Petrological and geochemical signatures of carbonatites from Hogenakkal, Dharmapuri District, Tamil Nadu

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Abstract- The Hogenakkal carbonatites are found as discontinuous bodies within two pyroxenite dykes, forming veins and lenses within the pyroxenite. Through field observations, it's deduced that the sequence of their formation follows the pyroxenite first, then syenite, and finally carbonatites. These carbonatite complexes, dating back to the Neoproterozoic era, are set within the Archaean granulites. Additionally, smaller Paleoproterozoic (2.4 billion years old) carbonatite intrusions exist within two northeast-trending pyroxenite dikes. These carbonatite samples exhibit distinctive characteristics, including low levels of SiO2, FeO, and MgO, while featuring relatively high concentrations of CaO. This sets them apart from other types of carbonatites. Within the Hogenakkal carbonatites, there are variations such as sövite, distinguished by their elevated Sr and Ba contents and remarkable enrichment in light rare earth elements (LREE), showcasing steep slopes typical of carbonatites. Analyzing the chondrite-normalized Rare Earth Elements (REE) of these carbonatites reveals a slight abundance in LREE compared to Heavy Rare Earth Elements (HREE), with no negative spikes for Eu. This suggests a potential metasomatised source or the influence of garnet in the source material. The findings of this study shed significant light on the field, petrography, and geochemistry of the Hogenakkal alkaline carbonatite complex.

Key words: Cabonatite, Eu anamoly, REE, Palaeoproterozoic, Hogenakkal

INTRODUCTION

Carbonatites are exceptionally unique and rare magmatic rocks, defined as containing over 50% primary carbonate minerals and less than 20% silica according to the IUGS classification (le Maitre, 2002). Mitchell (2005) proposed broadening the classification to include rocks with more than 30% carbonate minerals, regardless of silica content. This expansion could encompass suites of genetically related carbonate-silicate rocks like calcitic pyroxenites. Derived from the mantle, carbonatites are typically emplaced in extensional tectonic settings such as rift systems, major faults, large-scale uplifts, and cratonic domains within continental regions, often associated with alkaline rock suites. Consequently, they offer valuable insights into the composition and temporal evolution of the subcontinental mantle (Bailey, 1993; Bell, 1998; Mitchell, 2005; Ernst and Bell, 2010). Woolley and Kjarsgaard (2008) documented 527 carbonatite occurrences worldwide, with only three from oceanic islands (Canaries, Cape Verde, and Kerguelen), underscoring the role of thickened continental lithosphere in CO2-rich magma generation. These occurrences are temporally linked to various geological events, including orogenesis, continental rifting, extension within continental margins during ocean opening, and mantle plumes (Woolley, 1989; Yang and Woolley, 2006; Kramm and Sindern, 2004; Tappe et al., 2007; Dahlgren, 1994; Pell, 1994; Bell, 2001; Bell and Tilton, 2001; Bell and Rukhlov, 2004; de Ignacio et al., 2006). Carbonatites associated with alkaline rock complexes may represent immiscible phases from carbonated melilitic and/or nephelinitic parent magmas, or mixtures of different melts (Simonetti and Bell, 1994; Bell, 1998; Palmer, 1998; Mitchell, 2005; Woolley and Kjarsgaard, 2008; Fischer et al., 2009; Guzmics et al., 2011). Many carbonatites are believed to originate from primary carbonate melts in the asthenosphere (Woolley and Kjarsgaard, 2008). The South Indian Granulite Terrane (SGT) has experienced carbonatite-alkaline magmatism during the Paleoproterozoic (2.4 billion years ago) and Neoproterozoic periods (Natarajan et al., 1994; Schleicher et al., 1997; Kumar et al., 1998; Miyazaki et al., 2000, 2003; Pandit et al., 2002). Neoproterozoic occurrences are more widespread, with carbonatite occurrences reported from several locations (Kumar et al., 1998; Pandit et al., 1998, 2002; Schleicher et al., 1998; Miyazaki et al., 2003), while Paleoproterozoic alkaline magmatism is confined to a single locality near Uttamali (Hogenakkal) village in Tamil Nadu (Natarajan et al., 1994; Kumar et al., 1998; Pandit et al., 2002). The Hogenakkal carbonatites were initially described by Natarajan et al. (1994). Kumar et al. (1998) suggested an enriched mantle source for the Hogenakkal carbonatites, proposing a long-lived enriched mantle beneath the South Indian continental region. In contrast, Pandit et al. (2002) argued for a depleted mantle source for the Hogenakkal (Paleoproterozoic) carbonatites, which was promptly criticized by Kumar et al. (2004) and Pandit et al. (2004). This article presents field, petrographic, and geochemical characteristics of the 2.4-billion-year-old Hogenakkal carbonatites to assess mantle sources and petrogenetic processes.

