

Carbonatite Occurrence in Ambaji-Sendra Belt of NW Indian Shield: Evidence of Carbonatitic Magmatism in the Subduction Setting

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Abstract

The paper represents a new discovery of a late Mesoproterozoic lenticular and discontinuous, carbonatitic body exposed at Basantgarh, Sendra and near the Abu-road area of the Ambaji-Sendra belt of the South Delhi Fold Belt. It is medium to coarse-grained and light to dark coloured compact rock. The common associates of the carbonatitic rock are felsic rocks, rich in alkalis. Carbonatite contains more than 50% carbonate minerals, the majority of which are calcite, dolomite, ankerite, augite-aegirine augite and plagioclase. It is classified as calcite carbonatite of the sövite variety due to its coarse-grained character, chemically as calcio-carbonatite and magnesio-carbonatite and even as silico-carbonatites for having more than 20% SiO₂. The ΣREE contents of calcio-carbonatite samples are nearly 100 times greater than magnesio-carbonatite. Chondrite normalised REE profiles of calcio-carbonatites are LREE enriched with nearly flat HREEs whereas the magnesio-carbonatite is characterised by flat REE patterns. The mantle-normalized incompatible trace element spidergram of Ambaji-Sendra belt carbonatites shows distinct negative anomalies of Ba, Nb, Ta, P, Sm, Eu, Ti and Y and positive at U and Pb by calcio-carbonatite whereas the magnesio-carbonatite displays negative kinks at K, Zr, Nb, Ta and Ti and positive at Th, Pb and Sr. The variable and/or contrasting enrichment/depletion in various elements in the two types of Ambaji-Sendra belt carbonatite is attributed either to significant differences in the type and modal proportion of different accessory mineral species or selective incorporation of metasomatic fluids during the subduction process. The chemical attributes of Ambaji-Sendra belt carbonatite suggest its emplacement in subduction settings.

Keywords

Aravalli Craton, Ambaji-Sendra Belt Precambrian Carbonatite, Subduction

Setting

1. Introduction

Carbonatite-rich magmatic rocks were first recognized by Högbom [1] from the Alnö Island alkaline-carbonatite complex of Sweden. However, the name “carbonatite” was first used by Brogger [2] for such magmatic rocks. Since then, there have been numerous and extensive discoveries of carbonatites across the globe [3] [4] [5] [6] [7]. The discovery of such rocks with anomalous mineralogy in India from Lower Narbada Valley is credited to [8]. Comprehensive reviews of carbonatite occurrences in India and subcontinent have been undertaken by various workers, e.g. [9] [10] [11] Paul *et al.* (2020), etc. More than 60 carbonatite-alkaline complexes have so far been reported from India, which are classified into two groups: subvolcanic-volcanic complexes and plutonic complexes [12]. Whereas on the basis of the ages and regional occurrence, a 3-fold division is proposed *i.e.* Precambrian (2400 - 700 Ma) mostly confined to southern Indian shield, Early Cretaceous (107 - 105 Ma) of North-Eastern (NE) India and Late Cretaceous (68 - 65 Ma) of North-Western (NW) Indian shield. Studies suggest the temporal formation of carbonatites in India viz. 1) 2533 to 2340 Ma, 2) 1510 to 1242 Ma and 3) 833 to 572 Ma, impacted by two metamorphic events (950 - 930 Ma and 570 - 485 Ma), synchronous to Grenvillian and Pan-African orogenic events [11]. It is interesting to note that the majority of Precambrian alkaline/carbonatitic magmatism is concentrated in the southern Indian shield, few in eastern shield and none except one in western shield, though western Indian shield is enriched in Late Cretaceous carbonatitic complexes, e.g. Amba Dongar, Mer-Mundwara, Sarnu-Dandali-Kamthai.

We report a late Mesoproterozoic carbonatitic body, lenticular and discontinuous, exposed at Sendra, Basantgarh, and near the Abu-road area of the Ambaji-Sendra belt (**Figure 1**, **Figure 2**). It is a medium to coarse-grained, light to dark-coloured, compact rock (**Figure 3**). Till date, ubiquitous consanguineous undersaturated alkaline rocks have not been recognized within or adjacent to the present rock. The common associate of this carbonatitic rock is felsic rocks, rich in alkalis (but not alkaline, personal data). There occurs an alkali syenite body near Deri, in the southern part of the Ambaji-Sendra belt [13], without any fenitized aureole, which precludes the possibility of being cogenetic. [14] also reported a carbonatite-type rock along with a few apparent fenites from the northern part of the Ambaji-Sendra belt. This suspected carbonatite was reported to be in intimate association with basic volcanics.

The presence of prosperous horizons of calc-silicates and marbles often pose difficulty in distinguishing the magmatic calcareous rocks from carbonate-rich metasediments [7]. Probably, it was the reason which led to interpret this carbonatite as calcareous inter-trappean [15], or component of turbidite sequence

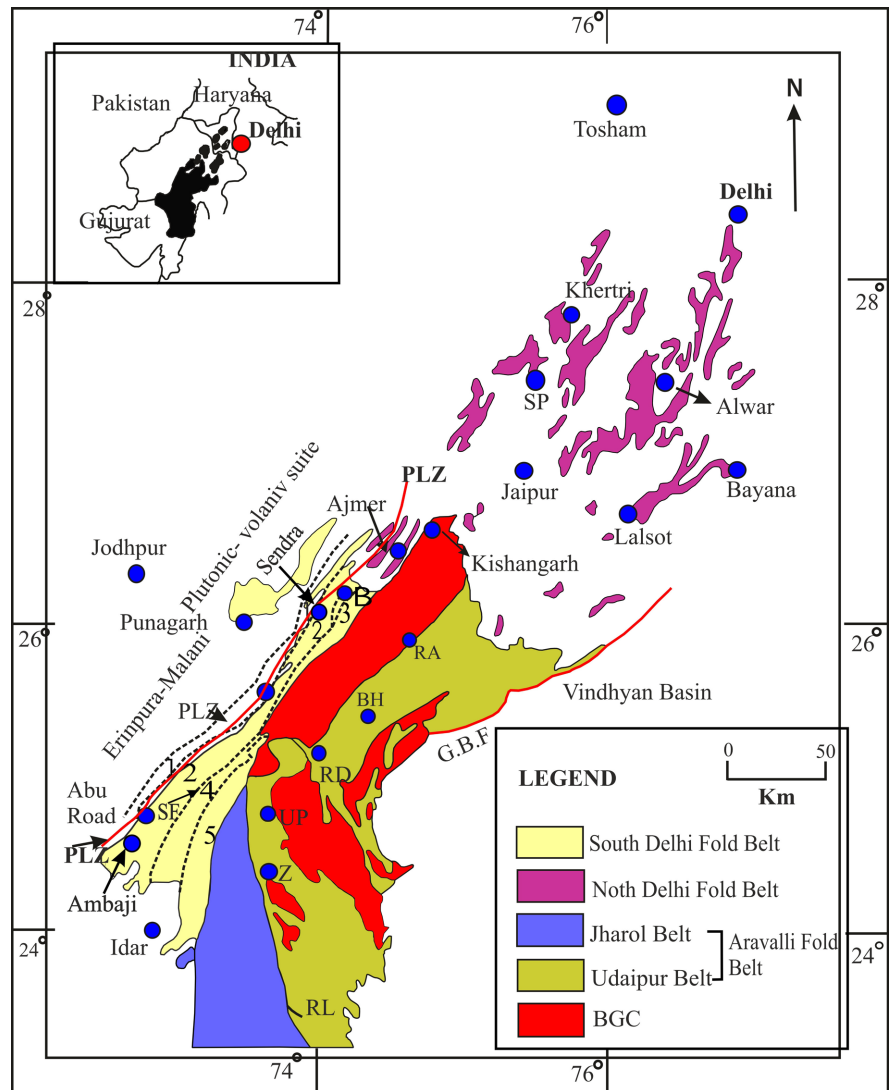


Figure 1. Simplified geological map of Aravalli-Delhi orogenic belt (after Heron 1953 & Gupta *et al.*, 1980), 1 - 5 longitudinal tectonic zones of Sen (1980). Index: B: Beawar; BH: Bhilwara; GBF: Great Boundary Fault; UP: Udaipur; RL: Rakhabdev Lineament; RA: Rampura-Agucha; RD: Rajpura-Dariba; SF: Sabarmati Fault; SP: Saladipura; Z: Zawar, PLZ: Phulad Lineament Zone.

as carbonate blanket on island arc flank [16] being in juxtaposition with basic volcanics of Phulad ophiolite [17] [18], particularly in the Sendra region, or as Kumbhalgarh calcgneiss [19]. The systematic petrographic study of this calcareous body in conjunction with its SEM and EDX-spectrums analyses as well as chemical analyses enabled us to ascertain its magmatic character and in turn, its recognition as a carbonatite body.

