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Quartz syenites from the Prakasam alkaline province, Southern India; A comparative study with special emphasis on their rare earth element contents

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ABSTRACT
This paper elucidates the petrographic, geochemical and petrogenetic aspects of the quartz syenites from the Purimetla and other quartz syenite bearing plutons of the Prakasam Alkaline Province (PAP), which are towards the east of the Cuddapah basin within the Cuddapah Intrusive Province (CIP), Southern India. A comparative study of the REE contents of these quartz syenite bodies is presented with emphasis on their LREE abundance. Petrographically these quartz syenites are composed of K-feldspar perthite, quartz and plagioclase, while hornblende and biotite are the mafic minerals. These metaluminous rocks are enriched in total alkalies especially K_2O, moderate in FeO^t and impoverished in MnO, MgO, and CaO. The normative hypersthene indicates that these rocks can be designated under sub alkaline category. The chondrite normalized REE patterns indicate the LREE enrichment over HREE with a significant negative Eu anomaly. Allanite, apatite, zircon and monazite are the accessory phases that host significant LREE in these syenites. Based on the geological settings of the syenite plutons, which has quartz syenites as an integral part and considering their proximity to gabbros has led to a new petrogenetic model. The thermal trigger caused by the induction of gabbroic magma into the continental crust initiated the partial melting of LREE enriched amphibolite crust, yielding a melt with the composition corresponding to melasyenite. This melasyenite upon fractional crystallization produced the quartz syenites within the various syenite plutons emplaced into the PAP.

Key words: Cuddapah intrusive province, Quartz syenites, LREE enrichment, negative Eu anomaly.

INTRODUCTION

Alkaline igneous rocks however are sparse in volumetric abundance in geological record. Significant syenitic magmatism corresponding to the Proterozoic eon has been found in various continental platforms around the world. This Proterozoic eon is characterized by an unusual abundance of ferroan feldspathic rocks that range in composition from granite to quartz syenites to feldspathoid-bearing syenites (Frost and Frost, 2013). Parental magmas for the Alkaline rocks are generally thought to be derived from the partial melting of metasomatised (LILE, LREE enriched lithospheric mantle) source (Fitton and Upton 1987), or asthenosphere mantle (Menzies, 1987) or mixed of these two. Some others opined that the alkaline rich syenitic magmas could generate by partial melting of lower crust with variable upper crustal contamination (Smithies and Champion 1999). Several syenite plutons – for reference, Superior Province (Sutcliffe et al., 1990), Yilgarn Craton (Smithies and Champion 1999) and Karelia (Mikkola et al., 2011, Heilimo et al., 2016) – known to contain alkali-rich quartz syenites, syenites and less abundant quartz monzonite.

Mesoproterozoic rifting between 1.35 and 1.5 Ga, resulted in the emplacement of alkaline complexes within the Great Proterozoic Fold Belt (GIPFB) of India (Vijaya Kumar et al., 2011). The emplacement of syenites in the Prakasam Alkaline Province (PAP) and Eastern Ghat Granulite Belt (EGGB) along with the granitic rocks in Nellore-Khammam schist belt (NKSB) between 1.3 to 1.5 Ga indicates rift related magmatism in East Gondwana (Babu, 2008; Sesha Sai, 2013). Alkaline (feldspathoidal and non feldspathoidal) and subalkaline rocks with varied mineralogical and geochemical characteristics are found in spatial and temporal association with each other and confined to the east of the cuddapah basin within rift and subduction settings respectively (Upadhyay et al., 2006; Upadhyay, 2008; Vijaya Kumar et al., 2015; Subramanyam et al., 2016).

In the PAP the association of undersaturated, saturated and oversaturated rocks in major alkaline plutons i.e. Elchuru (Leelanandam, 1980, 1981, 1989; Madhavan and Leelanandam, 1988; Nag et al., 1984; Czygan and Goldenberg, 1989; Upadhyay et al., 2006); Purimetla (Leelanandam and Ratnakar,1983; Ratnakar and Leelanandam, 1986; Subramanyam et al., 2016); Uppalapadu (Leelanandam, 1981; Krishna Reddy et al., 1998; Vijaya Kumar et al., 2007) offer interesting association to understand their interrelation. Such an association is witnessed in the above stated plutons confined to the rift zones in the eastern part of the cuddapah basin. This association along with gabbros and granitoids constitute the cuddapah intrusive province (CIP) (Madhavan et al., 1995a, 1999; Madhavan, 2002). The petrology, geochemistry, geochronology and genesis of diverse alkaline and subalkaline rock types in this province have been subjected to investigations during the last few decades (Leelanandam et al., 1989, Leelanandan, 1989; Madhavan et al., 1995a). Quartz syenite together with other syenite variants (saturated and undersaturated) constitutes either large plutons or minor intrusives in the PAP, which have spatial and temporal association with gabbros and granitoids.

