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Non-magmatic Features in Carbonatitic Rocks: A Re-examination of Proterozoic "Carbonatites," Southeast Rajasthan, Northwest Indian Craton

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Abstract

The Newania carbonatitic rocks (NCB), exposed as NW- trending, isolated linear bodies within Archean granitoids, are comprised mainly of Mg- and Fe-carbonate phases and volumetrically negligible Ca carbonate. The magmatic Mg-carbonatite shows partial metasomatic replacement by iron-rich solutions channelized along fractures. The C- and O-isotopic compositions further document the magmatic lineage of the Mg-carbonatite ($\delta^{13}C_{PDB}$ = –4.0 to –5.9‰ and $\delta^{18}O_{SMOW}$ = + 8.2 to 11.5‰, barring one sample characterized by a high value of +25.6‰). In contrast, the presumed ankeritic (Fe) and sovitic (Ca) carbonatites appear to be the result of metasomatism and hydrothermal activity, as indicated by corresponding enrichment in the heavier isotopes. The "atypical carbonatites" of Nayaphala, occurring as NW-trending dikes and veins of variable width (south of and colinear with the Newania trend), are nonmagmatic, and can be described as tectonic breccias. A nonmagmatic source for Nayaphala carbonates also is supported by the corresponding enrichment in the heavier C and O isotopes.

Introduction

CARBONATITES (magmatic in origin, with >50% carbonates by definition; Le Maitre, 1989) provide vital information for deciphering the evolution of continental lithospheric mantle because the carbonatitic melts potentially may sample a much larger volume of the mantle on account of their low viscosity. Their diagnostic geochemical and isotopic signatures further allow one to model mantle source heterogeneities (including carbon recycling) and the phenomena of silicate –carbonate melt immiscibility and crystallization. Their rarity and exclusive tectonic association further make them ideal candidates for investigating mantle evolution beneath the continental regions.

However, their identification is problematic and ideally should be based on simultaneous consideration of a number of characterstics such as rock association, field relations (including fenitization of the country rocks), texture, mineralogy, and geochemistry (REE and isotope chemistry). No single criterion is independently diagnostic (Barker, 1989, 1993). The metasomatic and hydrothermal carbonates of certain occurrences may be confused with true magmatic carbonatites because the high ductility of carbonate rocks may be misinterpreted as reflecting an "intrusive character." The igneous appearance of carbonate rocks must first be established by considering alternative mechanisms including ductile flow, fluidized particulate flow, carbonate metasomatism, carbonate precipitation from aqueous solutions, etc. In the present paper we offer a reinterpretation of the critical observations concerning the field setting and texture of the presumed carbonatites from Nayaphala and Newania, exposed within the Precambrian Aravalli craton of northwestern India (Fig. 1). These inferences are further substantiated by diagnostic C- and O-isotope