2. Regional Geology

The NW Indian shield preserves complete rock record of Precambrian age. The Aravalli Mountain Range (AMR) is the principal physiographic feature of AMR, extending from Delhi to Ahmedabad for over 700 km with variable thickness (20

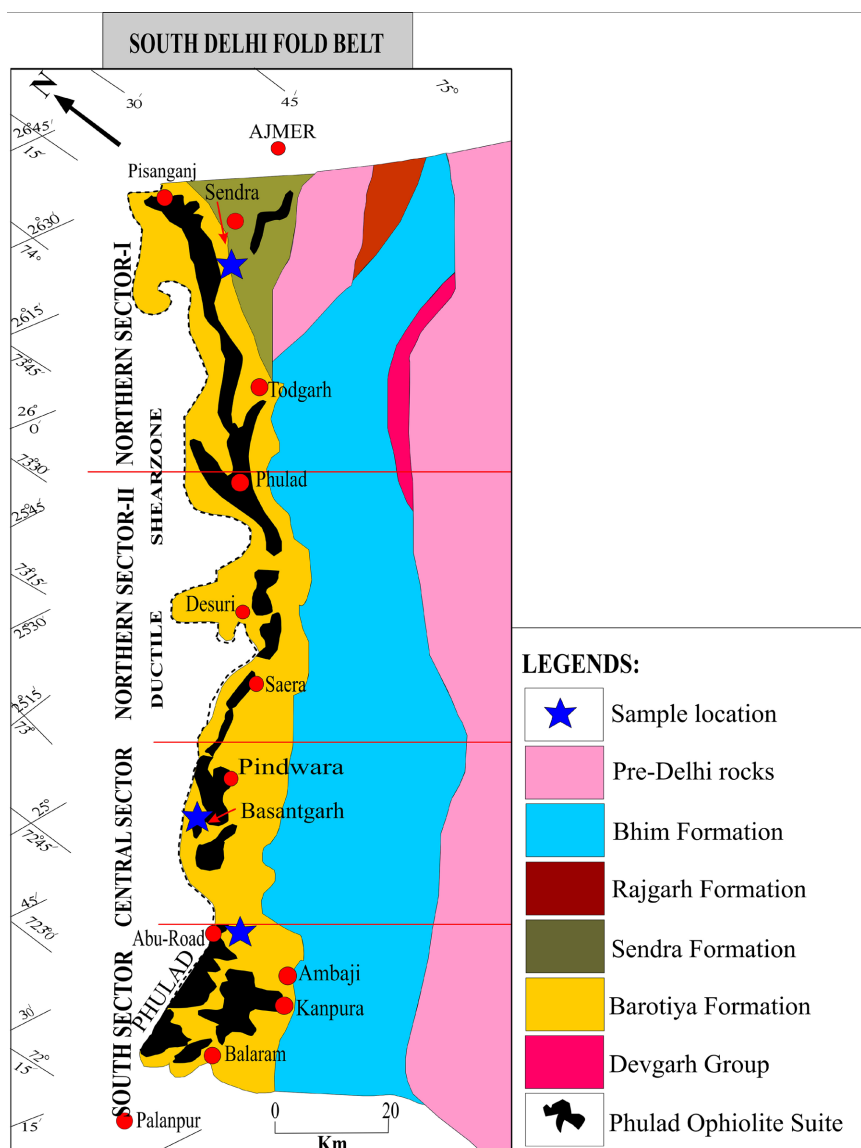


Figure 2. Simplified geological map of South Delhi Fold Belt (after Gupta *et al.*, 1991) showing sampling locations of Ambaji-Sendra belt carbonatite.

to 250 km) and NE–SW strike [20]. In terms of lithological make-up, AMR consists of an Archaean basement and two main unconformity-bound supracrustal sequences [17] [21]. Heron named the basement as Banded Gneissic Complex (BGC) on the basis of banding character of its gneisses. BGC (3300 Ma, [22] is predominantly an intimate admixture of igneous and meta-igneous rocks. The supracrustals, namely Paleoproterozoic Aravalli Supergroup and Mesoproterozoic Delhi Supergroup, rest unconformably over BGC [23] [24].

Lithosequence of Aravalli Supergroup is exposed in Udaipur belt (shallow water facies) and Jharol belt (deep water facies) (Figure 1). Similarly, Delhi Supergroup is also outcropped in two belts viz. North Delhi Fold Belt (NDFB) and South Delhi Fold Belt (SDFB). There is striking dichotomy in the geotectonic evolution of Delhi Supergroup [25].

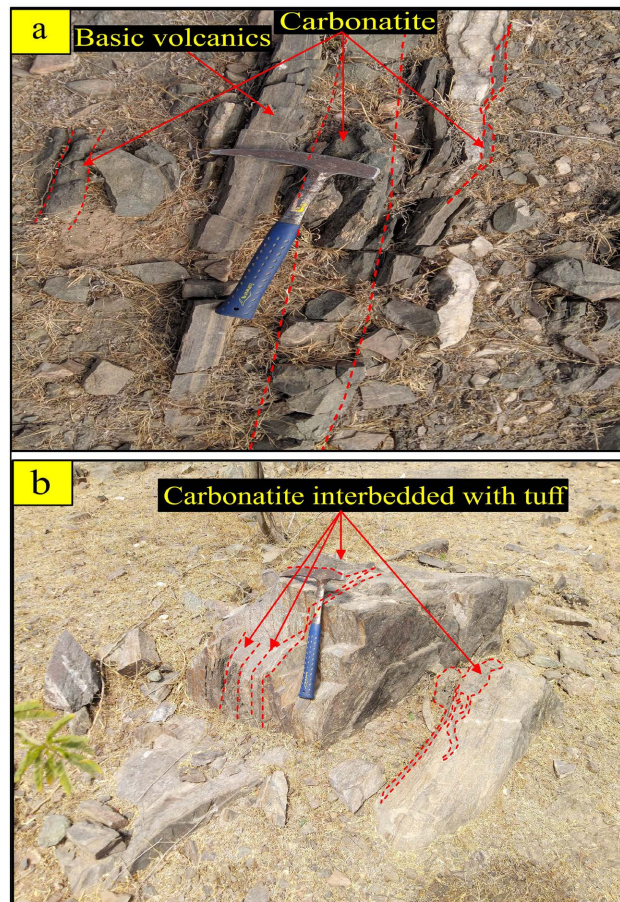


Figure 3. Field photographs of carbonatite: (a) Carbonatite associated with basic volcanics; (b) Carbonatite interbedded with volcanic tuff.

SDFB, is an ensemble of at least five tectonic units telescoped into each other through multiple structural and deformational events [26], and thus there is no consensus on any classification scheme [17] [18] [20] [26] [27] [28], recognized five longitudinal tectonic zones (from west to east) within the SDFB, each with considerable lithologic differences and proposed that the Delhi Supergroup should be restricted to the nearly consanguineous first three tectonic zones and zones 4 and 5 as pre-Delhi to post-Aravalli in age (Figure 1). In lieu to the Sen's observation, [29] established that SDFB is a subduction complex preserving rift-fill, trench and ophiolitic mélange sequences from west to east. Furthermore, they suggested that Sen's zones, 1 and 2 constitute the youngest part of SDFB, to which they named as Ambaji-Sendra terrain/belt of ~1.0 Ga age. This belt continuously runs for more than 200 kms between Ambaji in the south and Sendra in the north (Figure 2). Major lithologies of this belt are mafic volcanic rocks with significant proportion of felsic volcanics and metasediments.

A thin discontinuous linear carbonatite body has been discovered from Ambaji-Sendra belt of NE Rajasthan, which is located in close proximity of Phulad shear zone. This body occurs as a marker horizon between mafic and felsic volcanics of Ambaji-Sendra belt (Figure 2). The thickness of carbonatite outcrop

narrowly increases from south to north. The carbonatitic body is dark in colour and medium to coarse grained. Despite the complex structural state of the belt, the carbonatite seems to be an intrusive lithology suggesting its emplacement is related to the splay of Phulad shear zone.

3. Materials and Methods

Unweathered to least weathered samples, collected from Sendra, Basantgarh and near Abu-road area of Ambaji-Sendra belt were taken for the geochemical and Scanning Electron Microscope (SEM) analysis after their thin section screening. Chips from the samples were powdered in an agate mortar. The powder was finally sieved through a 200 ASTM mesh. The major element analysis has been carried out by X-Ray Fluorescence (XRF) Spectrometer (Axios, PAN analytical) and trace element analysis by high resolution Inductively Coupled Plasma Mass Spectrometer (HR-ICP-MS; Nu Instruments Attom, UK) in the geochemical lab of the CSIR-NGRI, Hyderabad. Powders used for XRF analysis were previously heated in a muffle furnace to 950°C for two hours to remove sample volatile contents. The XRF was calibrated using USGS standard. To analyse trace elements concentration of rock samples, solution was prepared by using the closed digestion method. Powdered rock sample of about 50 mg was dissolved in savillex vessels containing 10 ml acid mixture of HF:HNO₃ in a 7:3 ratio and kept on a hot plate at 150°C for 48 hours. After complete digestion, 2 - 3 drops of perchloric acid (HClO₄) was added and the entire mixture was evaporated to dryness. Ten milligrams of 1:1 HNO₃ was added to each savillex vessel containing residue and kept on a hot plate at ~80°C for 10 - 15 min. In the clear solution, 5 ml of Rh (1 ppm concentration) was added as an internal standard and made into 250 ml. Five millilitre of this solution was further diluted to 50 ml to prepare the final solution. Certified reference material SHARM-40 was run as standard to check the reproducibility. The instrumental techniques and data acquisition parameters are the same as given in Balaram and Gnaneshwara (2003). The precision and reproducibility obtained are better than 5% for trace elements (Satyanarayanan *et al.*, 2014).

Apart from microscopic examination of the carbonatite at the Department of Geology, AMU, Aligarh, its SEM study was undertaken at CSIR-NGRI, Hyderabad by Hitachi, S-3400 N Scanning Electron Microscope (SEM) with a linked EDS X-ray analysis system. The identification and imaging of the minerals were done by Backscattered Electron (BSE) images.

4. Nomenclature

The IUGS scheme of classifications defined carbonatite (*sensu stricto*) as an igneous rock comprising more than 50% primary modal carbonates including calcite, dolomite, ankerite, siderite and magnesite and less than 20% SiO₂ [5] [30] [31] [32]. In view of large variations in mineralogy and in turn in the chemistry of the carbonatites, Mitchell [6] [33] redefined carbonatite (*sensu lato*) as an igneous rock possessing greater than 30 vol.% primary igneous carbonate without

any conditional silica concentration. Varieties of carbonatite are named on the basis of either their bulk composition [32] as calcio- or calcite carbonatites, magnesio-carbonatites, ferro-carbonatites and silico-carbonatites or texturally as sövite or alvikite. The Ambaji-Sendra Belt Carbonatites (ASBCs) may be classified as calcite carbonatite of sövite variety due to its coarse-grained character (Figure 3). Chemically, this carbonatite body is classified as calcio-carbonatite and magnesio-carbonatite because its samples plot in these fields in the CaO-MgO-(FeO + Fe₂O₃ + MnO) diagram (Figure 4) [32]. In the molar proportions-based classification, recommended by Gittins and Harmer [33], the status of calcio- and magnesio-, remains unchanged. Since SiO₂ content in all the samples is more than 20%, these can also be referred to as silico-carbonatites.

