}/^{86}\text{Sr}=0.0827$  (DePaolo, 1988) for Bulk Silicate Earth (BSE);  $^{143}\text{Nd}/^{144}\text{Nd}=0.512638$  (Goldstein et al., 1984) and  $^{147}\text{Sm}/^{144}\text{Nd} = 0.1967$  (Jacobsen and Wasserburg, 1980) for Chondritic Uniform Reservoir (CHUR). The Sr-Nd isotopic compositions of the CRB samples with  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios varying between 0.702668 to 0.702841 and 0.512972 to 0.513068, respectively, correspond to a HIMU source. The coherence of  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  values of representative samples (Table 2) is consistent with their derivation from a common mantle source. All samples have negative  $\epsilon_{\text{Sr}}$  values ranging from -23.10 to -26.01 with positive  $\epsilon_{\text{Nd}}$  values (6.51-8.39). In terms of Sr-Nd isotopic compositions, the studied samples are coherent with a mantle source having HIMU signatures (Figs. 6A and 6B).

## 6. Discussion

The nature and longevity of steady-state magma chamber beneath diverging oceanic plates, the temporal and chemical variations of melt input from mantle along individual ridge segments are explicitly associated with the relative balance between tectonic and magmatic activity across global oceans. Global correlation studies of abyssal peridotite and MORB geochemistry suggest that the extent of mantle melting beneath mid-oceanic ridge segments increases with increasing spreading rate and that the spreading rate is a primary factor controlling both ridge morphology and lava composition. The geometry and depth of melting domain, MORB melt generation with different chemical attributes, its equilibration with the surrounding upper mantle having variable pressure, temperature and composition yield constraints on the mechanisms of flow of magma and solid mantle beneath diverging oceanic plate boundaries. These dynamic processes collectively invoke a 'passive' plate driven magma flow or 'active' buoyantly driven solid convection in the upper mantle. Geological and geophysical observations propound a passive magma flow which causes melts from a broad region of upwelling and melting to converge in a narrow zone at ridge crests. Global and local geochemical trends for MORB are a consequence of heterogeneity in source composition, total extents of mantle melting and mean pressure of mean extraction due to variations in mantle temperature. Experimental studies suggest that mid-ocean ridge basalts (MORB) are produced by 10-20% partial melting of the upper mantle at depths of 50-85 km (Elthon and Scarfe, 1984; Kushiro, 2001). The major chemical variation along ocean ridges correlates with temperature variations of 200 °C beneath global ocean ridges (Gale et al., 2014). There is also significant major element variation where ocean ridges approach hotspots and in back-arc basins. Slow-spreading ridges are characterized by lower extents of melting than fast-spreading ridges, due principally to thicker lithosphere, and hence extent of melting appears to be the dominant control on major element

compositions of derivative magmas. In contrast, overall trace element distributions in MORB broadly indicate heterogeneity in mantle source composition. Depletion in incompatible elements (K, Rb, Ba, Th, U, etc.) and LREE (La, Ce, Nd etc.) in MORB reflects a mantle source that has been impoverished in these elements by earlier magmatic events. Low  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{206}\text{Pb}/^{204}\text{Pb}$  and high  $^{143}\text{Nd}/^{144}\text{Nd}$  isotopic ratios also demand a mantle source that is depleted relative to chondrites. Incompatible element contents and isotopic ratios vary in MORB along ocean ridges and from ocean to ocean. It has been demonstrated that the Th-Nb-Ce systematics of oceanic basalts and their derivatives provide reliable proxies to evaluate their mantle source characteristics in terms of mixing between three mantle components viz. DMM (Depleted MORB mantle), RSC (recycled residual slab component) and SDC (recycled subduction-derived component) (Saunders et al., 1988; Sun and McDonough, 1989; Safonova et al., 2008). The enriched and chemically heterogeneous composition of sub-oceanic upper mantle beneath a mid-oceanic ridge-rift system can be equated with (i) influence of a mantle plume carrying recycled residual slab component (RSC) from paleo-subduction events (low Ce/Nb and Th/Nb) (ii) infiltration of recycled subduction-derived components (SDC) through lithosphere-asthenosphere interaction (high Th/Nb and Ce/Nb) and (iii) subduction-induced recycling of oceanic and continental lithosphere into upper mantle. The mechanism of lithospheric recycling is primarily delineated by subduction-driven delamination and convective downwelling of oceanic crust, pelagic sediments and sub-arc mantle wedge during accretionary and collisional orogeny at continent-ocean-continent convergence processes or thermal erosion, convection removal and recycling of continental margin lithosphere and lower continental crust in response to continental disintegration and opening of ocean basins (Levander et al., 2014; Scott et al., 2014; 2019; Ashwal et al., 2017; Zhang et al., 2018; Barruol et al., 2019).

