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Review Article

Recent Advancement in Studies of Deccan Trap and Its Basement; Carbonatites and Kimberlites – An Indian Perspective in Last Five Years

JYOTIRANJAN S RAY[1] and G PARTHASARATHY[2,*]

[1]*Physical Research Laboratory, Ahmedabad 380 009, India*
[2]*School of Natural Sciences and Engineering, National Institute of Advanced Studies, Indian Institute of Science Campus, Bengaluru 560 012, Karnataka, India*

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We made an attempt to provide a status report on volcanic rocks and mantle derived rocks with a special focus on studies related to Deccan flood basalt, carbonatites and kimberlites from India, during last five years. The important problems related to the Deccan volcanism include 1. Origin of Deccan Trap whether plume related or impact induced or triggered volcanism (2) the details of composition, the internal structure and age distribution and (3) the relation between the large igneous provinces and major mass extinction. Carbonatites are mantle derived rocks, which are helpful in modelling the Earth's interior. They vary in age from Archean to recent, and are found mostly on continents and thus provide valuable information about the evolution of the sub-continental mantle through time. This article also reviews most of the research contributions on Indian carbonatites of the last five years. Building on existing information on their modes of occurrences, field dispositions, chronology, petrology and geochemistry, we use the recent data to provide a comprehensive view on the origin and evolution of these carbonatites.

Keywords: Deccan Trap; Kimberlites; Mantle Rocks; Carbonatites; Mineral Physics; Phyllosilicates

Introduction

Geological Society of India (GSI) has brought out many interesting review books and memoirs related to the Deccan Volcanic Province (Suubarao, 1999), kimberlites and related mantle derived rocks (Fareeduddin and Mitchell, 2012). In recent years there has been a tremendous growth in the field and laboratory data related to Deccan Trap and mantle derived rocks from India. The aim of the present work is to review some important findings related to the Deccan Trap, carbonatites and kimberlites from India with a special focus on the work carried out during the last half a decade.

The ca.65Ma Deccan volcanic terrain, forming one of the prominent large Igneous Provinces (LIP) on the surface of the earth, has remained seismically active since historical times, including the famous Reservoir Triggered Seismicity in the Koyna region (1967 Koyna Earthquake) the 1993 Killari earthquake (Mw 6.3). Recently Gupta (2017) has edited a comprehensive collection of 25 original articles covering different geophysical aspects of Koyna Earthquake (Gupta 2017 and the references therein). In this article we provide a brief review of the work carried out in Deccan Volcanic Province near Killari region, which is equally important for the stable continental earth quake and geodynamic understanding. To study the seismotectonics of this earthquake-prone province in general and Killari earthquake region in particular, several boreholes were drilled in and around epicentral area. It included 617 m deep KLR-1 borehole, drilled 80 m south of surface scarp on the hanging wall near the Killari village (18°03'07"N, 76°33'20"E)**.** It penetrated 338 m thick basalt flows, followed by 8 m of infratrappean sediments and a further 270 m of the Neoarchean crystalline basement.

Detailed geoscientific studies (including seismic, elastic and petrophysical studies) on the representative

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**Author for Correspondence: E-mail:drg.parthasarathy@gmail.com*