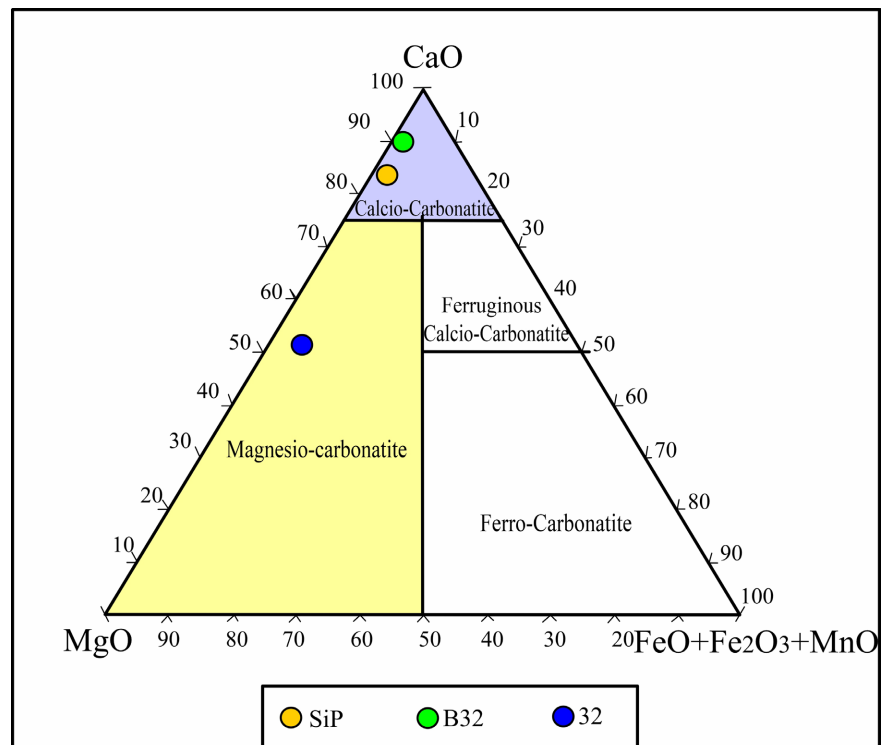


Figure 4. CaO-MgO-(FeO + Fe₂O₃ + MnO) diagram (Woolley & Kempe, 1989) of Ambaji-Sendra belt carbonatite classifying it as calcio-carbonatite and magnesio-carbonatite.

5. Mineralogy

Under polarizing microscope, the carbonatite, under study, contains more than 50% carbonate minerals, majority of which are calcite (Figure 5). Dolomite, ankerite, augite-aegirine-augite and plagioclase are present in minor amounts both as coarse grains as well as phenocrysts enclosed in calcitic groundmass. SEM and EDX, analyses indicate the presence of following minerals and chemical variations within the carbonatites of Ambaji-Sendra belt.

Calcite (CaCO₃): Calcite grains are dominant in microphotographs of thin section (Figure 5(a)) with their rhombohedral cleavage under plan polarizing light. Crystals of calcite grains are also visible with minor amount of quartz grain

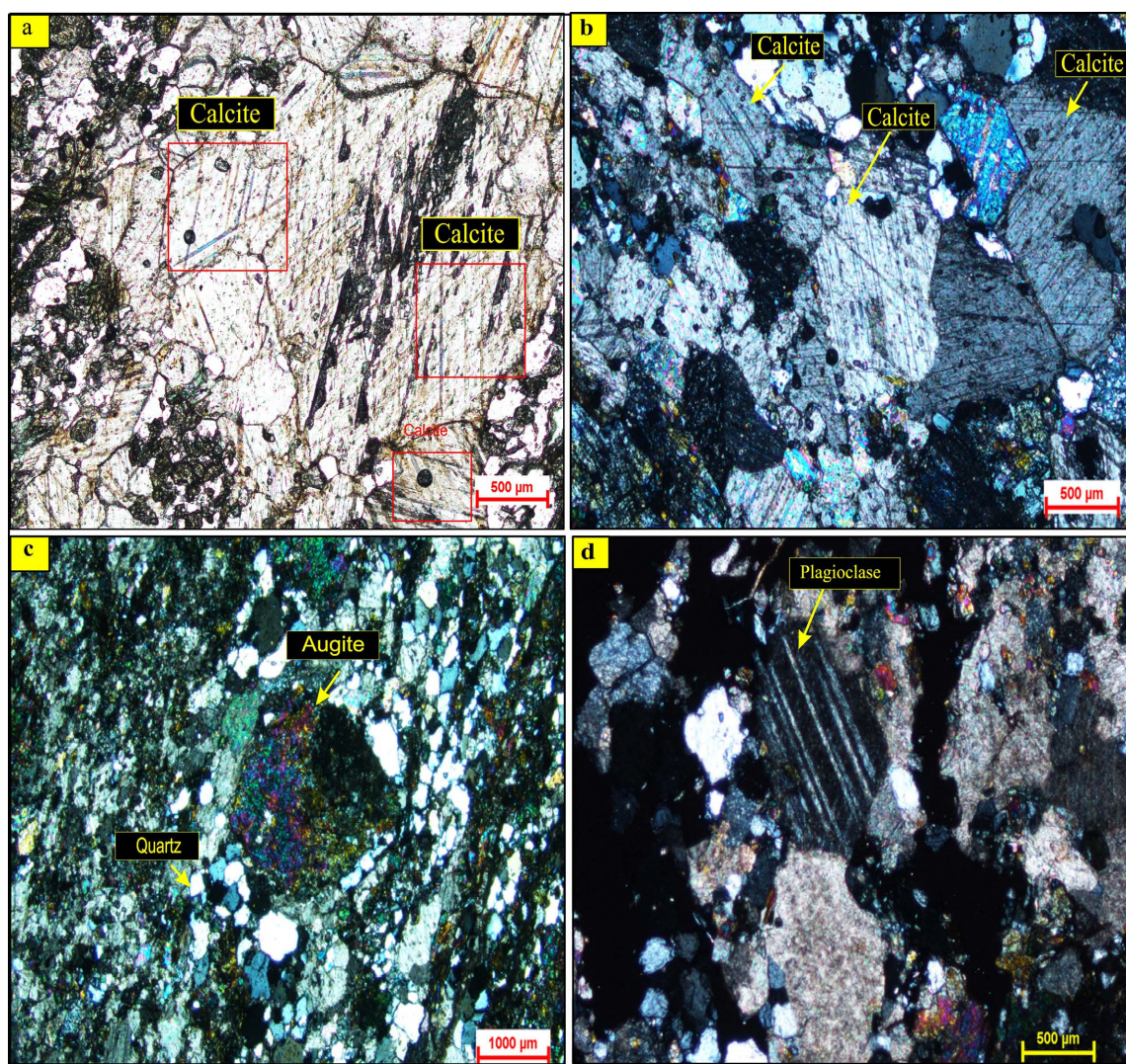


Figure 5. Microphotographs of Ambaji-Sendra Belt Carbonatite showing: (a) Calcite with its rhombohedral cleavage-PPL; (b) Calcite crystals-BCN; (c) Augite crystals surrounded by fine grained calcite and quartz-BCN; (d) Plagioclase grain with distinct lamellar twinning-BCN.

between crossed nicol (**Figure 5(b)**). The SEM-EDX analysis (facing page) consisting primarily of calcium supports thin section identification of calcite grain. Total 13 calcite grains were scanned by SEM (**Figure 6, Figure 7(a)**). Their EDS analysis indicates presence of minor amounts of Mg (probably part of the calcite), Fe (a solid solution precipitate, in the form overgrowth around calcite seeds) and Si and Al (probably from clay mineral inclusions within the calcite grains). Two analysed EDX spectrums of calcite suggest that it also occurs as inclusion within augite grain.

Authigenic Siderite (FeCO_3): The presence of siderite grains has been confirmed by SEM images (**Figure 6, Figure 7(b)**). Identification of the crystals as siderite is based on their rhombic habit and EDX spectrum (facing page) consisting primarily of Fe and a minor amount of Ca, Mg, and Mn. Minor contents of Si, Al and other elements in the spectrum is the contamination from adjacent grains.

