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Review Article

Kimberlites, Lamproites, Lamprophyres, Carbonatites, other Alkaline Rocks, and Mafic Dykes from the Indian Shield: Glimpses of Research (2012-2016)

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Major highlights of researches carried out on kimberlites, lamproites, lamprophyres, carbonatites, other alkaline rocks and mafic dykes from the Indian shield during 2012-2016 are presented. New findings involving field mapping, petrology, geochemistry (including high quality mineral based *in situ* isotopic studies) and geophysics have provided remarkable insights on the mode of their occurrence, timing of emplacement, mineralogy and bulk-rock composition, redox conditions, relative contribution of the lithosphere and asthenosphere, as well as their economic potential. Several large-scale geodynamic aspects such as plume-lithosphere interactions, ancient subduction events, layered structure of the sub-continental lithospheric mantle, spatial extent of the Precambrian large igneous provinces and supercontinent configurations could be unraveled from these studies on deep-mantle derived small-volume magmatic rocks.

Keywords: Kimberlite; Lamproite; Lamprophyre; Carbonatite; Mafic Dyke; Mantle Petrology; India

Introduction

The past five years of 2012-2016 witnessed a number of research contributions on kimberlites, lamproites, lamprophyres, carbonatites and other alkaline rocks, besides the mafic dykes and mafic dyke swarms from the diverse cratons and mobile belts of the Indian shield. These researches, involving diverse sub-disciplines of petrology, geochemistry, geochronology and geophysics, have profoundly contributed to our understanding of the nature, composition and evolution of the underlying sub-continental lithospheric mantle. Glimpses of some major highlights involving some of these researches published in peer-reviewed journals are discussed below under separate headings.

Kimberlites

Detailed petrography, groundmass mineral composition and new bulk rock geochemistry data for a number of kimberlites discovered by De Beers Exploration from the Narayanpet field (NKF), Eastern Dharwar craton, southern India, are reported (Chalapathi Rao *et al*., 2012a). The presence of volcaniclastic (fragmental textured) facies kimberlite belonging to the diatreme portion of the intrusion has been brought out along with rarity of olivine macrocrysts and groundmass diopsides. Low fO2 of the kimberlite magma (ΔNNO (nickel–nickel oxide) = –1.9 to –3.2), indistinguishable from that of diamondiferous kimberlites world wide, thereby indicating that redox conditions were favourable for diamond prospectivity, and that magmatic emplacement could, instead, have played a major role in their low diamond potential (Chalapathi Rao *et al*., 2012a). The Wadagera kimberlite is the largest pipe in a cluster discovered by De Beers during exploration in the Raichur field of the Eastern Dharwar craton and has been dated at 1,083.8 ± 5.3 Ma (Lynn *et al*., 2013). The major element garnet mineral chemistry represents a dominant lherzolitic population. Diamond proxy composition garnets are rare or absent. The nature of the sub-continental lithospheric mantle at Wadagera contrasts with that reported within the diamondiferous Wajrakarur kimberlites (further south)

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and Banganapalle lamproite clusters (Cuddapah basin) (Lynn *et al*., 2013). The kimberlite near Undraldoddi (Raichur Kimberlite Field) of the Eastern Dharwar Craton, has been identified as 'Tuffisitic kimberlite' (Das *et al*., 2013). It is primarily composed of macrocrysts/microcrysts of abundant pseudomorphed olivine, minor spinels, rare phlogopite, Cr-diopside and abundant magmaclasts set in a cryptocrystalline chlorite–phlogopite–diopside dominated interclast matrix. Some of the xenocrystal phlogopite shows a Group-I kimberlite trend, whereas a majority show Group-II kimberlite trend. The whole rock REE patterns of these kimberlites show a Group-I kimberlite trend. A remarkable similarity between Undraldoddi kimberlite and the diamondiferous tuffisitic kimberlites of Wesselton Mine, South Africa has been demonstrated (Das *et al*., 2013).

New U–Pb ages of groundmass perovskite determined by secondary ion mass spectrometry for diamondiferous kimberlites from the Wajrakarur field (WKF) gave ages ranging from 1099±12 Ma to 1129±12 Ma (Chalapathi Rao *et al*., 2013c). The non-diamondiferous kimberlites from the Narayanpet field (NKF) gave ages ranging from 1123±17 Ma to 1141±18 Ma. One kimberlite (Siddanpalle cluster) from the poorly diamondiferous Raichur field has an indistinguishable age of 1093±18 Ma. Despite their contemporaneous ages, initial $^{87}Sr/^{86}Sr$ ratios of Narayanpet perovskites are notably higher (0.70302–0.70339) than those (0.70240–0.70255) from the Wajrakarur Field. Similarly, the εNd(t) of Narayanpet perovskite (+0.6 to +1.9) is relatively lower than that (+2 to +2.9) of the Wajrakarur perovskites and provides clear evidence for the involvement of distinct isotopic mantle sources for these different kimberlite fields (Chalapathi Rao *et al*., 2013c). The diamondiferous to non-diamondiferous Timmasamudram kimberlite cluster, Wajrakarur kimberlite field, in the Eastern Dharwar craton of southern India has been dated by U-Pb (perovskite) method (Chalapathi Rao *et al*., 2016c). Two kimberlite pipes from this cluster gave similar Mesoproterozoic ages of 1086 ± 19 Ma (TK-1) and 1119 ± 12 Ma (TK-3). However, a perovskite population sampled from TK-1 pipe gave a much younger Late Cretaceous age of 86.8 ± 3.4 Ma implying multiple kimberlite pulses in this cluster; the latter being supported by field, petrography as well as bulk-rock geochemistry. The Nd-isotope composition of 1100 Ma perovskites in the cluster show depleted $\varepsilon_{Nd(T)}$ values of 2.1 ± 0.6 to 6.7 ± 0.3 whereas the 90 Ma (TK-1) perovskites have enriched $\varepsilon_{Nd(T)}$ values of -6.3 ± 1.3. As the Late Cretaceous age, within its error, of the younger (TK-1) kimberlite perovskites is indistinguishable from that of the Marion hotspot-linked extrusive and intrusive igneous rocks from Madagascar and India, it has been considered to be a part of the Madagascar Large Igneous Province (Chalapathi Rao *et al*., 2016c; Fig. 1).

The two different intrusions belonging to coherent facies are observed in the Pipe-2 kimberlite of Wajrakarur field which are texturally and geochemically distinct. Differences between aphanitic and macrocrystic varieties in their chondrite

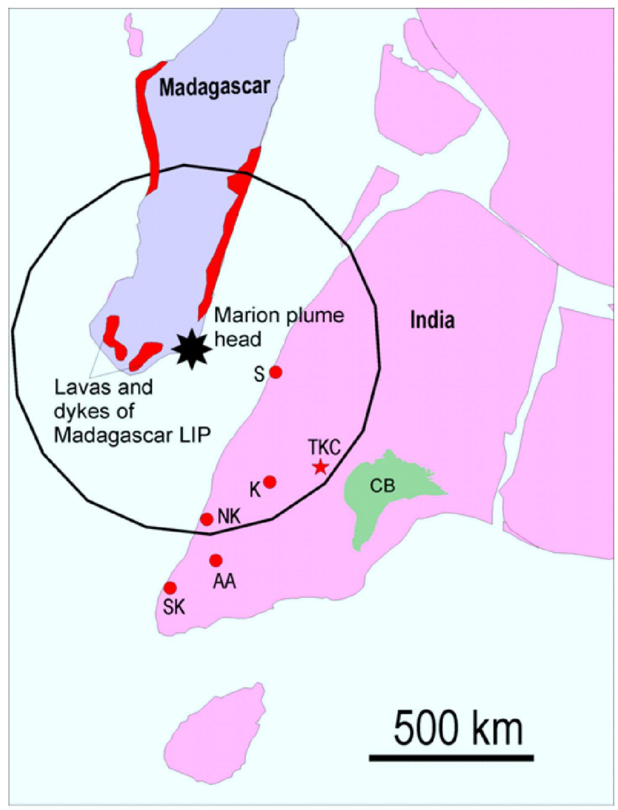

Fig. 1: A paleogeographic reconstruction map (after Reeves, 2014) showing the India-Madagascar reconstruction at 88 Ma, the position of the Marion plume, and the location of various igneous rocks of that age (from Storey *et al*., 1995, 1997; Anil Kumar *et al*., 2001). CB = Cuddapah basin; SK = south Kerala dykes; NK = north Kerala dykes; AA = Agali-Anaikatti dykes; S = St. Marys island volcanics; and K= Kunigal dykes. Radius of the circle of influence of the Marion plume is 1100 km (see Chalapathi Rao *et al*., 2016c for all the above reference details)

normalized REE abundance patterns can be explained by about 5% crystal fractionation of primary magma (Dongre *et al*., 2014). Combined petrology and whole rock geochemistry including compatible and incompatible element abundances and their ratios confirm that Pipe 2 kimberlite intrusions are archetypal Group I kimberlites and not lamproites. Ti-rich garnets are reported in the groundmass of the P-15 and KL-3 kimberlites from the diamondiferous Wajrakarur field in the Eastern Dharwar craton of southern India (Dongre *et al*., 2016). The Ti-rich garnets in the groundmass of these two kimberlites are intimately associated with chromian spinels, perhaps suggesting that the garnet formed through the replacement of spinel. Raman spectroscopy provides evidence for low crystallinity in the spinels which is likely to be a result of their partial transformation into andradite during their reaction with a late-stage magmatic (kimberlitic) fluid. The close chemical association of these Ti-rich garnets in TiO_2-FeO-CaO space with those reported from ultramafic lamprophyres (UML) is also consistent with results predicted by experimental studies, and possibly implies a genetic link between kimberlite and UML magmas (Dongre *et al*., 2016).