Geological setting

The Precambrian geological history of the Indian peninsular region revolves around four major Archaean-Proterozoic Cratonic nuclei: the Bundelkhand-Banded Gneiss Complex (BGC) in the north, the Bastar and Singhbhum cratons in the east, and the Dharwar craton in the south. Their amalgamation during the end-Archaean era, along with the emplacement of ~2.5-billion-year-old granitoids in the Dharwar (Closepet Granite) and Bundelkhand-BGC (Berach Granite) cratons, signifies a significant stabilization phase (Stein et al., 2004; Meert et al., 2010). However, some alternative perspectives suggest that this stabilization occurred later, around 1.6 billion years ago (Bhandari et al., 2010; Pisarevsky et al., 2013), or even as late as 1.1-1.0 billion years ago (Bhowmik et al., 2012). South of the Dharwar Craton lies the Southern Granulite Terrane (SGT), comprising a mosaic of three late Archaean to Neoproterozoic age, high-grade metamorphic blocks. These blocks are interconnected by several crustal-scale shear zones (Naqvi, 2005; Meert et al., 2010). The Northern Block of the SGT, also known as the Salem Block, lies south of the Archaean-Proterozoic Dharwar Craton, separated by the 'Fermor Line'. The Salem Block is bounded to the south and east by the Moyar-Bhavani and Attatur Shear Zones (MBSZ and ASZ), respectively. The MBSZ, a complex network of mobile belts, also delineates the northern limit of the Central Block (CB), which further divides into the Nilgiri Block (NiB) in the west and the Madras Block (MaB) in the east. The MaB is adjacent to the south by the Palghat-Cauvery Shear Zone (PCSZ), indicating a suture between the Archaean Northern and Central blocks and the Proterozoic Madurai Block (MdB). The Madurai Block is juxtaposed to the south by the Trivandrum Block through a region of pronounced magnetic and seismic anomalies and the NE-trending Achankovil Shear Zone (Harris et al., 1994).

The Salem Block underwent granulite facies metamorphism during the late Archaean to earliest Proterozoic and experienced deformation along discrete kilometer-scale shear zones, such as the Salem-Attur Shear Zone (Chetty, 1996; Chetty and Rao, 1998). High-pressure metamorphism (>14 kbar) during the early Neoproterozoic is documented in this region, with indications of additional metamorphism during the Ediacaran-Cambrian periods (Ghosh et al., 2004; Bhutani et al., 2007). Lithologies in the Salem Block mainly comprise charnockite and granite gneiss, alongside migmatites, with minor occurrences of mafic granulites and metasedimentary rocks (Devaraju et al., 2007; Clark et al., 2009). These lithologies extend to the Palghat-Cauvery Shear System (PCSS) in the south, an approximately 100 km wide system of intersecting shear zones cutting through migmatitic mafic gneisses and high-pressure granulites (Chetty, 1996). The Sm-Nd ages of rocks within the Salem Block, ranging from 3.3 to 2.68 billion years old, suggest an Archaean protolith, likely originating from the Dharwar Craton (Bhaskar Rao et al., 2003; Devaraju et al., 2007). Therefore, the Salem Block stands apart from other SGT blocks, which exhibit Neoproterozoic-Cambrian thermal signatures (Collins and Windley, 2002; Bhaskar Rao et al., 2003). Several Neoproterozoic (Samalaptti, Sevattur, and Pakkanadu-Mulakkadu) and one Paleoproterozoic (Hogenakkal) carbonatite-alkaline complexes are situated within the Salem Block. These complexes were intruded into Archaean granulites within a northeast-trending zone characterized by intense faulting and thrusting, marking the transition between cratonic, non-charnockitic (amphibolite facies) terranes in the north and the charnockitic granulite facies terranes in the south (Condie et al., 1982; Condie and Allen, 1984). Geological Survey of India (GSI) mapping confirms the presence of anastomosing shear/fault zones in this region.