The present study is aimed to decipher the geological, mineralogical and geochemical characteristics along with the REE concentrations of quartz syenites from Purimetla and to compare with those from other quartz syenites of the PAP (figure 1A) i.e. Vikurthi (Srinivas, 1992, Madhavan, et al., 1995b), Kotappakonda (Madhavan, et al., 1995b), Elchuru (Ratnakar and Vijaya Kumar, 1995), Settupalle (Srinivasan, 1981, Leelanandam et al.,1989), Purimetla (Ratnakar and Leelanandam, 1986) and Uppalapadu (Krishna Reddy et al.,1998; Czygan and Goldenberg, 1989), intrusive quartz syenites of the Proterozoic Podili granite towards the east of Cuddapah basin (Prasada Rao and Ahluwalia, 1974; Madhavan and Sugrive Reddy, 1990; Sesha Sai, 2013) and Chanduluru (Sharma and Ratnakar, 2000). Minor quartz syenite occurrences are also found at Mundlamuru of Pasupugallu gabbro pluton (Jyothender Reddy, 1989) and Vemanabanda, which are not covered in the present study. All the syenites are emplaced within the suture/rift zone confined to the east of the cuddapah basin and exactly in between the Dharwar craton and the Eastern Ghat Mobile Belt (EGMB) (Leelanandam, 1981, 1989, Leelanandam et al., 1989; Sharma and Ratnakar, 1994; Subba Rao, 1994; Madhavan, et al., 1999; Upadhyay et al., 2006). The above mentioned syenite bodies are constituted by undersaturated saturated and few oversaturated components. All these alkaline and subalkaline intrusives form a part of the recently recognized deformed alkaline rocks and carbonatites (DARC) (Leelanandam et al., 2006). Elchuru, Purimetla and Uppalapadu syenite complexes are predominantly composed of feldspathoidal rocks, which dominate the non feldspathoidal counterparts. Whereas the Vikurthi, Settupalle, Chanduluru syenite plutons are mainly constituted by non feldspathoidal syenites.

GEOLOGICAL SETTING

The discrete syenite complexes associated with quartz syenites show variation in their geology and areal extensions as they are emplaced within suture/rift zone/subduction zones close to eastern margin of the cuddapah basin. All the syenite complexes trend in a row parallel to NE-SW direction. The distorted spindle shaped Purimetla alkaline pluton (Figure 1B) (Prasada Rao et al., 1988; Ratnakar et al., 1980) has an aerial extension of 7 sq km and is located midway between the Elchuru and Uppalapadu alkaline complexes. The Rb-Sr isochron and U-Pb of zircon dating ages indicate that the Purimetla alkaline complex was emplaced during 1369±33 Ma (Sarkar et al., 1994) and 1334±15 Ma (Subramanyam et al., 2016) respectively with an initial Sr_i ratio of 0.70409.

Subsolvus and hypersolvus nepheline syenite is the predominant constituent of the pluton followed by subordinate hornblende syenite and less abundant quartz syenite. The mafic rocks are mainly represented by gabbros, malignite and later formed ocellar lamprophyres. The alkaline lamprophyres (Comptonite) show an intrusive relationship. The details of the quartz syenite representing other syenite plutons are listed in (Table 1).

PETROGRAPHY

The nepheline syenite which is the major rock type of the pluton is found as minor outcrops as it is mostly concealed under the soil. A minor quartz syenite exposure is found at the junction of amphibolites and hornblende syenite towards the NE part of the Purimetla pluton (Figure 1B). The quartz syenite of Purimetla which is grey in colour and medium to coarse grained exhibits hypidiomorphic texture. Subhedral to euhedral amphibole shows moderate pleochroism in shades of dark green to brownish green. Subhedral orthoclase frequently exhibits perthitic and myrmekitic textures. The discrete plagioclase conspicuously shows lamellar twinning. Granular quartz is mainly found interstitial between the feldspar grain boundaries. Amphibole and biotite are occasionally seen as clusters along with feldspar and quartz. Opaque phases are represented by magnetite with hematite lamina. Allanite, zircon, diamond shaped sphene, garnet along with prominent apatite and calcite are the accessory phases (Table 2). Zircon occurs as inclusions within K-feldspar perthite and mafic clusters.