### **6.1 Tectonic implications, source characteristics and petrogenesis**

The geochemical attributes of the CR basalts marked by relatively high Ce/Nb (2.8-6.76) but low Th/Nb (0.1-0.2) reflect a deviation from typical, depleted N-MORB (DMM) pattern and shows affinity to an E-MORB signature. This enriched signatures of CRB can be interpreted in terms of inhomogeneous upper mantle composition and refertilization of depleted N-MORB mantle by discrete or collective contributions from (a) mantle plume component (b) recycled, subducted oceanic crust and (iii) delaminated fragments of continental lithosphere. Low  $(\text{Nb}/\text{La})_{\text{PM}}$  ratios for the CRB samples attest to recycled lithospheric components contributing to the endogenous mantle enrichment. Chondrite-normalized REE patterns and Primitive mantle normalized trace element abundances (Fig. 5) for the CR basalts characteristically reflect depleted compositions of the parent magmas in comparison with the trace and REE compositions of average OIB. However, the lack of

positive Nb-Ta anomalies, elevated LILE, LREE HFSE abundances narrow down/restrict the possibility of plume influence or contribution from plume-derived melts. Rather, LILE>HFSE, LREE> HFSE and depleted primitive-mantle normalized Ba, Nb, Th, Zr-Hf patterns for these basalts precludes role of mantle plume component and reconciles delamination, convective downwelling and shallow recycling of ancient subduction-modified, metasomatized oceanic lithosphere into the asthenospheric upper mantle thereby accounting for the enriched signatures of magmas precursor to these rocks. Negative Nb anomalies with lower Nb/Y (0.04-0.11) and Zr/Y (2.5-3.5) discard the role of a mantle plume. This contention is further substantiated by higher Zr/Nb (25.5-71.5) and Th/Nb (0.6-0.42) compared to OIB (Zr/Nb:5.8; Th/Nb: 0.08) deciphering the role of a subduction modified lithospheric component in the source mantle. The Nb/La vs. La/Yb variation plots (Fig. 7A; Abdel-Rahman and Nassar, 2004) suggest a lithosphere-asthenosphere interaction for the origin of the studied rocks. This lithosphere-asthenosphere interaction can be translated in terms of a melt extraction by shallow level melting of a chemically heterogeneous upper mantle characterized by depleted asthenospheric components and recycled subducted components. On Nb/Y vs. Zr/Y plot (Fig. 7B; Condie, 2005), the studied basalt samples cluster in the domain of a non-plume mantle source. HFSE and REE compositions (Zr/Ta\* vs. Ce/Y) of these rocks (Fig. 7C) depict a marked deviation from typical depleted N-MORB compositions and the array of plots conforms to an E-MORB affinity.

Geochemical characteristics of modern volcanic rocks such as MORB, OIB and IAB are strongly controlled by their geodynamic conditions of eruption. In this regard, the high field strength elements (HFSE, such as, Nb, Ta, Zr) serve as reliable geochemical proxies to constrain the tectonic environments associated with magmatism in oceanic and continental realms (Komiya et al. 2002). Similarly, the REE and HFSE remain least sensitive to alteration and consequently their ratios have been successfully applied to distinguish different geodynamic conditions involved in the process of magmatism (Condie, 2001; Song et al., 2008; He et al., 2010). On the Zr/Y vs Zr tectonic discrimination plot (Fig. 8A), the CRB samples plot in two clusters, one corresponding to the typical MORB field while the other falling in the overlapping domain of MORB and volcanic arc basalts. This volcanic arc affinity of the samples with a discernible nonconformity with typical MOR setting is in compliance with chemical modification of the depleted upper mantle by recycling of lithospheric component metasomatized by paleo-subduction events. The pristine N-MORB type chemical composition of the melts parental to these Carlsberg Ridge basalts has been overprinted by subduction signatures. This can be translated in terms of parent magma generation from a source that inherited subduction components and this was invariably reflected in the studied clinopyroxene