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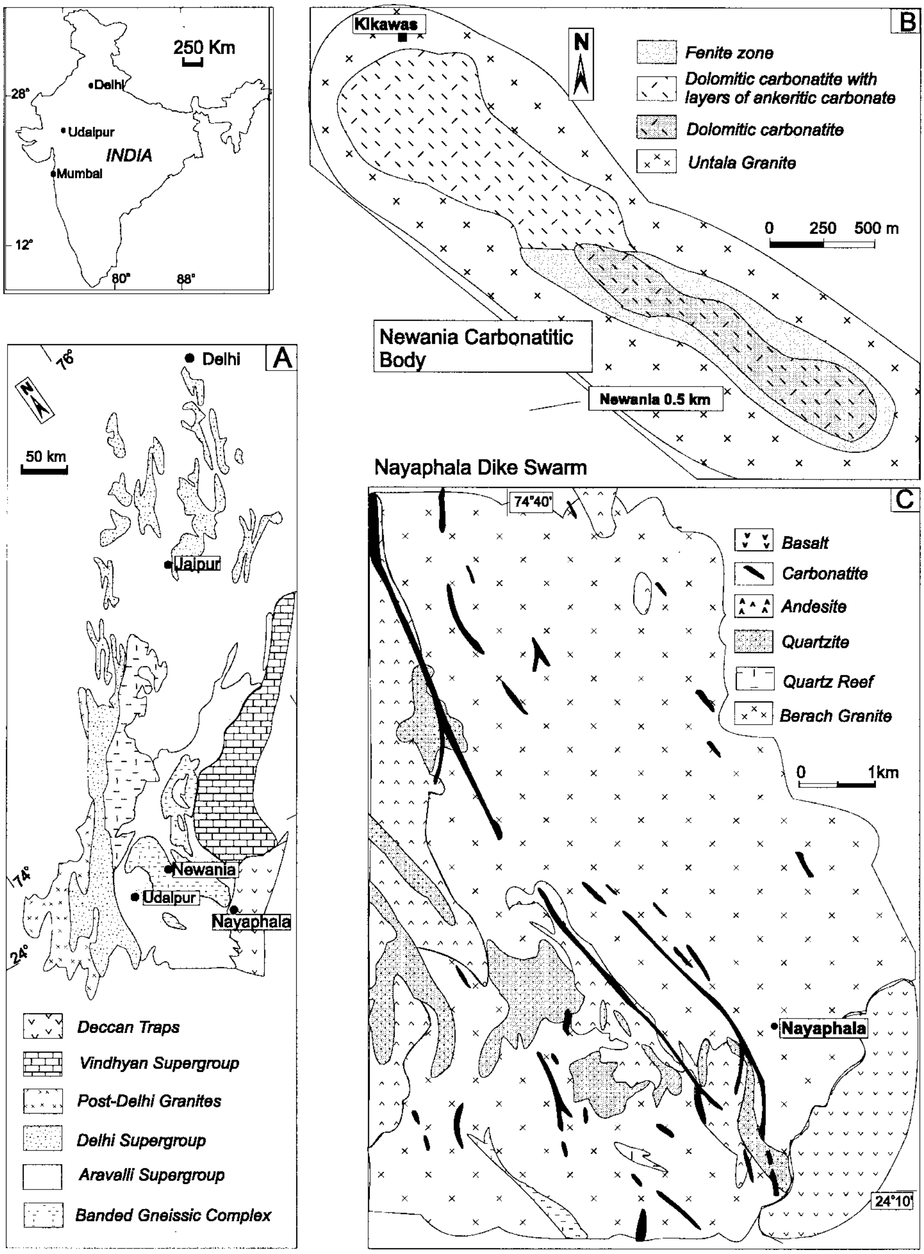

FIG. 1. A. Simplified geological map of the Aravalli Mountain region (and further east) showing the distribution of major stratigraphic units and the locations of Newania and Nayaphala (map compiled from the literature and those published by Geological Survey of India). B. Map of the Newania Carbonatitic Body showing a NW trend and presence of fenite zone in the southern part (modified after Golani and Pandit, 1999). C. Geological map of the Nayphala area (modified after Ray et al., 1989) showing the distribution of NW-trending carbonate veins traversing all lithologies except the Deccan basalts.

compositions. The two studied carbonatitic complexes, although located along the same major lineament, are temporally distinct and evolved through diverse processes.

Geological Setting

The NW-trending, 3 km long, Newania Carbonatitic Body (NCB) occurs within the Archean Banded Gneissic Complex (BGC) of southeastern Rajasthan, in northwestern India. Dar (1964) reported carbonatitic features from the NCB, which was mapped by earlier workers (Gupta, 1934; Heron, 1953) as Aravalli limestone. Subsequent studies have provided detailed information on the mineralogy, geochemistry (including fenitized zone), and geochronology of the NCB (Phadke and Jhingran, 1968; Viladkar, 1980; Viladkar and Wimmenaur, 1986; Chattopadhyaya et al., 1988; Krishnamurthy, 1988; Viladkar and Pawaskar, 1989; Schleicher et al. 1997; Viladkar, 1998). All of these studies were based on the consideration that the entire NCB is a "carbonatite" *sensu stricto*. Recently, Golani and Pandit (1999) reported epithermal features and encouraging gold values from the "ankeritic" component of the NCB. Considering the atypical order of emplacement (Mg- → Fe-→ Ca-carbonatite), different from normal carbonatite emplacement (Ca- → Mg- → Fe-carbonatite), and evidence of hydrothermal activity, they suggested a mixed magmatic (Mg-carbonatite) and non-magmatic (Fe- and Ca-carbonates) source for the NCB. Viladkar (1998) also recommended exploration of the NCB for sulfide mineralization.