43 basement cores from various depths from the borehole indicated the Neoarchean crystalline basement to be made up of mainly amphibolite to granulite facies transitional, pervasively metasomatised, mid-crustal rocks with a few samples belonging to tonalite and granodiorite (Pandey *et al.*, 2014, 2016a; Pandey 2016; Tripathi *et al.* 2012a, b; Tripathi 2015). The basalts are iron-rich compared to other basalts (average FeO_T: ~ 9 wt %) and characterised by an average density of 2.82 g/cm^3, with corresponding P- and S-wave velocities of 6.17 and 3.61 km/s respectively. Retrogressive alterations like saussuritization, biotitization, sericitization and iron enrichment have severely affected these rocks, including the reduction in measured velocities by as much as 15% (Pandey *et al.*, 2016). Petrologically, they contain clinopyroxene, horneblend, calcic plagioclase biotite and minor orthopyroxene (Fig. 1), apart from accessories like ilmenite, magnetite, titanite, epidote etc. Geothermobarometric studies indicate that the basement below Killari was subjected to temperatures between 700 and 860ºC and pressure, 5-7 kb, (Tripathi *et al.*, 2012) before their exhumation to the surface indicating that almost 15-20 km granitic upper crust has been eroded from this region even before the onset of Deccan volcanism, due to persistent geodynamic process of uplift and erosion. Besides, this amphibolite granulite facies basement has halogen-rich amphiboles and mantle derived carbonates with 2 wt % of CO_2 emanated from the mantle (Pandey *et al.*, 2014). Carbon and oxygen isotopic studies on couple of extracted carbonate samples do confirm their mantle origin, suggesting large scale crust-mantle thermal fluid interaction beneath Killari seismic zone. Underlying mantle is still quite warm below areas covered by Deccan volcanics (Pandey *et al.*, 2017). Rohilla *et al.* (2018) have made detailed analyses of shear wave velocity structure beneath Koyna region and found an unusually high upper crustal shear-wave velocity of about 4 km/s at 5 km depth that is comparable with that of the lower crust.

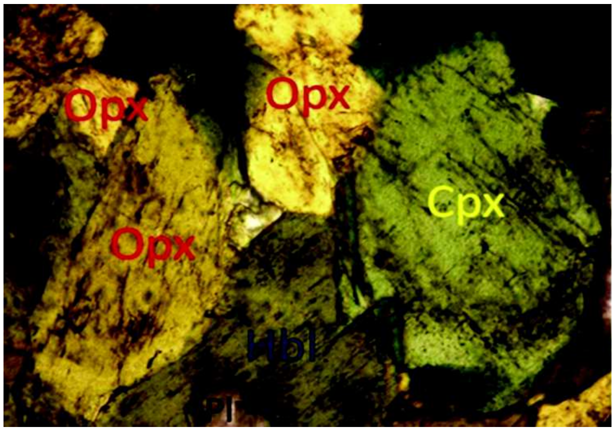

Fig. 1: Photomicrographs taken from thin section of the basement sample, KIL-12 from the KLR-1 borehole drilled in Killari. Hbl, Cpx, Opx and Plg refer to hornblende, clinopyroxene, orthopyroxene and plagioclase respectively

However, not much study has been carried out on the 338 m thick volcanic sequence which is comprised of eight flows, belonging to two prominent formations, Ambenali and Poladpur, representing the Wai Subgroup. The entire column is made up of fine to medium grained, rarely coarse-grained, and highly massive to vesicular basalts. Massive basalt core samples are heavy and greenish black to dark black in color with metallic lustre. In comparison, vesicular samples, which are usually found at the top of the flows, are greyish brown to dark brown in color. Petrological and geochemical examination of these samples indicates that the studied basalt rocks are relatively Fe and Mg-rich and silica deficient in composition and basically contain plagioclase, pyroxene phenocrysts, and microphenocrysts and occasionally, altered olivine as major constituents and magnetite and secondary silicates as accessory minerals. Quite a few samples are extremely glassy in nature (Fig. 2), while many of these contained abundant microlites and plagioclase laths. Some of the samples are filled with secondary minerals, and other forms of silicates, formed mainly by alteration of pyroxene and plagioclase grains.

The saturated massive basalt cores of the Deccan volcanic sequence have a mean density of 2.91 g/cm^3 and mean P- and S-wave velocities of 5.89 km/s and 3.43 km/s respectively. In comparison, vesicular basalts show a much lower density of 2.62 g/cm^3 as well as P- and S- wave velocities of 4.00 km/s and 2.37 km/s respectively. Based on this study, the Deccan volcanic sequence can be assigned a weighted mean density of 2.74 g/cm^3 and on an average, a quite low V_p and V_s of 5.00 km/s and 3.00 km/s, respectively. Lowering in velocities can be primarily attributed to the presence of glassy material, high iron contents, and large-scale inclusion of