compositions which straddle the orogenic and non-orogenic fields (Fig. 3B). Trace element compositions are effective indicators of the mantle source characteristics, providing information with regard to degree and depth of partial melting, crustal assimilation and fractional crystallization (Lassiter et al., 1995; Condie, 2001; Reichow et al., 2005; Shellnut et al., 2014). Additionally, REE compositions are sensitive to mantle melting conditions and help constraints the understanding of the degree and depth of partial melting. Relative abundance in REE, similarly, are strongly dependent on the extent of partial melting and the nature of aluminous phase (spinel or garnet) occurring in the mantle as a source of peridotitic composition (Lassiter et al., 1995; Reichow et al., 2005; He et al., 2010). Likewise, La, Ce, Sm and Gd are incompatible, and the Ce/Yb and La/Sm ratios are strongly fractionated when melting occurs in the garnet stability field and slightly fractionated during melting in the spinel lherzolite domain (Irving and Frey, 1978; Kelemen, 1990; Rollinson, 1993; Storey et al., 1997; Yaxley, 2000; Xu et al., 2005; Song et al., 2006; Zhao and Zhou, 2007; Lai et al., 2012). The Ce/Yb and La/Sm ratios give a measure of LREE/HREE and LREE/MREE fractionations and are particularly sensitive to the amount of garnet left in the restite, which in turn reflects the degree of melting of a garnet lherzolitic source (Condie, 2001). The present suite of basalts from the Carlsberg Ridge show  $(Ce/Yb)_{CN}$  ratio ranging from 0.72-1.1 and  $(La/Sm)_{CN}$  ratio varying between 0.17 and 0.85 that corroborate feeble, depleted LREE/HREE and LREE/MREE fractionation trends respectively corresponding to partial melting in a shallow level mantle regime in the stability field of spinel lherzolite. Furthermore, the partial melting in the garnet stability field, in general, results into high Dy/Yb ratio ( $>2.5$ ), whereas melting in the spinel stability field accounts for low Dy/Yb ratio ( $<1.5$ ; Yang et al., 2014; Manikyamba et al., 2015; He et al., 2017). The Dy/Yb ratio for the studied CR basalts depicts a narrow range from 0.99 to 1.11 implying mantle melting under spinel peridotite facies condition. The Sm/Yb ratio can be a useful tool to constrain the mantle source mineralogy, for Sm, being an incompatible element, is affected significantly by variation in the source mineralogy (e.g., garnet or spinel), whereas Yb is compatible with garnet but not with clinopyroxene or spinel (Aldanmaz et al., 2000; Zhao and Zhou, 2007; Liu et al., 2012). Sm/Yb ratio of spinel lherzolite source partial melts remain similar to those of mantle and thus, form a horizontal melting trend that lies within, or close to, a mantle array. Such array is defined by depleted mantle (DM, McKenzie and O'Nions, 1991) and an enriched subcontinental lithospheric mantle (SCLM, Aldanmaz et al., 2000). On the other hand, partial melts from a garnet-lherzolite source (with garnet residue) will have significantly higher Sm/Yb ratio than mantle source (Aldanmaz et al., 2000; Yang et al., 2014; Manikyamba et al., 2015; He et al., 2017). In the present study  $(Sm/Yb)_{CN}$  ratio vary between 0.93 and 1.17 points towards partial melting of a spinel lherzolitic mantle. Plots of CR basalts on melting curve of Sm/Yb vs. Sm diagram (Fig. 8B) substantiates derivation of parent magmas at shallow level

through 10% melting of a lherzolitic mantle within the stability field of spinel (Yaxley, 2000; Xu et al., 2005; Lai et al., 2012). Thus, the overall REE signatures for CR basalts are marked by depleted  $(La/Yb)_{CN}$ ,  $(La/Sm)_{CN}$  and  $(Gd/Yb)_{CN}$  ratios corroborating high degree partial melting of spinel peridotite mantle at a shallow depth (<60 km; Rollinson, 1993; Condie, 2001). Geothermometric estimations based on clinopyroxene compositions of CRB record a temperature of equilibration ranging from ~1050°–1190°C.

On Th/Yb vs. Nb/Yb plot (Fig.9A), the sample array reflects a transitional composition from N-MORB to E-MORB; the samples falling out of the MORB-OIB domain distinctly conform to contributions from subduction-derived components in the source mantle. A transitional depleted to enriched mantle signatures concomitant to recycling of subducted lithospheric components into asthenospheric mantle is corroborated by Zr/Nb vs. Nb/Th plot (Fig.9B). A chemically heterogeneous, hydrated source mantle with input from recycled subduction-derived components accounts for the origin of parent magmas for CR basalts. These basalts straddle fields of N-MORB and E-MORB on Nb/La vs. Ba/Rb (Fig.9C) plot thereby complying with a transitional and heterogeneous chemistry of the source mantle. The higher Zr/Hf (avg. 40.5) and Zr/Sm (avg. 30.9) in conjunction with lower Nb/Ta (avg. 4.6) values for CR basalts in comparison with that of primitive mantle (Zr/Hf:36, Zr/Sm: 25 and Nb/Ta: 17) corroborate recycling/infiltration of lithospheric components into N-MORB type depleted asthenospheric mantle. The Zr/Nb ratios of these rocks depict a wide range from 25.5-71.5 (avg. 51.75) in conformity with that of recent oceanic arc tholeiites (Zr/Nb:9-87) thereby indicating depleted to enriched nature of the mantle source marked by interaction between asthenosphere and recycled lithospheric components (Sun and McDonough, 1989; Pearce and Peate, 1995). Therefore, the HFSE chemistry for the CR basalts is in compliance with the phenomenon of depleted mantle refertilization by recycled lithosphere. Nd/Hf ratios ranging from 3.71 to 4.67 suggest LREE enrichment relative to HREE that conspicuously implicate enrichment of a depleted mantle source by subduction-processed oceanic lithosphere or metasomatized mantle wedge. Ba/Nb ratio is an effective geochemical proxy indicating the fluid/water content in the mantle source, while Ba/La can be used as a tracer for the total slab-derived input into the mantle wedge (Cervantes and Wallace, 2003; Gribble et al., 1996; 1998). The Ba/Nb ratios for the studied samples ranging from (27.7-133.5) (avg. 103.88) corroborate the presence of hydrous minerals (e.g. phlogopite or amphibole) in the source region, while their Ba/La (4.1 - 10.6; avg. 7.77) and Ba/Th (59.6-147.5; avg. 103.88) ratios reflect overprinting of refractory, depleted N-MORB type mantle by recycled, subduction-processed, metasomatized components including oceanic crust, pelagic sediments and hydrated mantle wedge thereby implying pronounced