Based on mineral chemistry studies some of the previously studied kimberlites from the Wajrakarur field (Pipes 2, 5, as and 13), southern India, are re-interpreted to be lamproites (Kaur and Mitchell, 2013; Kaur *et al*., 2013; Mitchell and Kaur, 2016). Composition of the liquidus phases and their evolutionary trends, where applicable, such as phlogopite, spinel, perovskite and pyroxene have been deployed in these endeavour. However, the published geochemical and radiogenic isotope data (for the minerals and whole-rocks) available for these rocks is more consistent with their nomenclature as kimberlites and highlights the overlapping nature of these metasomatized mantle derived magmas in this domain. Two new kimberlite occurrences have been reported from the Wajrakarur cluster (Pipe-15; Dongre *et al*., 2015b) and from the Kalyandurg cluster (Kl-7; Mukherjee *et al*., 2014) of the Wajrakarur kimberlite field and their preliminary petrography and geochemistry are provided.

First Re-Os isotope data for samples from Mesoproterozoic kimberlite and lamproite occurrences from the Eastern Dharwar craton and end-Cretaceous Kodomali orangeite from the Bastar craton, India are reported (Chalapathi Rao *et al*., 2013d). These data reveal: (i) the involvement of Proterozoic lithosphere in the genesis of the kimberlites, (ii) coupling of the continental crust of the Eastern Dharwar craton and the underlying sub-continental lithospheric mantle from 2.5 Ga to at least 1.1 Ga, and (iii) its similarity with the emplacement age of large igneous provinces of similar age and magmatism in the Eastern Dharwar and Bastar cratons (India), the Superior Craton (Canada) and the Kaapvaal craton (southern Africa). However, data from two of the kimberlite samples (from Raichur and Narayanpet kimberlite fields) suggest involvement of multiple sources (e.g., subduction, plume or metasomatised lithosphere) in their genesis. The lamproites from Dharwar craton have very radiogenic γOs_i values, similar to those displayed by the lamproites of the Italian peninsula, and indicate a source with elevated Re/Os, possibly a subducted component (Chalapathi Rao *et al*., 2013d).

Widespread and abundant spinel is the only primary mineral of petrogenetic significance preserved in the hydrothermally altered, crater-facies, Neoproterozoic ($\geq$620 Ma) Tokapal kimberlite pipe that intruded the Indrāvati basin, Bastar craton, Central India. Two distinct spinel populations have been reported (Chalapathi Rao *et al*., 2012c): (i) finer-grained (<50 μm) microcrysts which are zoned from titaniferous magnesiochromitechromite to magnetite; and (ii) larger macrocrysts (>400 μm) with cores having distinctly chromium-rich (Cr_2O3 up to 63.67 wt%), and TiO_2-poor (<0.68 wt%) compositions. From their morphology and chemical composition the macrocrysts are inferred to be disaggregated mantle xenocrysts and their compositional range extends well into the diamond stability field (Chalapathi Rao *et al*., 2012c).

Geochemical studies on the Tokapal kimberlite system (Dhote *et al*., 2013; Chalapathi Rao *et al*., 2014b) display strong affinities to Group II kimberlites from southern Africa and Central India as well as to 'transitional kimberlites' from the Eastern Dharwar craton, southern India, and those from the southern Africa. A striking similarity in the depleted-mantle (T_{DM}) Nd model ages of the Tokapal kimberlite system, Bastar craton, the kimberlites from NKF and WKF, Eastern Dharwar craton, and the Majhgawan diatreme, Bundelkhand craton, with the emplacement age of some of the lamproites from within and around the Palaeo-Mesoproterozoic Cuddapah basin, southern India, is highlighted (Chalapathi Rao *et al.*, 2014b). The 'transitional' geochemical features displayed by many of the Mesoproterozoic potassic-ultrapotassic rocks, across these Indian cratons are inferred to be memories of the metasomatising fluids/melts imprinted on their source regions during the break-up of the supercontinent of Columbia (Chalapathi Rao *et al*., 2014b). Garnierite (a general term referring to Ni-Mg bearing hydrous silicates in laterites) has been reported from the crater-facies Tokapal kimberlite of the Bastar craton, Central India. (Chalapathi Rao *et al*., 2014c). Garnierite occurs as discrete ovoid or amoeboid segregations (up to 200 mm) or as veinlets with up to 18.1 wt% NiO and high iron contents (up to 36.2 wt% FeO^T; Fig. 2). Chemical composition of the garnierite implies its derivation from a magnesium-rich protolith. Extensive lateritisation of the large crater-facies (~2.5 km diameter) saucer-shaped kimberlite under tropical weathering conditions, aided by suitable topography, drainage and favourable structural set-up, are the factors inferred to be responsible for the formation of garnierite in the Tokapal system (Chalapathi Rao *et al*., 2014c).

Petrology and bulk-rock geochemistry of the Mainpur orangeites (Group II kimberlites) and the composition of their mantle-derived xenocrysts are presented (Chalapathi Rao *et al*., 2013a). The bulk-rock geochemistry of both the Behradih and Kodomali pipes has a more fractionated nature compared to southern African orangeites. The pyrope population in the Mainpur orangeites is dominated by the calcic-lherzolitic variety, with sub-calcic harzburgitic and eclogitic garnets in far lesser proportion. Garnet REE distribution patterns from the Behradih and Payalikhand pipes display ''smooth'' as well as ''sinusoidal'' chondrite normalised patterns. They provide evidence for the presence of a compositionally layered end-Cretaceous sub-Bastar craton mantle, similar to that reported from many other cratons worldwide. U–Pb dating of zircon xenocrysts from the Behradih pipe yielded distinct Palaeoproterozoic ages with a predominant age around 2,450 Ma (Chalapathi Rao *et al*., 2013a). Platinum group element (PGE) concentrations of twelve bulk-rock samples from the Behradih and Kodomali orangeites, which are emplaced synchronously with the Deccan flood basalts, are either similar or even lower than those from the Mesoproterozoic and Cretaceous kimberlites and orangeites from the Kaapvaal craton (southern Africa), Cretaceous kimberlites from the Sao Fransisco craton (Brazil), Ordovician kimberlites from the North China craton and the Mesoproterozoic southern Indian kimberlites from the Eastern Dharwar craton (Chalapathi Rao *et al*., 2014a). Lack of unusually high abundances of PGE in the Mainpur orangeties as well as in the co-eval Deccan flood basalts and associated alkaline rocks implies that the anomalous iridium enrichment reported at the K–Pg boundary sections was not sourced from the mantle and likely originated from an extraterrestrial source (Chalapathi Rao *et al*., 2014a).

Major and trace elements as well as the first oxygen isotopes are reported on eclogite xenoliths from the Mesoproterozoic KL2 and P3 kimberlite pipes of the Wajrakarur kimberlite field, Eastern Dharwar craton, Southern India (Dongre *et al*., 2015). Equilibration temperatures indicate derivation from 4.5 to 5.3 GPa and 1060 to 1220 C for the KL2 samples and 3.6 GPa, 918 C for the P3 sample. Similar to many other eclogite suites worldwide, the Wajrakarur Group 1 and Group 2 eclogite suites shows evidence for an origin, similar to that of the oceanic crust, which was subducted and imbricated under the Eastern Dharwar craton (Dongre *et al*., 2015). Physical and infrared characteristics of diamonds recovered from the Wajrakarur field, Banganapalle quartzites and alluvial gravels of the Pennar and Krishna rivers have been investigated (Ravi *et al*., 2013). Different thermal regimes recorded by these diamonds imply their derivation from differing depths. Some diamonds from the conglomerates and gravels show altogether different nitrogen characteristics possibly implying hitherto undiscovered primary kimberlitic source (Ravi *et al*., 2013). On the other hand, a majority of the diamonds from the Behradih orangeite, Batar craton, central India, are colourless, with a small population of light brown and pale yellow diamonds (Mainkar *et al*., 2013). The microdiamonds have experienced significant resorption after crystallization whereas the macrodiamonds are mostly broken fragments, but several grains exhibit identifiable octahedral or dodecahedral faces. Infrared spectroscopic studies on macrodiamonds show that of them belong to the IaAB diamond Type and are similar to those reported from major primary diamond deposits worldwide (Mainkar *et al*., 2013).