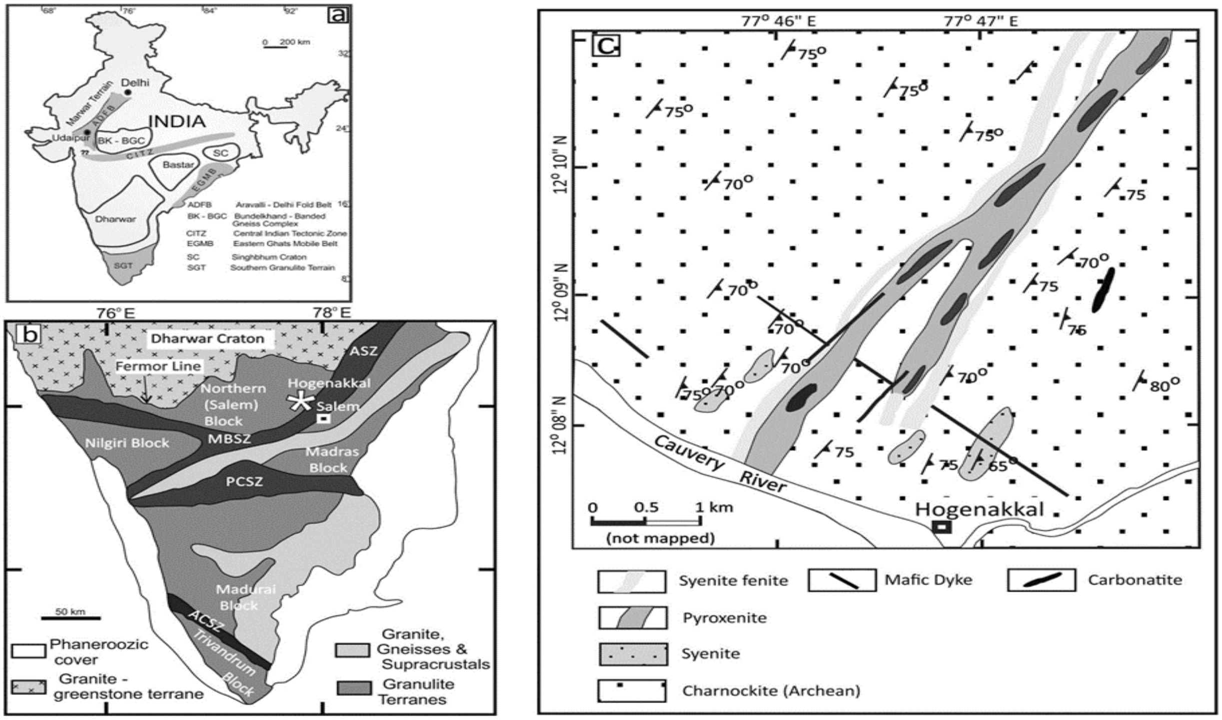

Fig. 1. (a) Map of India showing Precambrian cratonic regions and mobile belts. (b) Map of the Southern Indian Granulite Terrane (SGT) showing different blocks separated by shear zones (compiled from Harris et al., 1994; Meert et al., 2010). Location of the study area around Hogenakkal town (Figure 1c) is indicated by the asterisk and Neoproterozoic carbonatite occurrences within SGT are also indicated (open circle). ACSZ, Achankovil Shear Zone; ASZ, Attatur Shear Zones; MBSZ, Moyar–Bhavani Shear Zone; PCSZ, Palghat–Cauvery Shear Zone. (c) Geological map (mapped by M. Kumar) of Hogenakkal region showing carbonatite bodies hosted within two NE-trending pyroxenite dikes in a regional charnockite terrane (adapted from Kumar and Sukumaran, 2008).