All the quartz syenites of the PAP are leucocratic to mesocratic, coarse to medium grained and hypidiomorphic textured (seldom porphyroclastic). Principally, they are constituted by microcline or orthoclase perthitic feldspar (vein or braided, ≥ 60), amphibole (dark green to brownish green, 15-20%, with very few less than15%) as the major components along with granular quartz (5-12%), discrete plagioclase (3-5%) and biotite (brownish yellow to reddish brown) as the minor components. Calcite, sphene, garnet, zircon, allanite and apatite are found in trace amounts. However, allanite, euhedral zircon, elongated apatite and monazite are more abundant in Purimetla quartz syenites (Figure 2). Myrmekitic intergrowths are found often in most of the quartz syenites of the PAP. Invariable presence

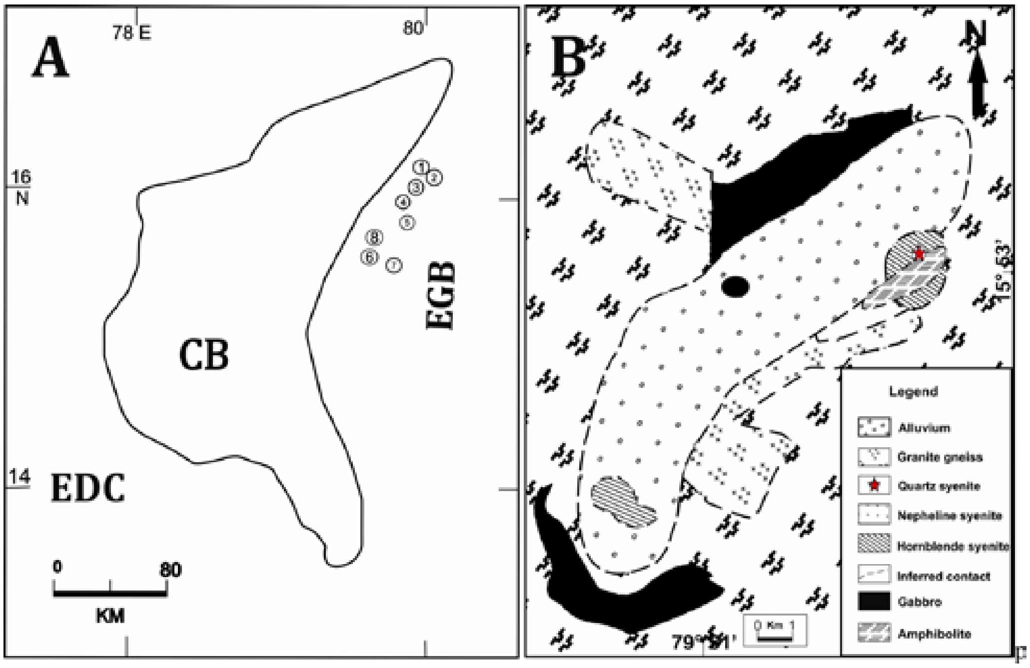

Figure 1. A. Map showing the generalized outline of the Cuddapah basin and its contiguous EDC (Eastern Dharwar Craton) and EGB (Eastern Ghats Belt) with the quartz syenite locations on the eastern margin. 1.Vikurthi; 2.Kotappakonda; 3.Elchuru; 4.Settupalle; 5.Purimetla; 6.Podili; 7. Uppalapadu; 8. Chanduluru. B. Geological map of Purimetla alkaline pluton (after Leelanandam and Ratnakar, 1983) showing the quartz syenite location (indicated as star).

Table 1. Major Quartz syenite occurrences in the Prakasam Alkaline Province (PAP).

S. No	Location	Age	Areal extension	Major rock types	Country rock	Category
1	Vikurthi	Mesoproterozoic	4 Km^2	Quartz syenite, fine grained quartz syenite, mafic xenolith enclave, pegmatite, quartz reef	Archean Granite	SOS
2	Kotappakonda	NA	NA	nepheline syenite and quartz syenite	Archean Granite and Eastern Ghat charnokites	SUS, SOS
3	Elchuru	Mesoproterozoic	16 Km^2	Shonkinite, malignite, nepheline syenite, mica lamprophyre, quartz syenite	Charnokite, Khondalite, gabbros, quartzo feldspathic schists, Archean gneiss	SUS, SOS
4	Settupalle	Mesoproterozoic	40 Km^2	Quartz syenite, hornblende syenite, ferrosyenite and minor nepheline syenite	Archean granite gneiss, gabbro, amphibolite	SUS, SS,SOS
5	Purimetla	Mesoproterozoic	7 Km^2	Shonkinite, malignite, nepheline syenite, hornblende syenite, quartz syenite	Archean gneiss, gabbro, amphibolite	SUS,SS,SOS
6	Chanduluru	NA	NA	Melasyenite, hornblende-quartz syenite, biotite-quartz syenite, syenite	Granite, gabbro, quartzite, biotite schist/ phyllite	SS,SOS
7	Uppalapadu	Mesoproterozoic	30 Km^2	Nepheline syenite, hornblende syenite, Quartz syenite, ferrosyenite	Granite gneiss, gabbros, amphibolite, biotite schist	SUS,SS,SOS
8	Podili	NA	12Km^2	Quartz syenite, nepheline normative micro syenite, alkali ferrosyenite	Granite, gabbro	SS,SOS

SUS: Silica undersaturated; SS: Silica saturated; SOS: Silica oversaturated. NA-Not available of discrete plagioclase denotes that these rocks must have crystallized under subsolvus conditions (Madhavan, et al., 1995b). Among all the quartz syenites of the PAP, those from Vikurthi and Kotappakonda consist of modal pyroxenes (Table 3). The petrographic characters of the PAP quartz syenites are listed in Table 2.

