Research Article

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An Overview of the Carbonatites from the Indian Subcontinent

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Abstract: Carbonatites are carbonate-rich rocks of igneous origin. They form the magmas of their own that are generated in the deep mantle by low degrees of partial melting of carbonated peridotite or eclogite source rocks. They are known to occur since the Archaean times till recent, the activity showing gradual increase from older to younger times. They are commonly associated with alkaline rocks and be genetically related with them. They often induce metasomatic alteration in the country rocks forming an aureole of fenitization around them. They are host for economically important mineral deposits including rare metals and REE. They are commonly associated with the continental rifts, but are also common in the orogenic belts; but not known to occur in the intra-plate regions. The carbonatites are known to occur all over the globe, majority of the occurrences located in Africa, Fenno-Scandinavia, Karelian-Kola, Mongolia, China, Australia, South America and India. In the Indian Subcontinent carbonatites occur in India, Pakistan, Afghanistan and Sri Lanka; but so far not known to occur in Nepal, Bhutan, Bangladesh and Myanmar. This paper takes an overview of the carbonatite occurrences in the Indian Subcontinent in the light of recent data. The localities being discussed in detail cover a considerable time range (>2400 Ma to <0.6 Ma) from India (Hogenakal, Newania, Sevathur, Sung Valley, Sarnu-Dandali and Mundwara, and Amba Dongar), Pakistan (Permian Koga and Tertiary Peshawar Plain Alkaline Complex which includes Loe Shilman, Sillai Patti, Jambil and Jawar), Afghanistan (Khanneshin) and Sri Lanka (Epapwala). This review provide the comprehensive information about geochemical characteristics and evolution of carbonatites in Indian Subcontinent with respect to space and time.

Keywords: Carbonatite, Sevathur, Newania, Sung Valley, Amba Dongar, Koga, Peshawar Plain, Khanneshin, Epapwala

1 Introduction

Carbonatite melts are known to form by very low degrees of partial melting of the carbonated olivine-rich (peridotitic) mantle forming interconnected melts at fractions lower than 0.05 wt%. The grain size is considered to be of the order of 1 mm with low dihedral wetting angles ($\sim 28^\circ$) and low viscosities [1, 2]. Such mantle is envisaged as a veined and metasomatically enriched source region [3]. The carbonatitic magma so generated represent ionic solutions and hence are unpolymerised melts with lower viscosity ($\sim 5 \times 10^{-3}$ poise), high ascent rates (20–65 m/s), lower heat of fusion (~ 175 J/gm), higher thermal diffusivity ($\sim 4 \times 10^{-3}$ J/cm sec K), very high chemical reactivity and electrical conductivity [4–7]. These are some of the reasons why such magma loses heat rapidly (thermal death) and vigorously react with host rocks and induce metasomatic transformation (chemical death). Therefore, a large number of carbonatitic magmas may not reach above the surface of the crust [8]

Carbonatites are spatially and temporally related to orogenic belts and constructive and destructive plate margins. They commonly occur on uplifted or domed areas that vary from tens to thousands of kilometers in diameter, typically associated with major faulting and rifting related to doming [9, 10]. Carbonatite activity has initiated in the earth as early as Late Archaean and gradually increased over time. Peak activities recorded between 750 Ma and 500 Ma coinciding with the Pan African orogeny and another peak starting at around 200 Ma coinciding with the Gondwana breakup [9]. More activities towards the end of Cretaceous (~ 65 Ma) and mid-Quaternary (~ 30 Ma) in the Indian subcontinent could be attributed to plume related Deccan Trap magmatism and Himalayan orogeny respectively [11–13].

The carbonatites from subcontinent have received considerable attention during last two decades. Significant

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Figure 1: Distribution and location of Carbonatites within Indian Subcontinent [41, 67, 78, 82, 85, 110, 154, 157], Pakistan [12, 28, 29, 54], Afghanistan [35], and Sri Lanka [32, 36].

amount of data on trace elements and isotope geochemistry has been published, which helped better understanding of these rocks with similar and/or different geodynamic setting and its global correlation [12, 14–42]. The present paper attempts to review the carbonatite bearing alkaline complexes of the Indian subcontinent; except Bangladesh, Nepal, Bhutan and Myanmar due to absence of carbonatite occurrences (Figure 1). Recently Xu *et al.* [10] and Yang *et al.* [43] have taken comprehensive review of carbonatites in China; which is a good reference for Asian carbonatites. Similarly, Deans and Powell [14] have done trace element and strontium isotope studies of Indian and Pakistan carbonatites. Ray *et al.* [31] described

the stable isotopic composition of Indian carbonatites. Kumar *et al.* [21] explained about the carbonatite magmatism of Northeastern region of India, whereas Schleicher *et al.* [22] and Pandit *et al.* [26, 27] explained isotopic signatures and characteristic of mantle source for carbonatites of South India. Basu and Murthy [44] discussed the evidence of incomplete homogenization of mantle and recycled components by nitrogen and argon concentration and isotopic ratios in Sung Valley and Ambadongar carbonatite complexes of India. Despite several new additions to the existing knowledge about the Indian carbonatites, there is great paucity of data on the carbonatite complexes of Pakistan, Afghanistan and Sri Lanka.

Therefore, in this review we present detailed description of carbonatite complexes of India (Hogenakal, Newania, Sevathur, Sung Valley, Sarnu-Dandali, Mer-Mundwara, Chhota Udaipur and Purulia), Pakistan (Sillai Patti, Loe Shilman, Koga and Jhambil of Peshawar Plain Alkaline Complex), Afghanistan (Khanneshin) and Sri Lanka (Eppawala and Kawisigamuwa). Figure 1 gives geographic location of the carbonatite complexes listed in Table 1, which summarizes the data being discussed in this paper. Tables 2 lists other carbonatite occurrences reported during nineties, which either do not form major occurrence or lack significant data and create confusion about their primary nature. Such occurrences are not considered further in this review.

2 Purpose, Scope, Rationalae, and Limitations

There were several reviews of Indian carbonatites in the past (see for e.g. Sukheswala and Viladkar [63], Krishnamurthy [150], Krishnamurthy *et al.* [163]); each of which provided useful information at that time due to increasing number of discoveries of new occurrences and new information generated in between two successive reviews. However, despite of the published reports of carbonatites in Pakistan, Afghanistan, and Srilanka; no compilation of these occurrences is available. The carbonatites of Afghanistan and Pakistan are much younger compared to the Srilankan carbonatites. The Indian subcontinent is an ensemble of exotic tectonic blocks amalgamated together in the geological past. The high-grade terrain known as “Southern Granulite Terrain” in India correlates well with the high-grade terrain of Srilanka [190]. Similarly, the collision of Indian plate with the Eurasian plate responsible for the Himalayan orogeny, has a profound tectonic influence on the geology of India, Pakistan, Nepal, Bhutan and Afghanistan. Therefore, their correlation beyond the geopolitical boundaries is very useful. Moreover, younger occurrences from Afghanistan and Pakistan and older occurrences such as Hogenakkal in India, makes the spectrum of carbonatite magmatism in the Indian Subcontinent complete in space and time. While compiling the information, the care has been taken to provide proper representation to all the countries of the subcontinent and different cratons in India, different time domains, economic importance, and availability of information. However, the major constraint for this review, as with previous reviews, is the availability of one kind of information from different occurrences. For e.g. the geochronological and stable iso-

Figure 2: Diagram showing time and space relationship of carbonatite magmatism within Indian Subcontinent.

topes data is available for a limited number of complexes. Notwithstanding above, the present review highlights important and distinguishable characteristics of each of the carbonatite complexes.

3 Carbonatites in space and time

Carbonatite occurrences in India, Pakistan, Afghanistan and Sri Lanka (henceforth referred to as subcontinent) range over a considerable time span from Archaean to sub-recent (Figure 2). In India, carbonatites can be divided into three groups on the basis of currently available geochronological data, viz., southern Indian, north-eastern Indian, and western Indian carbonatites (Figure 1). The southern Indian complexes are Precambrian (2400–700 Ma), the northeastern complexes were emplaced during the Early Cretaceous (107–105 Ma), and the western Indian complexes except for Newania were intruded during the Late Cretaceous (68–65 Ma). Oldest known carbonatite complex is Hogenakal in Tamilnadu, which was dated to 2415 and 2401 Ma [46] by Rb-Sr and Sm-Nd methods and 2415 [27, 41] by Sr-Nd method. Earlier, Natarajan *et al.* [17] determined the age of whole complex to be around ~2000 Ma using Rb-Sr mineral isochron method. Next in age is Newania carbonatite complex of Rajasthan, which has been variously dated from 2270 to 900 Ma [31, 33, 45].

Deans and Powell [14] dated alkali amphibole and fenites from this complex using K-Ar method that yielded an age of 959 ± 24 Ma, which is now considered to represent a high temperature metamorphic event in this region [45, 47]. The whole rock and mineral separates dated using Sm-Nd and U-Pb method by Gruau *et al.* [48] vary in age between 1200 Ma to 1400 Ma. Schleicher *et al.* [45] reported whole rock Pb-Pb ages for the complex and suggested that the dolomitic carbonatites of Newania were emplaced at 2270 Ma and the ankeritic carbonatites at 1551 Ma. However, high MSWD values of these isochrones cast uncertainty over precision of these data [49]. Third Precambrian occurrence is Sevathur carbonatite complex of Tamilnadu. Few dates of this complex are available; however, not much variation is hitherto known. Kumar and Gopalan [16] reported first dates of this complex to be 771 Ma and 773 Ma for carbonatite and pyroxenite respectively using Rb-Sr isochron method. Subsequently, Schleicher *et al.* [45] determined the age using Pb-Pb method at 805 Ma. Also, Kumar *et al.* [46] have given precise (MSWD 0.49) Rb-Sr isochron age of 767 Ma. Similarly, 715 Ma monazite ages from Kambam or Kambambettu carbonatite were also reported [50]. These data confirm late Proterozoic age for Sevathur to Kambambettu complex [50, 51], which corresponds with a major alkaline activity in southern India. Next major carbonatitic magmatism in the subcontinent is reported from Eppawala carbonatite complex, which was related with the Pan-African orogeny at around 550 Ma [52, 53]. However, Manthilake *et al.* [32] proposed older age for Eppawala carbonatite body at around 808 ± 185 Ma using Sm-Nd whole rock-apatite isochron. The latter date makes this complex more or less coeval with the Sevathur and Kambambettu complexes.