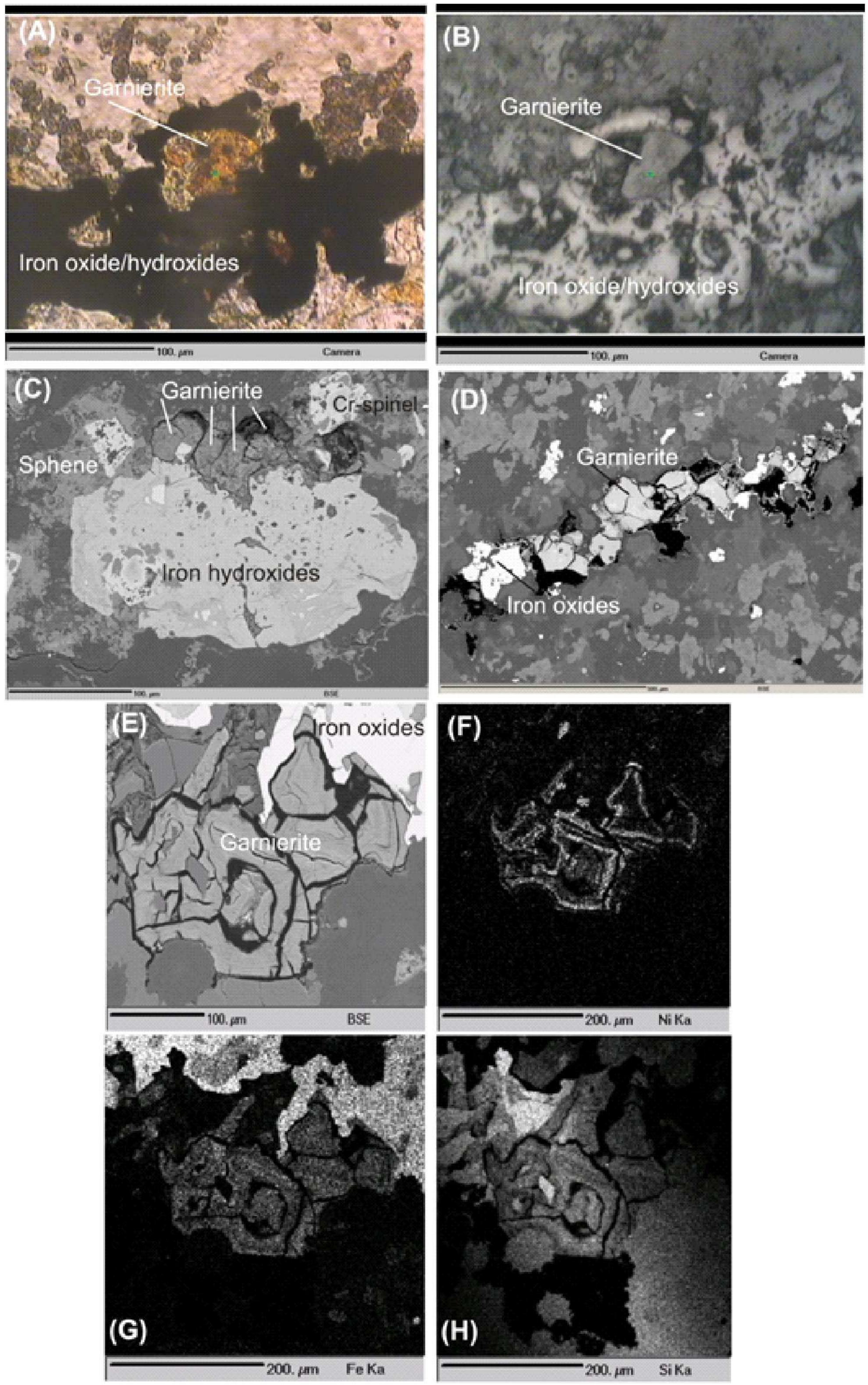

Fig. 2: Plane polarised light microphotographs of the garnierite and iron hydroxide/oxide grains under transmitted (A) and reflected light (B) captured by CAMECA-SX100 EPMA. Back-scattered electron (BSE) images depicting the mode of occurrence of the garnierite grains as amoeboid aggregates (C) and as veinlets (D). (E) A high magnification BSE image of a garnierite grain and its X-ray element mapping for Ni Ka (F), Fe Ka (G) and Si Ka (H) spectral lines depicting the distribution of these elements (see Chalapathi Rao *et al*., 2014c for details)

New palaeomagnetic and rock magnetic results reported for 1.1 Ga Mesoproterozoic kimberlites from the distinct fields of Wajrakarur (WKF), Narayanpet (NKF) and Raichur (RKF) occurring within the Eastern Dharwar craton, southern India (Venkateshwarlu and Chalapathi Rao, 2013). These results support a Mesoproterozoic closure age of the upper sedimentary horizons for the 'Purana' sedimentary basins and provide evidence for accretion of the northern and southern Indian cratonic blocks prior to 1.1 Ga. This work also concludes that in 1.1 Ga palaeomagnetically based Rodinia reconstructions, India occupies a lower palaeolatitudinal position, was much separated from Australia and that East Gondwana very likely did not form an assembly until the terminal Neoproterozoic (Venkateshwarlu and Chalapathi Rao, 2013). Using Ps (SV and SH) and Sp receiver functions, Das Sharma and Ramesh (2013) recovered depth images of the lithospheric mantle beneath southeast India encompassing the Eastern Dharwar–Bastar cratons and the adjoining Eastern Ghats mobile belt. These images reveal the presence of two significant velocity anomalies of contrasting nature at different depths beneath the study region. Das Sharma and Ramesh (op.cit) inferred that the positive velocity contrasts at L-depth represent preserved oceanic remnants of a ca. 1.6 Ga paleosubduction event in southeast India whereas the shallower anomaly represents a mid-lithospheric discontinuity. They concluded that the craton beneath southeast India is underlain by a thick lithospheric root/ keel in excess of 200 km, suggesting an environment conducive to the stability of diamond. Regional geophysical data, involving magnetic and gravity, are integrated with the local geology to understand the structural controls in the emplacement of kimberlites in the Eastern Dharwar craton (Vani *et al*., 2013; Reddy, 2014). Zones of intersection of geologically confirmed lineaments are recognized to be favourable locii for the emplacement of kimberlites. A thin (~80 Km) lithosphere-asthenosphere boundary beneath the eastern Indian craton has been interpreted from the Magneto-telluric data (Shalivahan *et al*., 2014) and delamination during Himalayan orogeny has been invoked to account for the 'lost' lithosphere which was in existence at least till 117 Ma, when the ultrapotassic dykes of the Damodar valley were emplaced.

Lamproites

A rare accessory groundmass mineral of K-rich titanate, having a composition close to that of potassium triskaidecatitanate ($K_2Ti_{13}O_{27}$), has been reported from an underground drill-core sample of ultrapotassic rock from southwestern part of the Jharia coal field in the Damodar valley, at the northern margin of the Singhbhum craton, Eastern India (Chalapathi Rao *et al*., 2013b). Potassium triskaidecatitanate is regarded as a typomorphic mineral of orangeites (Group II kimberlites) of Kaapvaal craton, southern Africa, and its occurrence in the Jharia ultrapotassic rock is attributed to its unique geodynamic setting (involving a thinned metasomatised lithospheric mantle and inheritance of an Archaean subduction component) at the northern margin of the Singhbhum craton (Chalapathi Rao *et al*., 2013b). Likewise, a Ba-Fe titanate and the unnamed titanosilicate minerals that developed at the last-stage of crystallisation have been reported from the lamproite dyke of Nonia Nala, Barakar Formation, Gondwana coal fields (Maitra and Bhattacharya, 2015). The bulk-geochemical and petrographic characteristics of the ultrapotassic intrusive rocks from previously unstudied localities of Raniganj and Jharia Gondwana sedimentary basins, Damodar Valley, eastern India, are shown to be similar to those of ultramafic lamprophyres and liquidus mineral composition are closer to that of lamproites (Chalapathi Rao *et al*., 2014d) and are strikingly comparable to ultrapotassic rocks reported from the Denizli region (Western Anatolia, Turkey), Karinya Syncline and Mt. Bundey (Australia) and the Polayapalle, eastern Dharwar craton (southern India). Initial Sr-Nd isotopic ratios of the Damodar Valley ultrapotassic intrusives are very different from those of (i) kimberlites and orangeites from India and southern Africa and (ii) primitive Kerguelen plume component but indistinguishable from those of the pristine Kerguelen mantle plume derived basalts. The depleted mantle (T_{DM}) model ages (0.95–1.4 Ga) of the Damodar Valley ultrapotassic rocks are strikingly similar to (i) those of the Deccan-age orangeites from the Bastar craton, central India, and (ii) the emplacement ages (1.1-1.4 Ga) of kimberlites and lamproites from the eastern Dharwar craton, southern India (Chalapathi Rao *et al*., 2014d).

The De Beers' India's exploration discovered of a number of dykes within the Cuddapah basin basin, near Garledinne, with petrographical and geochemical similarities to lamproites (Joy *et al*., 2012). Far-field stresses related to the Eastern Ghats Mobile Belt (EGMB) are suggested to have provided extensional sites during the time of lamproite emplacement. Zircons recovered from heavy mineral stream samples in the area exhibit a number of age groupings, including one in the range of 1287–1370 Ma. This age is interpreted as the emplacement age of the dykes in this region. Kimberlitic indicator minerals recovered from conglomerate waste dumps, indicate the uniqueness of the garnet population relative to that of the known Wajrakarur field kimberlite clusters to the west of the basin. The possibility of these lamproites representing the source of the diamonds in the Banganapalle conglomerates was suggested (Joy *et al*., 2012). Mineralogy, petrology and geochemistry of the Ramadugu (Eastern Dharwar craton) and Garledinne (Cuddapah basin) lamproites are closely similar to other well-characterised lamproites worldwide, including examples from the Eastern Dharwar Craton, Leucite Hills, West Kimberley, Smoky Butte and Labrador (Chalapathi Rao *et al*., 2014e; Chalapathi Rao *et al*., 2016a). Their magmas have been derived from a metasomatised harzburgite within the garnet stablilty field. Geochemical modeling highlights a substantial involvement of the sub-continental lithospheric mantle, apart from convecting asthenosphere, in their genesis.