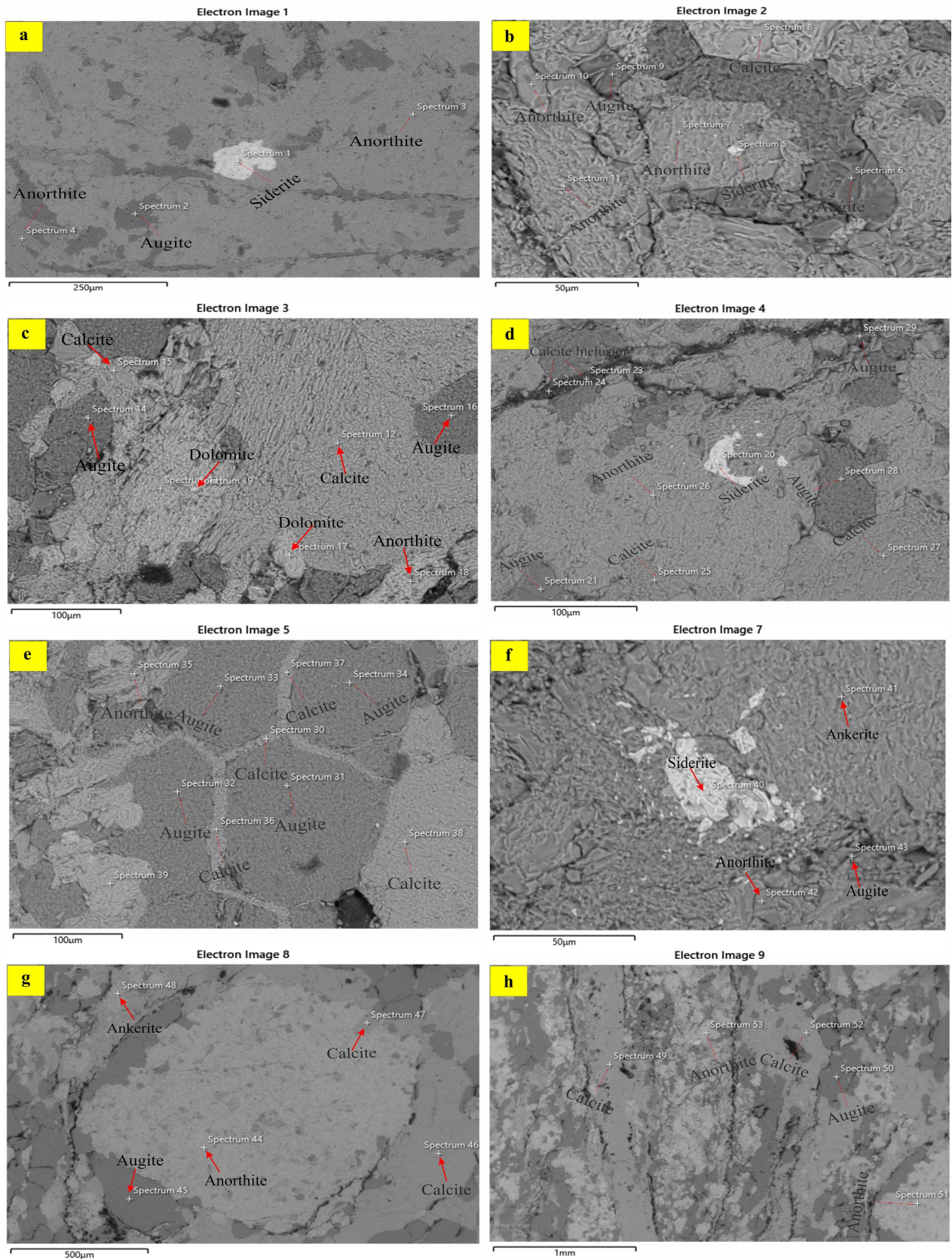


Figure 6. SEM images: (a, b, c, d, e, f, g) and (h) of carbonatite showing calcite, siderite, augite, anorthite, dolomite and ankerite grains.

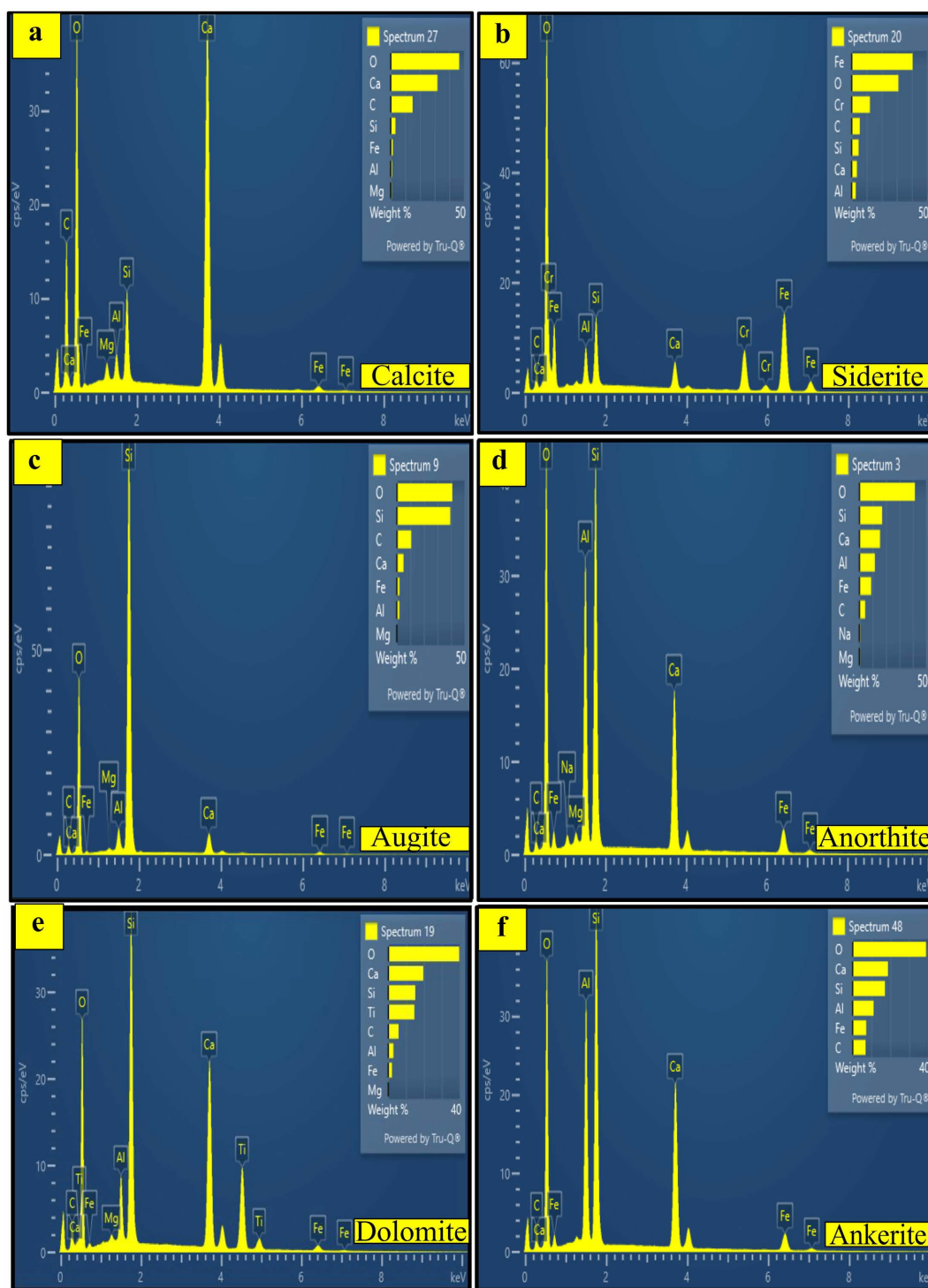


Figure 7. Representative EDX spectrums of the minerals of Ambaji-Sendra belt carbonatite.

Augite: $(Ca, Na)(Mg, Fe, Al, Ti)(Si, Al)_2O_6$: EDS analyses confirm the microscopic identification of augite surrounded by fine grained calcite and quartz (Figure 5(c)). There are 15 grains of augite recognised by SEM images (Figure 6, Figure 7(c)). The augite is primarily composed of O, Si, C, Ca, Fe and Al. Some EDS spectrum of augite also have very small concentration of Mg and Cr.

The heights of the peaks of various elements are consistent with the formula for augite.

Plagioclase Feldspar: Plagioclase grains with distinct lamellar twinning are clearly visible in thin sections (**Figure 5(d)**). 13 EDS analyses of plagioclase grain classify it as calcic-plagioclase mainly anorthite (**Figure 6, Figure 7(d)**). The anorthite $[\text{Ca}(\text{Al}_2\text{Si}_2\text{O}_8)]$ is primarily composed of O, Si, Ca (Na) and Al along with minor concentration of Fe and Mg as contaminants. The relative peak heights justify the calcic nature of plagioclase feldspar.

Dolomite-Ankerite: There are 4 EDX spectrums of these grains (**Figure 6**) consisting primarily of Ca, Si, Al, Fe, C, Mg and Cr. In one of the spectrums, Ti is also present in substantial amount. The relative peak heights of representative EDX spectrum of calc-silicate grains are consistent with the formula for dolomite $[\text{CaMg}(\text{CO}_3)_2]$ (**Figure 7(e)**) and ankerite $[\text{Ca}(\text{Fe, Mg, Mn})(\text{CO}_3)_2]$ (**Figure 7(f)**).

6. Results and Discussion

Geochemically, the samples of ASBC are high in CaO (20.89 to 38.92 wt%), Fe_2O_3 (2.71 to 6.01 wt%), P_2O_5 (0.06 to 0.12 wt%), and low in SiO_2 (23.50 to 40.27 wt%) content (**Table 1**). The mafic silicate and carbonate phases such as pyroxenes and or dolomite are added variable amounts of MgO ranging from 2.89 to 12.97 wt% in the chemical composition of these carbonatites. The calico-and magnesio-varieties of ASBC are chemically distinct in most of the elements. The magnesio-carbonatite is significantly enriched in SiO_2 , MgO, Fe_2O_3 and depleted in CaO, K_2O compared to the calico-carbonatite samples (**Table 1**). However, Al_2O_3 , TiO_2 and Na_2O contents are nearly same in both varieties. The high concentration of SiO_2 in ASBC reflects presence of silicate minerals including quartz in significant proportions (**Figure 5**).

Table 1. Geochemical analysis of Ambaji-Sendra belt carbonatite.

Locality	Near Abu-road	Sendra	Basantgarh
Sample. Code	SiP	B32	32
Sample No.	1	2	3
SiO_2	24.17	23.50	40.27
Al_2O_3	6.78	5.91	6.79
TiO_2	0.38	0.29	0.21
Fe_2O_3	3.61	2.71	6.01
MnO	0.04	0.05	0.16
MgO	4.07	2.88	12.97
CaO	36.29	38.92	20.89
Na_2O	0.13	0.47	0.57
K_2O	1.91	1.64	0.05
P_2O_5	0.06	0.07	0.12

Continued

LOI	5.76	2.14	11.80
SUM	77.42	76.44	88.04
SUM + LOI	83.18	78.58	99.84
Sc	7.44	6.65	21.12
V	43.79	61.75	138.16
Cr	13.07	12.10	437.07
Co	16.50	5.05	26.60
Ni	15.55	3.49	96.06
Cu	81.73	21.79	28.24
Zn	43.12	21.48	108.03
Ga	7.05	7.39	6.37
Rb	56.57	71.66	1.54
Sr	911.01	1259.36	251.12
Y	13.65	16.83	6.91
Zr	165.38	274.12	13.37
Nb	9.56	6.27	0.93
Cs	4.62	3.92	0.09
Ba	689.24	241.47	17.11
La	27.69	21.10	1.18
Ce	77.11	60.31	2.83
Pr	7.11	5.27	0.39
Nd	25.23	19.72	1.86
Sm	4.88	3.84	0.62
Eu	0.90	0.90	0.21
Gd	3.91	3.77	0.85
Tb	0.70	0.73	0.16
Dy	3.86	4.22	1.06
Ho	0.52	0.84	0.24
Er	1.31	2.42	0.69
Tm	0.23	0.41	0.11
Yb	1.45	2.45	0.75
Lu	0.22	0.40	0.12
Hf	6.38	7.97	0.44
Ta	0.66	0.98	0.05
Pb	72.56	4.64	4.79
Th	3.13	5.47	1.55
U	7.98	4.22	0.06

Similarly, the samples of calico-carbonatite are depleted in transition trace elements but enriched in large ion lithophile and high field strength elements compared to magnesio-carbonatite. It suggests that the melts of calico-carbonatites were fractionated before crystallisation, while magnesio-carbonatite melt underwent little or no fractionation [34]. The calico-carbonatites also possess higher contents of Zr, Nb, Th and U compared to magnesio-carbonatite.