In contrast, the Nayaphala Carbontitic Dike Swarm (NPD) has not received much petrologic/mineralogic attention aside from the initial report by Ray et al. (1989), who described it as an "atypical carbonatite dike swarm." The NPD also occurs as NW-trending subparallel dikes and diatremes that intrude all the Precambrian lithologies exposed in the region (Fig. 1), including the Berach Granite (Archean), Bari Sadri Quartzite (Aravalli–Paleoproterozoic ?), and Khairmalia Andesite (Lower Vindhyan). The Cretaceous–Early Eocene Deccan Traps have not been affected by the NPD, restricting the carbonatite emplacement age to the pre-Cretaceous (and more likely, Proterozoic). The trend of the carbonate veins of the NPD is colinear to, and coincides with, the southward extension of the NW-trending NCB, suggesting some tectonic relationship between the two.

FIG. 2. Replacement of dolomitic carbonatite (grey) by iron-carbonate solutions (dark), channelized along fractures. Note thin calcite veins (white) representing the terminal phase of hydrothermal activity in the Newania Carbonatitc Body (cm scale).

Lithology and Field Relations

Two main carbonate groups (dolomitic and ankeritic) were distinguished in the NCB by Golani and Pandit (1999), who also offered some modifications to the previously published maps of the NCB. The Mg- and Fe-carbonate phases are intricately mixed (Fig. 2): the ankeritic-carbonate occurs as fracture-related, impersistent bands replacing the Mg-carbonatite (at places simulating banding). The Ca-carbonate, generally a minor constituent of the NCB, and occurring as fracture-associated thin veinlets and impregnations, marks the terminal phase of hydrothermal activity (Fig. 2). However, the NCB can be divided broadly into a predominantly ferroan northern part, and a magnesian southern part (Golani and Pandit, 1999). The fenite zone, representing alkali metasomatism of the country rocks, is developed only on either side of the Mg-rich southern part (Fig. 1). The field relations clearly point out that the "ankeritic carbonatite" is the result of metasomatism of Mg-carbonatite, and does not represent a separate magmatic phase. This feature also can be observed on a petrographic scale, where Fe-rich solutions, replacing the Mg-carbonatite, can be traced along the cleavage planes of dolomite. Besides the predominant carbonate phase (dolomite), the mineralogy of the NCB includes sodic amphibole, magnetite, apatite, phlogopite, zircon, and Nb-silicates. Freshly broken surfaces of the Mg-carbonatite show fine specks of unaltered sulfide minerals. The Fe-carbonates consist of ankerite-

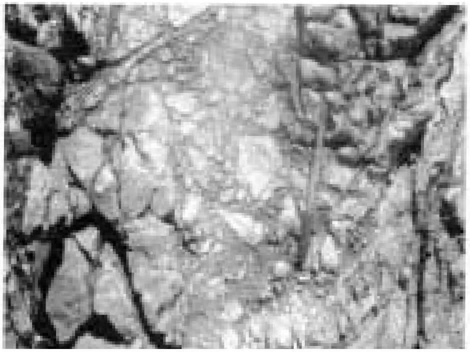

FIG. 3. Angular fragments of Berach Granite enclosed in carbonate matrix near Nayaphala, giving rise to agmatitic structure.

FIG. 4. Highly ductile carbonate material draping around brittle fragments of the Berach Granite near Nayaphala.

siderite, with hematite predominating over magnetite. Chattopadhyaya et al. (1988) also reported sodic pyroxene from the NCB. Associated fenites mainly comprise K-feldspar (microcline) and ferri-eckermanite, with variable amounts of albite, anorthoclase, biotite, sodic amphibole, and accessory apatite (Viladkar, 1980; Viladkar and Pawaskar, 1989).