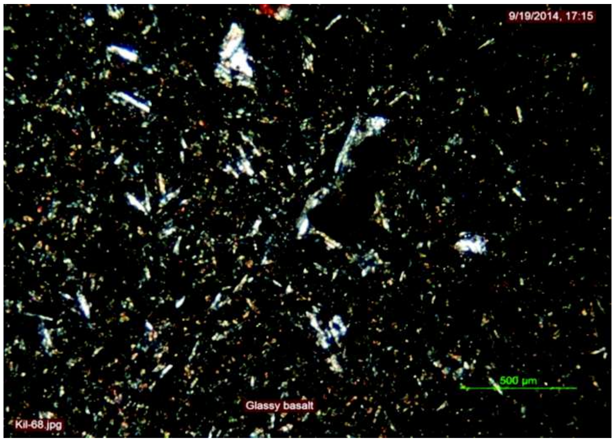

Fig. 2: Photomicrographs taken from the thin sections of Deccan basalt sample KIL-68 from the KLR-1 borehole drilled in Killari, showing glassy nature

secondary minerals. High order of attenuation is also reportedly noted in some of massive basalt cores, besides vesicular samples. It is argued that composition of the basalt itself could be a major contributing factor towards seismic attenuation. Recent studies over this region (Pandey *et al*., 2016) indicated that in comparison to Deccan volcanics, the subsurface thick Mesozoic sediments, can be seriously considered as a leading option for geologic CO_2 sequestration, while pervasively fractured, faulted and highly deformed, on-land exposed volcanics, should be given least priority.

Studies on Indian Carbonatites

Carbonate magma is unique because of its ability to enrich elemental carbon with respect to its silicate mantle source, where carbon is a trace element. Owing to its extremely low viscosity and short residence time in the crust carbonate magma passes through the crust without significant contamination. In addition, very high contents of most of the incompatible trace elements, many of which are used as elemental or isotopic tracers in mantle studies, tend to buffer any such contamination. Therefore, carbonatites preserve mantle signatures more efficiently than most other magmatic rocks and thus are the best known samples to study the secular evolution of mantle geochemistry and the long-term carbon cycle in Earth.

Carbonatites occur both in continental and oceanic settings but are found mostly in the former and hence, provide useful information about the less understood sub-continental mantle. Even though they are volumetrically minor, because of their widespread spatial and temporal distribution they provide valuable information about the secular evolution of the sub-continental mantle on the whole-Earth scale. The observation that many carbonatites are associated with Large Igneous Provinces (LIPs) or Continental Flood Basalt (CFB) provinces has led to the speculation that they too like the LIPs/CFBs could be genetically linked to the deep mantle plumes. The plume derivation hypothesis derives its support, albeit unconvincingly, from the observations that many carbonatites (1) occur within LIPs or CFBs (Ernst and Bell, 2010), (2) carbonatites generally possess isotopic ratios of Nd-Sr-Pb similar to that of the Oceanic Island Basalts (e.g., Nelson *et al*., 1988), (3) show lower (un-degassed) mantle noble gas isotopic signatures (Sasada *et al*., 1997; Tolstikhin *et al*., 2002), and (iv) have a HIMU (high $^{238}U/^{204}Pb$) component, which is usually found in plume derived melts (Bell and Tilton, 2002). However, a great majority of carbonatites show (1) overwhelming presence in continental crust, (2) geochemical and isotopic signatures akin to lithospheric mantle (Ashwal *et al*., 2016), (3) repeated magmatic activity in a given complex, separated by several millions of years (e.g., Woolley and Bailey, 2012), (4) derivation from mantle that is much cooler than plumes (Bailey and Woolley, 1995), and alkaline silicate rock association and their diversification which would require significant involvement of continental lower crust (Ray, 2009). All these point to the possibility that carbonatite magmas most likely are derived from sub-continental lithospheric mantle. Other important aspects of carbonatite magmatism those have not been fully understood include, nature and source of carbon (primordial vs. recycled), nature of origin of magma (primary melt vs. magmatic differentiation), and environmental effects of the release of large amounts of fluids associated with its eruption/emplacement.