After a considerable time-interval, next carbonatite occurrence in the subcontinent was recorded at Koga in the Ambela complex of north Pakistan. Le Bas *et al.* [12] first dated the silicate rocks (nepheline syenite and ijolite) and proposed Carboniferous age (297 Ma to 315 Ma) for this complex. Later Khattak *et al.* [54] quoted an unpublished U-Pb age of calcite from Koga carbonatites and confirmed Carboniferous age (~ 300 Ma) for this rock. Tilton *et al.* [24] considered Jambhil complex to be of same age based on their Sr-Nd-Pb concentrations similar to that of Koga; however, Khattak *et al.* [28] dated these rocks and found them to be much younger, that is, 15.7 ± 0.4 Ma of age. Next in age is Jurassic Sung Valley carbonatite complex in Meghalaya. Sarkar *et al.* [55] dated a phlogopite in sovite using K-Ar method and determined an age of 149 ± 5 Ma. Subsequently, Veena *et al.* [23] analyzed calcite and whole rock separates of carbonatites using Pb-Pb method and determined an age of 134 ± 20 Ma for these carbonatites. Sev-

eral alkaline intrusive bodies, including the Sung Valley carbonatite complex are genetically related to Kerguelen hotspot, which produced basaltic lava for about 130 Ma and extended upto the Ninety-East Ridge in the Indian Ocean. The Purulia carbonatites and nepheline-syenites of West Bengal are intruded within the Chandil formation of 1500-1600 Ma age and lies in the close proximity of the Chotanagpur Granite Gneissic Complex (CGGC) [56]. The ages reported from variants of syenites is 1510 Ma with poly-phase metamorphic imprints ranging from 1300-960 Ma age. The Pb-Pb model age suggest that the Purulia carbonatite is at least > 1370 Ma of age [57].

Significant carbonatite magmatism reported in the western part of India occurred towards end of Cretaceous, coeval with the Deccan Trap basaltic eruption. Three complexes, namely, Sarnu-Dandali and Mundwara in Rajasthan and Phenai Mata in Gujarat were dated by Basu *et al.* [13] as 68.57 ± 0.08 Ma, 68.53 ± 0.16 Ma and 64.96 ± 0.11 Ma using Ar-Ar method. However, number of workers reported similar ages ~ 65 Ma for Amba Dongar carbonatite alkaline-complex. Ray *et al.* [58] dated the phlogopite separate from a carbonatite of Amba Dongar using same method that yielded ages of 64.8, 64.7 and 65.5 Ma. Fosu *et al.* 2018 dated the apatite from carbonatite from same complex that yielded an age of 65.4 ± 2.5 Ma. The younger carbonatite occurrences in the subcontinent were recorded from Tertiary Peshawar Plain alkaline igneous province of NW Pakistan. Le Bas *et al.* [12] dated carbonatites from Loe Shilman and Silai Patti areas using K-Ar method of biotite separates to be 31 ± 1.9 Ma. Subsequently Qureshi *et al.* [59] dated zircon from Silai Patti carbonatites using fission track dating method and found a closely comparable age of 32.1 ± 1.9 Ma. More recently, Khattak *et al.* [28] determined fission track age of apatites from Jawar area as 25.2 ± 1.0 Ma and Jambhil area as 15.7 ± 0.4 Ma. Thus the overall age of carbonatite magmatism in the Peshawar plain alkaline-carbonatite complex of Pakistan (and bordering Afghanistan) ranges between 15 Ma to 33 Ma. However, the youngest of all carbonatite occurrences from the subcontinent is the Khaneshin carbonatite complex of Afghanistan. Vikhter *et al.* [60] and Abdullah *et al.* [61] observed that age of these carbonatites is Quaternary (Pliocene) ranging between 1.4 Ma – 2.4 Ma and 5 Ma. Ayuso *et al.* [62] quoted even younger K-Ar date of 0.61 ± 0.05 Ma for these carbonatites.

Among the carbonatites being discussed here, Chhota Udaipur alkaline-carbonatite subprovince hosts biggest occurrence of carbonatites (1200 sq. kms) in the form of a near complete calcite carbonatite (sovite) ring dyke with ferrocarbonatite (ankeritic) as plugs at Amba Dongar, a large sill of carbonatite breccias at Siriwasan and small plugs and dykes in Panwad-Kawant region [58, 63–

68]. Next is probably 3 Km long and $\frac{1}{2}$ Km wide continuous ridge of dolomitic carbonatite with small dykelets of ankeritic carbonatite at Newania [69] and zoned cone sheets, dykes and veins of carbonatites of Sevathur area [70, 71]. A prominent and interesting volcanic vent-like structure of ~ 4 Km² diatreme of Khanneshin Carbonatite Complex, Southern Afghanistan [72, 73] is noteworthy. The diatreme, consisting of coarse-grained sövite and dike-intruded agglomeratic alvikite, a thin marginal zone (<1 km wide) of outwardly dipping (5° – 45°) and alkali-metasomatized Neogene sedimentary strata, and a peripheral apron of volcanic and volcanoclastic strata extending for another 3 to 5 km away from the central intrusive vent [35]. This carbonatite body is exposed above the ground at the elevation of ~ 700 feet, whereas other alkaline complexes in the region are buried under the desert of Quaternary sand. Looking at the younger age of this body and its current location, it may only remain as small outcrop after a considerable span of continental erosion and tectonic deformation. This also provides an indirect clue that many older carbonatite occurrences of the subcontinent, which are now occurring as small outcrops would have been of considerable size, extent and magnitude. All other occurrences are in the form of dykes, veins, stocks, lenses and stringers of small dimensions (refer Table 1, Figure 1).

4 Host rocks and associated silicate rocks

Since the carbonatitic magmas are highly reactive and volatile rich, they have strong effects on the country rocks through which they intrude. Fenitization is often a function of permeability and presence of fractures in the country rock. All the Precambrian carbonatites intrude through charnockites and granitic gneisses (e.g. Hogenakal and Sevathur in Tamil Nadu, Newania in Rajasthan, Eppawala and Kawisigamuwa in Sri Lanka. Palaeozoic Koga carbonatite and Cenozoic Silalai Patti, Jambil, Jawar and Loe-Shilmen carbonatites of Pakistan intrude through metasediments and gneissic rocks [12], whereas Khanneshin carbonatite of Afghanistan has intruded through Neogene sediments [35]. Mesozoic Sung valley carbonatites with associated alkaline rocks are intruded into the Precambrian Shillong series meta-sediments (quartzite, phyllite and quartz sericite schist) [30, 58, 74, 75], whereas, Sarnu-Dandali carbonatites intrude through rhyolites, tuffs of Malani igneous suit and Cretaceous sediments [76], Mundwara carbon-

atites have intruded through Erinpura granite [77] and Chhota Udaipur carbonatites are emplaced within the Deccan Trap basaltic lava flows which are blanketed over the Precambrian (2950 Ga) Untala granite gneiss [78–82] and Bagh sandstones and limestones [66]. Purulia carbonatites crop-up through metasedimentary phyllite, quartzite, mica schist and amphibolites [56, 83–86]. Several small carbonatite occurrences within Peshwar Plain Alkaline Complex of Pakistan intrude through different formations, viz., schistose metasediments, slates and phyllites in the Loe Shilman area and through granitic gneisses in the Silai Patti and Jawar areas [28, 54]. The Khanneshin carbonatite has intruded through Neogene sedimentary rocks of the Sistan Basin, Helmand Province, Afghanistan [87] (Figure 1 and Table 1).

Commonest of the associated intrusive rocks are pyroxenites followed by syenites, lamprophyres and extrusive alkaline rocks such as nephelinites, phonolites, ijolites, tephrites, tinguaites, melteigites and melilitites. Gabbros, dolerites and trachytes are also common in most of the complexes. The ultrapotassic rocks such as leucite phonolite and leucitite rarely occur in the Khanneshin carbonatite complex of Afghanistan and the pseudoleucite-tinguaite occurs in Panwad-Kawant area in Chhota Udaipur carbonatite alkaline complex in India. However, it is surprising that none of the carbonatites of subcontinent are associated with ultramafic lamprophyres, except possibly, Jungel valley [193]. There is an intimate association of pyroxenite and carbonatite in Hogenakal, Sevathur, Sung valley, Barmer and Purulia areas. Tongues and apophyses of carbonatites within pyroxenites are seen even at microscopic scale in Sevathur, Samalpatti, Hogenakal, and Sung valley area, but they occur as separate entities and do not form a homogeneous crystal mush. A variety of syenites also shows spatial and temporal association with carbonatites in some of the localities i.e., in Sevathur, Samalpatti, Hogenakal in southern India; Sung Valley in Northeastern part of India and Koga in Pakistan; similarly carbonatite-lamproite or carbonatite-kimberlite association is also not known from the studied areas, though these rocks are likely to share a common parentage [88, 108].

5 Enclaves, Xenoliths and Xenocrysts

A number of field evidences suggest that the carbonatites (both intrusive and extrusive) are known to carry mantle and crustal xenoliths and xenocrysts over the surface [89].

The presence of xenoliths within the carbonatites also indicates their forceful injection and support their magmatic origin [90–97]. The occurrence of xenoliths in most of the Indian subcontinent carbonatite complexes are rare or absent. Exceptions are the Hogenakal complex, where xenoliths of syenite (up to 2 meters) and pyroxenites (< 10cm) are reported. Similarly, several xenocrysts of pyroxenes and perthite often rimmed by sphene or phlogopite are also common in Hogenakal complex [17, 41, 46]. The Sevattur carbonatite incorporates a number of xenoliths of basement gneisses, syenite and pyroxenite [22, 70, 98, 99]. In case of Amba Dongar, the monomineralic calcite carbonatite cumulates being present as xenoliths [67, 100]. Similarly, shattered angular pieces of granite, gneisses, basalt and sandstones that are fenitized occur within carbonatites of Amba Dongar and Mundwara complexes [101]. Other than India, the Khanneshin complex in Afganistan is only location which contain xenoliths of glimmerite, fenite and older sovite [62, 87]. The carbonatite breccias also reported in several localities of Indian subcontinent, which mainly contain several xenoliths of earlier carbonatite intrusions along with other host rocks and xenocrysts [66, 78]. In the Indian carbonatites, carbonatite-breccias occurs in the Chhota Udaipur alkaline - carbonatite complex, Gujarat, where the Amba Dongar carbonatite breccia intruded within ~68Ma old tholeiitic flows [102] and also occupy the central depression of the complex [100]. Similarly, Siriwasan Sill in the Chhota Udaipur carbonatite-alkalic complex also contain carbonatite breccia with a lateral extent of ~11 km and an average width of 150 m mainly enclosing fragments of sandstone, metamorphic rocks (gneiss, schist, phyllite, quartzite), basalt and minerals such as quartz, pyroxene, olivine, and others [82]. The Khanneshin complex contain brecciated dolomitic ankerite, which occurs within host alvikite, indicating that a hydrothermal fluid, or fluid-rich magma penetrated the barite-strontianite alvikite at a later stage [35] (Figure 1). Furthermore, Pitawala *et al.* [37] has interpreted the coarse-grained olivine present in Eppawala carbonatites as possible xenolithic fragments of peridotitic mantle, which were latter considered to be a part of carbonatitic magmatism Manthilake *et al.* [32].