geochemical heterogeneity of mantle beneath the Carlsberg Ridge in NWIO.  $^{143}\text{Nd}/^{144}\text{Nd}_{\text{initial}}$  vs.  $^{87}\text{Sr}/^{86}\text{Sr}_{\text{initial}}$  isotope correlation plot (Fig. 10A) for the studied basalts corroborates a heterogeneous mantle source with a HIMU component. This observation reconciles  $\epsilon_{\text{Nd}}$  vs.  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope correlation diagram for CR basalts showing their affinity towards HIMU mantle. The HIMU affinity of the samples provides a conspicuous evidence for role of subducted and recycled oceanic crust which suffered extraction of Pb from basaltic part of slab during alteration. This contention is further substantiated by higher Th/Nb (0.1-0.2) compared to OIB (0.06) thereby endorsing the role of a subduction-modified mantle component in the source. Lower Nb/U (6.1-37.9) values with higher Ba/Nb (6.1-21.9), Ba/Th (59.6-147.5) and Ba/La (4.1-10.6) compared to OIB and N-MORB suggest derivation of the basalts from a heterogeneous mantle source that experienced metasomatism by recycled oceanic lithosphere from paleo-subduction events. Absence of EMI signatures discard the role of SCLM and the HIMU affinity of the CRB yields unequivocal evidence for shallow recycling of subduction-processed, altered, ancient oceanic crust into depleted N-MORB type upper mantle that further contributes to the heterogeneity of NWIO. This observation is complemented by  $\epsilon_{\text{Nd}}$  vs.  $\epsilon_{\text{Sr}}$  and  $\epsilon_{\text{Nd}}$  vs. La/Nb plots for CRB (Figs. 10B and 10C) which reflect a possible influence of  $\sim 1.5$  Ga altered, metasomatized oceanic crust for the refertilization of Indian Ocean MOR mantle.

## **6.2 Mantle reservoirs and the global chemical heterogeneity**

The identification, distribution and secular evolution of geochemically distinct asthenospheric reservoirs is important in understanding the pattern of large-scale mantle convection and the origin and provenance of global-scale mantle chemical domains. The agents and processes responsible for the generation of mantle heterogeneities posit important constraints on the composition and differentiation of the Earth at different scales (Zhang et al., 1999). The two viable processes that attribute to elemental and isotopic heterogeneity of the mantle include (i) refertilization through melt-rock and melt-fluid reaction processes and (ii) recycling of ancient, subduction-processed oceanic and continental lithospheric components. The components that have been recycled into the mantle since the inception of subduction-driven plate tectonics include lower continental crust, sub-continental lithospheric mantle, altered ocean crust, pelagic sediments, subduction modified mantle and materials from large low shear velocity provinces (Barry et al., 2017). The variable and distinct isotopic signatures of the different mantle reservoirs and the global chemical heterogeneity cannot be ascribed to a consistent standard model or any specific mechanism. Rather, the inheritance of the compositional diversities and anomalies in the mantle have been linked to supercontinent reconfigurations and associated subduction-collision-recycle tectonics through the earth's evolution. Radiogenic isotope systems have distinguished a series of large-scale, chemically heterogeneous

domains in the upper mantle that undergo partial melting to generate melts inheriting respective source signatures. The isotopically distinct primary mantle reservoirs include (i) DM, (ii) EM-I, (iii) EM-II and (iii) HIMU components. Apart from these there are mantle reservoirs with unusual isotopic signatures such as 1) a mantle domain residing in the Indian Ocean and outlined by oceanic basalts with anomalous Pb and Sr isotope signatures referred to as the Dupal anomaly (Hart, 1984), 2) the Indian Ocean mid-ocean ridge (MOR) type mantle (Ito et al., 1987), and the Gondwana lithospheric mantle (Mahoney et al., 1996). The primary fertile components attributing to the compositional heterogeneity of asthenospheric mantle beneath a mid-oceanic ridge-rift system include (i) Recycled oceanic crust (ROC) manifested as HIMU-type (high U/Pb ratio) component, (ii) Lower continental crust (LCC) and subcontinental lithospheric mantle (SCLM) manifested as EMI type (enriched mantle) component. The geochemical variations in Indian Ocean MORB rarely comply with EMII type mantle component characterized by upper continental crust (UCC) recycled into the mantle via subducted pelagic sediments, limestones and marls and silicic rocks such as granite, rhyolite and gneiss sliced from distal and proximal margins, respectively. They are largely coherent with HIMU or EM I component reflecting modification of a typical Atlantic-Pacific type upper mantle with ancient subducted and recycled components comprising altered oceanic crust with minor pelagic sediment (Rehkämper and Hofmann, 1997; Stracke and Hoffmann, 2005; Willbold and Stracke, 2006; Jackson and Dasgupta, 2008; Panter et al., 2006; Pettke et al., 2018; Jackson et al., 2018). Partial melting and melt generation events periodically extract incompatible trace elements from the upper mantle and render a typical depleted mantle (DM) character. The upper mantle heterogeneity beneath oceanic spreading centres is a widely recognized phenomenon and its compositional disparity with typical depleted mantle (DM) component can be equated with cycling enrichment mechanisms governed thermo-tectonic processes. These involve (a) influx of mantle – derived silicate melts and hydrous/carbonic fluids into depleted mantle elevating incompatible trace element abundances (b) dehydration and melting of subducted oceanic slab triggering infiltration of fluids and melts into a depleted mantle wedge and metasomatism enrichment (c) interaction of depleted asthenosphere with mantle plumes carrying enriched components or metasomatized oceanic or continental lithospheric fragments. Recycling of oceanic or continental lithosphere into the mantle invoke thermal erosion by upwelling asthenosphere or subduction-driven delamination of lithosphere during accretion-collision processes (Eiler et al., 2000; Elliott et al., 2006).