GEOCHEMISTRY

Analytical Methods

The major oxide analysis of quartz syenites of both the Purimetla and Settupalle are carried out in NGRI, Hyderabad. A Philips MagiX PRO, Model PW 2440, wavelength dispersive X-ray fluorescence spectrometer, coupled with an automatic sample changer PW 2540 and provided with suitable software SUPER Q 3.0, was used for this study (Philips, Eindhoven, Netherlands). SY-2 is the standard used for the correlation. The REE data is obtained from the AMD laboratories, Hyderabad. REE concentrations are determined by ICPAES (Inductively coupled plasma atomic emission spectrometer) ULTIMA-2, JOBINYVON, France made instrument. ICPAES is calibrated using mixed standard solution. The solution samples are introduced into plasma for measuring the emission intensities. Unknown concentrations are calculated from the calibration curves.

RESULTS AND DISCUSSIONS

Major oxides

For this comparative study, the geochemical data of quartz syenites of PAP, published by different authors is used. The Purimetla quartz syenites have higher amounts of SiO_2, total alkalies chiefly K_2O over Na_2O and are of metaluminous nature. On the other hand, these are low in FeO_t, MnO, MgO, CaO, TiO_2 and P_2O_5. Among all the quartz syenites of the PAP, the Vikurthi and Kotappakonda quartz syenites are peculiar in their geochemical characteristics as they are enriched in alkalies, FeOt, MgO, CaO, TiO_2, and P_2O_5, moderate in Al_2O_3 and relatively low in silica. All the remaining quartz syenites from the PAP show enrichment in total alkalies, with the K_2O over Na_2O denoting a high K_2O/Na_2O ratios (generally >1.5), along with variable Al_2O_3 (Table 4). Higher K_2O content is however noted to be a general feature in all other alkaline plutons of PAP (Krishna Reddy et al., 1998; Madhavan et al., 1999). Except the Vikurthi and Kotappakonda quartz syenites all the others are impoverished in MnO, MgO, CaO, TiO_2, P_2O_5 and enriched in SiO_2 contents. When the quartz syenites of PAP are plotted in the DI (Differentiation index (normative Q+or+ab+ne+lc, Thornton and Tuttle 1960) vs major oxide diagram they form a perfect fractionated trend from the melasyenite (inferred here as the parentage for the quartz syenites of the PAP) (Figure 3).

All the quartz syenites are hypersthene normative (Table 4), although some samples do not contain normative hypersthene, may be because of their alkaline affinity. The present study (Purimetla and Settupalle) samples show very low to moderate hypersthene abundance in their norm this could be due to their alkaline affinity. Thus, normative hypersthene imparts the subalkaline character to these quartz syenites. The high differentiation index (DI) (Table 4) of all the quartz syenites of the PAP reflects their most evolved compositions.

REE concentrations

The chondrite normalized REE patterns (Figure 4) of Purimetla quartz syenite depict a characteristic anomalous LREE enrichment over HREE with a steep inclination towards the HREE from LREE along with a significant strong negative Eu anomaly. Among all the studied quartz syenites of the PAP, the Purimetla and Chanduluru quartz syenites show enrichment in total REE concentration with special reference to LREE 1484-1826 ppm and 1116-1147 ppm respectively. The total REE concentrations (Table 5) of the quartz syenites from different suits of the PAP show a wide range. The PAP quartz syenites depict enrichment in LREE and depletion in HREE, with a pronounced negative Eu anomaly. The LREE/HREE ratios of these rocks are high in Purimetla, Vikurthi and moderate in Chanduluru and low in Elchuru and Settupalle. A pronounced negative Eu anomaly is probably produced by the progressive fractionation of plagioclase from the residual melts. Absence of considerable negative Eu anomaly in the melasyenite and presence of it in the quartz syenites imply that the quartz syenites are evolved from the melasyenite. Besides the above the Vikurthi and Uppalapadu quartz syenites also have considerable LREE enrichment. The remaining suits contain an extremely low to moderate concentrations of REE especially LREE. The LREE budget of these quartz syenites is thought to be controlled by the presence of allanite, apatite, zircon and monazite. The variability in the HREE patterns of the present study could have been controlled by garnet, sphene, which were probably retained with the residuum (Sharma and Ratnakar, 2000).

A similarity is seen in the major oxide and high LREE concentrations with negative Eu anomaly in quartz syenites of Purimetla, Chanduluru (Table 4 and 5) and Barrel Spring pluton, southeastern California, USA (Gleason et al., 1994). The quartz syenite of Barrel Spring pluton shows La (488 ppm), Ce (846 ppm) and Nd (292 ppm). Both in Barrel spring pluton and Purimetla, Chanduluru plutons the LRRE enrichment is connected to the presence of allanite, apatite, zircon and monazite.