FIELD AND STRUCTURAL FEATURES

The carbonatites are found as discontinuous bodies within two nearly parallel NNE-SSW trending pyroxenite dykes, intruding Precambrian chamockites (Fig. 1). The western dyke stretches for 3 km, while the eastern dyke extends NNE for approximately 14 km. In the study area, the general foliation trend is NE-SW, with folds displaying varying dimensions of hinge zones with pinched and shearing limbs depending on the lithological formations. One of the faults runs alongside the Cauvery River near Hogenakkal waterfalls, located near the south-westerly bend of the river. Each carbonatite body comprises discrete veins and lenses within pyroxenite, which has been permeated and soaked to different extents by the carbonatites. These lensoidal carbonatite bodies range in surface width from 3 m to 45 m and in strike length from 25 m to 800 m. Seven such bodies from the western dyke and four from the eastern dyke have been examined. A range of compositions, from calcite carbonatite to pyroxenite, is observed in these bodies due to the mechanical mixing of invading carbonatite and early-formed pyroxenite. Additionally, carbonatites (rarely) occur in the bordering pyroxenite-syenite-fenite zone. Natarajan et al. (1994) dated the Hogenakkal carbonatites at 1.99 billion years ago (Ga) using whole rock-mineral Rb-Sr isochron age, and also reported a 2401 ± 25 million years ago (Ma) age based on a five-point whole rock Sm-Nd isochron for the nearby Pikkli Hill syenite. Kumar et al. (1998) conducted a combined carbonatite-syenite Rb-Sr isotopic analysis, providing a better constrained whole rock Rb-Sr isochron (seven points; two carbonatites and five syenite) age of 2415 ± 10 Ma for the Hogenakkal alkaline rocks. The 2415 Ma age aligns closely between two independent methods and likely represents the crystallization age of Hogenakkal carbonatites. Subsequent deformation following the emplacement of carbonatites is indicated by minor shear zones and contortions, with no significant recrystallization associated with this deformation.

Petrography

The Hogenakkal carbonatite exhibits a medium to coarse-grained texture, appearing light pink or occasionally light grey. Typically, xenomorphic and sometimes inequigranular or equigranular, it occasionally displays porphyritic textures. Alongside dominant calcite, the rock contains variable amounts of apatite, with minor occurrences of phlogopite and sporadic aegirine-augite. The carbonatite appears melanocratic and medium-grained, with calcite constituting 45-65% of the rock. Pyroxenes, phlogopite, and apatite make up the remainder, with subhedral aegirine-augite and altered brown phlogopite often present. Magnetite is observed along cracks and fractures in pyroxene. Apatite occurs in various sizes, typically sub-rounded, subhedral, or rarely euhedral. In fenitized and xenolithic pyroxenite, the modal content of pyroxene decreases while the contents of phlogopite and other minerals (sodic pyroxene, hornblende, apatite, calcite) increase. Coarse syenite consists primarily of orthoclase (approximately 90%), with the remainder comprising sodic pyroxene, apatite, calcite, sphene, phlogopite, and magnetite. Xenolithic syenite fragments often exhibit rounded and resorbed features, sometimes displaying a rim of reddish-brown sphene. Calcite veinlets are occasionally observed within them. Pyroxene syenite is medium to coarse-grained, foliated, inequigranular xenomorphic, and predominantly composed of perthite and aegirine-augite.