The carbonatite complex in India was first discovered by Sukheswala and Udas (1963). Ever since, more than 20 complexes have been identified (Krishnamurthy *et al*., 2000; Ray and Ramesh, 2006). In spite of years of research, questions on the origin of many of these complexes remain poorly understood. Most of the Indian carbonatites occur within major fracture zones (Krishnamurthy *et al*., 2000) and some are associated with Deccan and

Table 1: Summary of current chronological status of important carbonatite complexes of India

	Complex	Age (Ma±2s)	Dating Method	Reference	Remark
1)	Hogenakkal, Tamil Nadu	2406±32	Sm/Nd min-wr isochron (carbonatite + pyroxenite + minerals)	Kumar *et al*. (1998)	Weighted Mean of 3 age data
2)	Kambamettu (Kambam), Tamil Nadu	i. 2498±16 &2470±15 (magmatic) ii. 608±6 (crustal?) iii. 715±42	i. U/Pb zircon ii. U/Pb zircon iii. Th/Pb monazite	i. Renjith *et al*. (2016) ii. Renjith *et al*. (2016) iii. Catlos *et al*. (2008)	Four phases of magmatic activity? Age of monazite is deemed hydrothermal (Ranjith *et al*., 2016)
3)	Newania, Rajasthan	i. 1473±63(magmatic) ii. 904±2(thermal event)	i. Sm/Nd wr isochron ii. ^{40}Ar/^{39}Ar plateau (phlogopite)	Ray *et al*. (2013)	Earlier age estimates: 2.24 Ga to 959 Ma
4)	Sevattur, Tamil Nadu	i. 767±8 ii. 801±11 iii. 756±11	i. Rb/Sr wr isochron (syenite) ii. Pb/Pb isochron (carbonatite) iii. Rb/Sr isochron(syenite + pyroxenite)	i. Kumar *et al*. (1998) ii. Schleicher *et al*. (1997) iii.	Accepted age: 770 Ma (average of all reliable ages) Miyazaki *et al*. (2000)
5)	Sung Valley, Meghalaya	i. 107.2±0.8 ii. 106±11	i. ^{40}Ar/^{39}Ar plateaus (phlogopite from carbonatite + pyroxenite) ii. Rb/Sr isochron (wr-mineral from both carbonatite + pyroxenite)	i. Ray *et al*. (1999); Ray and Pande (2001) ii. Ray *et al*. (2000)	Accepted age: 107 Ma
6)	Jasra, Assam	105.2 ± 0.5	U/Pb of zircon/baddeleyite	Heaman *et al*. (2002)	
7)	Mundwara, Rajasthan	i. 102-110 ii. 80-84	^{40}Ar/^{39}Ar plateaus	Pande *et al*. (2017)	Earlier age estimate: 68 Ma by Basu *et al*. (1993); Repeated alkaline magmatism
8)	Sarnu-Dandali, Rajasthan	i. 88.9-86.8 ii. 66.3±0.4	i. ^{40}Ar/^{39}Ar plateaus (alkaline silicates) ii. ^{40}Ar/^{39}Ar plateau: (melanephenite)	Sheth *et al*. (2017)	Same as Mundwara
9)	Chhota Udaipur alkaline-carbonatite sub-province, Gujarat	65.0	^{40}Ar/^{39}Ar plateaus(alkaline silicate rocks; phlogopite from carbonatite)	Ray and Pande (1999); Ray *et al*. (2000); Ray *et al*. (2005)	Complexes/isolated bodies: Amba Dongar; Siriwasan; Tawa

Rajmahal-Sylhet CFBs (Fig. 1). All except Newania are carbonatite-alkaline silicate rock complexes. The ages of emplacement of the important carbonatite complexes are reviewed in Table 1.

