Geochemistry and Petrogenesis of the Danduvaripalle syenites, Eastern Dharwar Craton, southern India

G. Nagaraju[1], K. Rajendra prasad[1], M. Srinivas[1], K. Soni[1]
[1]*Department of Geology, Osmania University, Hyderabad-500007*

***Abstract**: The Eastern Dharwar Craton (EDC) contains many Late Neoarchean to Paleoproterozoic syenites, whose origin is ambiguous. This work presents a geochemical analysis of the Danduvaripalle syenites (DVS), located at the western boundary of the Paleo-Mesoproterozoic Cuddapah Basin in the Eastern Deccan (EDC). The DVS has a metaluminous, alkaline, and magnesian geochemical composition. These metaluminous rocks are characterized by high overall alkali content, particularly K_2O, moderate FeOt levels, and low MnO, MgO, and CaO concentrations. The chondrite-normalized REE patterns demonstrate LREE enrichment relative to HREE, with no Eu anomaly seen. Allanite, apatite, zircon, and monazite are the accessory minerals that contain substantial amounts of LREE in these syenites. The syenites lack MgO, Ni, Cr, and Sc, possess highly fractionated REE patterns, and have negative Nb–Ta–Ti anomalies, with low Nb/U and elevated Th/U ratios, indicating a subduction zone environment. The Danduvaripalle syenite has geochemical affinities with arc-related alkaline rocks and volcanic arc granitoids in tectonic discrimination diagrams. These geochemical characteristics align with their formation by partially melting a mafic crustal source, which later saw fractionation of amphibole and garnet. We propose that the crustal source of these syenites experienced partial melting due to thermal influence from the ascending plume during the Paleoproterozoic expansion.*

***Key words**: Alkaline rocks, Danduvaripalle syenites, Partial melting, Lower crust, Garnet*

I INTRODUCTION

Alkaline igneous rocks are limited in volumetric abundance within the geological record. Substantial syenitic magmatism associated with the Proterozoic time has been identified in several continental platforms globally. The Proterozoic time is distinguished by a notable prevalence of ferroan feldspathic rocks, varying in composition from granite to quartz syenites to feldspathoid-bearing syenites [1]. Parental magmas for alkaline rocks are often considered to originate from the partial melting of metasomatised lithospheric mantle enriched in LILE and LREE [2], the asthenospheric mantle [3], or a combination of both sources. Others suggested that alkaline-rich syenitic magmas may originate from the partial melting of the lower crust, accompanied by varying degrees of upper crustal contamination [4], [5].

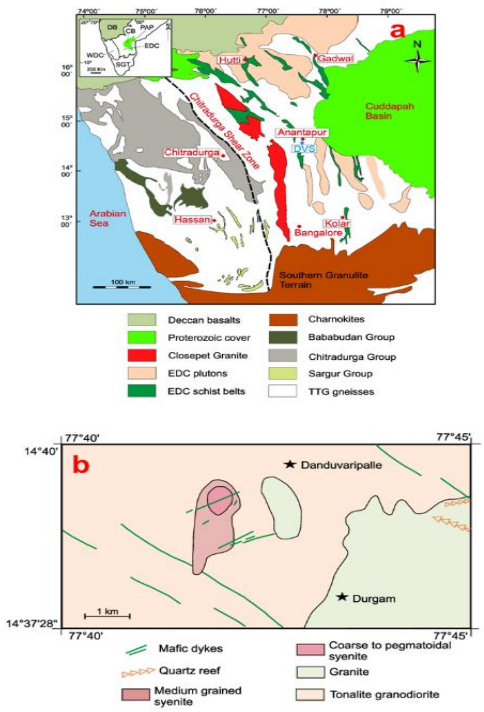

Fig. 1 (a) Geological map of the Dharwar Craton (after Chardon et al. 2008) showing locations of the DVS syenites. (b) Danduvaripalle syenite (DVS) (after Suresh et al. 2010).

The Neoarchean to the Cretaceous period's alkaline igneous rocks can be found in the Eastern Dharwar Craton (EDC), which is in the southern Indian Shield [6]–[8]. A group of syenites from the Paleoproterozoic Dancherla alkaline complex [4] and the Late Neoarchean Koppal syenite pluton [6], have been found in the EDC, which is next to the western edge of the Paleo-Mesoproterozoic Cuddapah Basin. The petrogenesis of these syenites is still not clear. Syenites develop from different geochemical sources, such as the deep continental crust [9], and the metasomatized lithospheric mantle [2], [9]. They evolved because of many magmatic and hydrothermal processes [4]. This paper presents a thorough bulk rock geochemical analysis of the syenites located at Danduvaripalle, situated on the western margin of the Cuddapah Basin within the Eastern Dharwar Craton. These syenites are part of the Paleoproterozoic Dancherla alkaline complex, and the study aims to elucidate their petrogenesis and geodynamic implications.