6 Type of magmatism (intrusive / extrusive)

Carbonatites in general occur as intrusive, volcanic, hydrothermal and replacement bodies. Carbonatite magma forms rare lava-flows and tephra, plugs, cone sheets, dykes

and rare sills, but apparently never form as a large homogeneous plutons [103]. Carbonatite magmatism in the studied complexes is intrusive in the form of concentric ring dyke (Amba Dongar [58, 63, 66, 67, 104]), zoned cone sheets (Sevathur [14, 98, 105, 106]), a strato-volcano or intrusive vent or massif (Khanneshin [35, 60] and also in the form of plugs (e.g. Panwad-Kawant-Gujarat, Jambhil-NE Pakistan), dykes (e.g. Khamambettu-Tamil Nadu; Panwad-Kawant-Gujarat, Newania-Rajasthan Purulia-West Bengal), sills (e.g. Siriwasan-Gujarat, Sillai Patti, Jambhil and Loe Silman-NE Pakistan), stocks, stringers, veins, veinlets and blebs in different areas (especially in Sung valley-NE India, Sarnu-Dandali and Mundwara-Rajasthan, Koga-NE Pakistan, Kawisigamuwa and Eppawal-Sri Lanka) (Figure 1). Extrusive carbonatite activity is reported at Mongra near Amba Dongar [107] and elsewhere in the complex [108]. The carbonatite injection at Newania resulting into brecciation of country rock towards contacts and flow banding having parallel layers of magnetite, mica and veins of apatite are reported in Newania [33, 69, 109–111]. The carbonatite breccias occurring in large quantity at Siriwasan and Panwad-Kawant sectors of Chhota Udaipur also indicate forceful and violent injection of the carbonatitic magma [66, 78, 112]. Similarly, a flow banding of apatite and magnetite rich streaks has been reported within carbonatites of the Sung valley and Sevathur. However, alvikite (C2-type) usually shows marked flow banding at Sarnu-Dandali, Rajasthan [113].

7 Carbonatite varieties

Initially, Brogger [91] proposed nomenclature and definition for the carbonatites after detailed study of around 400 samples, which was reviewed and recommended by Heinrich [132] for IUGS classification. The carbonatites that are dominantly composed of calcite are known as sovites and alvikites, the dolomite rich carbonatite varieties are rauhaugite and beforsite and the iron-rich varieties are known as ankerite or sideritic carbonatites. The carbonatites are also classified according to the weight proportions of CaO, MgO and $\text{FeO} + \text{Fe}_2\text{O}_3 + \text{MnO}$, such as 'calciocarbonatites' (>80% CaO), magnesiocarbonatites ($\text{MgO} > \text{FeO} + \text{Fe}_2\text{O}_3 + \text{MnO}$) and ferrocarnatites ($\text{FeO} + \text{Fe}_2\text{O}_3 + \text{MnO} > \text{MgO}$) [97]. Figure 3 shows plot of variety of carbonatite of Indian Subcontinent.

Calciocarbonatites are dominantly present in all the complexes followed by ferrocarnatites (Table 1). However, magnesiocarbonatite has limited occurrences and mostly reported in Newania-Mudwara-Sarnu Dandali ar-

Figure 3: Carbonatite classification diagram (after Wooley and Kempe [97]). Indian Subcontinent carbonatites show compositional variation from calicocarbonatite to ferrocarbonatites with decreasing Fe/Mg.

eas of Chhota Udaipur carbonatite complex [63, 110, 111, 114] as well as in Sevathur [63, 98, 99, 105, 115] and Khamambettu [116] area of Tamil Nadu as dominant phase, whereas small occurrences are present in Pakistan [12, 28, 29] and Sri Lanka [32, 36, 37]. Interestingly, besntonite (Ba-Sr rich variety of carbonatite was also reported at Samalpatti-Jogipatti areas in Sevathur carbonatite complex [117, 118]. However, all of the carbonatite complexes of the subcontinent are devoid of phoscorite (P-rich carbonatite) except in Purulia, West Bengal, India [119].

8 Fenitization

The terms fenite and fenitization were coined by Brogger [91] for certain rocks of the intrusive complex at Fen in southern Norway. He described fenite as any rock, whether felsic or mafic, produced by *in situ* metasomatism of older country rock in contact with the igneous rocks of Fen complex. There was long debate on fenite, whether it is a product from alkali silicate or carbonatite magma. However, the fact that about 80% of carbonatites occur in association with alkaline-silicate rocks in time and space [120, 189], is a strong argument that they are genetically associated. Von Eckerman [121] also suggested that the fenite actually meant an 'in situ' alteration of the pre-existing rock, irrespective of their original composition [189].

Fenitization is a peculiar phenomenon common to carbonatites and alkaline rocks such as ijolite and syenite. Fenites around carbonatites come in many varieties. Hein-

rich [122] identified three principle types: potassic, sodic-potassic and sodic as Elliotta *et al.* [189] has elaborately discussed in his recent review. All are syenitic in appearance, and some are easily mistaken as igneous syenites unless close attention is paid to the mineralogy, chemical composition and field relationship. It either converts to the host rock into K-feldspar rich rock (*i.e.*, potassic fenitization) or alkali feldspar with alkali amphibole and sodic pyroxene rich rock (*i.e.*, sodic fenitization). The presence of amphiboles, micas and apatite, particularly in the sodic fenites, suggest that the fluid included hydroxyl and fluorine ions [122, 123, 189]. Primary mantle-derived carbonatite melts carry appreciable Na and K in widely varying proportions that can be subsequently lost to fenitization. The fenitizing fluids carrying the Na and K are halide-rich (principally F); whereas CO₂ is commonly absent. The H₂O content varies with locality and may depend on the country rocks. Barium is characteristically enriched in potassic and sodic fenites. However, in some cases they are also enriched in Fe, Sr, Sc, V, Zn and Rb [122, 124, 189]. All the carbonatite complexes display fenitization except Eppawala where Fenitization is not noticed [32, 39]. In the remaining carbonatite complexes both sodic and potassic fenites are formed; former being more common than the later.

In Hogenakal area a very coarse plagioclase zone is formed within pyroxenite, whereas in Newania area, ~75 meters aureole is developed within the granitic gneiss (Figure 1). Partial transformation of microcline to orthoclase, strong development of ferri-eckermannite in the form of euhedral crystals, and increase in orthoclase-ferri-

eckermannite in the inner zone of syenite indicates fenitization in the Newania area [69]. In Sevathur complex fenitization of pyroxenite has resulted in the formation of apatite + vermiculite + tourmaline rich fenite zone. In Koga area of Pakistan both sodic and potassic fenites are known. Feldspathic syenites contain cloudy, twinned rims of microcline, rimmed by ~ 2 cm albite; large prisms of aegirine are randomly distributed in sodic fenites. But, in case of potassic fenites Ba shows gradual increase with K_2O , whereas there is no change observed in REE abundance [124, 125]. About 200 m to 100 m zone of potassic $\pm$ sodic fenite is developed within phyllites and quartzites of Sung valley [74]. In Sarnu-Dandali-Barmer area strong sodic fenitization has been reported [76, 126]; similarly in Mundwara area the host granite is fenitized by soda-rich fluids [101]. In Purulia area alkali pyroxenite shows sodic fenitization [56] and so is the case with Loe Shilman, Silai Patti, Jawar and Jambil areas of Pakistan where phyllites and gneisses show development of sodic amphiboles and soda feldspars indicating prominent sodic fenitization (Figure 1). However, increased percentage and grain size of K-feldspar, surrounded by clusters of small globules of albite, increased concentration of biotite near Fe-oxides indicate presence of strong potassic fenitization [15, 124, 127, 128]. Intense potassic fenitization is also known to occur at Khanneshin complex [87]. In Amba Dongar area six types of fenites were recognized, namely, ultrapotassic fenites (orthoclases), potassic fenites (quartz + feldspar(s) rocks), sodic potassic fenites (microcline + orthoclase $\pm$ albite + aegirine-augite fenite and orthoclase + aegirine fenite), sodic fenite, ultrasodic fenites (albitites) and melanocratic fenites are reported by [67]. Such systematic study will be useful in other areas to understand process of fenitization in a more comprehensive manner.

9 Mineralogy and Mineral chemistry

The mineralogical composition of carbonatites is very complex in nature. Their cognate mineralogy is often difficult to distinguish from the acquired mineralogy. Such difference is due mostly to the wide assimilation of minerals or unassimilated xenocrysts in the host magma [129]. The collective studies by [130–132] have reported ~200 species of minerals within carbonatites, part of which may be considered as typical of these rocks. These minerals are grouped and classified according to their chemical composition into native elements, fluorides, sulfides, oxides and silicates.

Commonly observed minerals from the carbonatite complexes from subcontinent are apatite, magnetite, phlogopite-biotite, pyroxenes (salite, diopside, augite, Ti-augite, aegirine and aegirine augite), amphiboles (tremolite, ackermanite, hornblende, magnesio kataphorite, richterite, and arfvedsonite), pyrochlore, monazite, perovskite; less commonly, allanite, zircon, muscovite, celsian feldspar, olivine, melanite garnet; and rarely scapolite, wollastonite, hematite, spinel, vermiculite and quartz (Table 1).

Relatively large number of data are available on the above discussed minerals from Indian carbonatites rather than Pakistan, Sri Lanka and Afganistan. Some of them, especially olivine, magnetite, pyroxene, fluoro-apatite, zircon and amphibole are used as a petrogenetic indicator and track the changes during magma evolution of carbonatites and also provide their link with the associated rocks, if any. The differences in their major oxide and trace element compositions are known to be an admixture from different sources, which can be attributed to compositional differences of their parental rock types [133–135]. In particular, the REE content of zircons from the carbonatite might have been influenced by the high volatile components in these rocks [136].

Ramasamy *et al.* [71] has reported opaque dust-like and large euhedral phenocrystic (upto 10 cm) magnetite variety from Sevattur carbonatite. Both of these varieties have different origin *i.e.*, fine dust-like inclusions formed at a late stage through dissociation of ankerite to calcite and magnetite, during upward migration of melts from a deep magma chamber that subsequently suffered secondary oxidation. In contrast, the phenocrystic magnetite shows comagmatic crystallisation and represented as primary mineral phase in the carbonatite.

Viladkar and Bismayer [137] described the compositional variation in core and rim in pyrochlore from Amba Dongar, Gujarat and linked with changing magmatic chemistry. They also interpreted that final carbonatite phase in Amba Dongar was ankeritic and rich in hydrothermal fluids, which gives rise to extreme compositional zoning and introduction of diverse elements (Si, U, Sr, Th, Fe), in the pyrochlore. Accordingly, many Indian carbonatite occurrences contain pyrochlore in considerable concentrations though no workable economic deposit has been reported so far. Viladkar and Ghose [138] reported highly uraniferous pyrochlore (U_3O_8 : 20 to 22%) from the Newania carbonatite, similar to that reported earlier from the Sevathur carbonatite [98]. The Sung Valley carbonatite hosts high Nb pyrochlore and good concentrations of Nb are found in the overlying soil [139].

Table 1: Summary of carbonatites characteristics from Indian Subcontinent (Including India, Pakistan, Afghanistan and Sri Lanka).