The NPD (atypical carbonatite of Ray et al., 1989) occurs as linear, subparallel, NE-trending "dikes" of variable width (2 to 40 m) that intrude all the Precambrian lithologies exposed in a very small area (Fig. 1). The Cretaceous–Eocene basalt flows of the Deccan Traps have not been affected by the NPD. A closer examination of the "dikes" reveals them to represent tectonic breccia zones, where angular fragments of the country rocks embedded in a carbonate matrix give rise to typical agmatitic structure (Fig. 3). The carbonate matrix also drapes around the fragments of country rocks (Fig. 4). Sharp boundaries of the granite/andesite fragments in contact with the carbonate matrix (Fig. 5) rule out any chemical interaction between the two phases (normally expected when a hot carbonate magma interacts with the pre-existing granitic rocks), thus precluding the existence of a carbonate melt. Subsidiary carbonate veins emanating from the major ones occupy fracture planes and give rise to phlebitic structure (also reported by Ray et al., 1989). At places the country rock is traversed by thin, subparallel carbonate diatremes (Fig. 6). This feature is also visible at microscopic scale, where carbonate material cuts the granite fragments along roughly parallel submicroscopic fractures (Fig. 7) without involving chemical reaction/alteration. This feature was probably misinterpreted by Ray et al. (1989) as "carbonatization."

FIG. 5. Fragments of Berach Granite enclosed in carbonate matrix. Note the sharp boundaries of the fragments in contact with carbonate matrix, indicating the absence of chemical interaction between the two phases.

The NPD consists predominantly of a mosaic of medium- to coarse-grained subhedral dolomite, with accessory rutile, ilmenite, and skeletal hematite (also present as subrounded aggregates). Prismatic calcite crystals show elongation perpendicular to the contact with the granite, resulting in development of a "comb structure," a feature commonly associated with non-magmatic carbonates (Katz and Keller, 1981). Our observations do not support carbonate melt–affected chemical alteration of the granite/andesite country rocks, and the relationship between clasts and matrix can be explained as simple mechanical interaction in response to external stress. There is also a conspicuous absence of fenite

FIG. 6. Closely spaced subparallel carbonate diatremes traversing the host Berach Granite (near Nayaphala).

FIG. 7. Photomicrograph showing an alkali feldspar phenocryst (Berach Granite) crosscut by closely spaced carbonate veins, without chemical reaction (longer axis of photograph measures approximately 1.5 mm).

zones in the NPD. Fenitization of the country rocks is considered to be a diagnostic feature of carbonatite magmatism.

C and O Isotopes

General

The geochemistry and geochronology of the NCB and associated fenite zone have been studied in detail (Viladkar and Wimmenauer, 1986; Viladkar and Pawaskar, 1989; Schleicher et al., 1997; Golani and Pandit, 1999). With the exception of one sample, the NCB samples define a much lower range of ΣREE (245.14 to 393 ppm) (Viladkar and Pawaskar, 1989) and trace-element abundances compared with typical carbonatites; the latter usually are extremely enriched in LREE, and have the highest LREE/HREE ratios among all the igneous rocks (Woolley and Kemp, 1989). Pandit and Golani (2000) pointed out certain geochemical inconsistencies in the NCB and stressed the need to reconsider the petrologic status of the "Newania Carbonatite." The trace element data for the NPD (Ray et al., 1989) are semiquantative, and therefore cannot be used for meaningful petrogenetic interpretations. Despite these limitations, the available trace element data provide ample evidence against carbonatite magmatism, inasmuch as they differ from the trends displayed by typical carbonatites. A relatively high Ti content can be attributed to the presence of moderate amounts of modal rutile.

Stable isotopic ratios, particularly of C, are regarded as conclusive in the identification of carbonatites (Deines, 1989). In contrast to the large variability of C-isotopic composition in other magmatic material (meteorites, diamonds, basalts and high-temperature volcanic glasses, etc.), carbonatites show a remarkably narrow range of C-isotopic variation, presumably because they represent melting products of a relatively large volume of their mantle sources. Moreover, C-isotopic ratios are unlikely to be affected by most crustal processes, whereas O isotopes are susceptible to alteration by circulating fluids. The C-isotopic ratios thus can be considered as critical evidence, even in moderately altered samples.