II THE GEOLOGY STUDYAREA

The Dharwar Craton of the Indian Shield consists of the separate Eastern and Western Dharwar cratons (Fig. 1a), which vary in basement age, characteristics, lithology, prevalence of greenstone belts, crustal thickness, and metamorphic intensity [10], [11]. Furthermore, the Western Dharwar Craton is distinguished by a scarcity of alkaline magmatism compared to its eastern counterpart. Both blocks are stitched along the pronounced mylonitic zone to the eastern edge of the Chitradurga greenstone belt, referred to as the Chitradurga shear zone (Fig. 1a) [12]. The Precambrian lithologies associated with the Dharwar Craton include Archean tonalite–trondhjemite–granodiorite (TTG)-type gneisses interspersed with two generations of greenstones, extensive calc-alkaline granitoids of relatively younger origin, distinct Paleoproterozoic mafic dykes, the crescent-shaped intracratonic Cuddapah Basin from the Paleo-Mesoproterozoic era, and Mesoproterozoic mafic alkaline dykes [10].

Alkaline rocks in the EDC are found in three distinct spatial domains: (1) the Mesoproterozoic (approximately 1400 Ma) intraplate alkaline rocks of the Prakasam Alkaline Province (PAP) at the eastern margin of the Cuddapah Basin, adjacent to the contact zone of the EDC and Eastern Ghats Mobile Belt (EGMB) [13]; (2) the Mesoproterozoic (approximately 1400–1100 Ma) alkaline rocks situated at the western and northern margins, as well as within the Cuddapah Basin, which encompass kimberlites, lamproites, and lamprophyres (Rao et al., 2013 and references therein); and (3) the Paleoproterozoic (approximately 2.21 Ga) Dancherla alkaline complex located outside the western margin of the Cuddapah Basin within the craton (Suresh et al., 2010). The Dancherla alkaline complex, situated to the west and southwest of the Paleo-to Mesoproterozoic Cuddapah Basin (Fig. 1a), consists of syenite bodies located at Dancherla, Peddavaduguru, Vannedoddi, Chintalacheruvu, Danduvaripalle, and Reddypalle [4]. This research examines the Danduvaripalle syenites situated in regional tensional to transtensional crustal zones. The Danduvaripalle syenite (14°39′16″ N, 77°41′50″ E) is oval-shaped plug exhibiting a NNE–SSW strike, situated along the Ragulapadu fault, which offsets the Penakacherla schist belt and TTG gneisses, and is intersected by NE–SW trending mafic dykes (Fig. 1b) [4], [15].

III GEOCHEMISTRY

The syenites are petrographically constituted of K-feldspar perthite, quartz, and plagioclase, with hornblende and biotite as the mafic minerals. Geochemically, these syenites are classified within the syenite area of the figure by [16] (Fig. 2a). The host granites are mostly of a metaluminous (I-type granites) composition (Fig. 2b), exhibiting a saturation index (A/CNK) generally below 1[17]. The analyzed rocks exhibit low MgO content (0.74 wt%) and a Mg# value (36.4 - 46.5). The syenites exhibit high alkali content ($Na_2O + K_2O$= 11.7-12.5), with a K_2O/Na_2O ratio varying from 0.8 to 1.13 (Table 1). The modified alkali–lime index (MALI: $Na_2O + K_2O–CaO$) for these syenites, as reported by [17], and is situated inside the alkalic field on the MALI against SiO_2 diagram(Fig. 3a). The analyzed syenites possess lower Fe-numbers below 0.8 (Fig. 3b), categorizing them as magnesian [17].

Large ion lithophile elements, including Ba, Sr, and Rb, are prevalent in the Danduvaripalle syenite. These syenites exhibit elevated light rare earth element (LREE) contents (600 times chondrite) and are enriched in comparison to heavy rare earth elements (HREEs) on chondrite-normalized REE plots (Fig. 4a). Conversely, a notable reduction of medium rare earth elements (MREE) and heavy rare earth elements (HREE) is seen in Danduvaripalle. The chondrite-normalized REE patterns of the host granites demonstrate to moderate levels of fractionation, as shown by the LREE/HREE ratios $(La/Yb)_N$ = 23.3–49.8 (Table 2). The primitive mantle-normalized multi-element pattern has significant negative troughs at Nb, Ta, La, Ce, Sr, P, and Ti (Fig. 4b), Negative 'TNT' (Ta–Nb–Ti) anomalies are well recognized as indicators of crustally derived rocks and subduction-related rocks.