	Hogenakal Pyroxenite- carbonatite complex, Tamilnadu, India	Newania carbonatite complex, Rajasthan, India	Sevathur carbonatite complex, Tamilnadu, India	Eppawala Carbonatite Complex, Sri Lanka	Koga Carbonatite, Ambela Complex, North Pakistan	Purulia carbonatite complex, West Bengal, India	Sung Valley carbonatite complex, Meghalaya, India	Chhota Udaipur alkaline - carbonatite complex, Gujarat, India	Tertiary Peshawar Plain Alkaline igneous Province (PAIP), NW Pakistan	Khaneshin Carbonatite complex, Afghanistan Why this, please remove
Age	2415 & 2401 Ma (~2 Ga)	2.27 Ga and 1551 Ma; also 1200-1400 Ma; 900-950 Ma; 959 Ma	1300 – 600 Ma; 767 Ma; 771 Ma; 805 Ma	550 Ma; 818±185 Ma	297 – 315 Ma; 317.8±10.5 Ma	> 1.37 Ga	134±20 Ma; 149±5 Ma; 84±13	65 Ma; 61 Ma	15 – 31 Ma	0.61± 0.05 Ma, 1.4 – 2.8 Ma to 5.0 Ma
Latitude/ Longitude/ spatial extent and subdivisions	N12° 7' - N12° 12'; E77° 47' - E77° 51'; Width: 3m - 4.5m & Length 25m - 800m (>10 bodies known); Two separate pyroxenite host bodies of ~3km and 14 km length	N24° 38', E74° 03'; ~3 Km ² ; No subdivisions known	N12° 25', E78° 32'; ~5 Km ² ; Jagipatti- Samalpatti- Onakarali	N 08° 10', E 80° 25'; >6 Km ² ; hundreds of unmapable exposures are scattered within the Eppawala village and its surroundings	N34° 30' - 40'; E72° 45' - 55'; generally <50 Km ² ; Subdivisions not known	N22° 55' - N23° 05'; E86° 20' - E86° 40'; Small bodies; exposure at ground level re only at Beldih	N25° 31' - N25° 36'; E92° 02' - 92° 10'; ~35 Km ² ;	N21° 55' - 22° 10'; E73° 50' - 74° 10'; ~1200 Km ² ; Amba Donar (ring dyke), Panwad-Kawant (plugs), Sriwasan-Dugdha (major sill & dykes) sectors	N34° 35' - E71° 73'; generally <50 Km ² ; Six complexes within PAIP: (i) Loe Shilman in Khyber Agency; (ii) Silai Patti in Malakand Agency; (iii) Jambli in Swat; (iv) Tarbela and (v) Mardan; and (vi) Khungai in Jawar near Silai Patti	N30° 25' - N30° 35'; E63° 30' - E63° 40'; ~25 Km ² ; consisting of central intrusive vent of ~4km ² , fertilized zone of <1 Km, volcaniclastic strata of 3-5 Km, and small satellite intrusions of <400 meters
Form	A series of discontinuous lensoid bodies within two pyroxenite dykes	3 Km long and 1/2 Km wide edge of magnesian dike with dykelets of ferrocarbonate and probably also calcocarbonatite	Zoned cone sheets along NE trending linear, an arcuate and crescent shaped outcrop	Series of individual carbonatite exposures forming dyke-like carbonatite bodies intruding high-grade metamorphic rocks of the Wann Complex	Plug and small veins within nepheline syenite intrusion	Small veins and discontinuous lenses	Smaller dykes within pyroxenite, also with stocks, lenses, veins and stringers localized along the outer and to inner margins of ijolite bodies	Major ring dyke and a sill with several other small dykes, sills and plugs; also lava flows	E-W striking 170 m wide and 2.5 Km long intrusive sheets of ~4- carbonatite at Loe Shilman; 2-20 m thick & 12 Km long sheet of fertilized sediments dipping outwards, carbonatite at Silai Patti; small sills and plugs elsewhere	The complex is divided into four major parts: (i) A central vent of ~4- Km diameter; (ii) a thin marginal zone of > 1 Km wide of fertilized sediments dipping outwards, (iii) a peripheral apron of volcanic and volcaniclastic strata and (iv) small satellite intrusions of sub-volcanic origin
Intrusive / Extrusive	Intrusive (lenses and veins of separate pulses)	Intrusive (with little brecciation towards the country rock contacts, flow character indicated by parallel bands of magnetite and mica, veins and thick bands of apatite)	Intrusive	Intrusive	Intrusive	Intrusive	Intrusive	Both intrusive as well as extrusives are known to occur	Intrusive	Intrusive as well as extrusive carbonatites are known to occur.
Host Rock	Precambrian (~2.5 Ga) chamockites	Precambrian (2.95 Ga) Untala granite gneiss	Precambrian gneisses	High-grade metamorphic rocks of upper amphibolites to granulite grade metamorphic rocks.	Nepheline syenite emplaced into metasediments and gneissic rocks	Precambrian (~1.5 - 1.6 Ga) Chandil formation comprising of chlorite-phyllite, quartzite, mica schist, amphibolite	Pyroxenite	Aravalli granite gneisses, Bagh sandstones and limestones, Deccan Trap basaltic lava flows	Palaeozoic schistose metasediments, dolerites, over Precambrian slates and phyllites (Loe Shilman); granite gneiss and pelitic schist (Silai Patti & Jambli)	Neogene sedimentary rocks (sandstones and shales). A peripheral apron of volcanic and volcaniclastic Strata extend for another 3-5 km away from the central intrusive vent.
Associated intrusive rocks	Pyroxenite, syenite, pyroxene- syenite and plagioclase	None (Lack of associated alkaline rocks)	Pyroxenites and alkali syenites	None; albeit veins of mica and quartz which occur parallel to the strike of carbonatite dykes are found in the vicinity of mine site.	Nepheline syenite and ijolite	Alkali pyroxenite, apatite magnetite	Peridotite, ijolite, and syenites	Nephelinites, phonolites, ijolite, trachytes, lamprophyres, alkaline intrusive at Silai Patti, Jambli and Jawar dolerites	Potassic igneous rocks and lamprophyres (Loe Shilman); no alkaline intrusive at Silai Patti, Jambli and Jawar dolerites	Leucite phonolite and leucitite.

Carbonate varieties	Calciocarbonatite	Magnesiocarbonatite, also ferro- and minor calciocarbonatite	Calciocarbonatites, ferrocarbonatites and also magnesio-carbonatites	Calciocarbonatites	Calciocarbonatite	Calciocarbonatite and magnesio-carbonatites	Calciocarbonatites and ferrocarbonatite breccias common	Calciocarbonatites; ankeritic carbonatite, biotite-, amphibole-carbonatites (Loe Shilman); biotite-apatite soviet, amphibole-apatite soviet (Slai Patti)	Coarse grained sovite and brecciated and agglomeritic barite-ankerite alvikite
Fertilization	Very coarse plagioclase around proterite indicates (sodic?) fertilization	~75 meter aureole of fertilization developed in the granitic gneiss; mostly sodic fenite with apatite also potash fertilization	Predominantly potassic	Not known	Sodic fertilization observed within alkali pyroxenite	~20–100 m zone of potassic and also sodic fertilization of phyllites and quartzites developed	Complete range of fertilization viz. ultrapotassic, sodic-potassic, sodic, ultrasodic & melanocratic	Predominantly sodic; aureole developed within phyllites and gneisses containing sodic amphiboles and sodic feldspars	Potassic
Xenoliths / xenocrysts	Coarse grained (up to 2 meters), sub-angular, sub-rounded or ovoid xenoliths of syenite. Pyroxenes and perthite xenocrysts rimmed by sphene or phlogopite present within carbonatite bodies	Not known	Number of xenoliths of basement gneisses, syenites and pyroxenites	Coarse-grained carbonatites were initially interpreted as possible xenolithic fragments of peridotitic mantle ^a ; which was later considered to be of magmatic origin ^b	Not known	Not known	Several xenoliths and xenocrysts within tuffaceous carbonatites, but not known in pure carbonatite varieties (???)	Not known	In some of carbonatite plugs, very large (>1 m diameter) xenoliths of coarse-grained sovite, fenite and "glimmerite" are abundant and large, and some outcrops have the appearance of giant intrusive breccias. i.e., brecciated dolomitic ankerite present within host alvikite
Tectonic setting	Boundary between craton and mobile belt having a zone of intense faulting and thrusting. The characteristic main uplifted and overthrusted onto the craton	Aravalli rift zone	Eastern Ghats paleo-rift system	Likely related to large-scale regional faulting of the Indian subcontinent and associated generation of mantle magmas and emplacement of carbonatite intrusions in south India and Sri Lanka.	Purulia Spear Zone marking boundary between Singhbhum Group of rocks and Chotanagpur granite gneiss	NS trending lineament within the Shillong horst bounded by Dauki fault towards north and Baramhutra graben towards south	Son-Narmada rift valley	All carbonatite complexes are situated between Main Mantle Thrust (Indus Suture Zone) and Main Boundary Thrust; Synorogenic intruded along thrust planes associated with collision of Indian and Asian plates	The terranes of the carbonatite complex are undergoing SW translation due to internal dilation due to continued northward thrusting of the Indian Plate. The complex is situated on the crest of a faulting node of faults in region of relative dilation
Associated (accessory) minerals	Apatite, phlogopite, salite, aegirine-augite, scapolite, monazite, allanite and zircon	Muscovite, magnetite, zircon, apatite, monazite, tremolite, eckermanite, hematite	Pyroxene, amphibole, phlogopite, biotite, magnetite, apatite	Apatite, ilmenite, forsterite, magnetite, phlogopite, magnesite, enstatite, tremolite and spinel. Traces of calc. monazite and rutile	Amphibole (magnesian, kaophorite & richterite), biotite-phlogopite, apatite, magnetite	Magnetite, apatite, phlogopite, olivine, diopside, allanite, pyroxene, perovskite and spinel	Pyroxene, amphiboles, mica, melanite garnet, pyroxenite, niobian-zirconolite, fluorite	Apatite, pyroxenite, biotite, arvetsonite	Biotite, apatite, fluorite, barite, strontianite. Typical mineral: Khammesite-(Ce) (formula: (Na,Ca) ₃ (Ce,Ba,Sr) ₃ (CO ₃) ₅)
Mineralization	Monazite and REE mineralization (?)	Apatite and REE mineralization; associated rare metals	Vemiculite mineralization; also pyroxenite, magnetite, zircon and monazite in soils	Apatite being mined for rock phosphate	Nb, apatite, magnetite, REE	REE, Nb, P and Fe	Huge hydrothermal fluorite mineralization	~200 Mt of phosphate ore at Loe Shilman Uranium at Slai Patti	~1.29 Mt of REE Ore. Also enriched in Ba, Sr, P and U.

Nearby alkaline-carbonatite complexes in the region	Ijolites & nepheline syenites of Pikkili Hills (no carbonatites known)	Not known	Sevvattur – Koratti (this one); Jogipatti – Samalpatti – Omakara, Tirupattur together known as carbonatite-alkalic complex	Kawisigamuwa carbonatite bodies in Wannai Complex	Several Tertiary carbonatite complexes of Peshawar Plain Alkaline Igneous Province (PAIP)	~100 Km long Northern Shear Zone starting from Khatra in Bankura, West Bengal to Tamar in Jharkhand through Beldih, Medinipur, Kumi, Chirugora, Sushina and Tamakhun (carbonatites in drill core sections only); alkali syenite at Sushina Hill	Other complex in NE are Swangkri and Samchampi	Lower Narmada Valley	Carboniferous Koga carbonatite complex and possible equivalents; adjoining areas in Afghanistan	Evidence of carbonatite activity has been observed in the volcanics and a ten-metre horizon of trachyandesite-dacite tuff with up to 30 per cent in carbonate content was reported in fragments within an area of a few dozen sq. km (Abdullah, 1980)
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Table 2: Some reported carbonatite occurrences in the Indian subcontinent © The reported carbonatite occurrence is disputed for its magmatic origin.