Analytical Procedures and Results

C- and O-isotopic data (reported using standard ‰ notation with reference to PDB and SMOW, respectively) for 18 representative samples (Mg-carbonatite, ankeritic-carbonate of NCB, and NPD-carbonates) are given in Table 1. Powdered samples were reacted with 100% H_3PO_4 at 25°C to release the CO_2 (McCrea, 1950). Because most of the samples contain variable amounts of different carbonate species minerals, an extended reaction period of four to five days was preferred (instead of increasing the reaction temperature) to eliminate possible fractionation effects. The $\delta^{13}C$ and $\delta^{18}O$ values were measured on cryogenically cleaned CO_2 (Craig, 1957) in a triple-collector SIRA II mass spectrometer. Borborema Skarn Calcite (BSC), calibrated against NBS-18, NBS-19, and NBS-20 standards, was used as the reference gas, and in general the reproducibility of measurements was better than ± 0.1‰. The values obtained for NBS-18 and NBS-20 (as unknowns) in a separate run against BSC

TABLE 1. Carbon- (‰ $_{PDB}$) and Oxygen- (‰ $_{SMOW}$) Isotopic Composition of Carbonate Rocks from the Newania Carbonatitic Body and Nayaphala Carbonatitic Dike Swarm, Northwestern Indian Craton

Sample no.	Sample	$\delta^{13}C$	$\delta^{18}O$	Remarks
1	NCB/8	+0.1	+34.3	Ankeritic carbonates from Newania
2	NCB/9B	– 2.1	+23.9	
3	NCB/10	–0.4	+32.0	
4	NCB/17	–2.2	+26.2	
5	NCB/7	–2.6	+23.3	
6	NCB/11	+1.3	+36.9	
7	NCB/2A	–5.0	+8.5	Mg-carbonatites from Newania
8	NCB/3	–4.1	+11.5	
9	NCB/9A	–5.9	+8.5	
10	NCB/21	–4.8	+8.2	
11	NCB/4	–4.0	+25.6	
12	NPD/2	–0.4	+17.9	Carbonate veins and dikes from Nayaphala
13	NPD/3	–0.8	+17.8	
14	NPD/4A	–0.2	+17.8	
15	NPD/6	–0.1	+22.1	
16	NPD/6A	–1.4	+18.1	
17	NPD/6B	–0.6	+19.6	
18	NPD/7	–0.8	+18.4	

yielded $\delta^{13}C$ = –5.08 and –1.05‰$_{PDB}$; $\delta^{18}O$ = –23.19 and –4.22‰$_{PDB}$, respectively. These values are in close agreement with those reported by the U.S. National Bureau of Standards (–5.00‰$_{PDB}$, –1.06‰$_{PDB}$ and –23‰$_{PDB}$, –4.14 ‰$_{PDB}$, respectively).

The isotopic ratios in the conventional $\delta^{13}C$–$\delta^{18}O$ diagram (Fig. 8) show a wide range in both $\delta^{13}C$ (–5.9 to +1.3 ‰$_{PDB}$) and $\delta^{18}O$ (+8.2 to +34.3 ‰ $_{SMOW}$) values; however, the Mg-carbonatite and Fe-carbonates from NCB, as well as NPD carbonates, plot in distinct fields. The Mg-carbonatites plot within the primary/magmatic field (Plysunin et al., 1980; Deines, 1989), inside or very close to the "mantle box," except for one sample that is enriched in ^{18}O, but with the C isotopic ratio in perfect agreement with magmatic values. Such uncorrelated ^{18}O enrichment can be attributed to secondary processes affecting only the O-isotopic composition (Deines, 1989), while retaining the pristine $\delta^{13}C$ values. The Fe-carbonates of NCB show remarkable covariance in C- and O-isotopic compositions, and correlatable enrichments in both of the heavier isotopes. Such correlations cannot be attributed to magmatic fractionation processes, inasmuch as the carbonatites do not define any covariance between C and O isotopes beyond the $\delta^{18}O$ level of 15‰$_{SMOW}$ (Deines, 1989). The samples also plot outside the primary magmatic field. The positive correlation between C and O isotopic values, therefore, is more likely an inherent characteristic indicating metasomatic activity. The C and O isotopic ratios rule out a magmatic source for the ankeritic carbonates, substantiating field and petrographic observations. The NPD-carbonates are homogeneous in terms of C- and O-isotopic compositions, and plot in a close cluster, quite distinct from the other trends. Their nonmagmatic origin is also confirmed by the definitive isotopic ratios, because they plot clearly away from the magmatic/primary field. The isotopic data thus provide conclusive support for a mixed mantle and terrigeneous source for the NCB. The magne-