### **6.3 Recycled ancient oceanic lithosphere and Indian Ocean MOR Mantle: the Gondwana connection**

The compositional dichotomy between the asthenospheric mantle reservoirs of Pacific, Atlantic and Indian Oceans can be correlated with the thermo-tectonic evolution of the earth delineated by cyclic amalgamation and dispersal of continental blocks with opening and closure of ocean basins. The domain of the Pacific Ocean and its predecessor Panthalassa were devoid of continents post 340Ma and the mantle in this region experienced constant supply of plume-derived melts carrying EMI components sourced from underlying LLSVP. However, the sub-oceanic asthenospheric mantle in the Atlantic and Indian Ocean domains were covered by continents that eventually separated and drifted apart giving rise to the ocean basins. The phenomenon of continental disintegration and birth of oceans invoke recycling of SCLM and lower continental crust into the mantle in response to the convective erosion and lithospheric delamination at continent-ocean transition zone (COTZ). Alpine-type orogenic belt, as documented from Canavese Zone, Western Alps, preserves remnants of a Jurassic COTZ that represents emergence of Alpine Tethyan ocean basin and associated disintegration of Pangean Supercontinent (Festa et al., 2020).

The tectonothermal, geomorphological and paleoclimatic evolution of the Indian plate involved a 9000km northward migration spanning over 160Ma punctuated by sequential events of supercontinent dispersal, sea-floor spreading, birth of ocean basins, mantle plume activity, transform fault movements, subduction-accretion-collisional processes and orogenic episodes. The Phanerozoic configuration of the Indian subcontinent including the adjacent ocean basins squares with its separation from the Gondwana supercontinent at 130Ma to amalgamation with European supercontinent at 52 Ma. Consequently, the origin of the Indian Ocean at 125 Ma and its evolutionary process was eventually linked to the disintegration and drifting of African, Indian, Australian, Antarctic and Arabian continental landmasses from the Gondwana supercontinent. The break-up of Gondwana at 167 Ma and consequent opening of Indian Ocean was influenced by the ongoing subduction of Tethyan ocean floor beneath the southern margin of Eurasia (Chatterjee et al., 2013). The Northwest Indian Ocean originated in response to the dispersal of Indian and African continental plates at 84 Ma and thus represents a potential zone to decipher ocean basin evolution, oceanic plate divergence, crustal accretion, propagation and segmentation of ridges. The initiation of the Carlsberg Ridge in the northwest Indian Ocean involved an episode of ridge propagation and accommodated the Seychelles-India and India-Africa divergent plate motions (Eagles and Hoang, 2014). The Indian Ocean is the most bathymetrically complex of the global oceans and the Indian Ocean MOR mantle preserves elemental and radiogenic isotopic signatures distinct from Pacific and



Atlantic type mantle domains. The Indian Ocean type MOR mantle extends from the Southern Atlantic through the Indian Ocean to the Australian-Antarctic discordance (AAD) including the CIR, CR, SWIR and SEIR. The mid-ocean ridge basalts (MORBs) of the Indian Ocean are compositionally distinct from those of the Atlantic and Pacific oceans. The most definitive characteristics of the Indian Ocean MORBs are particularly manifested in Pb, Nd, Hf and Sr isotopic signatures. The distinct isotopic features of the Indian Ocean MORBs have been commonly described as DUPAL anomaly. The DUPAL anomaly itself being ascribed to a variety of lithospheric processes that include incorporation of ancient crustal materials in the magma source. The Indian Ocean type MOR mantle is isotopically distinct from the Pacific Ocean and Atlantic Ocean type MOR mantle in having relatively high  $^{87}\text{Sr}/^{86}\text{Sr}$ , low  $^{143}\text{Nd}/^{144}\text{Nd}$  with deviation of  $^{207}\text{Pb}/^{204}\text{Pb}$  and  $^{208}\text{Pb}/^{204}\text{Pb}$  ratios from a Northern Hemisphere reference line (NHRL; Hart, 1984).