Sr. No.	Name of the locality	Description	Reference
1.	Murud-Janjira, Maharashtra, India (N 18°18'06" E 72°58'02")	Small veinlets of less than 1 cm within the stock like bodies of ijolite within the Decan trap basaltic lava flows. Associated rocks include nepheline syenite and alkaline lamprophyre.	Sethna and D'Sa (1991)
2.	Kala Doongar, Kachchh, Gujarat, India (N 23°47'15"- 23°51'00" E 69°49'30"- 69°54'15")	Plug like occurrence of two carbonatite outcrops intruding within a layered complex consisting of pyroxenite, layered gabbro / norite with microlayers of anorthosite and leucogabbro. Associated rocks include nepheline syenite and alkaline lamprophyres.	Karkare <i>et al.</i> (1991)
3.	Lower Narmada Valley carbonatites, Gujarat, Madhya Pradesh, India (N 22°00'-22°45' E 74°15'-74°50')	Small dykes varying between 4 meter and 100 meters are reported on northern and southern side of Narmada river at several localities near Dhadgaon and Mulgi south of Ambadongar.	Sant <i>et al.</i> (1991)
4.	Kudangulam, Cape Comorin, Tamilnadu, India (N 08°11' E 77°43')	Dykes and veins of coarse grained sövite beforeites and ferrocarbonatite ranging in size from 1.0 m x 0.01 m to 100 m x 2.0 m, occur within charnockites and granitic gneisses. Tongues and apophyses of carbonatites occur within charnockites and pyroxenites. Silicocarbonatites were also reported.	Ramasamy (1995)
5.	Kannegiri Hills, Khammam district, Andhra Pradesh, India (N 17°15'-17°20' E 80°35'-80°40')	Two bodies of dolomitic carbonatite having dimensions of 33 m x 20 m and 33 m x 8 m were reported. They intrude pyroxene granulites, charnockite and garnetiferous gneiss. One body posses hornblende xenoliths (<1 cm to 20 cm), whereas another body shows undeformed layering. Fenitization is feeble.	Sarvothaman <i>et al.</i> (1998)
6.	Ajippuram, Kollegal Taluk, Karnataka, India (N 12°03' E 77°12')	Several lensoid bodies of carbonatite occur within a wide zone of fenitization in the granulite terrain. These are emplaced along deep NNE-SSW fracture system and associated with pyroxenite, talc tremolite schist showing varying degree of fenitization.	Ananthramu <i>et al.</i> (1995)
7.	Pakkanadu and Malakkadu, Salem district, Tamilnadu, India (N 11°40'15" E 77°50'10" & N 11°44'30" E 77°50'20")	Carbonatites are associated with pyroxenites and occur as discontinuous lenticular bodies intruding syenites. Carbonatites are pure calcite-rich soviet with biotie and ankerite. Apatite, monazite, maganetite, allanite, barite, zircon and cerianite are associated minerals.	Suryanarayana Rao <i>et al.</i> (1978)
8.	Kollegal carbonatite dykes, Dharmapuri District, Tamil Nadu, India (N12°07' E 77°47')	Small lenticular bodies of varying mineralogy and texture. The carbonatite-syenite orthoclasite dyke complex is emplaced within the migmatites. Carbonatite varieties are soviet, diopside-biotite-apatite soviet and carbonatite agglomerate. (<i>this area is extension of the Hogenakal carbonatite complex discussed in detail</i>)	Ramakrishnana <i>et al.</i> (1973)
9.	Vinayakupam-Kunavaram, carbonatites, Tamil Nadu, India (N 17°22'50" E 81°06')	Carbonatites occur in association with nepheline syenites as thin veins with width ranging from 1 cm to 5 cm and length ranging from few meters to 30 meters. The rock contains large crystals of calcite, K-feldspar, hastingsite, biotite, alkali amphibole, apatite, nepheline and zircon. Its genesis is disputed.	Janardhan Rao and Murthy (1970; 1973); Sharma <i>et al</i> (1971)

10.	Khambattu carbonatite, Tamil Nadu, India (N 09°44'40" E 77°14'35")	A small body of carbonatite is reported. The rock is characterized by presence of calcite, lumpus of magnetite, apatite, barite, phlogopite, monazite and bastnesite.	Balakrishnan <i>et al.</i> (1985); Burtseva <i>et al.</i> (2013)
11.	Munnar alkaline-carbonatite complex, Kerala, India	The alkaline complex of Munnar comprises of an alkali granite pluton with minor patches of syenite and carbonatite within Precambrian gneisses. Two carbonatite varieties occur, one is coarse-grained holocrystalline and second is very coarse calcite crystals with minor dolomite and mafic minerals up to 30%. Common minerals include pyroxenes, apatite, magnetite, phlogopite-biotite, with minor laths of albite.	Nair (1984); Santosh <i>et al.</i> (1987)
12.	Kawisigamuwa Carbonatites, Sri Lanka	Three main occurrence of carbonatite bodies extending towards N-S direction. These bodies are apatite rich moderated weathered, completely weathered but rich in magnetite and zircon and carbonatite with only magnetite mineralization.	Wijayarathne <i>et al.</i> (2013)
13.	Loe Shilman Carbonatite Complex, Pakistan -Afghanistan boarder areas	Carbonatite bodies not only occur as circular, plug- like bodies but also as tabular bodies in fold zones. The complex is of Tertiary age and is hosted by Paleozoic metasediments of the Landi Kotal Formation.	Hasan and Asrarullah (1989)
14.	Vinjamur Carbonatite, Udayagiri Taluk, Andhra Pradesh, India (N 14°50'; E 79°35') [⊙]	Carbonatite occurrences were grouped into two viz., fine-grained siderite-rich rock exhibiting flow banding, vugs and other features and second group consisting of sheets of carbonate-rich rock emplaced in conformity with the litho-layering trends of the enclosing meta-volcanics.	Vasudevan <i>et al.</i> (1977)
15.	Bora Complex, Eastern Ghats, India (N 18°15'; E 83° 3') [⊙]	Carbonatites are localized along a deep seated NW-SE fault system in the Eastern Ghats mobile belt. Genetically associated rocks include pyroxenite and syenite. Intense phlogopitization and presence of apatite-magnetite veins, high REE, presence of bastnaesite are considered favorable evidences; whereas presence of anorthite, fassite, scapolite and spinel were considered contra-indicators.	Le Bas <i>et al.</i> (2002) and references therein

Viladkar [140] also explain the Mg and Si rich nature of parental sövitic magma for Amba Dongar carbonatite from presence of Mg-rich pyroxenes (diopside) and Mg-rich mica (phlogopite) and the subsequent changes under high fO_2 conditions resulting in development of aegirine-augite and aegirine around rim. Similarly, Chakrabarty [85] interpreted the changes in physico-chemical condition during evolution of Purulia carbonatite from mineral chemistry of magnesiokatophorite and richterite. Their result suggests that, the difference in composition of the amphibole is characteristic for the intermediate to the late stage carbonatite development. These two co-existing amphiboles reflect a sudden variation in total pressure within the magma chamber during the intrusion of the carbonatite dyke. It was inferred that the magnesiokatophorite started crystallizing first along with calcite and apatite. Subsequently, the ascent of carbonatitic magma to a more shallow depth (hypabyssal) resulted in the formation of the richterite. The difference in amphibole composition reflects a variation in the total pressure within the magma chamber that took place during the formation of the Purulia carbonatite. The development of Tetra-Ferriphlogopite in Purulia carbonatite suggest probability of alkali metasomatism or phlogopitization [86].

Sesha Sai and Sengupta [141] have reported petrogenetic implications of resorbed forsterite from the Sung valley carbonatite, Meghalaya, NE India. Presence of Mg rich forsterite exhibiting spectacular resorbed texture in the carbonatite of Sung Valley Complex has indicated early crystallization of olivine and subsequent crystal-melt interaction between the early formed silicate and carbonate melt. Madugalla *et al.* [42] provided the detail variations in textures of dolomite and calcite followed by compositional differences in Eppawala carbonatites, Sri Lanka and their petrogenetic link. They explain two morphological forms for calcite *i.e.*, calcite-I and II, while dolomites were subdivided into five distinct morphological types *i.e.*, dolomite-I, II, III, IV and V. There geochemical variations indicate that type-I dolomite and type-I calcite are primary magmatic in origin. Type-II and type-III represent exsolved dolomite formed by exsolution from type-I calcite at minimum temperatures of exsolution of about 650 °C. Type-IV and type-V dolomites are recrystallized and reorganized dolomites of exsolved type-II and type-III dolomites.

Some rare minerals found in carbonatites elsewhere are also reported, *e.g.* niobian zirconolite from Amba Dongar [67] and Gonnardite from Sevathur [142]. REE-rich mineral phases are reported from Barmer by [164] such as, bastnesite (La), basnesite (Ce), synchasite (Ce), carbocernaite (Ce), ceranite (Ce), ancylite and parasite. Notwithstanding presence of these, there are number of miner-

als not directly related to primary carbonatite magma but subsequent hydrothermal phases are also known to occur. In Amba Dongar florencite-(Ce), strontianite, bastnasite, parasite and synchysite are reported [143]. Similarly, at Sevathur [106, 118] presence of minerals rutile, ilmenorutile, para-ankerite, gypsum, scapolite, galena, pyrite, chalcopyrite and pyrrhotite is known; and carbonates and REE bearing barite to late magmatic enrichment of volatile constituents like H_2O , CO_2 , SO_3 , P_2O_5 and F is also known. In the Khanneshin complex a variety of mineral phases occur, commonest are khanneshite-(Ce), barite, strontianite, and secondary synchysite-(Ce), parisite-(Ce), ankeritic dolomite, barite, apatite, and strontianite. Khanneshite-(Ce) being the type mineral of this complex [35].

Nevertheless, data on mineral physics and chemistry is either limited or discordantly distributed. That means for some complexes such as Amba Dongar huge mineralogical database is available on almost all mineral phases *e.g.* [67, 112, 137–140, 144, 145], whereas relatively less data is available from other complexes (*e.g.* Koga, Mundwara, Peshawar Plain). Nevertheless, some useful mineralogical data is also available, *e.g.* biotites and sodic amphibole from Loe Shilman and Silai Patti [12, 15] and amphiboles from Purulia [85]. Much new data is required on olivine, pyroxenes, amphiboles, micas, garnets, and especially apatite, magnetite and pyrochlore from majority of the carbonatite complexes, since these are common and economically important accessory minerals.

10 Whole rock geochemistry

In terms of the chemical composition, the carbonatites from Indian sub-continent have a complete series of variants, markedly Ca-carbonatites (calcite or calcio-), Ca-Mg-carbonatites (dolomite or magnesio-); Ca-Mg-Fe-carbonatite (ankerite or ferroan-) (Figure 3) except Ba-Sr-carbonatite (“benstonite”), which occur only in Jogipatti area of Samalapatti massif [117]. Benstonite-Ba-Sr carbonatites are found only in two localities in the world *i.e.*, the Murun massif in Siberia [146] and Jogipatti in Tamil Nadu, South India [117, 147]. Silicocarbonatites have been reported from Ambadongar and Panwad-Kawant area [68, “carbonatite-breccia” of 66 and 67] and Samalapatti area [99, 191].

Common features of the carbonatites discussed in this review, which are also common for the world carbonatites is that, they are generally enriched in total iron and P_2O_5 ; whereas depleted in SiO_2 and Al_2O_3 . Sr and Ba are generally high, former being higher than the later. The varia-

Figure 4: Binary diagram showing variation of CaO against major oxides (colour code for localities is same as in Figures 2 and 3).