Table 2. Details of the petrographic characteristics and mineral assemblages of quartz syenites of PAP, Vikurthi & Kotappakonda (Madhavan, et al., 1995b); Elchuru (Ratnakar and Vijaya Kumar, 1995); Settupalle (Leelanandam et al.,1989); Purimetla (Ratnakar and Leelanandam 1986 & Present authors) ; Uppalapadu (Krishna Reddy et al.,1998); Podili (Madhavan and Sugrive Reddy, 1990); Chanduluru (Sharma and Ratnakar, 2000)

S. No	Location		Crystallinity	Texture	Petrography	
					Essential minerals	**Accessory minerals**
1	Vikurthi		Coarse to medium grained	Equigranular hypidiomorphic	Perthitic microcline, pyroxene, hornblende, biotite, quartz, plagioclase	Sphene, ilmenite, magnetite, Apatite, calcite
2	Kotappakonda		Coarse to medium grained	Equigranular hypidiomorphic	Perthitic microcline, pyroxene, hornblende, biotite, , plagioclase, quartz,	Sphene, ilmenite, magnetite, Apatite, calcite
3	Elchuru		Medium grained	hypidiomorphic	Perthitic microcline, albite, amphibole (ferrohastingsite), biotite, quartz	Apatite
4	Settupalle		Medium to coarse	Equigranular hypidiomorphic	Microcline perthite, microcline, plagioclase, quartz, amphibole, biotite	Calcite, zircon, opaques
5	Purimetla		Coarse grained	Hypidiomorphic and seldom Porphyroclastic	Orthoclase perthite, amphibole, quartz, plagioclase, biotite	Magnetite, ilmenite, garnet, monazite, zircon, allanite, sphene, apatite
6	Chanduluru	HQS	Medium to coarse	hypidiomorphic	Perthitic orthoclase, amphibole, quartz, plagioclase	Zircon, sphene, garnet, apatite and fluorite
		BQS	Coarse grained	hypidiomorphic	Orthoclase perthite, quartz, biotite, amphibole	apatite, sphene, zircon, garnet, fluorite, magnetite
		M.Sye	Fine to medium	hypidiomorphic	Plagioclase, hornblende, K-feldspar perthite, quartz	apatite, sphene, zircon, garnet
7	Uppalapadu		Medium to Coarse grained	hypidiomorphic	K-feldspar perthite, quartz, amphibole, biotite, plagioclase	Calcite, zircon, magnetite, apatite
8	Podili		Medium to coarse	Equigranular hypidiomorphic	Microcline meso perthite, quartz, plagioclase, amphibole, biotite.	Magnetite, ilmenite, apatite

HQS: Hornblende quartz syenite; BQS: Biotite quartz syenite; M.Sye- Mela syenite.

Table 3. Average modal compositions of (Vol %) of quartz syenites of PAP (References are mentioned at table 4)

S.No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
	IS42	**IS11**	**QSK11**	**QSK10**	**J15/93b**	**S1**	**S20**	**Stp**	**P7**	**P11**	**PT81**	**PT52**	**U18**	**U66**	**U11**	**D26**	**D49**	**D30**	**PO**
K-Fl	53.8	57.4	47	56.4	93	51	53.8	53.6	52.4	51.9	39.8	58.4	61	72	64.9	44.8	50	62.9	57.27
Qtz	11.3	10.9	4.3	12.3	2	10.9	11.2	11.5	9.8	10	6.8	10	9	11	17.7	10.2	12.6	22.7	15.85
Plag	0.4	1.4	----	0.4	3	18	20.9	25	18.9	19.8	28.3	14.3	5	4	12.2	8.7	7.9	3.1	3.92
Pyr	3.6	5.2	7.5	0.9	----	----	----	----	----	----	----	----	----	----	----	----	----	----	0.8
Amp	10.7	13.8	22.5	6.9	2	7.6	8.2	8.2	19.2	18.7	22.5	10.7	16	8	3.3	25.7	18.9	0.5	15.97
Bio	18.2	9.6	11.2	20	Tr	2.8	3.2	3.52	1.2	1	Tr	1.8	3	2	0.4	8.2	6.8	7.3	3.95
Sph	0.9	0.5	6.2	2.5	----	0.5	0.5	0.7	0.5	0.4	0.4	0.5	----	----	0.4	Tr	0.4	0.6	1.2
Mag	1.2	0.4	0.6	1.1	----	0.8	0.7	0.9	0.7	0.9	0.8	1		----	0.7	0.2	0.3	----	2.63
Cal	----	0.4	0.4	----	----	0.4	0.3	0.4	0.3	0.2	0.4	0.4	----	----	----	----	----	----	----
Apa	----	0.4	0.3	----	----	0.3	0.6	0.8	1.5	1.6	1.6	1.5	3	2	1	0.8	0.9	0.9	0.7
Alla	----	----	----	----	----	0.4	0.3	----	2.3	2	1.2	1.4	----	----	----	----	----	----	----
Zir	----	----	----	----	----	0.6	0.9	0.9	1.3	1.7	1.3	1	Tr	1	0.8	1.5	2.5	0.8	0.6
Mon	----	----	----	----	----	0.2	0.4	----	0.3	0.6	0.4	0.3	----	----	----	----	----	----	----
Gar	----	----	----	----	----	----	----	----	0.3	0.2	0.2	0.2	----	----	----	----	0.2	0.9	----