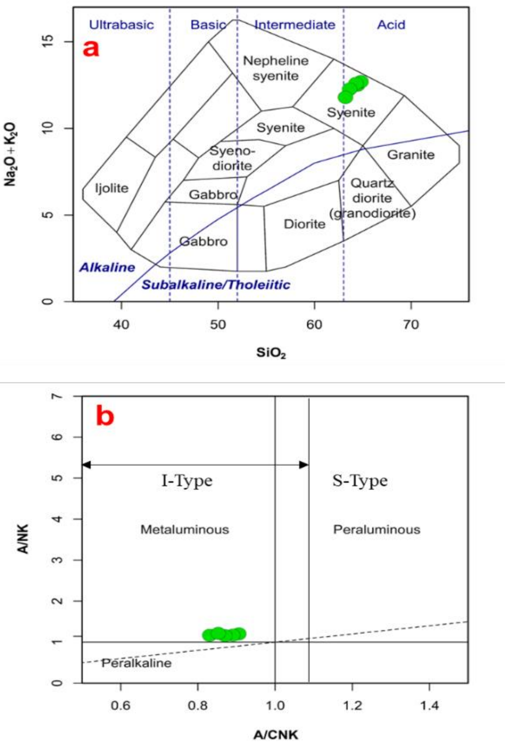

Fig. 2 (a) Total alkali (Na_2O + K_2O wt.%) *vs* SiO_2 diagram (Cox et al., 1979) diagram for the rocks of DVS. (b) Alumina saturation index diagram (Frost et al., 2001) for the rocks of DVS.

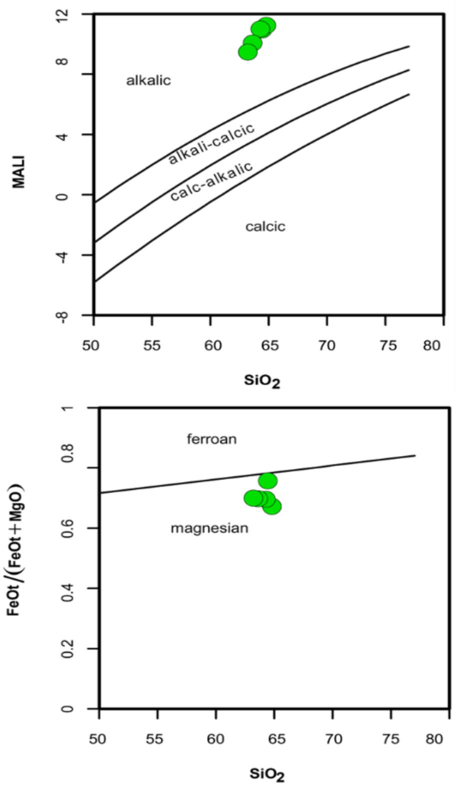

Fig. 3 (a) MALI *vs* K_2O plot (Frost et al. 2001 for the rocks of DVS showing alkaline nature. (b) Binary Fe #(FeO/FeO+MgO) *vs* SiO_2 diagram [17] showing magnesian nature of DVS rocks.

IV DISCUSSION

The syenites from Danduvaripalle exhibit negative LREE anomalies, indicative of increased K, which precedes La in the multi-element sequence (Fig. 4b). The rocks exhibit significantly fractionated LREE/HREE ratios (Fig. 4a), with REE patterns similar to those produced by high-pressure fractionation of an amphibole and garnet-dominated assemblage [18]. Amphibole and garnet may confine MREEs and HREEs, respectively, within their crystal lattice, and a negative and positive correlation between MREE/HREE (e.g., Dy/Yb) and an index of differentiation would indicate the fractionation of amphibole and garnet, respectively [19]. The correlation is illustrated in the analyzed syenites and the concave upward chondrite-normalized REE pattern (Fig. 4a), characterized by significantly depleted HREE concentrations, demonstrates the influence of garnet-dominated fractional crystallization of the parent melt of these syenites (Fig. 5a).