The Σ REE contents of calico-carbonatite samples are 155.12 ppm and 126.37 ppm, whereas that of magnesio-carbonatite is 11.07 ppm (Table 1) Furthermore, chondrite normalised REE profiles of calico-carbonatites are LREE enriched $[(La/Sm)_n: 3.7 - 3.5]$ with modestly fractionated or nearly flat HREEs $[(Gd/Yb)_n: 2.2 - 1.3]$. The magnesio-carbonatite, on the other hand, is characterised by flat REE patterns $[(La/Yb)_n: 1.1]$ (Figure 8). None of the samples of ASBC shows significant Ce or Eu anomaly which indicates that these carbonatites are formed under less oxidizing conditions [35]. The LREE enrichment levels in calico-carbonatite are high compared to magnesio-carbonatite, but in general quite low as carbonatites are characterized by very high LREE, LREE/HREE ratio among all the igneous rocks [36]. This can either be due to the absence of REE-rich accessory phases or LREE mobilization during metamorphic alteration. In the PM-normalised spidergrams, calico-carbonatites show deeper kinks at P and Ti than magnesio-carbonatite. Thus, control of apatite and titanite on the abundance of REEs seems to be a viable possibility. And the role of REE accessories like pyrochlore and perovskite does not seem to be significant because they can influence the bulk rock REE pattern only if present in appreciable amounts [36]. The broadly similar REE patterns for ASBC, in particular HREEs, thus speak for variable modal proportions of mineral phases associated with common parent magma.

Trace elements which are considered robust tools for adding petrogenetic information of igneous rocks become less effective in carbonatite systems due to the reversal of the incompatible nature of various elements and the role of mineral

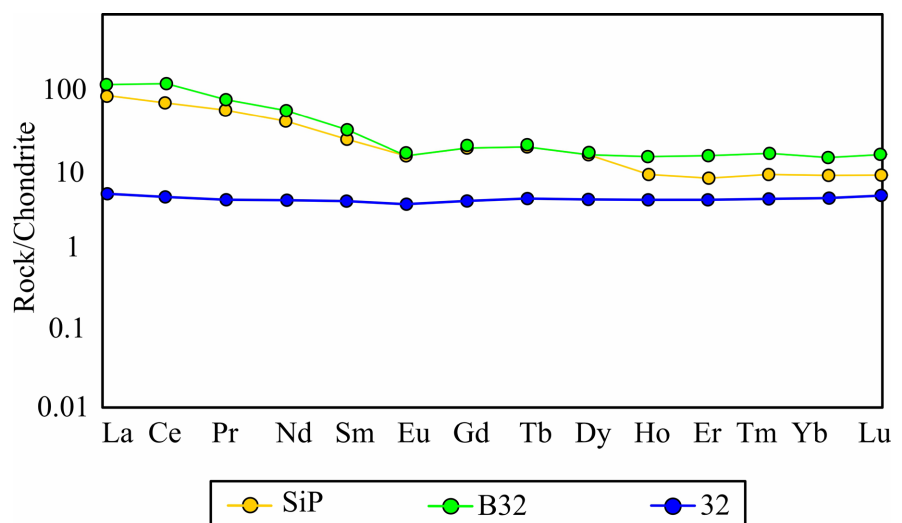


Figure 8. Chondrite normalized REE diagram of Ambaji-Sendra belt carbonatite. Normalizing values from Sun and Macdonough (1989).

settling, accumulation and veining in their genesis [37]. High to very high Ba and Sr contents coupled with a high Sr/Ba ratio *i.e.* more than 1 are peculiarities of carbonatites [38]. The Sr and Ba contents in ASBC are appreciably high and so is their Sr/Ba ratio which ranges from 1.3 to 14.7. The abundance of transitional trace elements (like Ni, Cr, Cs and V), despite being high in magnesio-carbonatite than calico-carbonatite, is in general of lower magnitude which indicates some degree of fractionation of the melts before crystallization.

Nb and Ta show strong coupling behaviour in most silicate igneous rocks but disengage in carbonatites due to immiscibility where Nb prefers silicate melts over its chemical affinity with Ta [39]. The mantle normalized Nb/Ta ratios in the ASBC are low (0.37 - 1.01) which eliminates the possibility of Nb enrichment and thus indicates a role of liquid immiscibility in the origin of ASBC [39]. The Zr enrichment (relative to Hf) indicates carbonate metasomatism in the mantle source [40]. In the ASBC, the $(Zr/Hf)_{PM}$ ratio is uniformly low (0.71 to 0.95) which speaks against Zr enrichment through mantle metasomatism.

The mantle-normalized incompatible trace element spidergram for ASBC (Figure 9) shows several depletions and enrichments, coherent with normal carbonatite trends [32]. Distinct negative anomalies of Ba, Nb, P, Sm, Eu, Ti and Y and positive at U and Pb are shown by calico-carbonatite plots. The spidergram of magnesio-carbonatite displays negative kinks at K, Zr and Ti and positive at Th, Pb and Sr. Enrichment in Th relative to Rb is a common feature of carbonatites as they normally have much higher Th abundance as compared to other igneous rocks. The magnesio-carbonatite is enriched in Th and calico-carbonatite in U compared to Rb and accordingly Th/U ratio is significantly high or low in respective varieties of ASBC. The high Th/U ratio generally indicates lithospheric mantle having got enriched in Th through metasomatism over the geological period [41] [42] [43]. The variable and/or contrasting enrichment/depletion in

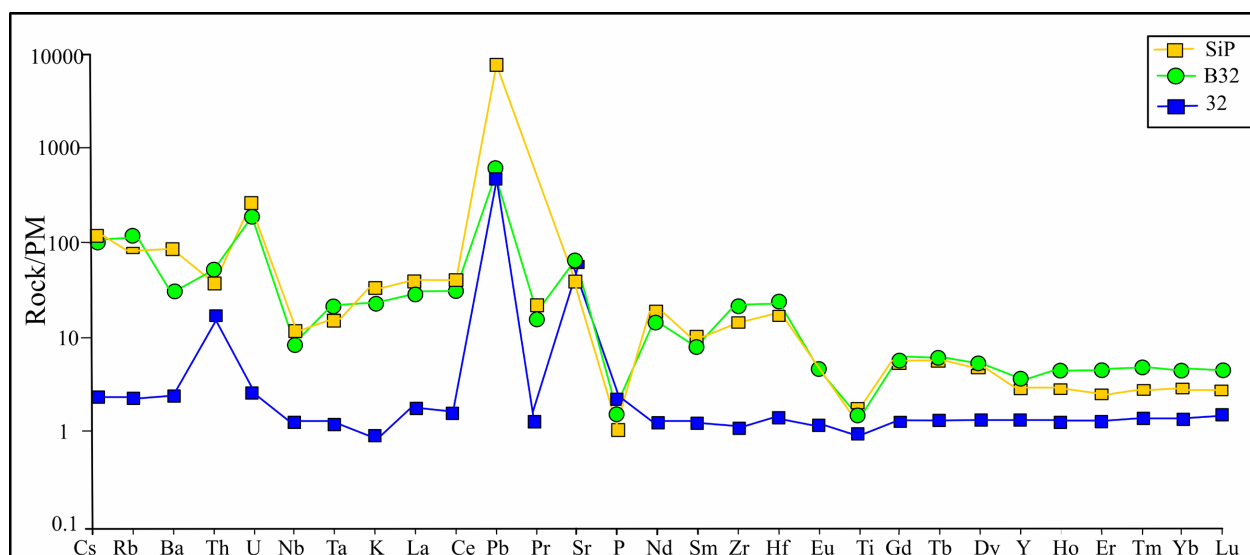


Figure 9. Primordial Mantle (PM) normalized spider-diagram of Ambaji-Sendra belt carbonatite. Normalizing values from Sun and Macdonough (1989).

various elements in the two types of ASBC does not prescribe two sources rather it can be attributed either to significant differences in the type and modal proportion of different accessory mineral species like pyrochlore, monazite and apatite [44] or selective incorporation of metasomatic fluids during subduction process [45] [46]. A consistent Nb-Ta trough in PM normalised spidergram of ASBC is the evidence of the role of the subduction mechanism [46].

The carbonatite melt origin is attributed to 1) immiscible separation of parental carbonated silicate magmas at crustal or mantle pressures [47] [48] [49]; 2) crystal fractionation of parental carbonated silicate magmas such as olivine melilitites or kamafugites [50] [51]; and 3) low-degree partial melting of carbonated mantle peridotite below 70 km depth [4] [52] [53] [54] [55] [56].

The geochemical features of ASBC (e.g. depleted contents of silica, Nb, Zr, Y, LILE, LREE) compared to other Indian carbonatites are suggestive of its origin through extensive liquid immiscibility wherein carbonatitic magma is separated from the carbonated silicate liquid [57] [58]. This magma suffered fractional crystallisation and loss of alkalis through fenitisation/or migration into associated felsic rocks which shows anomalously high alkalis (personal data) and thus becomes more Ca-rich. That also changed the trace element geochemistry of ASBC to become LREE depleted because LREE and LIL moved to associated rocks.

However, the absence of association of ASBC with an alkaline rock/pluton (melilitite, nephelinite, phonolite, trachyte or lamprophyre or kimberlite) refutes the possibility of a parent silicate melt or lamprophyre melt generated from melting of metasomatized mantle or asthenospheric kimberlite melt which could generate carbonatite through fractionation or liquid immiscibility. In this condition, the only possibility is that of direct generation of carbonatite melt from a metasomatized mantle, enriched by a previous subduction event. The presence of Mesoproterozoic Phulad ophiolite in the immediate vicinity is the testimony of such a subduction event (*i.e.* closure of south Delhi Ocean). Negative Eu anomaly (**Figure 8**) along with Pb enrichment (**Figure 9**) is the other evidence of a source modified by subducted sediments [41].