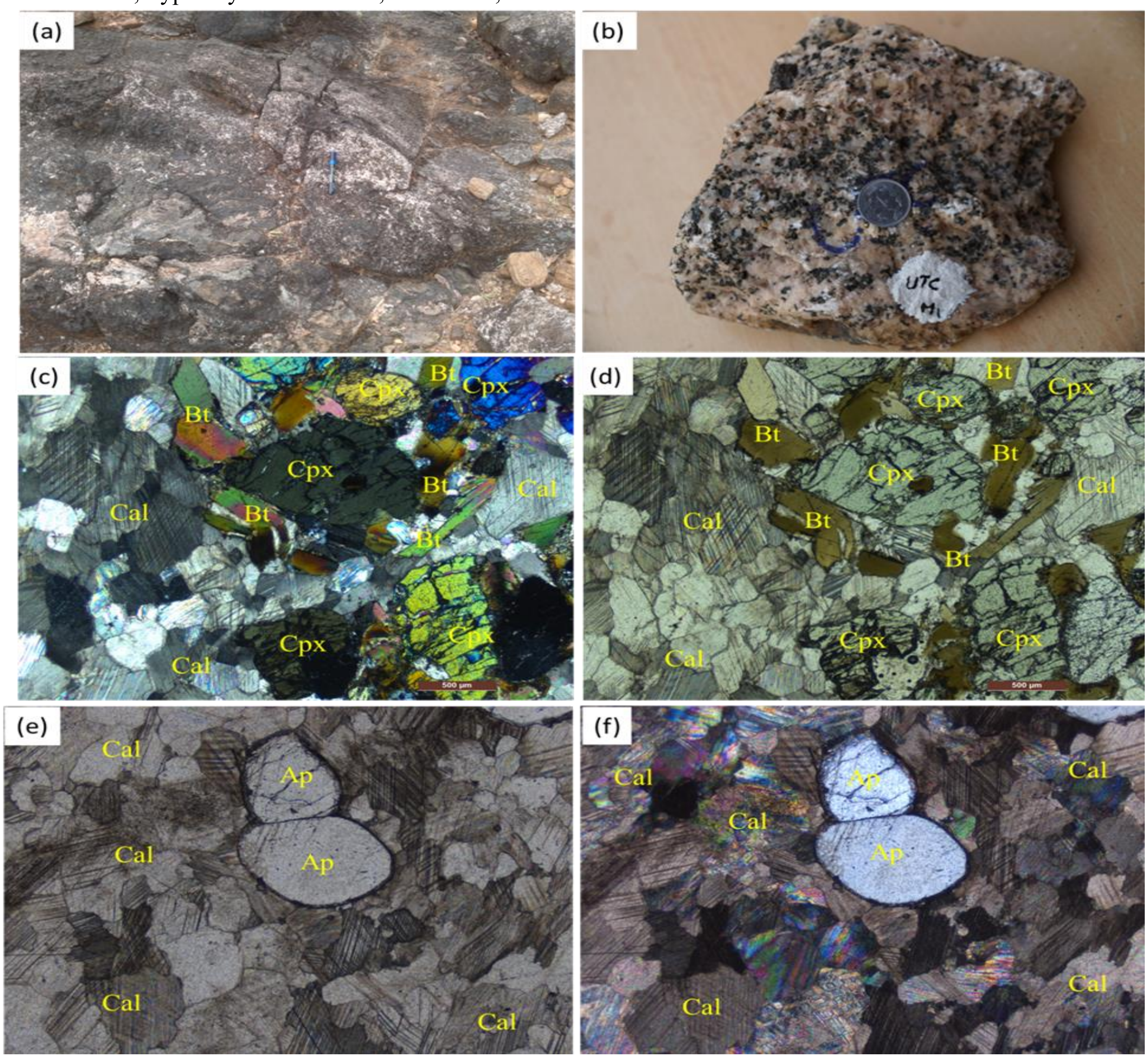

Fig. 2. Megascopic and petrographic characteristics of Hogenakkal carbonatites. (a) A filed photograph showing melanococratic nature of coarse grained sövite with subrounded xenoliths of host pyroxenite. (b) Hand specimen of melanocratic silicate sövite host pyroxenite. (c, d) Photomicrograph of sövite showing suhedral intergranular calcite crystals (Cal) associated with clinopyroxene (Cpx) and biotite (Bt) under XPL and PPL (e, f)) Photomicrograph of sövite showing suhedral intergranular calcite crystals (Cal) and apatite (Ap) with XPL and PPL.