Several proponents for the geochemical heterogeneity of Indian MORB mantle have attributed the enrichment of “normal” depleted mantle to (i) recycled oceanic crust plus pelagic sediments, (ii) mantle plumes and/or (iii) delaminated sub-continental lithosphere. Basalts erupted along variably spreading segments of IORS record diverse elemental and isotopic compositions owing to the inhomogeneous compositions of the Indian Ocean MOR mantle. Magma intrusions, melt migration and oceanic crust accretion at slow-spreading ridges like SWIR are primarily governed by (i) a large pervasive oceanic magma chamber nesting beneath and a deep magma plumbing system (ii) limited supply of melts in pulses, slow cooling and polybaric crystallization (iii) direct intrusion of magma into the lower crust, followed by successive upward diapiric flow by crystal mush and solid-state, crystal-plastic deformation and detachment faulting associated with asymmetric spreading (Dick et al., 2019; Meyer et al., 1989). The primitive to evolved compositions of lower crustal gabbros dredged from Atlantis Massif of SWIR are indicative of hybridization by late stage melt migration and extensive post-cumulus melt-rock interaction. Petrochemical aspects of adcumulate gabbros studied from a ridge segment of SWIR between the Islas Orcadas and Shaka Fracture Zones substantiate slow cooling in conjunction with polybaric fractional crystallization (Meyer et al., 1989). The SWIR gabbros share their inhomogeneous compositions with the basaltic counterparts collectively corroborating a mantle source that trapped both enriched and depleted components. Jurassic (180 Ma) zircons in gabbros recovered from Gallieni Fracture Zone of SWIR provide unequivocal evidence for crustal recycling and preservation of continental relics in the mantle beneath the MOR (Cheng et al., 2016). Sr-Nd-Pb-Hf data for retrieved 14Ma -28Ma basalts from ODP Leg 187 distinguish the respective mantle domains of Pacific Ocean and Indian Ocean and suggest recycling of subduction-processed enriched components like oceanic crust, pelagic

sediments and sub-arc mantle wedge into the refractory upper mantle (Kempton et al., 2002). The enriched FOZO component for MOR basalts from the northern CIR has been attributed to oceanic crust recycling associated with minor mantle plume activity (Kim et al., 2017). Isotopic signature for SEIR basalts corroborates variable mixing among depleted mantle component, delaminated continental lithosphere and mantle plume. The enriched mantle (EM I) signatures for SWIR and SEIR basalts can be explained by detached lower continental crustal and lithospheric fragments stagnated in the upper mantle since the inception of Indian Ocean basin (Nicolaysen et al., 2007; Meyzen et al., 2005). Among the three principal proponents for Indian Ocean MOR mantle heterogeneity such as i) mantle plumes ii) recycled ancient oceanic crust iii) delaminated continental lithosphere, the EM I signature conforms to thermal erosion and recycling of delaminated lower continental crust and continental lithospheric fragments of Gondwanan heritage into the upper mantle during the Gondwana supercontinent break-up and initiation of Indian Ocean at COTZ (Mahoney et al., 1989; 1996; 1998; Gautheron et al., 2015; Zong et al., 2019).

However, the trace and REE chemistry with the HIMU affinity for the CR basalts from NWIO are in compliance with refertilization and enrichment of an originally Atlantic-Pacific type depleted upper mantle by recycled, ancient, subduction-processed oceanic lithosphere. In this case, the hypothesis of oceanic crust recycling through paleo-subduction events concurrent with Gondwana amalgamation is preferred over the phenomenon of delamination of continental lithosphere during Gondwana break-up. It is thus envisaged that the genetic history of the Indian Ocean MOR mantle has a link with a protracted gestation of an asthenospheric reservoir beneath the Gondwana Supercontinent that trapped the components recycled during paleo-ocean closures and continental assembly. The phenomena of cyclic dispersal and amalgamation of continental blocks with opening and closure of ocean basins are contemporaneous and overlapping processes and evident from assembly of Western Gondwana and final Rodinia break-up, Gondwana dispersal and India-Eurasia collision (Santosh, 2010; Santosh et al., 2009; 2010; Abu-Alam et al., 2013; Tang and Santosh, 2018; Yoshida and Santosh, 2018). The continental assembly and ocean closing stages of supercontinent formation involves declining and terminal phases of ocean with subsequent ocean-continent and continent-continent convergence and collisional orogenic processes. The principal proponents for Supercontinent amalgamation invoke extroversion where the peripheral, exterior ocean basins flanking the continental landmasses are subducted and introversion in which the internal oceanic lithosphere formed between dispersing fragments of the previous supercontinent is subducted (Nance et al., 1988; Murphy and Nance, 2013, Yoshida and Santosh, 2014; Oriolo et al., 2017; Wilson et al., 2019). The formation of Gondwana Supercontinent invoked protracted and