Mineralogical, geochemical and $^{40}Ar/^{39}Ar$ geochronological data on hypabyssal facies lamproites near Kalmidadar and Darlimunda in the Nuapada Lamproite Field of the Bastar Craton, have been carried out (Sahu *et al*., 2013). Mineralogically, the Kalmidadar lamproite comprises phenocrysts of olivine (pseudomorphed by calcite and talc) and microphenocrysts of T-rich phlogopite set in a groundmass of chlorite and calcite. The Darlimunda lamproites have undergone pervasive hydrothermal and/or deuteric alteration, which has resulted in complete chloritisation of phlogopite and extensive silicification of the rocks. The genesis of the Nuapada lamproites is consistent with the derivation of the magma from a metasomatised subcontinental lithospheric mantle source. Whole-rock $^{40}Ar/^{39}Ar$ isotopic data for Kalmidadar and Darrimunda lamproites yielded an age of 1055 ± 10 Ma (Sahu *et al*., 2013). An ultrapotassic (lamproitic) dyke from Sakri (also from the Nuapada lamproite field) located at the tectonic contact between the easternmost margin of the Bastar craton and Eastern Ghats Mobile Belt, India, is shown to display kamafugitic affinities (Chalapathi Rao *et al*., 2016b). Its mineralogy strongly resembles a lamproite *sensu stricto* but its bulk-rock major element geochemical characteristics (viz., extreme silica-undersaturated nature) resemble *sensu lato* kamafugite from Toro Ankole, Uganda, East African Rift, and Alto Paranaiba Province, Brazil. $^{40}Ar/^{39}Ar$ dating gave a plateau age of 1045 ± 9 Ma. Its depleted mantle (T_{DM}) Nd model age of 2.56 Ga straddle the Archaean-Proterozoic chronostratigraphic boundary. The overlapping geochemical characteristics of lamproite and kamafugite (also displayed by two other lamproites of the Nuapada field at Amlidadar and Parkom) are related to the emplacement in a unique geological setting at the craton-mobile belt contact (Chalapathi Rao *et al*., 2016b).

Several new lamproite findings are recorded in the Eastern Dharwar craton (Kumar *et al*., 2013, 2016) and also at the contact between the Bastar craton and Eastern Ghats Mobile belt (Suryanarayana Rao *et al*., 2013) and their preliminary petrography and mineral chemistry have been reported. *In situ* U-Pb perovskite dates (124±4Ma) obtained on three samples of a newly discovered lamproite dyke emplaced in the Kutch rift, NW India, identify a previously unknown and relatively young (Mid-Cretaceous) magmatic event in this part of India (Karmalkar *et al*., 2015). In situ analysis of Nd isotopes in perovskite yielded a mean εNd=0.4±1 and a T_{DM} model age of 598±64 Ma, while in situ Sr-isotope analysis gives a mean $^{87}Sr/^{86}Sr$=0.70388±2 (2SE), corresponding to εSr=8.6±0.3 and suggest a mixing between lithospheric-mantle and depleted-mantle components. The lamproite has been suggested (Karmalkar *et al*., 2015) an earlier phase of rift related magmatism, different from the emplacement of the melanephelinite–basanites and basalts that dominate the igneous activity related to the Deccan volcanism in the Kutch mainland.

Lamprophyres

Petrology and geochemistry of a new find of lamprophyre dykes, intruding the Precambrian basement gneisses from the Chhota Udepur area, Narmada rift zone, Western India, reveal several overlapping characteristic features displayed by alkaline- and calc-alkaline lamprophyres (Chalapathi Rao *et al*., 2012b). Their Th/Yb, Ta/Yb, Nb/U and Ce/Pb ratios imply an OIB type-enriched mantle source, similar to that displayed by Deccan-related lamprophyres. A metasomatised (enriched) garnet lherzolite mantle source with very low degrees of partial melting that has subsequently undergone a large degrees of fractional crystallisation is capable of accounting observed bulk rock REE geochemistry (Chalapathi Rao *et al*., 2012b). Petrological and geochemical characters of lamprophyre rock types associated with mafic alkaline complexes, syenite intrusions and basic dyke rocks of the Southern Granulite Terrain exposed within Salem, Dharmapuri, Krishnagiri and Namakkal districts in Tamil Nadu are reported (Jayabalan *et al*., 2015). Their major and compatible trace elements reflect a mantle source while the incompatible elements, HFSE and REE reflect a crustal/subduction related source. The trace and REE elemental data suggests residual garnet, presence of residual amphibole, biotite, and clinopyroxene in the protolith or source region. Many of these lamprophyres appear to have been derived in a tectonic setting dominated by earlier to intermediate or progressive stages related to subduction zones while the rest suggest rifting 'within plate' environment probably related to deeper mantle source (Jayabalan *et al*., 2015). A new occurrence of alkaline lamprophyre (campronite) has been reported from the Bayyaram area of NE Eastern Dharwar craton (Meshram *et al*. 2015). Preliminary geochemical studies reveal the involvement of a subduction-related component in their genesis.

Occurrence of carbonate-rich ultramafic lamprophyres- close to aillikite composition- from the Chitrangi area, Mahakoshal supracrustal belt, central India has been reported (Srivastava, 2013). No direct genetic relationship between carbonatite and ultramafic lamprophyre samples on the basis of their chemistry could be established and hence they are likely derived from distinct parental melts. Geochemistry and presence of carbonate ocellae in ultramafic lamprophyre samples suggest genesis of these silicate rocks and associated carbonatites through liquid immiscibility, however possibility of their derivation through vein-plus-wall-rock melting model cannot be ignored. Early stages of rifting in the Mahakoshal region due to lithospheric thinning caused by possible plume activity is invoked for the genesis of ultramafic lamprophyre (possibly aillikitic) and carbonatitic melts which ultimately crystallized as dykes and plugs (Srivastava, 2013). Petrological and geochemical studies on an early Cretaceous potassic lamprophyre dyke, exposed near Rongjeng, East Garo Hills, Shillong plateau, north-eastern India, indicate its derivation from an alkaline magma comparable with those that filled the nearby Jasra potassic intrusion (Srivastava *et al*., 2016). However, geochemistry of the Rongjeng lamprophyre is distinctly different from that of the Damodar Valley lamproites, the Sung Valley carbonatitic-ijolitic intrusion, and the Antarctic ultramafic lamprophyres. The contrasting geochemical affinity is suggestive of heterogenous lithospheric mantle sources, rather than input of plume-related magmatism (Srivastava *et al*., 2015).

Carbonatites and Alkaline Rocks

The Newania carbonatite complex of India is one of the few examples of dolomite-dominated carbonatites of the world. It is also not associated with any alkaline silicate rock. New age data reveal that the complex was emplaced at ~1,473 Ma and parts of it were affected by a thermal event at ~904 Ma (Ray *et al*., 2013). The Sr–Nd isotopic data suggest that the primary magma originated from a metasomatized lithospheric mantle whereas the trace element modeling suggests that the source was a phlogopite bearing mantle, located within the garnet stability zone (Ray *et al*., 2013). In the end-Cretaceous Amba Dongar sub-volcanic complex, nephelinite plugs and dikes of phonolites were emplaced before the carbonatites. The fenitizing fluids released from carbonatite magma caused extensive fenitization in nephelinites. On the basis of detailed mineralogical study three processes of fenitization, namely, K-metasomatism (formation of hydromuscovite, phlogopite and Kfeldspar), zeolitization and CO_2-metasomatism along with hematitization are identified (Viladkar, 2015a). In melaphonolite of the Sarnu-Dandali, Badmer alkaline complex, NW India, high Ba- K-feldspar (sanidine) is reported as phenocrysts. Combined petrographic and electron microprobe studies reveal the incompatible behaviour of Ba and its enrichment in the melt during crystallization of magma (Viladkar, 2015b). A wide gamut of calico-carbonatites with associated alkaline rocks are discovered around Kamthai, Rajasthan (Bhushan and Kumar, 2013). Their main REE mineralogy includes carbocernaite, bastnaesite ± ancylite/synchysite as the dominant phases followed by parisite and other accessory minerals. Calcio-carbonatite occurs as intrusive veins, sills/dykes and plug, and inferred to be a product of crystallization of a primary carbonatite melt generated at upper mantle. A rift-related mechanism, invoking “Reunion plume – continental hot spot” at 65±2 Ma, that triggered Tertiary Deccan-related alkaline magmatism has been invoked to account its genesis (Bhushan and Kumar, 2013; Bhushan, 2015). Two petrologically distinct alkali feldspar syenite bodies from Chhotaudepur area, Deccan Large Igneous Province are reported and variation discrimination diagrams involving major and trace elements and their ratios demonstrate that these alkali feldspar syenites have a shoshonite affinity but emplaced in a within-plate and rifting environment (Hari *et al*., 2014). No evidence of crustal contamination is perceptible from combined petrography and their trace elemental ratios. The enrichment of incompatible elements in the alkali feldspar syenites is suggestive of the involvement of mantle metasomatism in the genesis of these syenites (Hari *et al*., 2014). A thin band of Tschermaks clinopyroxene (fassaite)-grandite-bearing calc-silicate skarn rock has been reported at the contact of the alkaline plug and limestone sediments at the alkaline plug of Nirwandh in Patchaam Island, Kutchh district, Gujarat (Maitra and Korakoppa, 2012). The alkaline plug is emplaced within the Jurassic limestone of Patcham Formation.. The mineralogical and textural evidences point out that the skarn rock is evolved by contact metamorphism due to fluid infiltration at shallower depth during very high temperature regime (Maitra and Korakoppa, 2012). A large number of igneous intrusions related to the Deccan magmatism are exposed in the western and central part of the Indian shield. Gravity and magnetic (G–M) surveys over some of these igneous intrusive bodies at Pavagadh and Phenaimata bring out gravity high and bipolar magnetic anomalies as the most characteristic geophysical signatures (Singh *et al*., 2014b). Joint G–M modeling of the Phenaimata complex reveals the presence of a dense mafic body (2.86 g/cm^3) characterized by a remanant magnetization that may correspond with the 29R polarity chron of Deccan magnetostratigraphy. Over the Pavagadh, a circular gravity and magnetic low of about “15 mGal and “500 nT respectively is reported for the first time which is surrounded by a gravity and magnetic high of about 30 mGal and 350 nT, respectively. The joint G–M modeling over the Pavagadh intrusive reveals the presence of a deep-seated cone shaped high-density (3.0 g/cm^3) gabbroic body which might extend up to a great depth (Singh *et al*., 2014b).