Tr: Trace, K-Fl: K Feldspar; Qtz: Quartz; Plag: Plagioclase; Pyr: Pyroxene; Amp: Amphibole; Bio: Biotite; Sph: Sphene; Mag: Magnetite; Cal: Calcite; Apa: Apatite; Alla; Allanite; Zir; Zircon; Mon: Monazite; Gar; Garnet. Abbreviations: IS- Vikurthi; QSK- Kotappakonda; J15/93b-Elchuru; S-Settupalle (Present study); Stp- Settupalle; P-Purimetla (Present study); PT-Purimetla; U-Uppalapadu; D-Chanduluru; Po-Podili.

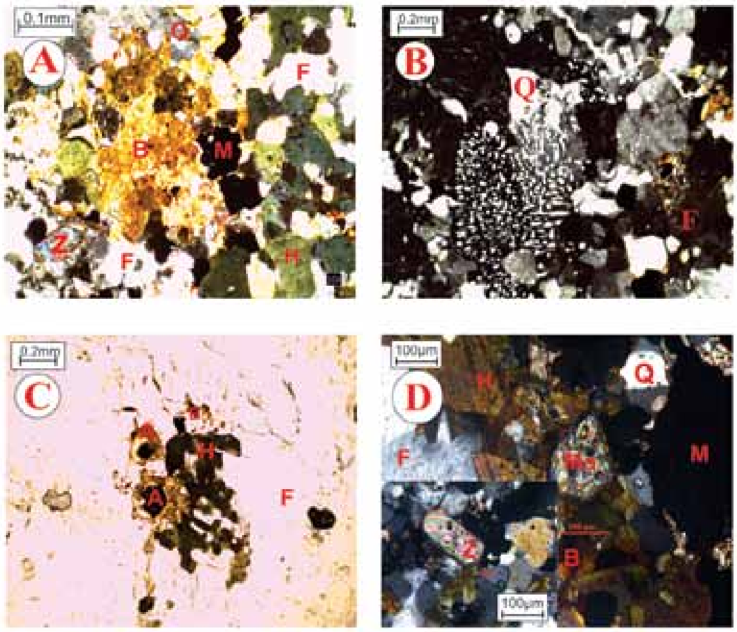

Figure 2. Photomicrographs of Purimetla quartz syenite. A. shows the hypidiomorphic texture. B. Myrmekitic texture. C. association of allanite with hornblende embedded in feldspathic ground mass. D. shows the monazite at its center along with the mafic and felsics. Inset microphotograph in D showing the euhedral zircon. All photomicrographs are taken under crossed nicols except C (Under polarized light). Q: Quartz; F: Feldspar; H: Hornblende; B: Biotite; M: Magnetite; Mo: Monazite; Z: Zircon; A: Allanite.