Figure 5: Binary diagram showing variation of strontium against other trace elements (colour code for localities is same as in Figures 2 and 3).

Figure 6: Binary variation diagram of La vs La/Yb and Ba+Sr vs TREE for carbonatites of the Indian Subcontinent (colour code for localities is same as in Figures 2 and 3).

tion of major oxide and trace element were plotted to compare their distribution in the Indian Subcontinent (Figure 4 and 5). They commonly show very high concentration of total rare earth elements ($\sum \text{REE}$), and show light-REE enriched, heavy-REE depleted patterns (Figure 6) with high La/Yb ratios without Eu anomalies (Figure 7).

The geochemical characteristics vary from one complex to another and also within varieties of carbonatites in the same complex. For example, Rajasthan and Gujarat has majority of carbonatite of pre-Deccan Flood Basalt carbonatite-alkaline activity (ca 68.5 Ma) except the Newania complex, which is associated with Aravalli orogeny of Proterozoic age [111]. There is significant variation observed in the trace elements *i.e.*, Ba, Sr and LREE, especially La, Ce and Nd [111] (Figure 5, 6, and 7). In Amba Dongar there is clear fraction of REE during crystallization of different phases of carbonatites. The REE (LREE) show increase from earliest alvikite (I) $\rightarrow$ sövite $\rightarrow$ alvikite (II) $\rightarrow$ dykes of ankeritic carbonatite $\rightarrow$ plugs of ankeritic carbonatite $\rightarrow$ sideritic carbonatite [34]. While, such an REE trend is not observed in the Siriwasan and Newania areas; it can be said that the concentration of REE increases with increase in concentration of minerals like pyrochlore, sphene, perovskite, etc [82, 148]. Similarly, low Sr isotopic composition and $-ve \epsilon \text{Nd}$ value indicate Newania carbonatite (rauhaugite) is derived from an old LREE enriched lithospheric mantle source, while others are product of magmatic fractionation of mantle derived nephelinitic magma [111]. Sarnu –Dandali ferrocarnatites are known to contain higher concentration of TiO_2 along with Cr, Ni, Co and Cu, which indicates that their distribution was essentially controlled by iron oxide minerals [76]. Similarly, Mundwara carbonatites are enriched in Ba, La, Y and Sc and depleted in Th, U, Zr, Ta

and Rb. $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratios being higher due to presence of aegirine and hematite [101]. Almost similar characteristics were observed for the Amba Dongar carbonatites [68] (Figure 5 and 6).

Similarly, the carbonatites from Southern India are quite variable in their geochemical characteristics like Rajasthan and Gujarat carbonatites, which also reflect the presence of wide range of silicate minerals. Their silica content ranges from 0.20% to 25.97% with an average of 12.87%. Sovietic carbonatites have $\text{CaO} \sim 50\%$ while other carbonatites have MgO and FeO^t contents up to 9% and 14%, respectively [27] (Figure 4). Very high abundances of Ba and Sr and $\text{Sr/Ba} > 1$ are characteristic of these carbonatites [149]. The Sr and Ba enrichment levels of the carbonatites in these areas are the highest among all other known carbonatite complexes of India [150] (Figure 5 and 6). Low to moderate abundances of compatible elements like Ni, Cr, Cs and V indicate some degree of fractionation of the melts before crystallization. The Nb and Ta behave as a conjugate geochemical pair in most silicate igneous rocks; however, a decoupling between the two in carbonatites has been considered a result of immiscibility where Nb shows a preference for the silicate melt [151].

In addition to these features, Hogenakal carbonatites are also depleted in total alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$). They possess higher Sr/Ba ratios (14.9 – 31.5) and very high concentration of $\sum \text{REE}$ (866 – 8020); due to presence of apatite (17). Their high CaO (also CO_2) and low alkali contents are unlikely to represent a Ca-rich magma generated after metasomatism of lherzolite, which can produce melts containing up to 85% CaCO_3 [41, 152]. On the other hand Sevathur carbonatites show slight enrichment in the alkalis, but there is a variation in Ba and Sr between calcitic and

Figure 7: Chondrite normalized REE Spider diagrams with normalizing values from [183] of carbonatites discussed in this study (colour code for localities is same as in Figures 2 and 3).

ankeritic varieties. These carbonatites are also rauhaugite variety (dolomitic) because of enrichment of MgO [70].

The Benstonite from South India contains up to 1.8% of SrO and 4.5% of TR_2O_3 . Their BaO and SrO contents also vary significantly depending on abundances of microcline and pyroxene (diopside-aegirine hedenbergite) in benstonite carbonatite [117].

The emplacement of the Eppawala carbonatites of Sri Lanka is likely related to large-scale regional faulting and associated mantle derived magmas of Southern Indian carbonatites, which also show similar characteristics [71, 99]. The Eppawala carbonatites show comparable $\sum$ REE concentration, but extreme depletion in Ni, Ti, Cs, Rb, Nb, Ta, Zr and Hf [32] (Figure 7 and 8). The REE pattern, specially MREE depletion in Eppawala carbonatite represents an apatite/pyrochlore fractionation or evolved magma sequence, which is believed to have been controlled by the low degree partial melting of the source (which retains HREE in residuum) [32].

The generalized geochemical characters are also common for the Sung valley carbonatites; however, a stronger mineralogical control over whole rock geochemistry of these carbonatites is proposed, viz. Zr, V, U and Th and Th/U ratio show wide variations conforming the inhomogeneous nature of these rocks in terms of minerals such as mica, pyrochlore, apatite and monazite [21, 74, 75]. The Samchampi carbonatite is enriched in the REE (LREE), Nb, Y, Zr, Sr, with high Sr/Ba ratios and Nd as compared to the Sung Valley carbonatite. Their U and Th concentrations also vary widely, reflecting the relative abundance of pyrochlore, apatite, monazite, baddelyite, perovskite and thorite. In contrast, Sung Valley carbonatite is enriched in Nb, Y, Ce, and Th. The enrichment in incompatible trace elements suggest for the alkali basaltic type parental magmatic source [21, 75]. The Purulia carbonatites are enriched in P_2O_5 as generally observed for other provinces, however, one of the samples show up to 5% SiO_2 concentration. They are enriched in $\sum$ REE and incompatible elements but also poorer in Nb, Th and Pb compared to the world average of calicocarbonatites [56]. The Primitive Mantle normalized spider diagrams show depletion peaks for Rb and Nb for these carbonatites. Chakrabarty and Sen [56] argued that such characteristics indicate carbo (hydro) thermal carbonatite magmatism proposed by Mitchel [153].

Loe Shilman and Silai Patti carbonatites represent the youngest carbonatite event (~30 Ma) in the Indian Subcontinent [12, 24, 28, 29]. Other carbonatites like Koga carbonatite and Ambela are emplaced around ~300 Ma [12, 24]. The Silai Patti carbonatite is enriched in $\sum$ REE upper limit ranges upto 2920 ppm with an average of 1965 ppm [24]. Carbonatites at Loe Shilman show very high values of SiO_2

in some of the samples (up to 19.03%) [160]; Sr concentration is also very high (up to 1.5%). The chemical characteristics suggest the strongly alkaline and carbonatitic magmatism occurred in two periods during the Phanerozoic of North Pakistan, one in the Carboniferous (~300 Ma) and other in the Oligocene (~30 Ma) [12]. The Khaneshin carbonatites are extraordinarily enriched in LREE also they are highly enriched in strontium, barium, fluorine and sulfur due to presence of exotic mineral phases like synchysite, parasite, bastnäsite, taeniolite, barite, and less commonly, celestine [87] (Figure 8).

However, there are little elemental variations within the complexes, e.g. the Sung Valley soviets are depleted in Sr, Ba, La and Ce when compared with Sevathur and Amba Dongar soviets, although their Nb contents are higher. Similarly, the average Amba Dongar sovite show maximum enrichment in Ba among the carbonatites with Ba/Sr > 1, although some individual samples conform to the normal pattern of Sr always in excess of Ba [74] (Figure 5 and 8).

11 Stable (Carbon and Oxygen) isotope studies

Large number of analyses of carbon and oxygen isotopes is available; however, again there is a great deal of discordance in the data from various provinces. On one hand there is a huge database on Amba Dongar carbonatites, whereas no published data is yet available from Khaneshin, Koga and Peshwar Plain carbonatites. A good coverage of data on Sevathur, Newania, Eppawala and Barmer carbonatites is available, but that of Hogenakal is very limited (Figure 9 and 10). Figure 10 provides a detail range of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of carbonatites of Indian Subcontinent. These data led to several significant conclusions which are summarized below.

- (i) The carbonatites bear mantle signature, e.g. Hogenakal [17, 26, 27, 41]; Sevathur [22, 26]; Newania [33, 111], Sung Valley [30]; Amba Dongar and Barmer [19, 25, 34, 58, 66, 68, 76]. However, Eppawala carbonatite in Sri Lanka and Siriwasan carbonatite in Chhota Udaipur, Gujarat show little deviation from primary mantle signatures and possibly represent assimilation of sediments or significant role played by Rayleigh fractionation [19, 25, 32, 58, 82]. Fractional crystallization of fluid-rich carbonate melts is responsible for variation in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values in the Deccan re-

Figure 8: Incompatible elements concentrations normalized to primitive mantle with normalizing values from [183] of carbonatites of Indian Subcontinent (colour code for localities is same as in Figures 2 and 3).

Figure 9: Variation of $\delta^{13}\text{C}_{\text{PDB}}$ vs $\delta^{18}\text{O}_{\text{SMOW}}$ for carbonatites of the Indian Subcontinent (Fields from [161] and [184]; (colour code for localities is same as in Figures 2 and 3).

Figure 10: Diagram displaying range of $\delta^{13}\text{C}_{\text{PDB}}$ and $\delta^{18}\text{O}_{\text{SMOW}}$ values for the carbonatites with respect to mantle values (MORB), primary carbonatite values and $\delta^{18}\text{O}$ carbonatite values from comparative alkaline complexes (colour code for localities is same as in Figures 2 and 3).

lated carbonatite magmatism at Amba Dongar and Barmer complexes [58, 154] and at Newania [33]. Low-temperature fluid-rock interaction has been envisaged at the number of localities, more importantly at Newania, which is a mantle-derived dolomitic carbonatite [33, 143]; whereas in Sevathur complex there are contrasting views. Pandit *et al.* [26] are in favor of this mechanism, but Schleicher *et al.* [22] maintained that no conclusive statement can be made on the question of possible interaction of hot-upwelling magma with crustal or meteoric fluids (Figure 9). Pandit *et al.* [27] observed $\delta^{13}\text{C}$ variations in south Indian carbonatites can be linked to variable enrichment of the mantle source under the influence of metasomatizing fluids. For example, Samalpatti carbonatite shows $\delta^{18}\text{O}$ high and $\delta^{13}\text{C}$ values can be attributed to low-temperature isotope exchange between minerals and fluid with variable $\text{CO}_2/\text{H}_2\text{O}$ ratio as suggested by Srivastava *et al.* [30]. However, in case of Amba Dongar carbonatites, though different workers agree on the low-temperature fluid-rock interaction, there are little variations in details, e.g. carbon exchange or contamination with organic matter bearing sediments [66]; Sub-solidus groundwater interaction [19]; fluid-related CO_2 bearing magmatic, hydrothermal or metasomatic secondary alteration process [58].