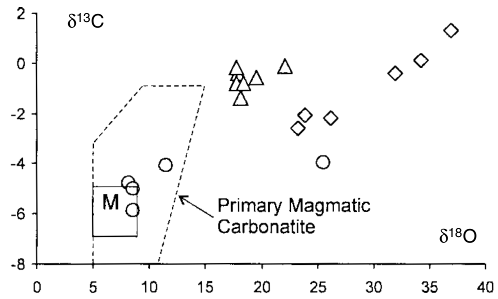

FIG. 8. Conventional $\delta^{13}C$–$\delta^{18}O$ (‰ with respect to PDB and SMOW, respectively) diagram showing primary magmatic affinity for Newania dolomitic carbonatites (circles); the ankeritic carbonates (diamonds), with positive correlation and enrichment in the heavier isotopes, plot away from the primary magmatic field. The Nayaphala carbonates (triangles) show homogeneous isotopic compositions and plot in a cluster, away from other samples. The small rectangle marked "M" represents the "mantle box" (Deines, 1992; Cartingy, et al., 1998) and the polygon with dashed outline indicates the field of unaltered "primary carbonatites" (Plysunin et al., 1980; Deines, 1989).

sian carbonate component represents the "carbonatite" *sensu stricto*, whereas the ankeritic and calcitic phases are a manifestation of the metasomatic and hydrothermal processes. The supposed "atypical carbonatites"of Nayaphala are simply recrystallized carbonates of nonmagmatic origin.

Discussion and Conclusions

The colinearity of NW-trending carbonate veins of the NPD and NCB (the latter being the northward extension of the NPD) implies a tectonic relationship between the two, such as derivation in a common NW-trending, deep-seated fracture system. The Newania–Nayaphala tectonic line also corresponds to the Mandli–Newania lineament (Mishra, 1987), which is parallel and proximal to a set of NW-trending lineaments in western India (Bakliwal and Ramasamy, 1987). The Pb/Pb geochronology of the NCB yielded two widely separate age clusters of 2.27 Ga and 1551 Ma for dolomitic and ankeritic carbonates, respectively (Schleicher et al., 1997). The Pb/Pb age data, therefore, argues against coevality between NCB and NPD events, the latter being younger than 1250 Ma, postdating the Lower Vindhyan Khairmalia andesite (Crawford and Compston, 1970). The coevality between NCB and NPD was presumed by Ray et al. (1989) on the basis of a K-Ar age of 959 Ma for the amphibole from NCB fenite (Deans and Powell, 1968), believed to represent the emplacement age of the carbonatite. This may rather represent the time of a Neoproterozoic metamorphic event, during which the K-Ar systematics were reset. Such an event also is indicated by the Rb/Sr isochron age of 955 Ma (whole rock, muscovite, and biotite) for the host Untala granite (Crawford, 1970); the whole-rock Rb/Sr isochron (nine samples) for the same granite corresponds to 2920 Ma (Choudhary et al., 1984), and can be taken as the emplacement age of the granite. The NPD, therefore, appears to be related to a later reactivation of the same tectonic zone during the Middle to Late Proterozoic.

Detailed field and petrographic observations, and stable isotopic signatures confirm a significant nonmagmatic component in the NCB, and call for a mixed mantle and terrigenous input. The NPD represents a simple tectonic breccia involving two rheologically distinct components. The apparent intrusive character of NPD carbonates (ductile flowage) is a manifestation of the difference in response by granite (brittle) and carbonate (plastic) to shear. The sharply defined margins of the angular fragments of granitic country rock within a carbonate matrix, and the absence of any reaction between granite and presumed "carbonatitic melt," rule out carbonatite magmatism. The absence of an associated fenite zone (a common feature of carbonatite magmatism) as well as the alkaline rock association further preclude a magmatic origin for the carbonates. The reported "carbonatization" (Ray et al., 1989) of granite host actually represents the ductile flowage of carbonate through closely spaced microfractures, a purely mechanical phenomenon, without any chemical interaction. The present study further concludes that the "atypical carbonatite" of Nayaphala is a "tectonic breccia," unrelated to any mantle-derived carbonatite magmatism.

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