multiple stages of terrane accretion, paleo-ocean closure and subduction-collisional orogeny throughout the Neoproterozoic era (800Ma - 550Ma). The amalgamation of Gondwana initiated at ~630 Ma coinciding with the rifting of Rodinia and extended to ~ 550-530 Ma involving episodic subduction-accretion-collisional activities and paleo-ocean closure. The closure of the Mozambique Ocean accreted East (India, Madagascar, Antarctica, and Australia) and West Gondwana (Africa and South America) and formed the Mozambique belt during 800 Ma -650Ma. The contemporaneous Brasiliano and Kuungaorogenies at ~ 650Ma-550Ma amalgamated India, Madagascar, Africa and South America, Australia, Antarctica, Africa respectively. Therefore, the Indian Ocean mantle represents an incubating, heterogeneous asthenospheric reservoir with a prolonged residence beneath the Gondwana Supercontinent that was periodically refertilized by subduction-driven recycling of ancient, metasomatized oceanic lithosphere during episodic ocean basin closure and collisional orogenies associated with Gondwana amalgamation. Thus, the compositional diversity of the Indian Ocean type MOR mantle as preserved in its volcanic derivatives like SWIR basalts, CIR basalts and presently studied CRB and its elemental and isotopic deviation from Atlantic-type depleted mantle (DM) reservoir collectively conform to two thermo-tectonic scenarios complying with the amalgamation and dispersal of Gondwana Supercontinent (i) subduction-driven delamination and recycling of ancient, metasomatized oceanic lithosphere concurrent with Mozambique ocean basin closure, ocean-continent collision and continental convergence during Gondwana assembly in Neoproterozoic (Fig.11) thereby substantiating the possibility of a long-lived residence of heterogeneous mantle asthenosphere with HIMU component beneath Gondwana that upwelled during divergence of India, Africa and Seychelles or (ii) thermal erosion, delamination and recycling of Gondwanan continental lithosphere and lower continental crust (EMI component) into the shallow upper mantle at COTZ consequent to the Mesozoic mantle plume activities, Gondwana rifting and inception of Indian Ocean. Petrological, geochemical and isotopic data for CRB yield comprehensive evidence complying with the refertilization of a depleted mantle source by ancient, metasomatized oceanic lithosphere subducted and recycled during the terminal phase of Mozambique ocean ensued by horizontal shortening and convergence of East and West Gondwana during 630-550 Ma (Fig. 11) and further contributed to the long-preserved compositional heterogeneity of Indian Ocean MOR mantle following the Gondwana break-up in Mesozoic. The Carlsberg Ridge basalts erupting at ~50 Ma (Chatterjee et al., 2013) were sourced from this heterogeneous Indian Ocean mantle that tapped remnants of ancient recycled oceanic lithosphere from paleo-subduction events (Fig. 12).

## 7. Conclusions

- Integrated petrological, geochemical and isotopic data for the Carlsberg Ridge Basalts (CRB) of the northwest Indian Ocean yield a comprehensive account for their petrogenesis coupled with the tectonic and chemical evolution of Indian Ocean mantle.
- Petrological and geochemical characteristics suggest tholeiitic to transitional composition of precursor melts for CRB that were derived by 10% partial melting of a chemically inhomogeneous spinel lherzolite mantle at a shallow depth beneath an oceanic spreading centre.
- LILE, HFSE and LREE compositions deviate from the typical depleted N-MORB composition and reflect distinct E-MORB affinity while the radiogenic Sr-Nd isotope signatures ( $^{87}\text{Sr}/^{86}\text{Sr}$ : 0.702668 to 0.702841 and  $^{143}\text{Nd}/^{144}\text{Nd}$ : 0.512972 to 0.513068) corroborate a heterogeneous mantle source with HIMU component.
- The HIMU source component preserved in the northwest Indian Ocean Mid Oceanic Ridge mantle can be equated with refertilization and enrichment of a depleted Mid-Atlantic Ridge type mantle through recycling of ancient subduction-modified oceanic lithosphere.
- The non-plume origin of CRB with distinct subduction imprint and enriched composition of source mantle is substantiated by Zr/Hf (33.8-47.3) and Zr/Sm (24.9-36.4) in conjunction with lower Nb/Ta (1.7-7.3) ratio, negative Nb anomalies with lower Nb/Y (0.04-0.11) and Zr/Y (2.5-3.5), higher Zr/Nb (25.5-71.5) and Th/Nb(0.6-0.42), lower Nb/U (6.2-37.9) values with higher Ba/Nb (6.1-21.9), and Ba/Th (27.7-147.5; avg. 103.9).
- The role of recycled subduction-derived components in the source mantle heterogeneity suggest modification of the Indian Ocean MOR-type depleted mantle by subduction-driven delamination and recycling of ancient oceanic lithosphere components that can be genetically linked to convergent margin processes associated with multiple stages of paleo-ocean closure and continental convergence during Neoproterozoic-Palaeozoic Gondwana assembly
- This study invokes a geochemically heterogeneous Indian Ocean mantle that experienced a protracted residence beneath the Gondwana Supercontinent prior to the inception of IORS and trapped recycled metasomatized oceanic lithosphere from ancient subduction episodes that eventually contributed to the compositional heterogeneity of Indian Ocean mantle following the dispersal of Gondwana Supercontinent.
- The studied CRB samples from northwest Indian Ocean explicitly manifest the heterogeneous elemental and isotopic signatures of the Indian Ocean MOR mantle source.

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## Figure captions:

### Figure 1:

- A. Indian Ocean Ridge system (IORS) (source: [www.nio.org](http://www.nio.org)) with study area within the box.
- B. Multibeam bathymetry map of the study area. The dredge locations are represented by red squares in the bathymetric map of the study area (modified after Kamesh Raju et al, 2008). The white lines indicate off-axis trace of the discontinuities of the ridge segments and TF represents the major transform fault in this area.