The older Newania carbonatite, located in Udaipur district, Rajasthan, part of NW Indian Shield, has also been suggested to have originated through direct partial melts from a metasomatized mantle [12] [59]. The isotopic data on carbonatites and associated alkaline silicate rocks from South Indian shield [60] [61] [62] indicated the existence of an enriched mantle source for Neoproterozoic carbonatites [44]. The genesis of ASBC also provides corroborative evidence for the presence of an older enriched mantle which was subjected to further enrichment by a younger subduction event.

The carbonatites are commonly associated with continental rifts, but they are also common in orogenic belts. In India, the carbonatites have been reported in different geological environments and structural configurations like Narmada and Trans-Aravalli rifts, Meghalaya Plateau, Eastern Ghat, Cuddapah basin, Aravalli rifts, as well as Western Ghat faults [12]. The ASBC adds a subduction set-

ting as the new habitat of Indian carbonatites.

The Indian shield is a collage of several discreet tectonic blocks with independent evolution histories and in turn lithological makeup. The amalgamation of these blocks created North and South Indian cratons, which got welded along a lineament (Narmada-Son-Brahmaputra lineament or the Central Indian Tectonic Zone, [63] during Mid-Proterozoic, and formed present-day Indian shield [64]. On the basis of preservation of the Precambrian lithotexture, this Indian shield is divided into south, east and northwest components. It is pertinent to mention here that Indian carbonatites show temporal distribution with respect to three parts of Indian shield. As stated earlier, the Southern Indian Shield (SIS) hosts Precambrian (2400 - 700 Ma), the North-Eastern Indian shield (NEIS) records early Cretaceous (107 - 105 Ma), and the North-Western Indian Shield (NWIS) preserves Late Cretaceous (68 - 65 Ma) carbonatites [9]. However, there occurs Paleoproterozoic Newania carbonatite (~2270 Ma, [65] [66] in NWIS also besides the one under study.

SIS contains two classic greenstone belts, 3.5 to 3.00 Ga and 3 to 2.5 Ga old. A large hiatus has been suggested after the formation of a younger greenstone belt which is evident from the fact that the 1.6 Ga old Proterozoic Nagari Quartzites unconformably rest upon the younger greenstone belt at Triputi. This period of non-deposition has been described as “Ep Archean” interval in the SIS [64] [67]. During this time span *i.e.* 2.5 to 1.6 Ga (Ep-Archean interval), NWIS witnessed large-scale volcano-sedimentary activity [68] [69]. However, a litho-comparison between SIS and NWIS reveals some peculiar differences. For example, MORB-type Archean peridotitic komatiites are abundant in SIS (Dharwar craton) but absent in NWIS (Aravalli craton) whereas scenario is reversed for enriched continental type Proterozoic basaltic komatiites [70]. Early Proterozoic magmatism of NWIS has been considered a manifestation of a transitional process between Archean greenstone and Phanerozoic continental suites [70]. These characteristics of two parts of Indian shield may also have bearing on other litho-components. In view of these facts, it is reasonable to compare ASBC with its contemporary carbonatites of SIS to glean information about their petrogenic antecedents. Gundlupet carbonatite [71] and Sevattur-Samalpatti carbonatites of Eastern Ghat Mobile Belt [44] are suitable candidates for comparison being in the approximately same age bracket.

In terms of CaO, ASBC (calico) finds its near chemical analogue from Sevattur, Pakkanadu and Samalpatti carbonatites whereas ASBC (magnesio) resembles with Samalpatti varieties. All other majors and/or trace elements of ASBC (both calico and magnesio) are either highly enriched (e. g. SiO₂, Al₂O₃, Fe₂O₃, MgO, Na₂O or K₂O) or severely depleted (nearly all trace elements) compared to their respective counterparts (Table 2). The carbonatite-fenite-like rocks, from the northernmost part of Ambaji-Sendra belt (location undefined), by Bose [14] broadly match in their CaO and trace elements with the respective varieties of ASBC (Table 2). This comparison suggests that the enrichment levels/magnitudes of various

Table 2. Average chemical composition of Ambaji-Sendra belt carbonatite compare with the carbonatites of same age.

Carbonatite Sample Code	Ambaji-Sendra Belt Carbonatite		Bose (1998)		Rakkiannan and Anbarasu (2019)	Brahma <i>et al.</i> (2022)		Pandit <i>et al.</i> (2002)		
	Basantgarh, Sendra Carbonatite		Phulad Carbonatite (Delhi Fold Belt)		Pakkanadu Carbonatite	Gundlupet Carbonatite		Carbonatite of Tamil-Nadu		
	Calsio.	Magnesio.	Calsio.	Magnesio.	Calsio.	Calsio.	Magnesio.	High-Calsio.	Low Calsio.	Magnesio.
	Avg.SiP & B32	32	Average		Average	Average	Average	Average	Average	Average
SiO ₂	23.83	40.27	14.67	53.57	1.56	3.67	62.63	2.60	12.28	25.13
Al ₂ O ₃	6.35	6.79	3.22	11.13	0.78	0.70	15.14	1.96	2.55	4.80
TiO ₂	0.34	0.21	0.22	0.64	0.45	0.07	0.21	0.23	0.00	1.31
Fe ₂ O ₃	3.16	6.01	0.62	1.28	2.12	2.89	3.51	3.75	3.74	9.39
MnO	0.04	0.16	0.06	0.12	0.62	0.50	0.13	0.23	0.70	1.96
MgO	3.48	12.97	2.51	4.61	4.30	1.55	1.29	2.34	5.83	7.88
CaO	37.60	20.89	40.51	16.75	44.90	50.34	3.49	48.97	35.23	18.99
Na ₂ O	0.30	0.57	0.56	1.52	1.78	0.21	4.07	0.31	0.81	3.19
K ₂ O	1.77	0.05	1.05	1.47	0.76	0.12	7.80	0.25	1.29	2.80
P ₂ O ₅	0.06	0.12	0.03	0.02	1.10	1.38	0.65	3.19	0.92	1.17
LOI	3.95	11.80	28.11	1.11	5.14	37.04	0.61	33.67	29.97	19.30
SUM	80.88	99.84	91.56	92.22	63.51	98.47	99.50	97.52	94.23	95.92
Sc	7.04	21.12	-	-	7.95	0.80	4.05	16.74	26.37	27.65
V	52.77	138.16	-	-	46.35	21.62	32.15	34.01	83.85	123.57
Cr	12.58	437.07	-	-	21.56	-	8.00	34.80	32.99	44.45
Co	10.78	26.60	-	-	8.94	-	-	29.49	28.15	28.31
Ni	9.52	96.06	10.40	25.53	21.22	19.50	12.00	19.83	32.99	31.72
Cu	51.76	28.24	-	-	9.54	19.67	9.00	32.68	63.19	291.11
Zn	32.30	108.03	-	-	34.03	50.60	92.00	116.65	1392.76	378.47
Ga	7.22	6.37	-	-	19.79	5.86	50.05	62.85	22.93	8.31
Rb	64.12	1.54	66.70	64.63	5.85	15.75	167.75	11.86	3.05	46.60
Sr	1085.18	251.12	1345.90	482.63	14912.48	8682.80	1934.90	9313.33	4850.00	2636.73
Y	15.24	6.91	13.40	18.13	32.96	119.00	29.85	134.10	86.12	41.38
Zr	219.75	13.37	-	-	25.66	87.10	227.95	34.95	6.56	30.48
Nb	7.91	0.93	4.73	6.49	13.23	11.50	15.50	8.07	3.77	57.86
Cs	4.27	0.09	6.70	37.13	0.15	-	-	16.73	0.08	0.25
Ba	465.36	17.11	289.60	221.30	19239.80	192.00	1592.00	1623.90	4811.74	7283.00
La	24.40	1.18	17.39	17.11	228.15	1299.26	152.60	1549.00	511.40	40.10
Ce	68.71	2.83	-	-	368.69	2576.74	343.75	1748.00	944.13	112.35
Pr	6.19	0.39	-	-	34.64	419.08	50.10	490.33	130.39	17.76
Nd	22.47	1.86	-	-	123.84	1695.84	208.70	827.00	617.57	95.82
Sm	4.36	0.62	-	-	17.86	46.24	8.25	274.12	118.20	23.82

Continued

Eu	0.90	0.21	-	-	8.70	210.80	37.05	51.27	37.98	8.62
Gd	3.84	0.85	-	-	12.48	12.44	2.40	90.16	72.01	18.29
Tb	0.71	0.16	-	-	1.48	113.12	20.35	25.66	6.91	2.15
Dy	4.04	1.06	-	-	6.43	44.26	9.15	35.63	31.15	11.43
Ho	0.68	0.24	-	-	1.08	5.84	1.25	12.84	3.97	1.64
Er	1.87	0.69	-	-	2.62	12.98	2.70	19.83	18.38	7.92
Tm	0.32	0.11	-	-	0.34	1.58	0.35	6.36	1.06	0.52
Yb	1.95	0.75	1.36	2.06	2.11	9.24	1.80	6.44	5.63	2.06
Lu	0.31	0.12	-	-	0.32	1.32	0.30	2.84	0.75	0.44
Hf	7.17	0.44	0.35	1.24	0.59	0.35	1.15	0.33	0.16	0.75
Ta	0.82	0.05	-	-	45.75	102.00	55.00	7.86	32.47	4.39
Pb	38.60	4.79	44.50	40.03	7.53	3.98	19.30	22.25	16.91	7.02
Th	4.30	1.55	6.34	12.37	1.56	13.88	180.90	3.99	1.21	2.39
U	6.10	0.06	1.10	1.36	-	10.00	12.00	8.62	-	-

Data Source: Phulad carbonatite (Bose, 1998), Pakkanadu carbonatite (Rakkiannan & Anbarasu, 2019), Gundlupet carbonatite (Brahma *et al.*, 2022) and Tamil-Nadu carbonatite (Pandit *et al.*, 2002).

elements in the mantle in NWIS were not similar to SIS. These differences were most probably caused by the incorporation of subducted sediments in the lithospheric mantle of NWIS.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Högbom, A.E. (1895) Über das nephelinsyenitgebiet auf der InselAlno. *Geologiska Föreningen i Stockholm Förhandlingar*, **17**, 214-256.
<https://doi.org/10.1080/11035899509442299>
- [2] Brögger, C. (1921) Die Eruptivgesteine des Kristianiagebietes. IV. Das Fengebiet in Telemarken, Norwegen. *Norske Vidensk. Akad. i Oslo, Skrifter, Mat.-Naturv. Kl.*,

No 9.