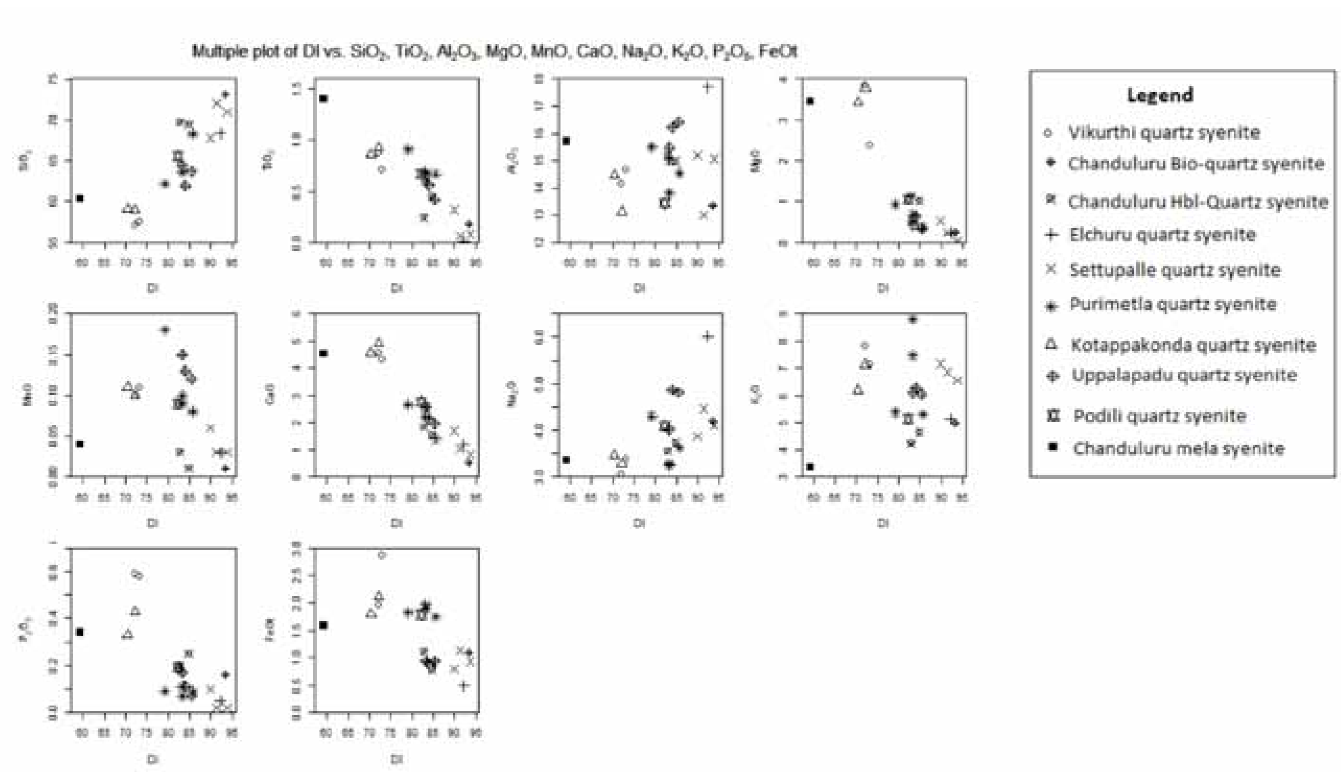

Figure 3. Differentiation index vs major oxides of PAP quartz syenites, exhibits the fractionation trends (Thornton and Tuttle1960).

Table 4. Major elemental concentrations of CIP quartz syenites. M.Sye - Mela syenite; Q.Sye - Quartz syenite; Q.Sye.G- Quartz syenite gneiss.