Ages of Carbonatites Emplacements

Based on available geochronological information, Indian carbonatites can be broadly classified into two groups. The southern Indian complexes and Newania of Rajasthan are *Proterozoic* (2500-750 Ma; Table 1); the northeastern and northwestern complexes are *Cretaceous* (110-65 Ma; Table 1). New age data suggest that Newania carbonatite was emplaced at ~1473 Ma and was affected by a thermal event at ~904 Ma (Ray *et al*., 2013), and these results contradict the earlier suggestion from Pb-Pb ages that the complex had seen recurring carbonatite activities at 2270 Ma and 1550 Ma (Schleicher *et al*., 1997). However, the pre-Deccan alkaline-carbonatite complexes of Mundwara and Sarnu Dandali clearly had multiple activities during 110-66 Ma (Pande *et al*., 2017; Sheth *et al*., 2017), a finding that would likely to change our view on the LIP/CFB-carbonatite connection. Based on the U-Pb zircon data Kambamettu of Tamil Nadu becomes the oldest carbonatite-alkaline complex of India (~2.5 Ga; Renjith *et al*., 2016).

Geology, Geochemistry and Mantle Sources

Comprehensive reviews of general geology and geochemistry including isotopic compositions of Indian carbonatite-alkaline complexes can be found in Krishnamurthy *et al*. (2000) and Ray and Ramesh (2006). Here we shall present only the important geological and geochemical findings of the last five years, and their bearing on the origin and evolution of these complexes.

Proterozoic Carbonatites

All the southern Indian carbonatites, i.e., Hogenakal, Sevattur, Samalpatti, Jogipatti, Pakkandau, Kambamettu, and one north Indian complex, i.e., Newania, were emplaced at various times during the Proterozoic and most complexes show effects of one/multiple post-magmatic thermal histories (e.g., Renjith *et al*., 2016; Ray *et al*., 2013). All these complexes are located within the Southern Granulite Terrain (SGT) and are associated with major fracture zones (Fig. 3).

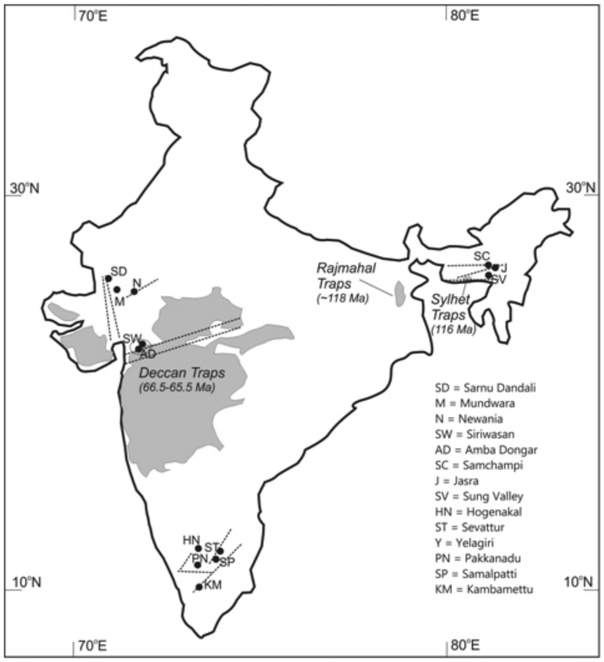

Fig. 3: Map of India (modified from Krishnamurthy *et al*., 2000), showing continental flood basalt provinces (grey shaded) and carbonatite complexes. Also shown are the major fracture zones/lineaments (dashed lines) in/along which the carbonatites occur. Ages of Deccan Traps, Rajmahal Traps and Sylhet Traps are from Renne *et al*. (2015), Bakshi (1995) and Ray *et al*. (2005), respectively