An *in situ* Sm–Nd isochron age of 1326±73 Ma, determined by LA-MC-ICP-MS on crystalline apatite grains from the Racherla alkali syenite occurring in the Palaeo-Mesoproterozoic Cuddapah Basin, southern India, has been reported (Chalapathi Rao *et al*., 2012d; Fig. 3). Incompatible trace element signatures (high La/Nb, Zr/Nb and La/Yb), $^{87}Sr/^{86}Sr$ (0.70432±10) and the lower Nd isotopic ratio (ε_{Nd}(t) –8.9) of the apatite suggest derivation of the Racherla syenite parent magma from an enriched mantle source. The obtained Mesoproterozoic age necessitates the Racherla syenite to be an intrusive into the sedimentary rocks of the Cuddapah Basin contrary to some previous suggestion that it represents an inlier of the basement pluton. This findings provide compelling evidence for the existence of ancient (*c*. 2.6 Ga) metasomatized lithospheric mantle, at the Archaean–Palaeoproterozoic boundary, beneath the Cuddapah Basin (Chalapathi Rao *et al*., 2012d).

Rio Tinto Exploration has discovered an unusual diamondiferous carbonatite-kimberlite clan rock (KCR) association at Khaderpet in the Anumpalle Cluster of the Wajrakarur Kimberlite Field in the Dharwar Craton of Peninsular India (Smith *et al*.,

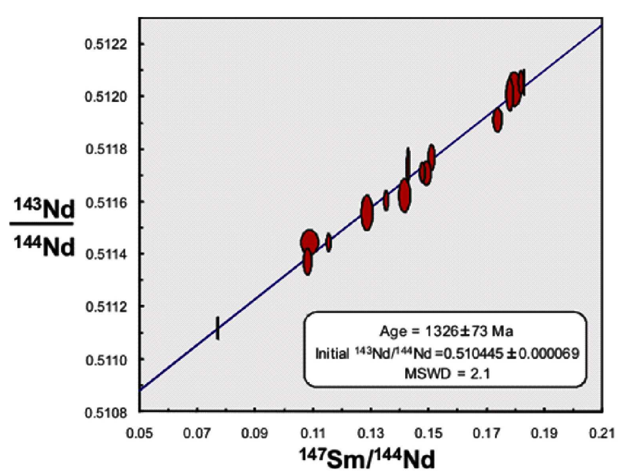

Fig. 3: Nd isotopic analyses (measured by LA-MC-ICP-MS) and isochron age of the apatite grains from the Racherla syenite (see Chalapathi Rao *et al*., 2012d)

2013). The Khaderpet pipe has a discrete sovite phase intrusive into KCR breccia, previously unreported from the Wajrakarur kimberlite field. The chemistry of the Khaderpet ultramafic component, suggests the KCR is transitional between kimberlite and ultramafic lamprophyres whereas the significant carbonate content and the presence of accessory Ti-andradite would lead to the KCR being classified as an ultramafic lamprophyre under the IUGS classification. The carbonatite component is considered to be a late-stage fractionation product of the Khaderpet diamond-bearing ultramafic magma (Smith *et al*., 2013). Unusual high Mg-mafic dykes of alkaline to subalkaline nature have been reported from the Gadwal area of the Paleo-proterozoic Mahbubnagar Large Igneous Province, in eastern Dharwar craton, southern India (Khanna *et al*., 2013). These dykes are neither deformed nor metamorphosed, and they exhibit well-preserved igneous textures and have uniform geochemical compositions with ocean island basalt-like characteristics. Numerical calculations suggest a melt segregation temperature of ~ 1390 °C at 2.2 GPa corresponding to an estimated depth of ~ 71 km. Geochemical modelling indicates low-percentage partial melting (~ 2%–6%) of a peridotitic mantle source in the garnet ± spinel stability field. The Gadwal alkaline dikes evolved from a common parental magma as a consequence of the partial melting of a metasomatised subcontinental lithospheric mantle by adiabatic upwelling of an asthenospheric plume source and are expressions of lithospheric thinning and extension (Khanna *et al*., 2013).

Mineralogy and mineral chemistry studies have been carried out on the Khamambettu carbonatites, southern granulite terrane, southern India. The mineralogical data points out that these rocks have been generated in magmatic and hydrothermal stages. Whereas the mineral geothermometry for carbonatite gave temperatures of 790°–980°C, the fluid inclusion measurements in monazite (hydrothermal stage) gave temperatures of 220°–290°C (Burtseva *et al*., 2013). U-rich pyrochlore has been reported from the Sevathur carbonatite complex, southern India (Viladkar and Bismayer, 2014) and a metamict origin has been suggested. Pandit *et al* (2016) carried out stable and radiogenic (Sr and Nd) isotopic study on the 2.4 Ga Hogenakkal carbonatites, emplaced within the southern granulite terrane, Their C- and O-isotopic ratios [$\delta^{13}C_{VPDB}$ = –6.7 to –5.8‰ and $\delta^{18}O_{VSMOW}$ = 7.5–8.7‰ represent unmodified mantle compositions. The εNd values indicate two groupings: group one with positive εNd values, close to CHUR (εNd = –0.35 to 2.94) and the second group having low-εNd negative values (–5.69 to –8.86), corresponding to depleted and enriched source components, respectively. The $^{87}Sr/^{86}Sr_i$ ratios of the high-εNd group have low $^{87}Sr/^{86}Sr_i$ ratios (0.70161–0.70244) while the low-εNd group shows higher ratios (0.70247–0.70319). A heterogeneous mantle source for the Hogenakkal carbonatites has been inferred (Pandit *et al*., 2016). Magma mixing process has been documented in syenite from the Yelagiri Alkaline Complex, South India (Renjith *et al*., 2014). Evidences such as (i) disequilibrium micro-textures in feldspars, (ii) microgranular mafic enclaves (MME) and (3) synplutonic dykes signify mixing of shoshonitic mafic magma with the syenite have been brought out and Yelagiri syenite magma chamber has been inferred to have evolved through multiple physical processes like convection, shear flow, crystal accumulation and magma mixing (Renjith *et al*., 2014). Two alkaline plutons - the Angadimogar syenite and the Peralimala alkali granite in the southern granulite terrane were studied through field, petrological, geochemical, zircon U–Pb and Lu–Hf studies (Santosh *et al*., 2014). The weighted mean $^{206}Pb/^{238}U$ ages of the magmatic zircons from three samples of the Angadimogar syenite are in the range of 781.8 ± 3.8 Ma to 798 ± 3.6 Ma and those from two samples of the Peralimala alkali granite have ages of 797.5 ± 3.7 Ma and 799 ± 6.2 Ma – all of Cryogenian age. The Lu–Hf data suggest the involvement of variable extent of older crust with distinct crustal residence times during the magma genesis. The disposition of these alkali plutons along two paleo sutures that weld the Meso-Neoarchean crustal blocks in the northern periphery of southern granulite terrane suggests that these zones of emplacement might represent an aborted rift (Santosh *et al*., 2014).

Microtextural evidence of fenitization has been documented at the 1.48 Ga Khariar alkaline complex in southeastern India (Upadhyay, 2012). Typical metasomatic textures such as the replacement of plagioclase by vein nepheline and albitic-plagioclase or by symplectitic nepheline + albite + Na-Al-rich clinopyroxene are observed. Whole rock mass balance calculations indicate that the fenitized variants gained alkalis (Na + K), some large ion lithophile elements

(Sr, Rb and Ba) and high field strength elements like Zr and Hf during the metasomatic exchanges. These results indicate that alkali and alkaline elements were exchanged freely between the fluid phase and the reaction zone whereas Si and Al released during plagioclase dissolution were consumed in the replacement zone to form nepheline and albite-rich plagioclase or Na-Al-rich clinopyroxene (Upadhyay, 2012). A new occurrence of thorianite from syenitic pegmatite near Bhaluchuan, Sambalpur district, Odisha, has been reported (Singh *et al*., 2014a). Chondrite-normalised rare-earth element (REE) plot of the thorianite reveals enrichment of light REE (LREE) over heavy REE (HREE) with pronounced negative Eu-anomaly (Eu/Eu* = 0.35). X-ray diffraction (XRD) pattern of the thorianite reveals an extensive substitution of Th by U.