### Figure 2:

Photomicrograph showing

- A. Occurrence of resorbed plagioclase phenocryst in glassy groundmass depicting porphyritic texture in Carlsberg Ridge Basalt
- B. Occurrence of clinopyroxene phenocryst in Carlsberg Ridge Basalt
- C. Occurrence of microphenocryst of olivine in Carlsberg Ridge Basalt
- D. Plagioclase grains partially enclosed by clinopyroxene grains depicting subophitic texture in the studied basalts
- E. Plagioclase microlites forming a triangular interspace which are filled up by volcanic glass indicating intersertal texture in groundmass of the studied basalt
- F. Occurrences of devitrified glass in the studied basalts

### Figure 3:

Plot of investigated pyroxene compositions of Carlsberg Ridge Basalts in

- A. Wo-En-Fs diagram (Morimoto et al., 1988)
- B. Ti vs. Ca diagram (after Leterrier et al., 1982)
- C. Projection of investigated plagioclase compositions in Or–Ab–An triangular diagram

### Figure 4:

- A. Plots of studied basalts in Total alkali vs. silica diagram (after LeBas *et al.*, 1986)
- B. Carlsberg ridge basalts showing a tholeiitic nature in (Na<sub>2</sub>O + K<sub>2</sub>O) – FeO\*– MgO (AFM) diagram (after Irvine and Baragar, 1971)
- C. Plots of Carlsberg Ridge basalts in Y vs. Zr discrimination diagram showing tholeiitic to transitional characters

### Figure 5:

- (A) Chondrite normalized REE patterns and (B) primitive mantle normalized multi-element spider diagram for the studied basalts (normalization values are from Sun and McDonough, 1989)

### Figure 6:

- A. Plots of Carlsberg Ridge basalt samples in  $\epsilon_{Nd}$  vs.  $^{87}Sr/^{86}Sr$  isotope correlation diagram showing their affinity toward HIMU mantle source. Fields of various Oceanic Plateau Basalts are after Hauff et al. (2000)
- B.  $^{143}Nd/^{144}Nd_{initial}$  vs.  $^{87}Sr/^{86}Sr_{initial}$  isotope correlation plot for the studied basalts. Main oceanic mantle components after Zindler and Hart (1986) are shown. The mantle array is defined by many oceanic basalts and bulk earth values of  $^{143}Nd/^{144}Nd$  and  $^{87}Sr/^{86}Sr$  can be observed from this trend (Faure, 1986; Dickin, 1995). The field for Kerguelen Plateau Basalt

is based on Michard et al. (1986), Dosso et al. (1988), Storey et al. (1992) and Mahoney et al. (1995).

**Figure 7:**

- A. Low Nb/La ( $\sim < 1$ ) and extremely low La/Yb ratios of the studied basalts suggest an interaction of recycled subducted components at lithosphere-asthenosphere mantle domain (after Abdel-Rahman and Nassar, 2004).
- B. Nb/Y vs. Zr/Y discrimination diagram showing Low Nb/Y ratios along with negative Nb anomaly discard influence of plume and indicate a non-plume source (after Condie, 2005).
- C. Zr/Ta\* vs. Ce/Y discrimination diagram suggests an affinity toward E-MORB for the studied basalts

**Figure 8:**

- A. Plots of the studied basalts in Zr vs. Zr/Y discrimination diagram indicating their MORB type characters.
- B. Plots of Sm/Yb vs. Sm (after Zhao and Zhou, 2007) for the studied samples suggest that the  $\sim 10\%$  melting to spinel lherzolite mantle melting for the derivation of CRB. Melting curves are after Aldanmaz et al. (2000). A pair of melt mode curves are drawn for spinel (Kinzler, 1997) and garnet (Walter, 1998) lherzolite.

**Figure 9:**

- A. Th/Yb vs. Nb/Yb plots for the studied samples showing N-MORB lineage (Pearce, 2008)
- B. Zr/Nb vs. Nb/Th plot reflecting role of depleted mantle for the generation of the studied rock (after Condie, 2015). A shifting from depleted mantle towards hydrated mantle source possibly fluxed by recycled subduction component.
- C. Array of plots in Ba/Rb vs. Nb/La reflects variable N-MORB chemistry, possibly attributed to increasing influence of recycled subducted components.

**Figure 10:**

- A.  $^{143}\text{Nd}/^{144}\text{Nd}_{\text{initial}}$  vs.  $^{87}\text{Sr}/^{86}\text{Sr}_{\text{initial}}$  isotope correlation plot for the studied basalts along Atlantic N-MORB, Pacific N-MORB, Indian Ocean MORB and E-MORB. Data sources: Ito et al., 1987; LeRoex et al., 1983, Ray et al., 2013
- B. Plots of studied sample in  $\epsilon_{\text{Nd}}$  vs.  $\epsilon_{\text{Sr}}$  reflect a possible influence of  $\sim 1.5$  Ga altered, metasomatized oceanic crust for the refertilization of Indian Ocean MOR mantle
- C. Plots of the studied sample in  $\epsilon_{\text{Nd}}$  vs. La/Nb diagram suggest a contribution of subducted oceanic crust in generation of CRB

**Figure 11:**

- A. Map showing the positions of cratons, shields and Mozambique oceans at the end of the Neoproterozoic (modified after Abu-Alam et al., 2013)
- B. A schematic model showing the closing the closure of Mozambique ocean and subsequent collision of India and African plate (modified after Wilson et al., 2019)

**Figure 12:**

- A. Map showing the paleogeographic position of India and Indian Ocean Ridge system during middle Eocene (after Chatterjee et al., 2013)
- C. A schematic model showing rifting stage of Indian and African plate and formation of Carlsberg Ridge in Indian Ocean during middle Eocene (modified after Wilson et al., 2019)