The most recent work on Kambamettu (Kambam) alkaline-carbonatite complex by Renjith *et al*. (2016) suggests that the complex had four distinct magmatic intrusions: i) quartz-monzonite (2.5 Ga) derived from a carbonated alkali-rich lower crustal source; ii) phlogopite-rich pyroxenite derived from carbonate metasomatized mantle; iii) mantle derived high Ba–Sr carbonatite (2.47 Ga); and iv) shoshonitic peralkaline syenite (0.61 Ga) derived from crustal source. We believe that the inference of crustal derivation for alkaline magmas is erroneous, what the younger ages and chemical compositions may actually mean is thermal resetting and/or metamorphism, and several such events, with the youngest being the 0.55 Ga Pan-African, are known to have affected the SGT. Pandit *et al*. (2016) carried out C-O-Sr-Nd isotopic study of the 2.4 Ga Hogenakal carbonatites and suggested their derivation from a heterogeneous mantle source (LREE depleted and enriched). Mineral Chemistry, stable carbon and oxygen isotopes of carbonatite from Salem- Attur shear zone indicated the mantle origin of the southern Indian carbonatites. (Kumar *et al.* 2001). Ackerman *et al.* (2017)'s work is the most recent addition to the research on Sevattur and Samalpatti carbonatites that provides a large amount of petrographic, geochemical (major-trace elements) and isotopic (C-O-Sr-Nd-Pb) data. This study confirms the findings from previous studies that there has been significant hydrothermal alteration in these complexes (e.g., Ray and Ramesh, 2006), however, failed to identify the nature of the mantle sources because of significant crustal contamination. The only north Indian Proterozoic carbonatite is Newania, which happens to be a pure dolomite carbonatite complex that has no alkaline silicate rocks. Using multiple geochemical (major-trace elements and isotopic techniques (C-O-Sr-Nd-Pb) Ray *et al.* (2013) established that the primary magma for the complex was a magnesio-carbonatite melt and that it was derived from a carbonate bearing mantle. This work also suggested that the source was a phlogopite bearing, metasomatized continental lithospheric mantle, which was located within the garnet stability zone.

Cretaceous Carbonatites

All northeastern and western Indian carbonatite complexes, except Newania, were emplaced within a short time in Cretaceous, during ~110 and 65 Ma (Table 1). Interestingly, these complexes are spatially and temporally associated with the Rajmahal-Bengal-Sylhet and Deccan CFBs, respectively (Fig. 3) and have been hypothesized to have been generated directly or indirectly by the Reunion and Kerguelen plumes, respectively (Basu *et al.*, 1993; Ray *et al.*, 1999; Ernst and Bell, 2010; Ghatak and Basu, 2013).

The northeastern Indian carbonatites (Swangkre, Sung Valley, Jasra, Barpunga and Samchampi) intrude into Archean basement rocks of the Proterozoic Shillong Group. They occur in a horst like feature called the Assam-Meghalaya Plateau that is bound by two major fractures (Fig. 3). The 107 million year old alkaline-carbonatite complex of the Sung Valley happens to be the best studied northeastern Indian carbonatite (Ray and Ramesh, 2006; Ray, 2009). Based on geochemistry (elemental and Sr-Nd-Pb isotopic) of carbonatites and associated alkaline silicate rocks Ghatak and Basu (2013) suggested that Sung Valley carbonatites were derived from a relatively primitive carbonated garnet peridotite source in the Kerguelen plume. The work also envisaged a similar model for Samchampi. N and Ar isotopic compositions of Sung Valley carbonatites suggest involvement of recycled (atmospheric/crustal) component in the origin of carbonatite magma in a heterogeneous sub-continental mantle (Basu and Murty, 2015). Studying petrogenesis of Samchampi complex with the help of geochemical and isotopic (Sr-Nd) tracers Saha *et al.* (2017) proposed that these carbonatites were derived from a metasomatized peridotitic source (LREE enriched) within the Kerguelen plume, similar to what was suggested earlier by Ghatak and Basu (2013). However, these studies failed to explain the highly radiogenic nature of Sr (^{87}Sr/^{86} Sr(i) > 0.709) and non-radiogenic nature of Nd ($_{\mathrm{Nd}}$(i) < -8) in these rocks.