- [3] Heinrich, E.W. (1980) The Geology of Carbonatites. Reprint Edition, Krieger Plub Co., Huntington, 585 p.
- [4] Bell, K. (1989) Carbonatites: Genesis and Evolution. Unwin Hyman, London.
- [5] Le Maitre, R.W. (2002) Igneous Rocks: A Classification and Glossary of Terms. Cambridge University Press, Cambridge.
<https://doi.org/10.1017/CBO9780511535581>
- [6] Mitchell, R.H. (2005) Carbonatites and Carbonatites and Carbonatites. *Canadian Mineralogist*, **43**, 2049-2068. <https://doi.org/10.2113/gscanmin.43.6.2049>
- [7] Woolley, A.R. and Kjarsgaard, B.A. (2008) Carbonatite Occurrences of the World: Map and Database: Geological Survey of Canada, Open File 5796, 1 CD-ROM, 1 Map, Scale 1:20,000,000.
- [8] Bose, P.N. (1884) Geology of the Lower Narbada (Narmada) Valley between Nimár and Káwant. *Memoirs of the Geological Survey of India*, **21**, 1-72.
- [9] Krishnamurthy, P. (1988) Carbonatites of India. *Exploration and Research for Atomic Minerals*, **1**, 15-81.
- [10] Randive, K. and Meshram, T. (2020) An Overview of the Carbonatites from the Indian Subcontinent. *Open Geosciences*, **12**, 85-116.
<https://doi.org/10.1515/geo-2020-0007>
- [11] Paul, D., Chandra, J. and Halder, M. (2020) Proterozoic Alkaline Rocks and Carbonatites of Peninsular India: A Review. *Episodes*, **43**, 249-277.
<https://doi.org/10.18814/epiiugs/2020/020015>
- [12] Krishnamurthy, P. (2019) Carbonatites of India. *Journal of the Geological Society of India*, **94**, 117-138. <https://doi.org/10.1007/s12594-019-1281-y>
- [13] Deb, M. (1980) Genesis and Metamorphism of Two Stratiform Massive Sulfide Deposits at Ambaji and Deri in the Precambrian of Western India. *Journal of Economic Geology*, **75**, 572-591. <https://doi.org/10.2113/gsecongeo.75.4.572>
- [14] Bose, M.K. (1998) Geochemistry of Metabasics and Carbonatitic Rocks of Phulad in Parts of Delhi Fold Belt; Implications for Tectonic History, In: Paliwal, B.S., Ed., *The Indian Precambrian*, Scientific Publishers, Jodhpur, 242-262.
- [15] Gupta, P., Mukhopadhyay, K. and Bose, U. (1988) Delhi Volcanics in Parts of Central Rajasthan and Their Significance. *Journal of the Geological Society of India*, **3**, 14-327.
- [16] Sinha-Roy, S. (1988) Proterozoic Wilson Cycle in Rajasthan. *Memoirs of the Geological Survey of India*, **7**, 95-107.
- [17] Gupta, S.N., Arora, Y.K., Mathur, R.K., Iqbaluddin, B.P., Sahai, T.N. and Sharma, S.B. (1980) Lithostratigraphic Map of the Aravalli Region, Southern Rajasthan and North-Eastern Gujarat. Geological Survey of India, Scale 1:1,000,000.
- [18] Gupta, S.N., Arora, Y.K., Mathur, R.K., Iqbaluddin, B.P., Sahai, T.N. and Sharma, S.B. (1997) The Precambrian Geology of the Aravalli Region, Southern Rajasthan and Northeastern Gujarat. *Memoirs of the Geological Survey of India*, **123**, 262 p.
- [19] Fatima, S. and Khan, M.S. (2012) Petrogenetic and Geochemical Characteristics of Mesoproterozoic Kumbhalgarh Clastic Rocks, NW Indian Shield: Implications for Provenance, Tectonic Setting, and Crustal Evolution. *International Geology Review*, **54**, 1113-1144. <https://doi.org/10.1080/00206814.2011.623032>
- [20] Roy, A.B. and Jakhar, S.R. (2002) Geology of Rajasthan (North-Western India): Precambrian to Recent. Scientific Publication India, Jodhpur.

- [21] Heron, A.M. (1953) Geology of Central Rajputana. *Memoirs of the Geological Survey of India*, **79**, 1-389.
- [22] Gopalan, K., Mac Dougall, J.D., Roy, A.B. and Murali, A.V. (1990) Sm-Nd Evidence for 3.3 Ga Old Rocks in Rajasthan, North Western India. *Precambrian Research*, **48**, 287-292. [https://doi.org/10.1016/0301-9268\(90\)90013-G](https://doi.org/10.1016/0301-9268(90)90013-G)
- [23] Crawford, A.R. (1970) The Precambrian Geochronology of Rajasthan and Bundelkhand, Northern India. *Canadian Journal of Earth Sciences*, **7**, 91-110. <https://doi.org/10.1139/e70-007>
- [24] Roy, A.B., Paliwal, B.S., Shekhawat, S.S., Nagori, D.K., Golani, P.R. and Bejarnia, B.R. (1988) Stratigraphy of the Aravalli Supergroup in the Type Area. *Memoirs of the Geological Survey of India*, **7**, 121-138.
- [25] Sinha-Roy, S. (1984) Precambrian Crustal Interaction in Rajasthan, NW India. *Indian Journal of Earth Sciences*, **11**, 84-91.
- [26] Sen, S. (1980) Precambrian Stratigraphic Sequence in a Part of the Aravalli Range, Rajasthan: A Re-Evaluation Quaternary. *Journal of Geology, Mine and Metal Society of India*, **52**, 67-76.
- [27] Singh, S.P. (1988) Stratigraphy and Sedimentation Pattern in the Proterozoic Delhi Supergroup, North Western India. *Memoirs of the Geological Survey of India*, **7**, 193-205.
- [28] Gupta, P., Mukhopadhyay, K., Fareeduddin and Reddy, M.S. (1991) Tectono- Stratigraphic Framework and Volcanic Geology of the South Delhi Fold Belt in Central Rajasthan. *Journal of the Geological Society of India*, **37**, 431-442.
- [29] Sinha-Roy, S. and Mohanty, M. (1988) Blue Schist Facies Metamorphism in the Ophiolite Melange of Late Proterozoic Delhi Fold Belt, Rajasthan, India. *Precambrian Research*, **42**, 97-105. [https://doi.org/10.1016/0301-9268\(88\)90012-5](https://doi.org/10.1016/0301-9268(88)90012-5)
- [30] Heinrich, E.W. (1966) The Geology of Carbonatites. Wiley, New York.
- [31] Le Bas, M.J. (1981) Carbonatite Magmas. *Mineralogical Magazine*, **44**, 133-140. <https://doi.org/10.1180/minmag.1981.044.334.02>
- [32] Woolley, A.R. and Kempe, D.R.C. (1989) Carbonatites: Nomenclature, Average Chemical Composition. In: Bell, K., Ed., *Carbonatites: Genesis and Evolution*, Unwin Hyman, London, 1-14.
- [33] Mitchell, R.H. (2015) Primary and Secondary Niobium Mineral Deposits Associated with Carbonatites. *Ore Geology Reviews*, **64**, 626-641. <https://doi.org/10.1016/j.oregeorev.2014.03.010>
- [34] Rakkiannan, S. and Anbarasu, K. (2019) Trace and Rare Earth Elements Enriched Carbonatite Rocks of Pakkanadu Alkaline Complex, South India. *International Journal of Scientific and Technology Research*, **8**, 2664-2670.
- [35] Henderson, P. (1984) Rare Earth Element Geochemistry. Elsevier Science, Amsterdam, 243-249.
- [36] Hornig, I. and Kjarsgaard (1998) Rare Earth Elements in Sovietic Carbonatites and Their Mineral Phases. *Journal of Petrology*, **39**, 2105-2121.
- [37] Dunworth, E.A. and Bell, K. (2001) The Turiy Massif, Kola Peninsula, Russia: Isotopic and Geochemical Evidence for Multi-Source Evolution. *Journal of Petrology*, **42**, 377-405. <https://doi.org/10.1093/petrology/42.2.377>
- [38] Keller, J. and Spettel, B. (1995) The Trace Element Composition and Petrogenesis of Natrocarbonatites. In: Bell, K. and Keller, J., Eds., *Carbonatite Volcanism: Oldoinyo Lengai and the Petrogenesis of Natrocarbonatites*, Springer, Berlin, 70-86.