- (ii) Involvement of deep-seated (primordial) carbon reflecting the carbon isotope composition of the sub-continental upper mantle below Narmada rift zone of the Indian Subcontinent [155]; and that a particular batch of carbonatite melt at Amba Dongar bears a signature of recycled crustal carbon were proposed by Ray *et al.* [58], similarly, Manthilake *et al.* [32] also postulated mixing of primordial carbon with inorganic carbon (about 42%) during subduction process in the mantle source region in Eappawala carbonatites.
- (iii) Moreover, it was also observed for the Deccan related carbonatite complexes, a Reunion plume head was largely composed of mantle having $\delta^{18}\text{O}$ similar to that of the mean upper mantle and higher [154].

In conclusion, the stable isotopes data for the carbonatites of the Indian Subcontinent indicate mantle signatures coupled with involvement of various processes such as fractional crystallization of fluid-rich carbonatite melts, high-temperature interaction of CO_2 -rich fluids with the meteoric water and groundwater of the region, and low-temperature fluid-rock interaction. The information so far

available on selected carbonatite complexes also indicates involvement of primordial as well as recycled crustal carbon in the genesis of these rocks.

12 Radiogenic (Sr-Nd-Pb) isotope studies

Except for few complexes discussed in this review, good coverage of data on Sr-Nd-Pb isotope ratios is available (Figure 11). These data led to very significant conclusions which are summarized below.

- (i) Hogenakal carbonatites show two type of ϵNd values i.e., high ϵNd values, close to CHUR ($\epsilon\text{Nd} = -0.35$ to 2.94) with low $^{87}\text{Sr}/^{86}\text{Sr}_i$ ratios (0.70161–0.70244) and low ϵNd values ($\epsilon\text{Nd} = -5.69$ to -8.86) with high $^{87}\text{Sr}/^{86}\text{Sr}_i$ ratios (0.70247–0.70319) indicate its derivation from a heterogeneous mantle (both depleted and enriched) sources [27, 41]. Whereas Sevathur carbonatites are characterized by very low $^{143}\text{Nd}/^{144}\text{Nd}$ and corresponding $\epsilon\text{Nd}_{(o)}$ ratios (0.5116 to 0.5122; -9 to -20), and high Sr isotopic ratios (0.7045 to 0.7054) an EM-I-type enriched mantle component [27] (Figure 11). Eppawala carbonatites also has high $^{87}\text{Sr}/^{86}\text{Sr}$ (0.7049–0.7052) and high $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic ratios (0.5019–0.5020). These enriched Sr–Nd isotope character shown by the Eppawala carbonatites is common to most Indian carbonatites, indicating the presence of enriched lithospheric mantle beneath the sub-continent [2, 27, 32, 58]. Koga and Jhambil carbonatites have positive ϵNd (+3.2 to +3.7) and negative ϵSr values (-8.5 to -9.4 with low $^{87}\text{Sr}/^{86}\text{Sr}$ ratio: 0.703485 to 0.703550) [24]. The value of Sr-isotope also shows similarity with Newania [14]. In contrast, Loe Shilman and Sillai Patti carbonatites have negative ϵNd (-3.1 to -3.8) and positive ϵSr values (+2.4 to +5.6 with high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio: 0.704632 to 0.704859). The Loe Shilman and Sillai Patti carbonatites $^{206}\text{Pb}/^{204}\text{Pb}$ (19.025 to 21.362), $^{207}\text{Pb}/^{204}\text{Pb}$ (15.542 to 15.673) and $^{208}\text{Pb}/^{204}\text{Pb}$ (39.328 to 40.629), show similar isotopic characteristic/pattern like East African Rift carbonatites, which also suggests derivation from similar sources. The Koga and Jambil carbonatite have $^{206}\text{Pb}/^{204}\text{Pb}$ (18.643 to 18.872), $^{207}\text{Pb}/^{204}\text{Pb}$ (15.601 to 15.614) and $^{208}\text{Pb}/^{204}\text{Pb}$ (38.720 to 38.937) ratios [24] (Figure 11B and C). Whereas, the Sung valley carbonatites are characterized by $\epsilon\text{Sr}_{(i)}$ (6.0), $\epsilon\text{Nd}_{(o)}$ (2.0), $^{206}\text{Pb}/^{204}\text{Pb}$ (19.02), $^{207}\text{Pb}/^{204}\text{Pb}$ (15.67) and

Figure 11: A) Diagram Epsilon diagram for Sr–Nd initial ratios. End member compositions as of [185] (colour code for localities is same as in Figures 2 and 3). B) The $^{206}Pb/^{204}Pb$ vs. $^{143}Nd/^{144}Nd$ plot of rocks and mineral separates from the carbonatites of Indian Subcontinent. The generalized compositions of isotopic reservoirs are shown for comparison: DMM (depleted MORB mantle), MORB, HIMU (high $^{238}U/^{204}Pb$), EM I (enriched mantle), and EM II (another type of enriched mantle) [186]. Generalized field for MORB from [187]; OIB field not shown for clarity (field constrained by DMM, HIMU, EM I and EM II reservoirs). C) $^{206}Pb/^{204}Pb$ vs. $^{87}Sr/^{86}Sr$ plot of rocks and mineral separates from the carbonatites of Indian Subcontinent. D) $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ plot of rocks and mineral separates from the carbonatites of Indian Subcontinent. (EACL line is the East Africa carbonatite line (age < 40 Ma) [188]. (colour code for localities is same as in Figures 2 and 3).

$^{208}\text{Pb}/^{204}\text{Pb}$ (39.0). The higher Sr ratios of the source regions for Sung Valley indicate long-lived Rb/Sr enriched mantle sources. Their initial Sr and Nd ratios were calculated based on an age of 134 Ma, indicating EM II $\pm$ HIMU sources [23]. However, an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 107 Ma indicates EM I $\pm$ HIMU mixing line, which is commonly observed in many carbonatites younger than 200 Ma worldwide [58, 156] (Figure 11D). It has also been suggested that such an incorporation possibly resulted from the entrainment of subcontinental lithospheric mantle by the Kerguelen plume [23, 30, 58, 156]. On the other hand, Sr-isotopic ratios of Amba Dongar carbonatites show considerable variation (0.70549–0.70628), whereas most of the calcicarbonatites have similar initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios, the Pb-isotopic ratios of Amba Dongar carbonatites are somewhat higher in $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$. Similarly, low Sr isotopic composition and –ve ϵNd value indicate Newania carbonatite (rauhaugite) is derived from an old LREE enriched lithospheric mantle source, while others are product of magmatic fractionation of mantle derived nephelinitic magma [111]. A detailed Sr $\pm$ Nd $\pm$ Pb isotopic study of the carbonatites of Amba Dongar has suggested derivation of the parent magma from a long-lived elevated-Rb/Sr mantle source inherited from the Reunion $\pm$ Deccan plume like the flood basalts [19, 67, 157] (Figure 11). Young Peshawar Plain carbonatite complexes, which have unique isotopic characteristics in comparison with young (<130 Ma) carbonatite complexes of the world in that they have very negative ϵNd and positive $^{87}\text{Sr}/^{86}\text{Sr}$. However, Khanneshin carbonatite complex shows overall high degree of isotopic homogeneity. The averages include $^{206}\text{Pb}/^{204}\text{Pb}$ (18.814–18.877), $^{207}\text{Pb}/^{204}\text{Pb}$ (15.616–15.674) and $^{208}\text{Pb}/^{204}\text{Pb}$ (38.892–39.094); $^{87}\text{Sr}/^{86}\text{Sr}$ (0.708034–0.709577); and $^{143}\text{Nd}/^{144}\text{Nd}$ (0.512374–0.512462). Khanneshin carbonatite roughly suggest source combinations of enriched mantle, type EM I and HIMU. Its Sr isotopic data also highlighted the contribution of another source (EMII?) to account for the relatively high values of $^{87}\text{Sr}/^{86}\text{Sr}$ [62] (Figure 11A, C and D).

- (ii) In the carbonatite complexes of the subcontinent (and where Sr-Nd-Pb data is available), it is observed that two or more mantle components were involved in the genesis of these carbonatite magmas. The Sevathur, Koga, Sung, Amba Dongar, Peshawar and Khanneshin have HIMU as one of the components, whereas Eppawala, Sevathur, Koga, Peshawar and Khanneshin have involvement of EM-

I and Eppawala, Sung Valley and Amba Dongar have EM-II components. The later may be due to influence of mantle plumes. In addition to above, Koga and Jhambil carbonatites also show involvement of DMM component. The Eppawala carbonatites are unique in their radiogenic isotope characteristics in that they show involvement of both EM-I and EM-II components [32]. Similarly, for Khanneshin carbonatites possibility of involvement of third mantle component *i.e.* EM-II or ancient continental crust is also implicated [35, 62]. Sung Valley carbonatites suggest that pre-130 Ma Gondwana mantle had EM-II-type source characteristics, which gradually changed to EM-I-type after breakup as seen in younger products of Indian Ocean Plumes [19, 20, 22–24] (Figure 11).

- (iii) Carbonatites related to the Deccan Trap basaltic magmatism (Amba Dongar, Sarnu-Dandali and Mundwara) show radiogenic isotopes variations which were attributed to at least three of the following end-members: the asthenosphere, Indian MORB, old enriched continental lithosphere and the Reunion Plume mantle [19, 20].
- (iv) Carbonatites of Sevathur and related complexes (including Pakkanadu-Malakkadu) indicate mixing of two lead reservoirs. One of them can be characterized as a mantle component with low- μ and other with high- μ reservoirs. Newania carbonatites are also characterized by extremely high lead isotopic ratios [22]. Sr-Nd enriched mantle indicates interaction of two mantle components within and isotopically heterogeneous mantle of Sevathur carbonatites. One of them being even more enriched subcontinental lithosphere [22].
- (v) The Sr-Nd-Pb isotopic ratios of Koga and Peshawar Plain carbonatite complexes remain unaffected even after major tectonic disturbances such as transport of Indian plate from Africa to its present position and subsequent collision with Asia. These younger carbonatite ages suggest that the collision was older than 30 Ma in the Higher Himalayas [12].

13 Genesis of carbonatites

The carbonatite complexes of the subcontinent show spatio-temporal diversity, yet their combined study has revealed several fruitful results which are elaborated here. The carbonatites are believed to have crystallized either from a mantle-derived carbonatite magma or from secondary melts derived from carbonated silicate magmas

through liquid immiscibility or from residual melts of fractional crystallization of silicate magmas. Moreover, there is a small group of carbonatite occurrences that are considered to be formed by metasomatic reworking of the wall rocks or direct fractional crystallization from Ca-Sr-Ba bearing carbothermal fluids (the *carbothermal residua*) at relatively shallower depths [153, 158].