The western Indian Cretaceous carbonatites (Sarnu Dandali, Mundwara, Amba Dongar, Siriwasan, Panwad-Kawant) occur along two famous rift zones: the Barmer-Cambay and the Narmada-Son/Satpura (Fig. 3). Of these Amba Dongar, Siriwasan and many smaller plugs, dikes and extrusive bodies in Panwad-Kawant region of Chotta Udaipur district form a large alkaline-carbonatite subprovince within the Deccan LIP (Fig. 3; Gwalani *et al.*, 1993; Ray *et al.*, 2003). During the last five years only a couple of geochronological studies and one field based study have been done on Sarnu Dandali and Mundwara complexes (Tables 1 and 2). The works of Pande *et al.* (2017) and Sheth *et al.* (2017) suggest that there have been repeated alkaline magmatism in these two complexes after gaps of at least 20 and 40 Ma, respectively. These results clearly indicate that the initiation of magmatism in these complexes precedes the Deccan flood volcanism by a long time gap; therefore, the hypothesis of their origin from a Deccan-Reunion plume becomes untenable. Amba Dongar alkaline-carbonatite complex and its nearby smaller intrusive/extrusive bodies in Chotta Udaipur sub-province are by far the best studied carbonatites in India because of sustained efforts by Xavier College, Mumbai, Atomic Minerals Division, Gujarat Mineral Development Corporation and Physical Research Laboratory. Contributions by S.G. Viladkar and his group (e.g., Viladkar, 1996; Viladkar and Schidlowski, 2000; Simonetti *et al.*, 1995) and J.S. Ray and his group (e.g., Ray, 1998; Ray and Pande, 1999; Ray and Ramesh, 1999; Ray and Ramesh, 2000; Ray *et* *al*., 2003; Ray and Ramesh 2006) have resolved most of the outstanding issues about the origin and evolution of Ambam Dongar and nearby complexes. The notable contributions for these complexes during the last five years have been by Basu and Murty (2015) and Chandra *et al*. (2017). The former presented N and Ar isotopic data from Amba Dongar carbonatites and suggested their derivation from a heterogeneous sub-continental mantle, a conclusion confirmed by a detailed geochemical study by Chandra *et al*. (2017). The latter study also substantiated the earlier claim made by Ray and Shukla (2004) and Ray (2009) that the carbonatites and alkaline silicate rocks of these complexes are derived from a single parental magma through liquid immiscibility and that lower crustal assimilation plays a critical role in their diversification.

Studies on Kimberlites and Lamproites

Significant advances have been made in the research frontiers of kimberlites and related rocks from the Indian context during past five years. Chalapathi Rao and his group at Banaras Hindu University have been very productive in studying mineralogical, petrological and chronological characterization of several kimberlite clusters of Mesoproterozoic (ca. 1100 Ma) and late Cretaceous (ca. 90 Ma). (Pandey *et al*. 2017; Dongre etal. 2017; 2016; Rao *et al*. 2016a; 2016b; 2017). From the paleomagnetic investigations on the 1.1 Ga Mesoproterozoic kimberlites from the Dharwar craton, southern India, Venkateshwarlu and Rao (2013) have shown that 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. A layered mantle stratigraphy has been documented in the sub-Bastar craton lithosphere from a comprehensive study of kimberlite- derived xenocrysts and xenoliths (Rao *et al*., 2013a). K-rich titanite, a characteristic mineral of orangeites, has been reported from ultrapotassic dykes of Jharia field, Damodar valley highlighting the transitional (lamprophyre-lampropite-orangeite) characters (Rao *et al*., 2013b). PGE determination from the Deccan-age orangeites of Bastar craton, central India, lacks Ir enrichment thereby excluding the Ir enrichment at K-Pg boundary from deep mantle sources (Rao *et al*., 2013b). A number of previously undated kimberlites from the Wajrakarur field from the Dharwar craton gave precise U-Pb 1.1 Ga ages highlighting a major tectonomagmatic event during that time (Rao *et al*., 2013d). Contrasting lithospheric source regions for the kimberlites and lamproites from the Dharwar craton and for orangeites from the Bastar craton have been documented from Re-Os isotope systematics (Rao *et al*., 2013c). Nickeliferous silicate (garnierite) has been reported from the tuff facies Tokapal kimberlite and its prospectivity for nickel has been highlighted; petrogenesis of the Tokapal kimberlite has also been constrained (Rao *et al*. 2013d). A SCLM origin for Mesoproterozoic Ramadugu lamproites has been deduced (Rao *et al*., 2014). Imprints of Kerguelen plume have been confirmed in the melt sources of the ultrapotassic intrusives from the Gondwana sedimentary basins (Rao *et al*., 2014). Petrogenetic model has been proposed for the macrocrystic as well as aphanitic intrusions in the diamondiferous pipe-2 kimberlite of Wajrakarur field (Dongre *et al*., 2014). Ti-garnet occurrence in kimberlite groundmass as a resultant of breakdown of spinel has been delineated from the Wajrakarur field (Dongre *et al*., 2016). Petrogenetic studies and age determination have been carried out for the lamproites at Sakri, Bastar craton (Rao *et al*., 2016a) and Garledinne, Cuddapah basin (Rao *et al* ., 2016b) and their geodynamic significance brought out. A Late Cretaceous diamondiferous kimberlite event (90 Ma) has been documented for the first time from the Timmasamudram kimberlites, Wajrakarur field, Dharwar craton of southern India (Rao *et al*. 2016c) and their genesis has been brought out (Dongre *et al*., 2017). A cognate origin for the clinopyroxene megacrysts from the Udiripikonda lamprophyre, Dharwar craton has been deduced (Pandey *et al*. 2017a). The role of subduction tectonics in the modification of the SCLM beneath the Dharwar craton has been brought out from the geochemistry of calc-alkaline lamprophyres towards the western margin of the Cuddapah basin (Pandey *et al*., 2017b and c). Modal metasomatism, from phlogopite+apatite assemblage, has been documented for the first time beneath the sub-Deccan lithosphere in an ultramafic mantle xenolith entrained in a Eocene lamprophyre from the Dongargaon area, NW India (Pandey *et al*., 2017d). Single crystal geothermobarometry on a chrome diopside megacryst entrained in a lamprophyre from the polychromous (100-68 Ma) Mundwara alkaline Complex, NW India, implies that pre-Deccan lithosphere was ~100 km depth. Phani *et al*. (2017)