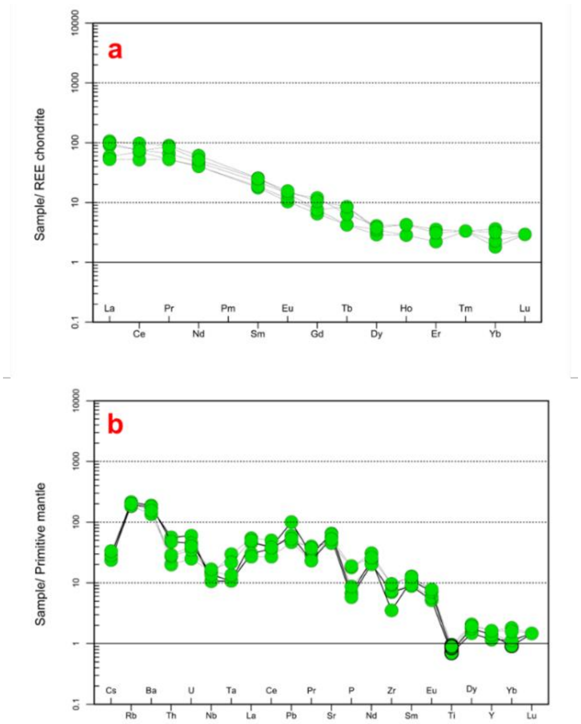

Fig. 4 (a) Chondrite-normalized REE patterns [20] for DVS rocks. (b) Primitive mantle normalized multi-elemental variation plot [21] for DVS rocks.

The negative TNT anomalies in primitive mantle-normalized multi-element patterns are considered indicative of calc-alkaline rocks formed in subduction environments or those originating from the lithospheric mantle that underwent a prior subduction event [22], [23]. Alternatively, rocks exhibiting these geochemical anomalies may originate from the crust since the continental crust has diminished amounts of these high-field strength elements [24]. The Nb/U ratios in the Danduvaripalle syenites are much lower than the mantle array established by mid-ocean ridge basalts (MORBs) and ocean island basalts (OIBs) [21], however they are equivalent to those of the lower continental crust (Fig. 5b). The Danduvaripalle syenite samples exhibit a Th/U ratio between 2.9 and 4.2, exceeding that of MORB melts (approximately 2.5; Sun and McDonough, 1989), while aligning with the ratios of lower continental crust melts (approximately 6.0; Rudnick and Gao, 2003), demonstrating the influence of mafic lower crust in their formation.

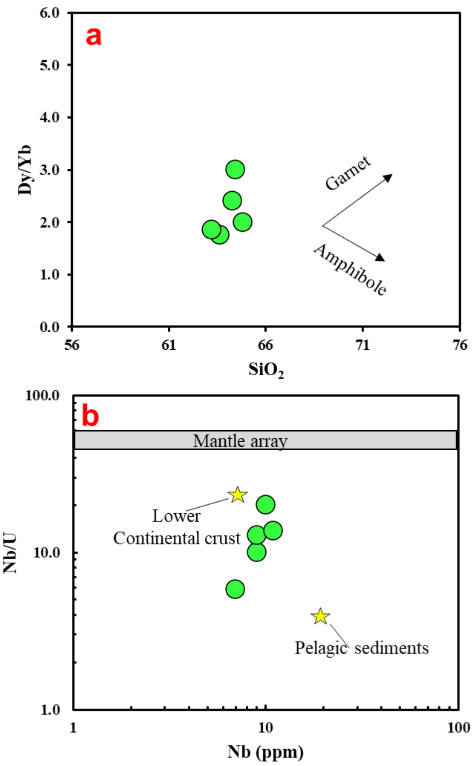

Fig. 5 (a)) SiO2 *vs* Dy/Yb diagrams illustrating the fractional of garnet for DVS samples. (d) Nb (ppm) *vs* Nb/U diagrams displaying the source of DVS samples.

The syenites result from the fractionation of melts characterized by garnet and amphibole, originating from the partial melting of juvenile mafic lower crust composed of garnet amphibolite. The Danduvaripalle syenites are metaluminous and deficient in Cr and Ni, characteristics indicative of I-type granitoids [25]. In the Y + Nb vs Rb and Y vs Nb trace element discrimination map by [26], all examined syenites are situated inside the volcanic-arc granites region (Fig. 6), which seems geochemically analogous to the I-type granitoids identified by [17], [25].