Majority of the carbonatites discussed here were shown to be of mantle origin (see sections 8 to 10 above). Srinivasan [159] believed that the carbonatite at Hogenakal represents high-temperature and deep-level intrusion of sub-volcanic origin; whereas, Natarajan *et al.* [17] envisaged that an ijolite magma may be parental to both pyroxenites and carbonatites. Pyroxenite represents intrusion of crystal mush formed by separation of pyroxenes from mela-nephelinite magma. Newania dolomitic carbonatite probably represents direct partial melting of the carbonated peridotitic mantle [33, 143]. Similarly, Sevathur calcio-carbonatites are also of mantle origin [22]. Ramasamy *et al.* [106] argued that the composition of parent magma for this complex is close in composition to that of shonkinitic magma, which might have been derived by liquid fractionation and separation from low degree of partial melt of mantle material. However, the unusual geochemical characteristics of Eppawala carbonatites prompted [32] to consider that the source material for this carbonatite was a carbonated eclogite and not peridotite as postulated in most of the carbonatite complexes.

In case of Koga, Loe Shilman and Sillai Patti carbonatites of Peshawar Plain, partial melting of carbonated mantle peridotites is proposed [160]. However, for Sung Valley carbonatites, Krishnamurthy [74] postulated that the carbonatite magma was derived by liquid immiscibility from a parent mela-nephelinite or alkali picritic magma. Subrahmanyam and Rao [101] believed that the carbonatite of Mer pluton, Mundwara alkaline complex was formed from the residual carbothermal fluids; whereas, Chandrasekaran and Srivastava [76] considered that the parent magma of Sarnu-Dandali carbonatites was separated into alkali silicate and carbonate magmas by liquid immiscibility. Overall, for the three carbonatite complexes related to Deccan magmatism, Ray and Ramesh [154] and Ray *et al.* [157] envisaged that the carbonatites were formed by fractional crystallization from CO₂-rich carbonate magmas, derived from parent carbonatite silicate magmas through liquid immiscibility.

Amba Dongar carbonatite complex has been most well studied and understood among the carbonatite complexes of the subcontinent. Viladkar [34] propounded the idea of primary calciocarbonatite magma for Amba Dongar carbonatites, which was initially more magnesian;

and during its evolution differentiated into two alvikites phases (I & II). Most of the other workers, however, considered that the original carbonated peridotitic magma has evolved through a combination of various processes such as magmatic degassing [66, 145]; liquid immiscibility [68] and fractional crystallization [100]; changing fO_2 conditions of magma [112]; and contribution of crustal contamination [58]. For Purulia carbonatites, Chakrabarty and Sen [56] preferred primary magmatic origin over low-temperature carbothermal fluids, keeping the issue 'open' for arguments.

It is indeed very interesting to note that there are carbonatites and carbonatites, as we categorize them: (i) primary mantle derived calcitic and dolomitic carbonatites, which commonly plot within primary magmatic carbonatite box of Keller and Hoeffs [161]. These are often related to the mantle plumes and deep crustal fractures, *e.g.* Amba Dongar, Newania and Sung Valley; (ii) those that are fractionates of the primitive (mantle derived) magma during later stages. These are often ankeritic and sideritic in composition and generally surrounded by a well-developed zone of fenitization and formed in an extensional regime, *e.g.* Hogenakal, Sevathur, Eppawala and Koga; and (iii) those that are formed by low P-T carbothermal fluids emplaced at shallow crustal levels and cooled rapidly. They could be formed at compressional as well as extensional tectonic regimes, *e.g.* Loe Shilman, Sillai Patti and may be Purulia.

14 Economic mineral deposits

Carbonatites are major source of Nb, phosphate and rare earth elements (REE); important ore minerals being ancylite, bastnaesite type minerals, britholite, crandallite-group minerals and monazite. Well known ore deposits related to carbonatites include Cu, Nb, REE, Mo, fluorite, apatite and vermiculite. In addition certain complexes also contain significant resources of other elements such as Zr, Fe, Ti, V, F, Na, Sr, Th and U, some of which can be a main or co-product [10, 162, 163]. Among the studied carbonatite occurrences apatite and rock phosphate forms most significant ore deposits in Loe Shilman, Sillai Patti, Khaneshin, Newania, Sevathur, Eppawala and Purulia; closely followed by REE-Nb-Ta mineralization or mineralization-potential at almost all localities where pyrochlore, bastnaesite and monazite minerals are reported in significant concentrations (see Table 1). In addition, magnetite-titanomagnetite, zircon and vermiculite deposits are also

known. A saga of hydrothermal fluorite mineralization at Amba Dongar is well known.

Currently active mines include vermiculite at Sevathur, apatite-rock phosphate mines at Loe Shilman and Epawala; and fluorite mine at Amba Dongar. Other smaller mines and quarries are also operational. First carbonatite hosted REE deposit in India has been recently established [164], whereas ~1.29 Mt REE deposit has been proved at Khanneshin [35].

The Khanneshin carbonatite complex consists of major REE deposits with LREE enriched zone occurring in two styles of REE mineralization: Type 1 Semi-concordant bands and veins in alvikite has 218 Mt deposit @2.77% LREE. Type 2 Discordant dykes and sheets enriched in F or P with 15 Mt deposit @3.28% LREE [35]. Saranu in Rajasthan is one of the only known significant carbonatite deposit within India before 2013, that carries notable concentrations of LREE and contains $\geq 5.5\%$ REO [165, 166]. Bhushan and Kumar [164], discovered a new deposit at Kamthai, Barmer district, in Rajasthan (very close to the Saranu deposit), which is the first carbonatite-hosted REE deposit containing the highest LREE grade of 17.31 wt% and a weighted average grade is 2.97 wt% LREO with a total volume of 1,38,428 tonnes. The main REE minerals hosted by this plug are bastnaesite (La), bastnaesite (Ce), synchysite (Ce), carboternaite (Ce), verianite (Ce), ancylite and parasite [164, 166, 167]. Surface exploration of Sung Valley carbonatite reveals an enrichment of LREEs with average $\sum$ REE value of 0.102% in 26 Bed Rock Samples, whereas, average $\sum$ REE values of 0.103 wt% reported from channel samples. Moreover, few samples from carbonatite bodies has indicated relatively higher values for Sn, Hf, Ta and U [168]. Other than above known deposits in the Indian subcontinent, other carbonatite complexes also have significant amount of REE mineralization, but they have not been qualified as the potential ore deposits.

A Significant quantity of apatite occur within Newania, Kutni-Beldih or Sevathur. A probable reserve of 1.2 million tons of vermiculite exists in Sevathur complex [169]. Basu [83], has estimated 12 Mt ore with 11% of P_2O_5 up to a depth of 30 m in the Kutni-Beldih. The apatite deposit of Loe Shilman carbonatite, Pakistan is consist of 59 Mt @ 4.4% P_2O_5 at surface; 142 Mt @ 5.5% P_2O_5 subsurface with 200m depth [170]. The preliminary surface exploration at Sillai Patti, suggest 200 ppm of uranium and 3% to 4% of P_2O_5 ore deposit, which was further upgraded upto 3% of U and 3% to 30% of P_2O_5 [171]. In some complexes apatite gets enriched in the residual soil either due to weathering or developed fairly thick lateritic cover [163]. The Sevathur soil contains up to 2.40% apatite [105], while Sung Valley area bulk soil samples contain up to 65% apatite [172]. Re-

serves of up to 10 Mt have been estimated up to a depth of 10 m with an average grade of 35% P_2O_5 [163].

Many Indian carbonatite occurrences contain pyrochlore in considerable concentrations though no workable economic deposit has been reported so far. Viladkar and Ghose [138] reported highly uraniferous pyrochlore (U_3O_8 20 to 22%) from the Newania carbonatite, similar to the Sevathur carbonatite [98]. The Sevattur carbonatite complex was explored in early 1970s to search for potentiality of Nb in pyrochlore, which mainly occurs in rauhaugite [115]. The pyrochlore occurred within early generation sovite unlike to most of other carbonatite complexes in the Indian Subcontinent. It contains 23.8% U_3O_8 in the Pyrochlore [98] and about 360 tons of Nb_2O_5 reserves have been proved over a strike length of 500 m and 250 meters depth [173]. Banerjee *et al.* [174] also analysed the 1.60% pyrochlore concentrates from Sevathur carbonatite that shows up to 29.4% $(Nb \pm Ta)_2O_5$ and 8.7% U_3O_8 [175–177]. The Sung Valley carbonatite hosts high Nb pyrochlore. Similarly, good concentrations of Nb were also found in the overlying soil horizon [139]. The residual soil cover in Sung Valley contains about 1300 tons of Nb spread over ~5 km² with 1 meter depth persistence amounting to 6.75 million tons of Nb ore with 0.02% Nb_2O_5 [175–177] and these pyrochlore are thorium-rich type (8.50% ThO_2) with less uranium (2.20% U_3O_8). In Samchampi Complex residual soil indicated 10970 tons of Nb_2O_5 [172]. In the Amba Dongar carbonatites pyrochlore occurs much more abundantly [67], but do not form economically mineable quantity [137]. The preliminary results on niobium contents in the panned concentrates of heavy minerals in north of Amba Dongar indicates up to 0.1% Nb_2O_5 [70]. In comparison to the well known Amba Dongar complex, not much work has been done on the Siriwasan carbonatite, which need some attention to access its economic potentiality. The above evidences provide the clue for further search to explore and evaluate the Nb potential of this extensively soil covered area.

The Amba Dongar carbonatite complex hosts one of the largest fluorite deposits of the world with reserves of 11.6 million tons of ore averaging 30% CaF_2 [178]. Fluorite occurs along the outer periphery of the sovite ring dyke as hydrothermal quartz-fluorite veins [70, 100, 179, 180]. A small deposit of (c. 1000 tons) fluorite was discovered at Hingoria [181] hosted in brecciated, calcareous and silicified rocks with suspected carbonatitic affinity [70].

Other carbonatite-hosted mineralizations in Indian subcontinent are also known, but economically less-significant quantities, e.g. 1 to 5% of barium occurs in Amba Dongar can become an important co-product with fluorite [67], Barite in the carbonatites of Pakkanadu can

also be a co-product with monazite. The presence of molybdenum within quartz-barite veins of Alangayam and Kurichi in the syenite-carbonatite association, northern Tamil Nadu [182] may be studied in detail to ascertain its economic importance. The uranium and thorium mineralization appear to be poorly developed in most of the carbonatites of the Indian Sub continent. Such feature may, at least in part, be attributed to the partitioning of uranium and/or thorium in the pyrochlore [70].

In many complexes such as Sevathur, Sung Valley, and Samchampi, magnetite-rich bands and pockets are found either solely or associated with apatite. In Samchampi complex, fairly large bodies of hematite rock (up to 3 km × 2 km) forming stock-like bodies occur. These are mainly composed of Ti-hematite after martitization of the original magnetite. Based on surface outcrops and assuming a depth persistence of 100 m a reserve of c. 300 million tons of Ti-hematite ore has been estimated [172].

In summary, the carbonatites of the Indian carbonatites shows diversity in every aspect. For the enthusiasts and lovers of carbonatites, the Indian subcontinent provides a unique opportunity to study this diversity.

Dedication: We dedicate this paper with reverence to our guru L. G. Gwalani. It is our heartfelt gratitude towards a teacher to who introduced us to the academic research. He advised KRR to write a review of Indian carbonatites, following which KRR prepared the manuscript extending the review to the carbonatite localities covering Indian subcontinent. Although Gwalani thought of contributing to this manuscript, he could not do so due to his deteriorating health. Subsequently, he succumbed to death leaving his legacy of research on carbonatites and alkaline rocks to the students like us. It is unfortunate that he could not see the publication of this review, but we are happy that we could make his wish come true.

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