An alkaline-carbonatite complex comprising alkali pyroxenite, nepheline syenite, phoscorite, carbonatite, syenitic fenite and glimmerite along with REE and Nb-mineralization are found at different centres along WNW-ESE trending South Purulia Shear Zone (SPSZ) in parts of the Mesoproterozoic Singhbhum Group of rocks (Basu and Bhattacharya, 2015). The carbonatite is composed dominantly of Sr-calcite along with dolomite, tetraferriphlogopite, phlogopitic biotite, aegirine augite, richterite, fluorapatite, altered magnetite, sphene and monazite. The minerals comprising of the carbonatite are indicative of middle stage of carbonatite development. Pyrochlore containing UO_2 (6.605%) and PbO (0.914%) in nepheline syenite has been chemically dated at 948 ± 24 Ma (Basu and Bhattacharya, 2015). The eudialyte-group of minerals (EGM) is one of the most important index minerals of the peralkaline (agpaitic) nepheline syenites and in India, the only agpaitic nepheline syenite gneisses of the Sushina Hill region are known to contain both late-magmatic as well as hydrothermal eudialytes. (Chakrabarty *et al*., 2012). Compositionally these are eudialytes and are comparable to the similar such occurrences at Ilímaussaq (Greenland), Tamazeght (Morocco), Mont-Saint Hilaire (Canada) and Pilansberg (South Africa; Chakrabarty *et al*., 2012). The detailed textural features together with mineral chemistry studies of the nepheline syenite gneiss from the Sushina Hill indicate metamorphic overprint of these rocks (Goswami and Basu, 2013). Metamorphic piemontite indicate greenschist facies metamorphism under high fO_2 (Hematite-Magnetite buffer). Presence of upto 15.34 mol% of jadeite component in aegirine suggests that the metamorphic grade of the nepheline syenite gneiss reached at least to greenschist-amphibolite transitional facies or even higher which is supported by the nepheline geothermometry which brings out temperature of metamorphism <500°C (Goswami and Basu, 2013).

Mineralogy and geochemistry of the Jasra intrusive complex (Shillong Plateau, northeastern India) has been documented (Melluso *et al*., 2012). Their mineralogy is dominated by clinopyroxene with which phlogopite, olivine, amphibole, feldspars, feldspathoids, oxides, orthopyroxenes, perovskite, titanite and other accessory phases are variably associated. Involvement of at least two distinct magmatic liquids is documented. The potassic affinity of the Jasra rocks differs from the nearby Sung Valley ijolitic-carbonatitic complex and from the ultrapotassic lamproitic rocks of the Damodar Valley, and suggest a major variability in the mantle sources of these small-volume alkaline volcanism in the Early Cretaceous of northeastern India (Melluso *et al*., 2012). Nd–Sr–Pb-isotopic and trace element data on discrete lava flows of the Rajmahal Traps, alkalic–carbonatitic–mafic–ultramafic rocks from four alkalic complexes, and three dikes from the Gondwana Bokaro coalfields, all belonging to the Rajmahal Flood basalt Province are reported (Ghatak and Basu, 2013). This new data show similarity with previous data of Rajmahal group I–II basalts, Sylhet Traps, Bunbury basalts, and lavas from the southern Kerguelen Plateau, indicating a relatively primitive KP source. Geochemical modeling indicates these lavas assimilated granulites of the Eastern Ghats, reducing the thickness of the continental Indian lithosphere. Lack of an asthenospheric MORB component in the Rajmahal province is indicated by various trace element ratios as well as the Nd-Sr isotopic ratios (Ghatak and Basu, 2013).

Mafic Dykes and Dyke Swarms

Since 2012, a number of significant publications on the dykes and dyke swarms of the Indian shield have been appeared in many refereed journals and, with age constraints, may be divided into two groups: (i) Phanerozoic mafic dykes and (ii) Precambrian mafic dykes.

(i) Phanerozoic Mafic Dykes

Studies on mafic dykes associated with the Deccan Large Igneous Province are dealt in detail in a paper on the 'Volcanism and associated igneous activity' in this volume. A few important findings have been summarized here. Two distinct Cretaceous mafic dykes have been identified from the Damodar valley within the Chhotanagpur Gneissic Complex at the northern-most margin of the Singhbhum craton, eastern India (Srivastava *et al*., 2014a). On the basis of distinct petrographic and geochemical characteristics, these authors have classified them into high-Ti dolerites and low-Ti dolerites; both derived from two distinct mantle melts. It is believed that the high-Ti dolerites are emplaced ~110–115 Ma and the low-Ti dolerites later at ~65 Ma. Geochemically they show their relation with the plume activity with the high-Ti dolerites having affinity to the early Cretaceous Kerguelen plume, whereas the low-Ti dolerites are probably associated to the late Cretaceous Reunion plume activity. The Chotanagpur Gneissic Complex is perhaps the only geological domain in the entire Indian shield which hosts the early Cretaceous Rajmahal as well as the late Cretaceous Deccan igneous activities (Srivastava *et al*., 2014a).

Sheth *et al*. (2014) have studied late Cretaceous tholeiitic dykes (and flows) exposed in the Ghatkopar–Powai in the Panvel flexure zone, western Deccan Traps for their geochemical characteristics. They believe that the dykes are post-Panvel flexure. Few mafic dykes have geochemical signatures similar to the Ambenali Formation of the Western Ghats, whereas other few show partial (e.g., Sr–Nd isotopic) similarities to the Mahabaleshwar Formation. Additionally, a group of mafic dykes have unusual, concave downward REE patterns, which may indicate residual amphibole and thus a lithospheric source. These dykes are inferred to have undergone no or little contamination and structural trends of the dykes indicate considerable east–west lithospheric extension during this late, though still magmatically vigorous, stage of Deccan volcanism (Sheth *et al*., 2014). The mafic dykes associated with the Sarnu-Dandali complex, NW Deccan Traps, are shown not to be controlled by basement structure, but related to contemporaneous, late Cretaceous regional ENE-WSW extension (Vijayan *et al*., 2016).

A number of early Eocene andesitic dykes (younger to the Deccan tholeiitic dykes), intruding the Ladakh batholith from 10 to 50 km west of Leh (NW India), have been studied to determine the extent and timing of dyke formation related to possible E–W extension along the southern margin of Eurasia during Early Cenozoic time (Heri *et al*., 2015). Hornblende grains, separated from these dykes, were dated by ^{40}Ar–^{39}Ar incremental heating method which gave ages between 50 and 54 Ma. Heri *et al*. (2015) further stated that structural field evidence with petrographic, isotopic and geochronological data demonstrates that although these dykes having formed in the same tectonic setting around the same time they did not form from a single, progressively differentiating magma chamber. Definitely, there are other processes such as crustal assimilation and magma mixing/ mingling, also played a significant role in magma petrogenesis.

(ii) Precambrian Mafic Dykes

Considerable work has been done on the Precambrian mafic dyke swarms of the Indian shield in the last five years; particularly from the eastern Dharwar, Singhbhum, Bastar and Bundelkhand cratons. These Archaean cratons are thought to be integral parts of the many Precambrian supercontinents (Ernst, 2014). Distinct Palaeoproterozoic mafic dyke swarms are well exposed in the eastern Dharwar craton (Srivastava *et al*., 2015 and references therein). Available U-Pb/Pb-Pb mineral ages on these dykes helped to identify five discrete mafic magmatic events in the eastern Dharwar craton. This includes (i) the NE–SW to E-W trending 2.36-2.37 Ga Bangalore swarm (Kumar *et al*., 2012a) (ii) N-S to NNW-SSE trending 2.21-2.22 Ga Kunigal swarm (Srivastava *et al*., 2014b), (iii) NW-SE to WNW-ESE trending ~2.18 Ga Mahbubnagar swarm (iv) newly identified N-S to NNE-SSW trending ~2.08 Ga Devarakonda swarm (Kumar *et al*., 2015), and (v) 1.88-1.89 Ga NE-SW to E-W trending Bastar (BD2)-Dharwar swarm along with mafic sills of the Cuddapah basin (i.e. the Bastar-Dharwar LIP; Srivastava *et al*., 2014c and references therein). Geochemical characteristics (Srivastava *et al*., 2014b, 2014c, 2015) and paleomagnetic data (Kumar *et al*., 2012a, 2012b, 2015; Belica *et al*., 2014) on these Paleoproterozoic mafic dykes are also presented in a number of recent publications. Geochemically all these distinct Plaeoproterozoic mafic dykes show different geochemical characteristics and fed from distinct mantle melts (Srivastava *et al*., 2015). Srivastava *et al*. (2015) suggested that the ~2.37 Ga swarm was fed from a melt originated at a shallower level (within the spinel stability field) by ~15–20% melting of a depleted lherzolite mantle source, whereas ~ 2.21Ga, ~2.18 Ga and ~1.89 Ga dyke swarms may have been fed from melts generated at greater depth (within the garnet stability field). The ~2.21 Ga swarm is derived from a melt generated at a relatively higher degree of melting (~25%), whereas ~15–20% melting is estimated for the ~2.18 Ga swarm. A low percentage of melting (~10–12%) is estimated for the ~1.89 Ga swarm.

Recently, a special issue of Precambrian Research on 'Precambrian Supercontinents' (Pesonen *et al*., 2014) incorporated a number of papers describing Precambrian supercontinents, in which different Indian Archaean cratons were considered an integral parts of these supercontinents. These assumptions are mostly based on the high-quality paleomagnetic results from various Indian cratons. Belica *et al*. (2014) have reviewed the drift history of Dharwar craton during Paleoproterozoic times (2.37–1.88 Ga), which provided four new key poles for India (Dharwar). The position of India in the Columbia supercontinent has also been discussed (Belica *et al*., 2014; Pisarevsky *et al*., 2014). Radhakrishna *et al*. (2013a) have also provided palaeomagnetic data on the Palaeoproterozoic mafic dykes in the basement along the margins of the Cuddapah basin, southern India. They constructed an apparent polar wander path for the Indian shield for a ~600 Ma interval of the Palaeoproterozoic eon (2.45–1.85 Ga). Radhakrishna *et al*. (2013a) suggested that between 2.45 and 2.37 Ga, the Indian shield was situated at higher latitudes similar to the Yilgarn craton of Australia and was subsequently located near the equator at 2.22, 2.18, 1.99 and 1.86 Ga. On the basis of their new palaeomagnetic data they do not support Slave-Dharwar connection in "Sclavia" or a Superior–Zimbabwe–India connection in "Superia". Also the close palaeomagnetic comparison between the Palaeoproterozoic dykes of Dharwar–Bastar–Bundelkhand cratons in India does not support juxtaposition of the Indian shield along the western margin of Laurentia in the Columbia reconstructions (Radhakrishna *et al*., 2013a). However, there are other recent contributions, mostly based on palaeomagnetic, geochemical and geochronological data, evidently support, with some modification, existence of the Columbia supercontinent and the Dharwar craton as a part of it (e.g. Nilsson *et al*., 2013; Belica *et al*., 2014; Pisarevsky *et al*., 2014; Ravi Shankar *et al*., 2014). Kumar *et al*. (2012a, 2012b, 2015) have also presented paleomagnetic data on the Dharwar giant dyke swarms and suggested different views.