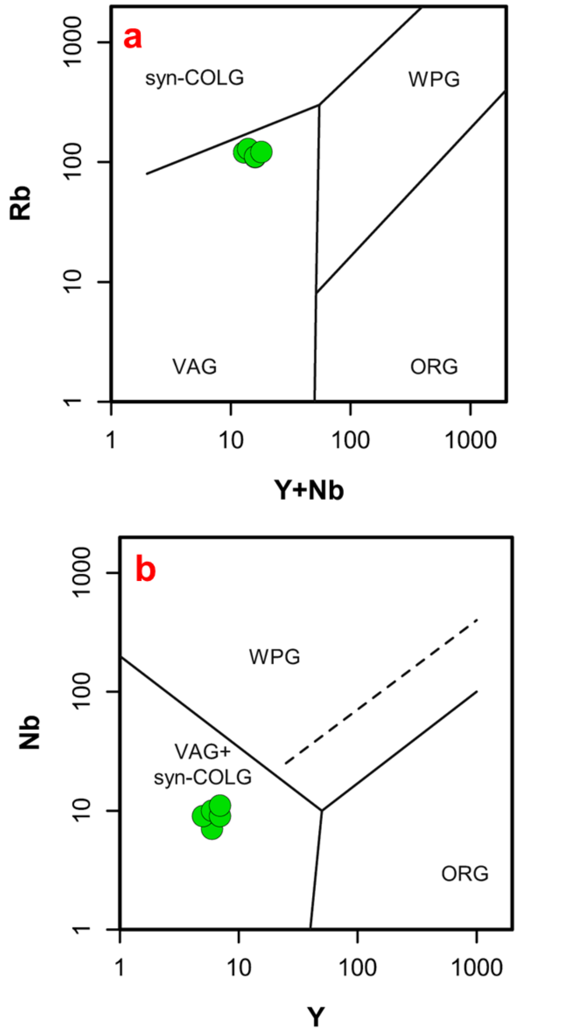

Fig. 6 Tectonic discrimination diagrams [26] depicting syn-collisional and volcanic-arc setting affinity for the DVS rocks.

Crustal thickening may convert the mafic lower crust into garnet-amphibolite and/or amphibole-granulite; however, there is currently no evidence of crustal thickening in the Eastern Dharwar Craton during the Paleoproterozoic. The mafic (amphibolitic) lower crustal source for these syenites was likely formed by the underplating of basalt produced by either mantle wedge or slab melting. Annen et al., 2006 shown by experimental and computational modelling, along with geophysical and petrological research, that the lower continental crust constitutes a deep crustal hot zone formed by the intrusion of hydrous basalts originating from subduction zone mantle as sills. The I-type granitoids are believed to originate from the melting of a meta-igneous source, and the characteristics of the Danduvaripalle syenites, together with their low MgO, Ni, Cr, and Sc content, indicate a crustal source. The ratios of trace elements, namely Nb/U and Th/U, are similar to those found in the lower continental crust [24].

The Dancherla alkaline complex is dated at 2210 ± 110 Ma using the Rb–Sr isochron technique, of which the analysed syenites are a component [4]. While comprehensive geochronological data for these syenites is absent, several general geodynamic hypotheses may be proposed. This alkaline complex is contemporaneous with the approximately 2.21 Ga north–south to NNW–SSE orientated mafic dyke swarm emplacement in the Dharwar Craton [28], [29]. The impingement of the mantle plume at the lithosphere's base likely induced an extensional tectonic regime and an anomalously hot ambient mantle, leading to significant mantle melting that produced mafic dykes supplying the accompanying large igneous province. The partial melting of the suggested mafic lower crustal source may have been initiated by the mantle plume contacting the base of the thinning lithosphere in an extensional environment.

V CONCLUSIONS

The Paleoproterozoic syenites located along the western boundary of the Cuddapah Basin, inside the Eastern Dharwar Craton, are mostly ferroan and metaluminous. The Danduvaripalle syenites have markedly low HREE concentrations and a fractionated, concave-upward REE pattern, indicating significant influence from amphibole and garnet fractionation. Similar to I-type granitoids, the Danduvaripalle syenites exhibit low concentrations of MgO, Ni, and Cr relative to the melts from oceanic slabs (experimental partial melts of amphibolites), while a heightened Th/U ratio suggests that the melt originated from a mafic lower crust that subsequently experienced fractionation of an assemblage primarily composed of amphibole and garnet. The Paleoproterozoic (2210 + 110 Ma) Rb–Sr isochron emplacement age of the Dancherla alkaline complex, which includes these syenites, aligns with the about 2.21 Ga mafic dyke swarm magmatism in the Dharwar region. The partial melting of the suggested mafic lower crustal source may have been initiated by the mantle plume impacting the base of the thinning lithosphere in an extensional environment.