- https://doi.org/10.1007/978-3-642-79182-6_6
- [39] Veksler, I.V., Nielsen, T.F.D. and Sokolov, S.V. (1998) Mineralogy of Crystallized Melt Inclusions from Gardiner and Kovdor Ultramafic Alkaline Complexes: Implications for Carbonatite Genesis. *Journal of Petrology*, **39**, 2015-2031. <https://doi.org/10.1093/petroj/39.11-12.2015>
- [40] Rudnick, R.L., McDonough, W.F. and Chappell, B.W. (1993) Carbonatite Metasomatism in the Northern Tanzanian Mantle: Petrographic and Geochemical Characteristics. *Earth and Planetary Science Letters*, **114**, 463-475. [https://doi.org/10.1016/0012-821X\(93\)90076-L](https://doi.org/10.1016/0012-821X(93)90076-L)
- [41] Sun, S.S. and McDonough, W.F. (1989) Chemical and Isotopic Systematics of Oceanic Basalts: Implications for Mantle Composition and Processes. *Geological Society, London, Special Publications*, **42**, 313-345. <https://doi.org/10.1144/GSL.SP.1989.042.01.19>
- [42] Williams, R.W., Collerson, K.D., Gill, J.B. and Deniel, C. (1992) High Th/U Ratio in Subcontinental Lithospheric Mantle: Mass Spectrometric Measurement of Th Isotopes in Gausberg Lamproites. *Earth and Planetary Science Letters*, **111**, 257-268. [https://doi.org/10.1016/0012-821X\(92\)90183-V](https://doi.org/10.1016/0012-821X(92)90183-V)
- [43] Carlson, R.W. and Irwing, A.J. (1994) Depletion and Enrichment History of Subcontinental Lithospheric Mantle: An Os, Sr, Nd and Pb Isotopic Study of Ultramafic Xenoliths from Northwestern Wyoming Craton. *Earth and Planetary Science Letters*, **126**, 209-220. [https://doi.org/10.1016/0012-821X\(94\)90124-4](https://doi.org/10.1016/0012-821X(94)90124-4)
- [44] Pandit, M.K., Sial, A.N., Sukumaran, G.B., Pimentel, M.M., Ramasamy, A.K. and Ferreira, V.P. (2002) Depleted and Enriched Mantle Sources for Paleo- and Neoproterozoic Carbonatites of Southern India: Sr, Nd, C-O Isotopic and Geochemical Constraints. *Chemical Geology*, **189**, 69-89. [https://doi.org/10.1016/S0009-2541\(02\)00136-5](https://doi.org/10.1016/S0009-2541(02)00136-5)
- [45] Waters, B.R. and Pearce, J.A. (1987) Metavolcanic Rocks of the La Ronge Domain in the Churchill Province, Saskatchewan: Geochemical Evidence for a Volcanic Arc Origin. *Geological Society, London, Special Publications*, **33**, 167-182. <https://doi.org/10.1144/GSL.SP.1987.033.01.12>
- [46] Pearce, J.A. (2008) Geochemical Fingerprinting of Oceanic Basalts with Applications to Ophiolite Classification and the Search for Archean Oceanic Crust. *Lithos*, **100**, 14-48. <https://doi.org/10.1016/j.lithos.2007.06.016>
- [47] Kjarsgaard, B.A. and Hamilton, D.L. (1989) The Genesis of Carbonatites by Immiscibility. In: Bell, K., Ed., *Carbonatites: Genesis and Evolution*, Chapman & Hall, London, 388-404.
- [48] Lee, W.-J. and Wyllie, P.J. (1998) Processes of Crustal Carbonatite Formation by Liquid Immiscibility and Differentiation, Elucidated by Model Systems. *Journal of Petrology*, **39**, 2005-2013. <https://doi.org/10.1093/petroj/39.11-12.2005>
- [49] Wyllie, P.J. and Lee, W.-J. (1998) Model System Controls on Conditions from the Mantle. *Journal of Petrology*, **39**, 1885-1893. <https://doi.org/10.1093/petroj/39.11-12.1885>
- [50] Ray, J.S. and Shukla, P.N. (2004) Trace Element Geochemistry of Amba Dongar Carbonatite Complex, India: Evidence for Fractional Crystallization and Silicate-Carbonate Melt Immiscibility. *Journal of Earth System Science*, **113**, 519-531. <https://doi.org/10.1007/BF02704020>
- [51] Veksler, I.V. and Lentz, D. (2006) Parental Magmas of Plutonic Carbonatites, Carbonate-Silicate Immiscibility and Decarbonation Reactions: Evidence from Melt and Fluid Inclusions. In: Webster, J.D., Ed., *Melt Inclusions in Plutonic Rocks*, Minera-

- logical Association of Canada, Montreal, Short Course 36, 123-149.
- [52] Wyllie, P.J. and Huang, W.L. (1976) Carbonation and Melting Reactions in the System CaO-MgO-SiO₂-CO₂ at Mantle Pressures with Geophysical and Petrological Applications. *Contributions to Mineralogy and Petrology*, **54**, 79-107. <https://doi.org/10.1007/BF00372117>
- [53] Eggler, D.H. (1978) The Effect of CO₂ upon Partial Melting of Peridotite in the System Na₂O-CaO-Al₂O₃-MgO-SiO₂-CO₂ to 35 kb, with an Analysis of Melting in a Peridotite-H₂O-CO₂ System. *American Journal of Science*, **278**, 305-343. <https://doi.org/10.2475/ajs.278.3.305>
- [54] Dalton, J.A. and Presnall, D.C. (1998) The Continuum of Primary Carbonatitic-Kimberlitic Melt Compositions in Equilibrium with Lherzolitite: Data from the System CaO-MgO-Al₂O₃-SiO₂-CO₂ at 6 GPa. *Journal of Petrology*, **39**, 1953-1964. <https://doi.org/10.1093/petroj/39.11-12.1953>
- [55] Harmer, R.E. and Gittins, J. (1998) The Case for Primary, Mantled-Derived Carbonate Magma. *Journal of Petrology*, **39**, 1895-1903. <https://doi.org/10.1093/petroj/39.11-12.1895>
- [56] Bell, K. and Rukhlov, A.S. (2004) Carbonatites from the Kola Alkaline Province: Origin, Evolution and Source Characteristics. In: Wall, F. and Zaitsev, A.N., Eds., *Phoscorites and Carbonatites from Mantle to Mine. The Key Example of the Kola Alkaline Province*, Mineral Soc. Ser. 10, Mineralogical Society of Great Britain and Ireland, Twickenham, 33-468. <https://doi.org/10.1180/MSS.10.13>
- [57] Freestone, I.C. and Hamilton, D.L. (1980) The Role of Liquid Immaximum Width of a Two-Liquid Field Must Ensure That Miscibility in the Genesis of Carbonatites: An Experimental Study. *Contributions to Mineralogy and Petrology*, **73**, 105-117. <https://doi.org/10.1007/BF00371385>
- [58] Le Bas, M.J. (2008) Fenites Associated with Carbonatites. *The Canadian Mineralogist*, **46**, 915-932. <https://doi.org/10.3749/canmin.46.4.915>
- [59] Ray, J.S., Pande, K., Bhutani, R., Shukla, A.D., Rai, V.K., Kumar, A., Awasthi, N., Smitha, R.S. and Panda, D.K. (2013) Age and Geochemistry of the Newania Dolomite Carbonatites, India: Implications for the Source of Primary Carbonatite Magma. *Contributions to Mineralogy and Petrology*, **166**, 1613-1632. <https://doi.org/10.1007/s00410-013-0945-7>
- [60] Kumar, A., Nirmal Charan, S., Gopalan, K. and Macdougall, J.D. (1998) A Long-Lived Enriched Mantle Source for Two Proterozoic Carbonatite Complexes from Tamil Nadu, Southern India. *Geochimica et Cosmochimica Acta*, **62**, 515-523. [https://doi.org/10.1016/S0016-7037\(97\)00341-4](https://doi.org/10.1016/S0016-7037(97)00341-4)
- [61] Schleicher, H., Kramm, U., Pernicka, E., Schidlowski, M., Schmidt, F., Subramanian, V., Todt, W. and Viladkar, S.G. (1998) Enriched Subcontinental Upper Mantle beneath Southern India: Evidence from Pb, Nd, Sr, and C-O Isotopic Studies on Tamil Nadu Carbonatites. *Journal of Petrology*, **39**, 1765-1785. <https://doi.org/10.1093/petroj/39.10.1765>
- [62] Miyazaki, T., Kagami, H., Shuto, K., Morikiyo, T., Mohan, V.R. and Rajasekaran, K.C. (2000) Rb-Sr Geochronology, Nd-Sr Isotopes and Whole Rock Geochemistry of Yelagiri and Sevattur Syenites, Tamil Nadu, South India. *Gondwana Research*, **3**, 39-53. [https://doi.org/10.1016/S1342-937X\(05\)70056-3](https://doi.org/10.1016/S1342-937X(05)70056-3)
- [63] Biswas, S.K. (1987) Regional Tectonic Framework, Structure and Evolution of the Western Marginal Basins of India. *Tectonophysics*, **135**, 302-327. [https://doi.org/10.1016/0040-1951\(87\)90115-6](https://doi.org/10.1016/0040-1951(87)90115-6)
- [64] Radhakrishnan, B.P. and Naqvi, S.M. (1986) Precambrian Continental Crust of In-

- dia and ITS evolution. *The Journal of Geology*, **94**, 145-166. <https://doi.org/10.1086/629020>
- [65] Schleicher, H., Todt, W., Viladkar, S.G. and Schmidt, F. (1997) Pb/Pb Age Determinations on the Newania and Sevattur Carbonatites of India: Evidence for Multistage Histories. *Chemical Geology*, **140**, 261-273. [https://doi.org/10.1016/S0009-2541\(97\)00022-3](https://doi.org/10.1016/S0009-2541(97)00022-3)
- [66] Ray, J.S. and Ramesh, R. (2006) Stable Carbon and Oxygen Isotopic Compositions of Indian Carbonatites. *International Geology Review*, **48**, 17-45. <https://doi.org/10.2747/0020-6814.48.1.17>
- [67] Naqvi, S.M., Sawkar, R.H., Subba Rao, D.V., Govil, P.K. and Rao, G. (1988) Geology, Geochemistry and Tectonic Setting of Archean Greywackes from Karnataka Nucleus India. *Precambrian Research*, **39**, 133-216. [https://doi.org/10.1016/0301-9268\(88\)90042-3](https://doi.org/10.1016/0301-9268(88)90042-3)
- [68] Raza, M. and Khan, M.S. (1993) Basal Aravalli Volcanism: Evidence for an Abortive Attempt to Form Proterozoic Ensilic Greenstone Belt in North Western Part of Indian Shield. *Journal of Geological Society of India*, **42**, 493-512.
- [69] Raza, M., Jafri, S.H., Alvi, S.H. and Khan, M.S. (1993) Geodynamic Evolution of Indian Shield during Proterozoic: Geochemical Evolution for Mafic Volcanic Rocks. *Journal of the Geological Society of India*, **41**, 455-469.
- [70] Khan, M.S. and Raza, M. (1993) Geochemical Attributes of Bari Lake Volcanics (Early Proterozoic), Udaipur, Rajasthan. *Bulletin of the Indian Geologists' Association*, **46**, 1-11.
- [71] Brahma, S., Sahoo, S. and Rajesh, D. (2022) First Report of Carbonatite from Gundlupet Area, Western Dharwar Craton, Karnataka, Southern India. *Journal of the Geological Society of India*, **98**, 35-40. <https://doi.org/10.1007/s12594-022-1924-2>