Paleomagnetic studies on 2.37 Ga swarm suggest that India was located at high (~69°) southerly latitudes and can be matched with the 2410–2418 Ma Widgiemooltha swarm of western Australia that had high southern latitudes (Kumar *et al*., 2012a). This suggests possible continental configurations involving Australia and India at ~2.4 Ga. On the other hand, paleomagnetic studies on the ~2.21 Ga swarm of the Dharwar craton has coeval poles from the Slave, Superior and Rae provinces and allows a Paleoproterozoic reconstruction of these cratons, though they are not sure whether the Dharwar was part of Sclavia or Superia (Kumar *et al*., 2012b). However, in a recent publication, Kumar *et al*. (2015) have suggested that a reconstruction of the paleopositions of Dharwar and Superior at ~2080 Ma does not suggest a close proximity for these provinces at that time. On the basis of new paleomagnetic and geochronologic results from the Dharwar craton, Belica *et al*. (2014) have presented a Paleoproterozoic Apparent Polar Wander Path (APWP) for the Dharwar craton, and examine paleogeographic relationships between India and other cratonic blocks for the 2.37–1.88 Ga time interval. In a recent review, based on available geochemical and geochronological data, Srivastava *et al*. (2015) have believed that the Dharwar and North Atlantic cratons coexisted at ~2.37 Ga and no similar event is reported for any other craton. Global occurrence of the ~2.21 Ga mafic magmatic event suggests breakup of the supercontinent Superia, which accommodated the Dharwar, Superior, North Atlantic, and Slave cratons and possibly other cratons. It is difficult to establish any reconstruction for the ~2.18 Ga mafic magmatic event as this age is not known from other cratons. Because the ~1.88–1.90 Ga mafic magmatic event is recorded globally, it is not very useful for reconstructions. Samal *et al*. (2015) have studied cross-cutting field relationships of distinct

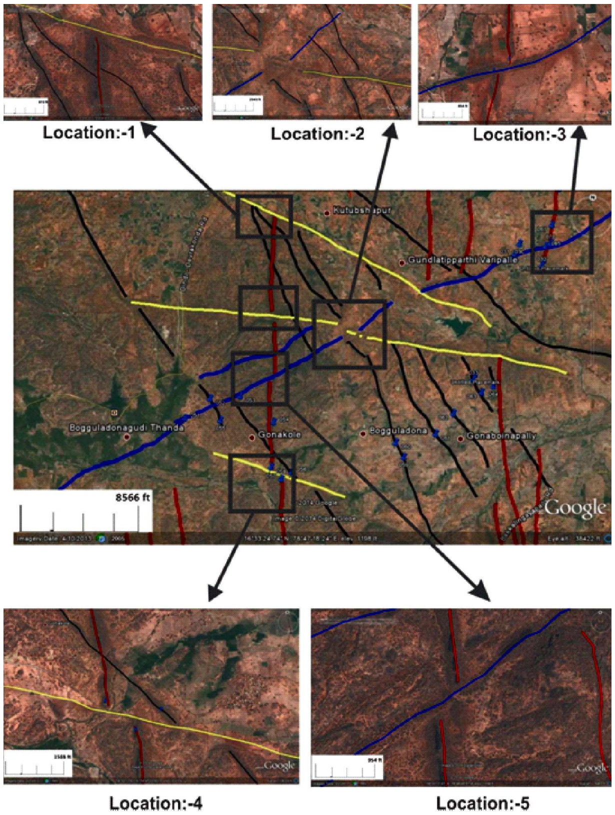

Fig. 4: Google™ earth images of different locations near Devarakonda area showing cross-cut relationships between distinct Paleoproterozoic mafic dykes (after Samal *et al.*, 2015). Different emplacement trends and radiometric ages of mafic dykes are defined by different colours. Blue: D1 (NE–SW); Yellow: D2 (WNW–ESE); Red: D3 (N–S); Black: D4 (NW–SE). Location 1: D3 cuts D4; Location 2: D2 cuts D4; Location 3: D1 cuts D3; Location 4: D2 cuts D3 and D4; Location 5: D1 cuts D3

Paleoproterozoic mafic dykes from Devarakonda area in the eastern Dharwar Craton with the help of Google™ earth image analyses and ArcGIS™ technique to establish relative emplacement ages (see Fig. 4) and mapping of mafic dykes (see Fig. 5). Perhaps this is the first genuine attempt to introduce mafic dyke map using ArcGIS technique for any region of India. They have suggested that NE–SW trending mafic dykes are youngest in age (probably belong to ~1.89 Ga dyke swarm), whereas NNW–SSE trending mafic dykes have oldest emplacement age. Further, the NNW–SSE mafic dykes are older to the other two identified mafic dyke swarms, i.e., WNW–ESE (~2.18 Ga) and N–S trending (~2.21 Ga) mafic dyke swarms, as dykes of these two swarms cross-cut a NNW–SSE dyke. It provides an evidence for existence of a new set of mafic dykes that is older to the ~2.21 Ga and probably younger to the ~2.37 Ga swarm. This work also supports existence of two mafic dyke swarms having similar trend (ENE–WSW to NE–SW) but emplaced in two different ages, i.e. ~2.37 Ga and ~1.89 Ga.

Not much has been done for the western Dharwar craton and the Southern Granulite Terrain (SGT) in recent years; however, they have a shared history of mafic dyke emplacement and related magmatism as observed in the eastern Dharwar craton. Dash *et al.* (2013) have presented paleomagnetic data on the 2.32 Ga mafic dyke swarm from the northeastern SGT and suggested that the 'Northern Block' of SGT was contiguous with the Dharwar craton at 2.32 Ga ago and consequently the high-grade rocks in this region could represent the deeper section of the Dharwar craton. The available palaeomagnetic data along with the present studies yield paleo-pole position which places India at high latitudes (~60°) during early Paleoproterozoic, similar to the paleomagnetic data obtained for the 2.37 Ga mafic dyke swarm of the eastern Dharwar craton (Kumar *et al.*, 2012a).

The Bastar craton also contains a number of mafic magmatic events during Precambrian, mostly in a form of dykes trend in NW-SE direction, and studied earlier by many workers. Although, early Precambrian mafic dykes are well exposed in the southern parts of the Bastar craton (Srivastava *et al.*, 2016), they have also been encountered in the middle (Srivastava and Gautam, 2012) and the northern (Pisarevsky *et al.*, 2013; Srivastava and Gautam, 2015) parts of the Bastar craton. Pisarevsky *et al.* (2013) have presented paleomagnetic, geochronological and geochemical data on the ~N-S trending Mesoproterozoic Lakhna dykes from the northern Bastar craton. Petrographically and geochemically Lakhna dykes show variation from alkaline (trachyte), felsic (rhyolite) to mafic (dolerite) derivatives. They have also dated zircon grains from a rhyolite dyke by U-Pb method and placed it at 1465±3 Ma. On the basis of their data, they tested reconstruction of supercontinent Columbia and suggested that juxtaposing western India against south-west Baltica is geologically the most reliably constrained and best fitting model. This reconstruction