Table 1. Whole-rock major oxide data for Danduvaripalle syenites (DVS).

S no	DV-3	DV-7	DV-9	DV-11	DV-15
SiO_2	64.45	64.81	64.28	63.62	63.21
Al_2O_3	17.71	17.61	17.52	17.32	17.54
Fe_2O_3	2.56	1.96	2.16	3.17	3.46
MnO	0.03	0.04	0.06	0.08	0.09
MgO	0.74	0.86	0.85	1.24	1.34
CaO	1.57	1.47	1.58	2.19	2.32
Na_2O	5.61	5.96	6.47	6.41	6.38
K_2O	6.89	6.74	6.11	5.85	5.41
TiO_2	0.15	0.14	0.17	0.19	0.18
P_2O_5	0.14	0.12	0.18	0.37	0.39
LOI	0.31	0.59	1	1	1.1
Sum	100.16	100.3	100.38	101.44	101.42
Na_2O/K_2O	0.81	0.88	1.05	1.09	1.17
Na_2O+K_2O	12.5	12.7	12.58	12.26	11.79

Table 2. Trace and Rare elememtal data for Danduvaripalle syenites (DVS).

S no	DV-3	DV-7	DV-9	DV-11	DV-15
Sc	1	1	2	2	2
V	27	24	25	49	51
Ba	1148	1241	1187	891	1021
Sr	1288	1087	1254	901	1045
Y	6	5	6	7	7
Zr	37	74	77	98	101
Cr	29	25	36	42	46
Co	4	4	5	8	9
Ni	29	22	26	22	24
Cu	11	12	11	11	13
Zn	50	32	35	41	46
Ga	16	16	18	16	19
Rb	120	128	110	111	121
Nb	7	9	10	9	11
Cs	0.5	0.6	0.5	0.6	0.7
La	29.89	19.6	17.5	35.1	32.4
Ce	65.21	61	45.2	84	64
Pr	7.4	5.9	5.9	10.1	9.5
Nd	29.56	25.6	25.3	38.5	32.5
Sm	4.5	3.6	3.8	5.2	5.1
Eu	1.1	0.8	0.9	1.1	1.2
Gd	2.1	1.8	2.1	3.3	2.9
Tb	0.4	0.2	0.2	0.3	0.4
Dy	1.2	1	1.2	1.4	1.3
Ho	0.2	0.2	0.2	0.3	0.3
Er	0.5	0.5	0.5	0.8	0.7
Tm	0.1	0.1	0.1	0.1	0.1
Yb	0.4	0.5	0.5	0.8	0.7
Lu	0.1	0.1	0.1	0.1	0.1
Hf	1	1.5	1.6	1.9	1.8
Ta	0.4	0.4	0.5	1.1	0.8
Pb	15	9	7	7	8
Th	4.5	3.8	1.6	2.2	2.3
U	1.2	0.9	0.5	0.7	0.8
Dy/Yb	3	2	2.4	1.75	1.85
Nb/U	5.8	10.0	20.0	12.9	13.8
Th/U	3.8	4.2	3.2	3.1	2.9
Eu/Eu*	1.1	0.97	0.98	0.82	0.96
La_N/Yb_N	49.82	26.13	23.33	29.25	30.86
La_N/Sm_N	4.09	3.35	2.83	4.15	3.91
Sum_REE	142.66	120.9	103.5	181.1	151.2

ACKNOWLEDGEMENTS

The authors thank the Head of the Department of Geology, Osmania University (Hyderabad), for pursuing research. This work forms a part of the Ph.D. thesis of the first author. Additionally, we would like to thank to Dr A. Ajay Kumar, for assistance with geological map of this study.

REFERENCES

[1] B. R. Frost and C. D. Frost, “A geochemical classification for feldspathic igneous rocks,” J. Petrol., vol. 49, no. 11, pp. 1955–1969, 2008, doi: 10.1093/petrology/egn054.

[2] M. de L. da S. Rosa et al., “Neoproterozoic anorogenic magmatism in the Southern Bahia Alkaline Province of NE Brazil: U-Pb and Pb-Pb ages of the blue sodalite syenites,” Lithos, vol. 97, no. 1–2, pp. 88–97, 2007, doi: 10.1016/j.lithos.2006.12.011.