GEOCHEMISTRY

The major and trace element composition of Hogenakal carbonatite reveals low levels of SiO_2, Al_2O_3, Na_2O, K_2O, and variable concentrations of MgO. Na_2O content tends to exceed K_2O, while the amount of P_2O_5 varies due to the variable presence of apatite in the rocks. These samples exhibit significant enrichment in CaO and depletion in other oxides, primarily due to substantial proportions of pyroxene, mica, and feldspar. In the CaO-MgO-FeO+Fe_2O_3+MnO classification diagram, carbonatites from Hogenakal plot within the field of sövitic affinity, along with adjoining samples categorized as calciocarbonatite (Fig. 3) (adapted from Wolley and Kempe, 1989).

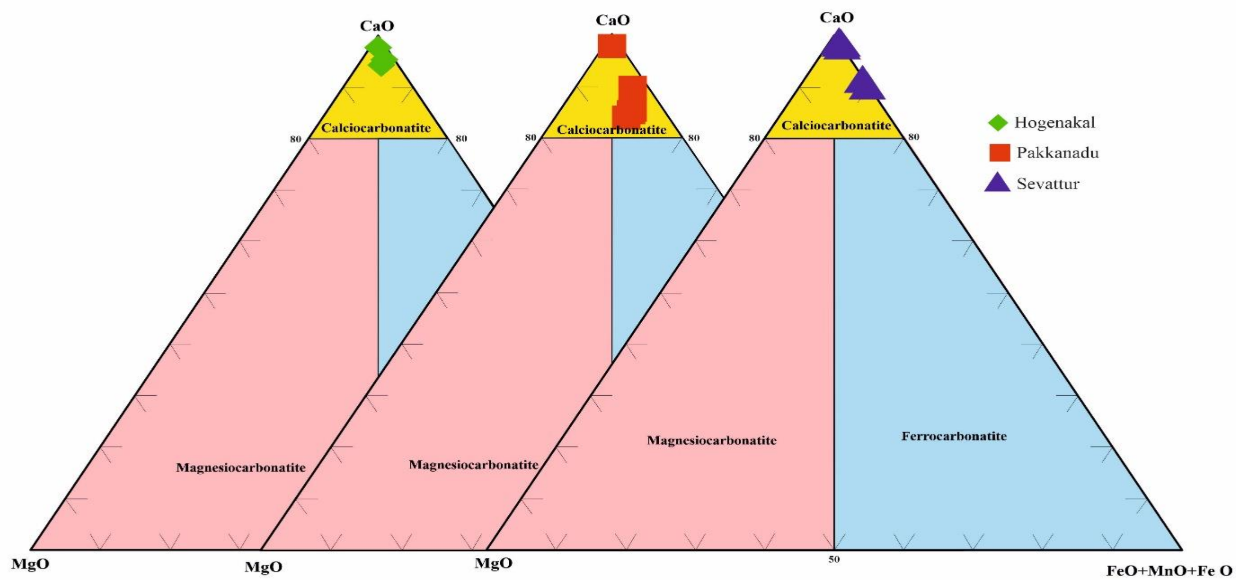

Fig. 3. CaO-MgO-total iron (wt.%) diagram for the carbonatitic rocks from Hogenakkal and compared with adjoining carbonatite complexes of Dharmapuri Suture Rift Zone.

Mantle-normalized multi-element spiderplots for Hogenakkal carbonatites (Figure 4a) reveal enrichment levels for Ba, Th, La-Ce, Sr, and Y, alongside negative spikes for Rb, K, Nb, Zr, and Ti. Such patterns, typical of carbonatites (Woolley and Kempe, 1989) and particularly common in Precambrian carbonatites (Nelson et al., 1988; Pearce and Leng, 1996), exhibit Nb depletion, which, although not unusual, has been reported in some Paleoproterozoic carbonatites (Antonini et al., 2003). A minor kink for Sr reflects extremely high levels of neighboring elements (Ce and Nd) rather than Sr depletion. In contrast to the 'silicate' system, trace element patterns in carbonatites may provide limited insight into geochemical evolution, as traditionally 'incompatible' elements may behave differently due to processes like accumulation, veining, and layering (Dunworth and Bell, 2001). Carbonatites are notably enriched in LREEs and exhibit the highest (La/Lu) ratios among all igneous rocks (Kjarsgaard, 1998). Similarly, the Hogenakkal carbonatites display very high LREE contents and elevated (La/Yb) ratios (~50 in silicate sövite to ~200 in the case of sövite), characteristic of carbonatites (Woolley and Kempe, 1989). Chondrite-normalized REE diagrams (normalized values from Sun and McDonnough, 1989) for Hogenakkal carbonatites, along with other comparative carbonatites excluding Pakkanadu, exhibit straight line log-linear patterns characterized by strong LREE enrichment, steep slopes, and the absence of any Eu anomaly (Figure 4b), indicative of a possible metasomatised source. The REE patterns suggest apatite as the major repository for REEs, with covariance between Th and LREEs suggesting some role of monazite and/or allanite in accommodating LREEs.