have discovered a new kimberlite in Lattavaram Kimberlite Cluster (LKC) of Anantapur district, Andhra Pradesh, India. This new kimberlite pipe has been located in the riverbed of Balkamthota Vanka (name of the stream used by local farmers) at its confluence with Penna River, close to Pennahobilam. The kimberlite constitutes olivine macrocrysts, serpentinsed olivine pseudomorphs with xenocrystic ilmenite, phlogopite, perovskite, magnetite, Cr-diopside, garn*et al*ong with calcite veins. The kimberlite has been classified as hypabyssal macrocrystic calcite-phlogopite kimberlite (Phani *et al*., 2017).

Lamproitic dykes from Sidhi Gnessic Complex, Central India have been investigated by Satyanarayanan *et al*. (2018), showing that lamproite magma attained carbonatitic character, underwent metasomatism at deep crustal level. The geochemical studies shown that the discovered Central Indian lamproitic dykes indicate their parental magmas were originated from a subduction induced metasomatism process contain phlogopite and garnet.

Industrial Applications and Future Studies

Deccan volcanic rocks provide several secondary minerals like zeolites, hydrous silica, and sulfates that are useful in many Industrial applications. Recent discovery of jarosite in Kutch area (Bhattacharya *et al*., 2016) not only serves as a Martian analog material, but also applied for adsorption and redox reactions occur between arsenic-containing pyrite and arsenate in the form of shwertmannite. Shwertmannite is proven to be a powerful scavenger for trivalent arsenic. Ferrous saponite from the Killari region of the Deccan Trap has been used in not only as for the study of Mars analogs system, but also for the adsorption and reduction of carcinogenic water soluble hexavalent chromium. Systematic studies of mineral chemistry of Indian carbonatites are found to be most useful in the exploration and utilization of rare-earth minerals. Future discovery of new carbonatites will be of tremendous use in improving the rare earth minerals resources of our country.

Conclusion

In this paper we presented a status report on the work carried out on Deccan Volcanism, carbonatites, and kimberlites during the last five years. There has been some significant advancement in terms of geochronology of Mundwara, Sarnu Dandali, Newania and Kambamettu carbonatites. Most other studies are on geochemistry and they mostly reaffirm the conclusions made by earlier studies. One clear conclusion, however, emerges from these studies is that the primary magmas for the Indian carbonatites originated from the sub-continental lithospheric mantle.

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