[3] G. Perini, F. J. Tepley, J. P. Davidson, and S. Conticelli, “The origin of K-feldspar megacrysts hosted in alkaline potassic rocks from central Italy: A track for low-pressure processes in mafic magmas,” Lithos, vol. 66, no. 3–4, pp. 223–240, 2003, doi: 10.1016/S0024-4937(02)00221-9.

[4] G. Suresh, R. Ananthanarayana, R. C. Hanumanthu, S. Ghosh, A. A. Kumar, and K. V. S. Reddy, “Geology of pulikonda and dancherla alkaline complexes, Andhra Pradesh,” J. Geol. Soc. India, vol. 75, no. 4, pp. 576–595, 2010, doi: 10.1007/s12594-010-0052-6.

[5] N. Sridhar, R. M. Reddy, and G. Nagendrababu, “Quartz syenites from the Prakasam alkaline province, Southern India; A comparative study with special emphasis on their rare earth element contents,” no. 5, pp. 507–517, 2018.

[6] B. Chadwick, V. N. Vasudev, and G. V. Hegde, “The Dharwar craton, southern India, interpreted as the result of Late Archaean oblique convergence,” Precambrian Res., vol. 99, no. 1–2, pp. 91–111, 2000, doi: 10.1016/S0301-9268(99)00055-8.

[7] N. V. Chalapathi Rao, A. N. Dongre, and V. S. Kale, “An alternate perspective on the opening and closing of the intracratonic Purana basins in peninsular India,” J. Geol. Soc. India, vol. 86, no. 1, pp. 118–119, 2015, doi: 10.1007/s12594-015-0289-1.

[8] N. V. Chalapathi Rao and R. K. Srivastava, “A new find of boninite dyke from the Palaeoproterozoic Dongargarh Super group: Inference for a fossil subduction zone in the Archaean of the Bastar craton, Central India,” Neues Jahrb. fur Mineral. Abhandlungen, vol. 186, no. 3, pp. 271–282, 2009, doi: 10.1127/0077-7757/2009/0151.

[9] N. Eby et al., “A-type Granites Classification and Petrogenesis A Multi-Dimensional Problem,” vol. 89, no. February 2012, pp. 37–41, 2010, doi: 10.1016/j.lithos.2005.10.002.

[10] R. Ramakrishnan, M., Vaidyanadhan, Geology of India, Vol. 1. Geological Society of India, Bangalore., 2008.

[11] M. Jayananda, M. Santosh, and K. R. Aadhiseshan, “Formation of Archean (3600–2500 Ma) continental crust in the Dharwar Craton, southern India,” Earth-Science Rev., vol. 181, pp. 12–42, 2018, doi: 10.1016/j.earscirev.2018.03.013.

[12] D. Chardon, M. Jayananda, T. R. K. Chetty, and J. J. Peucat, “Precambrian continental strain and shear zone patterns: South Indian case,” J. Geophys. Res. Solid Earth, vol. 113, no. 8, pp. 1–16, 2008, doi: 10.1029/2007JB005299.

[13] D. Upadhyay, M. M. Raith, K. Mezger, and K. Hammerschmidt, “Mesoproterozoic rift-related alkaline magmatism at Elchuru, Prakasam Alkaline Province, SE India,” Lithos, vol. 89, no. 3–4, pp. 447–477, 2006, doi: 10.1016/j.lithos.2005.12.015.

[14] N. V. C. Rao, F. Y. Wu, R. H. Mitchell, Q. L. Li, and B. Lehmann, “Mesoproterozoic U-Pb ages, trace element and Sr-Nd isotopic composition of perovskite from kimberlites of the Eastern Dharwar craton, southern India: Distinct mantle sources and a widespread 1.1Ga tectonomagmatic event,” Chem. Geol., vol. 353, pp. 48–64, 2013, doi: 10.1016/j.chemgeo.2012.04.023.

[15] A. Pandey, N. V. Chalapathi Rao, W. Rahaman, V. Seth, and S. Sahoo, “Paleoproterozoic metaluminous syenites synchronous with the c. 2.21 Ga mafic dyke swarms from the Eastern Dharwar Craton, India: implications for alkaline magmatism associated with the breakup of supercraton Superia,” Geol. Soc. Spec. Publ., vol. 513, no. 1, pp. 133–156, 2022, doi: 10.1144/SP513-2020-92.