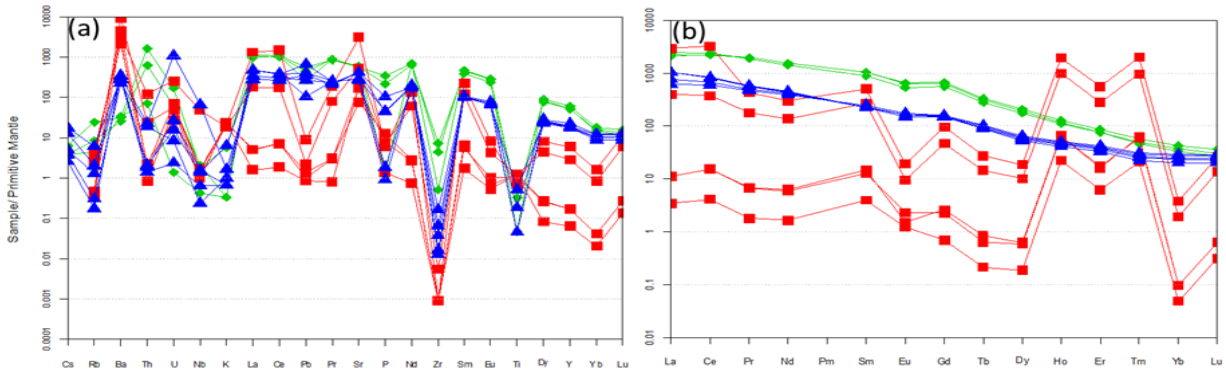

Figure 4. (a) Primitive mantle normalized (after Sun and McDonough, 1989) trace element spiderdiagrams for Hogenakkal carbonatites and other DSRZ carbonatite Complexes. (b) Chondrite normalized (after Boynton, 1984) REE patterns for Hogenakkal carbonatite and other DSRZ carbonatite Complexes.

CONCLUSION

The current study focuses on the field, petrographic, and geochemical characteristics of the Hogenakkal alkaline carbonatite complex. Petrographic analysis reveals inequigranular or equigranular textures, along with porphyritic textures, indicating a silica-undersaturated composition. The predominant mineral is calcite, accompanied by subordinate amounts of pyroxene, biotite, and apatite minerals. Pyrochlore and magnetite are observed along cracks and fractures in pyroxene and calcite. Geochemically, the investigated carbonates display characteristics of calcio-carbonatite, enriched in Large Ion Lithophile Elements (LILEs) while depleted in High Field Strength Elements (HFSEs). Negative Nb anomalies suggest an arc-related origin of magmas. A slight abundance in Light Rare Earth Elements (LREEs) over Heavy Rare Earth Elements (HREEs), without negative spikes for Eu. This suggests a possible source of parental magma generated by partial melting of metasomatized lithospheric mantle, with heat input from a convective asthenosphere or a mantle plume. This study provides insight into the genesis and source of mantle carbonatite.

ACKNOWLEDGEMENT

The authors extend their sincere gratitude to the Head of the Department of Geology, Osmania University, Hyderabad, for their generous support and encouragement. They also acknowledge the Department of Atomic Energy-Board of Research in Nuclear Sciences (DAE-BRNS), Mumbai, for providing a project to Prof. M. Srinivas. Additionally, the authors express their appreciation for the financial assistance provided through a Junior Research Fellowship (JRF).

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