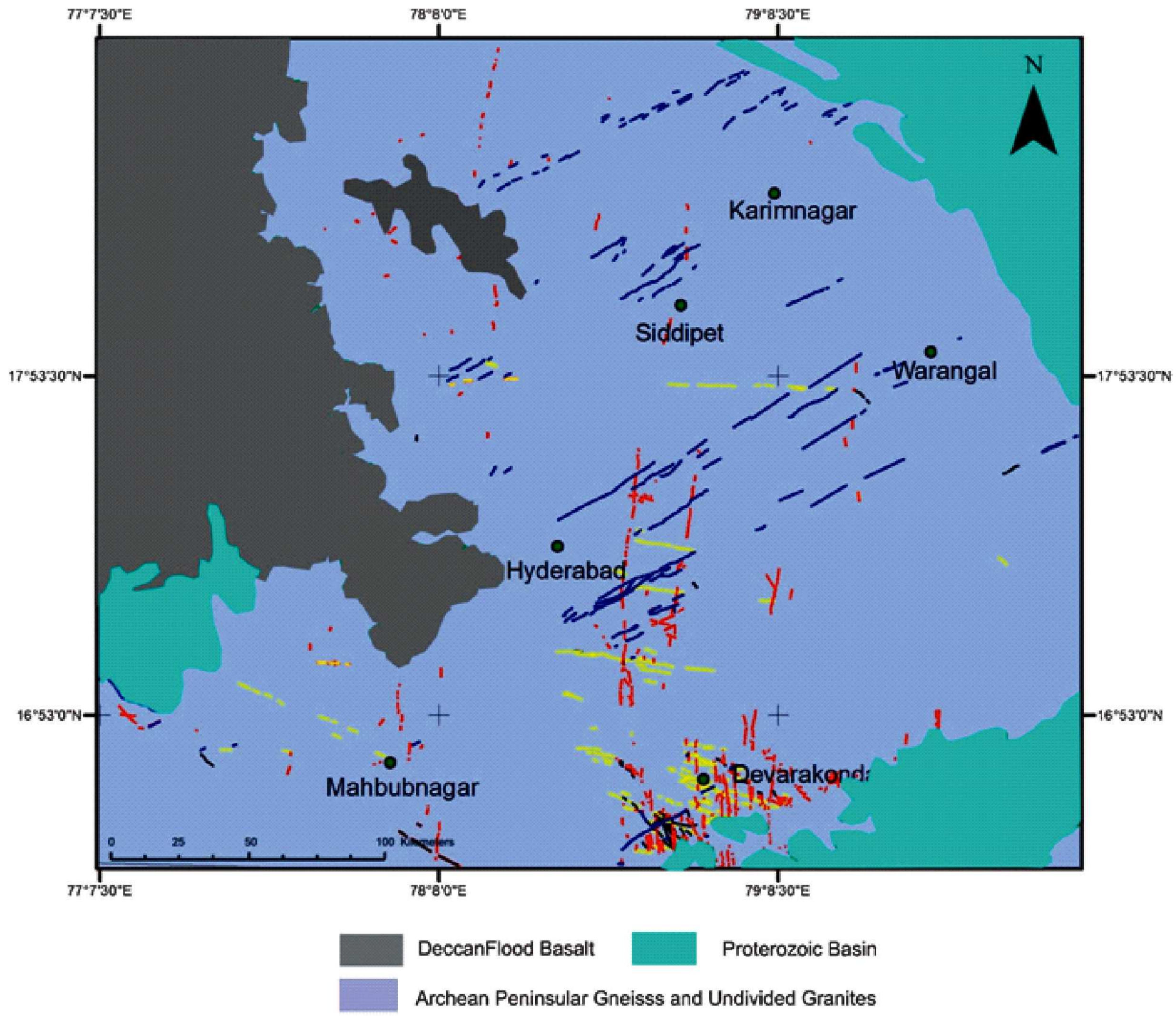

Fig. 5: Map showing Paleoproterozoic mafic dykes of northern parts of the eastern Dharwar Craton (after Samal *et al*., 2015), based on published dyke maps (e.g., Halls 1982; Murthy 1987; Radhakrishana *et al*. 2007, 2013a; French *et al*. 2008; French and Heaman 2010), field data, Google™ earth image and ArcGIS™. Blue colour: NE–SW; Yellow: WNW–ESE; Red: N–S; Black: NW–SE

implies a long-lived nearly linear Palaeo- to Mesoproterozoic mega-accretionary orogen along south-eastern Laurentia, south-western Baltica and eastern India. On the basis of new geochemical data on the early Precambrian mafic dykes from the northern Bastar craton, Srivastava *et al*. (2015) have identified four distinct dyke swarms. It includes (i) NW-SE trending Paleoproterozoic (~2.7? Ga) North Bastar swarm, ENE-WSW trending Paleoproterozoic Dongargarh-Chhura swarm, ENE-WSW trending ~1.42 Ga Bandalimal swarm, and N-S trending 1.44 Ga Lakhna swarm. These authors have further suggested that all the four sets are derived from different mantle melts and emplaced in a stable continental rift tectonic setting. The available geological, geochemical and geochronological data on the four identified sets of mafic dykes from the northern Bastar craton, also supported their relation to the assembly and break-up of Columbia supercontinent. The southern and central parts of the Bastar craton comprise three NW-SE trending mafic dyke swarms viz. ~2.7 Ga BD1, ~2.4-2.5 Ga BN, and ~1.88-1.89 Ga BD2 swarms (Srivastava and Gautam, 2012; Srivastava *et al*., 2016 and references therein). The 2.4-2.5 Ga (early Paleoproterozoic) BN swarm shows high-Si high-Mg nature and identified as boninite-norite swarm, emplaced in an intracratonic setting.

Srivastava and Ernst (2013) have studied and compared these BN swarm with the similar world-wide occurrences and suggested that the timing of BN magmatism is linked to crustal thickening and associated cratonization at the end of the Archaean. Prior to this cratonization event an extensive extraction of mafic magma developed refractory mantle, which, at later stage, was metasomatised by subduction associated with the assembly at ca. 2.7 Ga of many Archaean cratons. This modified mantle was provided bonintic melt due to arrival of mantle plume during Neoarchaean-Paleoproterozoic. Srivastava *et al*. (2016) have presented further lithogeochemical and Nd-isotope and on these BN swarm. They have identified three types of early Palaeoproterozoic high-Si high-Mg mafic rocks, mainly emplaced as dykes in an extensional tectonic setting, in the Archaean Bastar craton, which are not co-genetic and classified as high-Ca boninites, high-Mg norites, and high-Mg diorites. Nd-isotope data indicate that the high-Mg norite and the high-Mg diorite rocks have similar $^{143}Nd/^{144}Nd_{initial}$ ratios, whereas the high-Ca boninites have lower $^{143}Nd/^{144}Nd_{initial}$ ratios. These geochemical and isotopic features suggest that the three dyke types have different petrogenetic histories. The T_{DM} model ages also support their distinct origins as the high-Mg norites and high-Mg diorites yield younger T_{DM} model ages, between 2565 Ma and 2970 Ma, relative to the high-Ca boninites (3395–3612 Ma).

Radhakrishna *et al*. (2013b) presented paleomagnetic data on the Bastar as well as Bundelkhand cratons and suggested that there is a strong correlation between the characteristic remanence (ChRM) and palaeopole data across the cratons within the Indian shield. The distinct groups of palaeomagnetic pole determinations from dykes of the Bundelkhand and Bastar craton exhibit a remarkable match with palaeomagnetic poles determined from Precambrian mafic dykes in the Dharwar craton suggests close proximity since 2.45–2.5 Ga. On the basis of paleomagnetic and geochronological data two major mafic dyke swarms are identified in the Bundelkhand craton. These include the NW–SE trending ~1.98 Ga Bundelkhand swarm and ENE–WSW to NE–SW trending ~1.11 Ga Mohaba dyke swarm (Pradhan *et al*., 2012). Pradhan *et al*. (2012) have presented global paleogeographic maps for India at 1.1 and 2.0 Ga using these paleomagnetic poles. These new paleomagnetic results from the ~2.0 Ga NW–SE trending Bundelkhand dykes and the paleomagnetic data from the Bastar/Cuddapah suggest that the North and South Indian blocks of the Peninsular India were in close proximity by at least 2.5 Ga.

The Singhbhum craton of the eastern Indian shield consists of two major crustal provinces viz., Chotanagpur Gneissic Complex (CGC) and Singhbhum Granite Complex (SGC); separated by a Singhbhum Mobile Belt (SMB). There are a number of geological evidences suggesting that CGC is a cratonic block rather a mobile belt (Srivastava *et al*., 2012; Chalapathi Rao *et al*., 2014d). Ravi Shankar *et al*. (2014) have dated baddeleyite grains extracted from two prominent dykes from the WNW–ESE trending swarm in the south central region of the SGC using Pb–Pb method which yielded identical ages of 1766.2±1.1 Ma and 1764.5±0.9 Ma; interpreted as the time of emplacement of the WNW–ESE trending mafic dykes. This study also suggested that the Singhbhum craton was probably part of the supercontinent Columbia as similar mafic magmatic activities were also recorded from China, Australia, Brazil and Uruguay. Geochemical compositions of some mafic and ultramafic dykes from the Chaibasa area of the SGC have been determined to constraints their magma sources (Mir and Alvi, 2015). They suggested that mafic and ultramafic dykes do not have any genetic relationship and derived from different mantle melts; the ultramafic dykes are derived from a higher percentage of melting than the mafic dykes.

A number of ENE-WSW to E-W trending Paleoproterozoic mafic dykes are also encountered from the Mahakoshal supracrustal belt of the Central Indian Tectonic Zone (CITZ) (Srivastava, 2012). Geochemical compositions of these dykes divide them into two groups derived from two distinct mantle melts. On the basis of available geological and geochemical information, Srivastava (2012) has concluded that this region has experienced N-MORB type mafic magmatism (presently in the form of metabasite dykes) around 2.5 Ga and within-plate mafic magmatism around 1.5-1.8 Ga (metadolerite dykes and probably other alkaline and carbonatite magmatic rocks).

Mafic dykes intruding the composite Mt. Abu granite batholith as a minor and the last phase of magmatism are intensely to moderately sheared and intricately mixed with the host granitoids (Pandit *et al*., 2016). The mafic dykes bear evidence of assimilating the host granitoids during their ascent, seen as relicts, streaks and sub-rounded K-feldspar clasts in mafic dykes. The hybridization has resulted in unusual geochemical signatures of the mafic dykes e.g., higher silica levels, erratic and high incompatible trace element abundances and lack of any systematic trends. Shearing has played an important role in providing the channel ways and for sustained high temperatures to allow such hybridization (Pandit *et al*., 2016).

Summary

From the above documentation it is clear that in the past five years a huge new data base on kimberlites, lamproites, lamprophyres, carbonatites and other alkaline rocks and their entrained xenoliths as well as on mafic dykes and dyke swarms from the Indian shield has now become available. Apart from the availability of high precision mineral ages using the state-of-the-art techniques (viz., LA-ICP-MS), the application of multi-element isotope systematics and integration of the geological/geochemical data with paleomagnetism and geophysics has provided new insights on the evolution of the continental lithospheric mantle beneath the Indian shield. A number of large igneous provinces have also been recognised which led to a better understanding of the supercontinent amalgamations and break-ups during the Precambrian.

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