[16] K. G. Cox, J. D. Bell, and R. J. Pankhurst, “The Interpretation of Igneous Rocks George Allen and Unwin,” London, United Kingdom, 450p, 1979.

[17] B. R. Frost, C. G. Barnes, W. J. Collins, R. J. Arculus, D. J. Ellis, and C. D. Frost, “A geochemical classification for granitic rocks,” J. Petrol., vol. 42, no. 11, pp. 2033–2048, 2001, doi: 10.1093/petrology/42.11.2033.

[18] C. G. Macpherson, S. T. Dreher, and M. F. Thirlwall, “Adakites without slab melting: High pressure differentiation of island arc magma, Mindanao, the Philippines,” Earth Planet. Sci. Lett., vol. 243, no. 3–4, pp. 581–593, 2006, doi: 10.1016/j.epsl.2005.12.034.

[19] J. P. Davidson, D. J. Morgan, B. L. A. Charlier, R. Harlou, and J. M. Hora, “Microsampling and isotopic analysis of igneous rocks: Implications

for the study of magmatic systems," Annu. Rev. Earth Planet. Sci., vol. 35, pp. 273–311, 2007, doi: 10.1146/annurev.earth.35.031306.140211.

[20] N. Nakamura, "Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites," Geochim. Cosmochim. Acta, vol. 38, no. 5, pp. 757–775, 1974, doi: 10.1016/0016-7037(74)90149-5.

[21] S. S. Sun and W. F. McDonough, "Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes," Geol. Soc. Spec. Publ., vol. 42, no. 1, pp. 313–345, 1989, doi: 10.1144/GSL.SP.1989.042.01.19.

[22] L. Zhang et al., "Generation of leucogranites via fractional crystallization : A case from the Late Triassic Luoza batholith in the Lhasa Terrane , southern Tibet," Gondwana Res., vol. 66, pp. 63–76, 2019, doi: 10.1016/j.gr.2018.08.008.

[23] Q. Ma, Y. G. Xu, X. L. Huang, J. P. Zheng, X. Ping, and X. P. Xia, "Eoarchean to Paleoproterozoic crustal evolution in the North China Craton: Evidence from U-Pb and Hf-O isotopes of zircons from deep-crustal xenoliths," Geochimica et Cosmochimica Acta, vol. 278. pp. 94–109, 2020. doi: 10.1016/j.gca.2019.09.009.

[24] R. L. Rudnick and S. Gao, "Composition of the Continental Crust," Treatise on Geochemistry, vol. 3–9, no. 1976, pp. 1–64, 2003, doi: 10.1016/B0-08-043751-6/03016-4.

[25] B. W. Chappell and A. J. R. White, "Two contrasting granite types: 25 years later," Aust. J. Earth Sci., vol. 48, no. 4, pp. 489–499, 2001, doi: 10.1046/j.1440-0952.2001.00882.x.

[26] J. A. Pearce, S. J. Lippard, and S. Roberts, "Characteristics and tectonic significance of supra-subduction zone ophiolites," Geol. Soc. Spec. Publ., vol. 16, pp. 77–94, 1984, doi: 10.1144/GSL.SP.1984.016.01.06.

[27] C. Annen, J. D. Blundy, and R. S. J. Sparks, "The genesis of intermediate and silicic magmas in deep crustal hot zones," J. Petrol., vol. 47, no. 3, pp. 505–539, 2006, doi: 10.1093/petrology/egi084.

[28] A. Kumar, M. A. Hamilton, and H. C. Halls, "A Paleoproterozoic giant radiating dyke swarm in the Dharwar Craton, southern India," Geochemistry, Geophys. Geosystems, vol. 13, no. 1, Feb. 2012, doi: 10.1029/2011GC003926.

[29] R. K. Srivastava, M. Jayananda, G. C. Gautam, and A. K. Samal, "Geochemical studies and petrogenesis of ~2.21–2.22 Ga Kunigal mafic dyke swarm (trending N-S to NNW-SSE) from eastern Dharwar craton, India: Implications for Paleoproterozoic large igneous provinces and supercraton superia," Mineral. Petrol., vol. 108, no. 5, pp. 695–711, Oct. 2014, doi: 10.1007/s00710-014-0327-5.

[30] A. Ajay Kumar and C. Ashok, "Geochemistry and mineral chemistry of the armoor granitoids, eastern dharwar craton: implications for the redox conditions and tectono-magmatic environment," Acta Geochim., vol. 43, no. 1, pp. 110–133, 2024, doi: 10.1007/s11631-023-00647-1.