S.No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Sp.No	D125I	IS42	IS11	QSK12	QSK10	J15/93b	S1	S20	Stp	P7	P11	PT81	PT52	U18	U66	U11	D26	D49	D30	PO
Rock	M.Sye	Q.Sye	Q.Sye	Q.Sye	Q.Sye	Q.Sye	Q.Sye	Q.Sye	Q.Sye	Q.Sye	Q.Sye	Q.Sye	Q.Sye	Q.Sye	Q.Sye	Q.Sye.G	H.Qsy	H.Qsy	B.Qsy	Qsye
Pluton	Cha	Vik	Vik	Ktp	Ktp	El	Stp	Stp	Stp	Pu	Pu	Pu	Pu	Up	Up	Up	Cha	Cha	Cha	Po
SiO2	60.33	57.56	57.13	59.06	58.92	68.35	70.96	72.03	67.78	63.59	63.62	62.18	68.28	64.44	61.95	63.7	69.72	69.41	73.04	65.6
TiO2	1.4	0.71	0.87	0.86	0.93	0.01	0.08	0.06	0.32	0.6	0.69	0.91	0.67	0.66	0.56	0.42	0.24	0.45	0.18	0.67
Al2O3	15.7	14.66	14.14	14.45	13.13	17.72	15.07	12.99	15.19	15.03	13.81	15.5	14.55	15.49	16.22	16.41	15.23	14.98	13.34	13.44
Fe2O3	1.76	3.2	2.17	1.99	2.35	0.54	1.03	1.25	0.88	2.1	2.19	2.03	1.94	1.03	0.99	1.03	1.23	0.85	1.2	1.99
FeO	5.4	5.28	4.4	4	4.28	0.2	0.21	0.2	1.97	2.46	2.87	5.5	2.6	4.93	4.6	3.83	2.12	2.84	1.24	3.55
MnO	0.04	0.11	0.1	0.11	0.1	0.03	0.03	0.03	0.06	0.1	0.09	0.18	0.08	0.15	0.13	0.12	0.03	0.01	0.01	0.09
MgO	3.45	2.36	3.83	3.43	3.78	0.22	0.05	0.24	0.52	0.68	0.53	0.93	0.37	0.44	0.64	0.34	1.12	1.02	0.25	1.05
CaO	4.52	4.32	4.56	4.56	4.92	1.19	0.81	1.03	1.69	2.55	2.23	2.66	1.4	2.58	2.12	1.96	1.85	1.56	0.54	2.77
Na2O	3.36	3.37	3.05	3.47	3.29	6.02	4.11	4.46	3.87	3.27	3.25	4.31	3.63	4.02	4.87	4.82	3.55	3.74	4.19	4.1
K2O	3.36	7.12	7.84	6.19	7.13	5.12	6.53	6.86	7.16	7.46	8.8	5.38	5.31	6.11	6.27	6.05	4.23	4.65	4.99	5.14
P2O5	0.34	0.58	0.59	0.33	0.43	0.05	0.02	0.02	0.1	0.11	0.07	0.09	0.09	0.17	0.11	0.07	0.2	0.25	0.16	0.19
PI	0.89	0.91	0.96	0.86	1.00	0.87	0.92	1.14	0.93	0.90	1.08	0.83	0.81	0.85	0.91	0.88	0.68	0.75	0.92	0.92
Norm																				
Quartz	14.56	2.55	0	2.41	0.12	11	20.42	22.06	13.66	10.6	7.45	7.58	22.54	9.79	2.56	6.26	26.66	23.98	28.03	15.36
Plagioclase	48.23	32.36	25.61	34.93	27.84	56.52	38.16	28.62	35.68	31.97	22.04	43.53	37.07	40.19	45.09	46.06	37.91	37.75	37.09	37.78
Orthoclase	19.85	42.08	46.33	36.58	42.14	30.26	38.59	40.54	42.31	44.09	52	31.79	31.38	36.11	37.05	35.75	25	27.48	29.49	30.38
Diopside	0	11.43	13.81	12.08	17.47	0	0.27	1.9	4.06	6.35	9.09	4.76	0	4.82	5.12	3.49	0	0	0	7.9
Hypersthene	8.54	5.45	0	7.17	5.53	0.55	0	0	1.71	0.51	0.53	7.12	3.14	5.97	5.89	4.74	5.33	6.33	1.63	2.58
Ilmenite	0.08	1.35	1.65	1.63	1.77	0.02	0.15	0.11	0.61	1.14	1.31	1.73	1.27	1.25	1.06	0.8	0.46	0.85	0.34	1.27
Magnetite	0	4.64	3.15	2.89	3.41	0.71	0.54	0	1.28	3.04	0.76	2.94	2.81	1.49	1.44	1.49	1.78	1.23	1.74	2.89
Hematite	1.7	0	0	0	0	0.05	0.66	0	0	0	0	0	0	0	0	0	0	0	0	0
Apatite	0.8	1.34	1.37	0.76	1	0.12	0.05	0.05	0.23	0.25	0.16	0.21	0.21	0.39	0.25	0.16	0.46	0.58	0.37	0.44
DI	59.27	73.15	72.14	70.40	72.18	92.21	93.79	91.38	89.86	83.26	83.26	79.16	85.65	83.29	83.99	85.41	82.86	84.84	93.44	82.22

Source: S.No- 2-5 (Madhavan et al., 1995b); 6- (Ratnakar and Vijaya Kumar, 1995); 7&8 (present study); 9- (Leelanandam et al., 1989); 10&11 (Present study); 12&13-(Ratnakar and Leelanandam, 1986); 14&15- (Krishna Reddy et al., 1998); 16- (Czygan and Goldenberg, 1989); 1,17,19- (Sharma and Ratnakar, 2000); 20- (Madhavan and Sugrive Reddy, 1990).

Petrogenesis

The quartz syenites of the PAP show spatial and temporal relationship with the associated alkaline (feldspathoidal or non feldspathoidal) and subalkaline plutons with varying degree of silica saturation. Various models were formulated to explain the genesis of over saturated components of the PAP, based on the geochemistry of the syenite plutons intruded at the junction of EDC and EGMB (Ratnakar and Leelanandam 1986; Krishna Reddy, et al., 1998; Madhavan and Sugrive Reddy, 1990; Srinivasan, 1982, Leelanandam, et al., 1989; Madhavan, et al., 1995a,b, 1999; Ratnakar and Vijaya Kumar, 1995; Sharma and Ratnakar, 2000). The subalkaline rocks also constitute a closely interrelated genetic group with a distinct lineage as seen in alkaline rocks (Madhavan, et al., 1995b).

In the PAP, the mantle derived shoshonitic magma is inferred as parent for both the feldspathoidal and non-feldspathoidal alkali syenites, whereas the subalkaline syenites are formed from the gabbroic magma, which upon differentiation produce the trachybasaltic liquid followed by the trachytic fraction (Madhavan et al., 1995b). In PAP the melasyenite, which has compositional similarity with the trachy basalt in various syenite plutons is considered as the primary source for quartz syenites as it has higher modal abundance of mafic minerals and higher MgO, FeOt, CaO along with low REE, especially LREE concentrations (Madhavan et al., 1995b; Sharma and Ratnakar, 2000).
The melasyenite which is presumed as the source for the quartz syenites is produced by an anhydrous partial melting of LREE enriched amphibolite crust. The partial melting is attributed mainly due to the underplating of the gabbroic

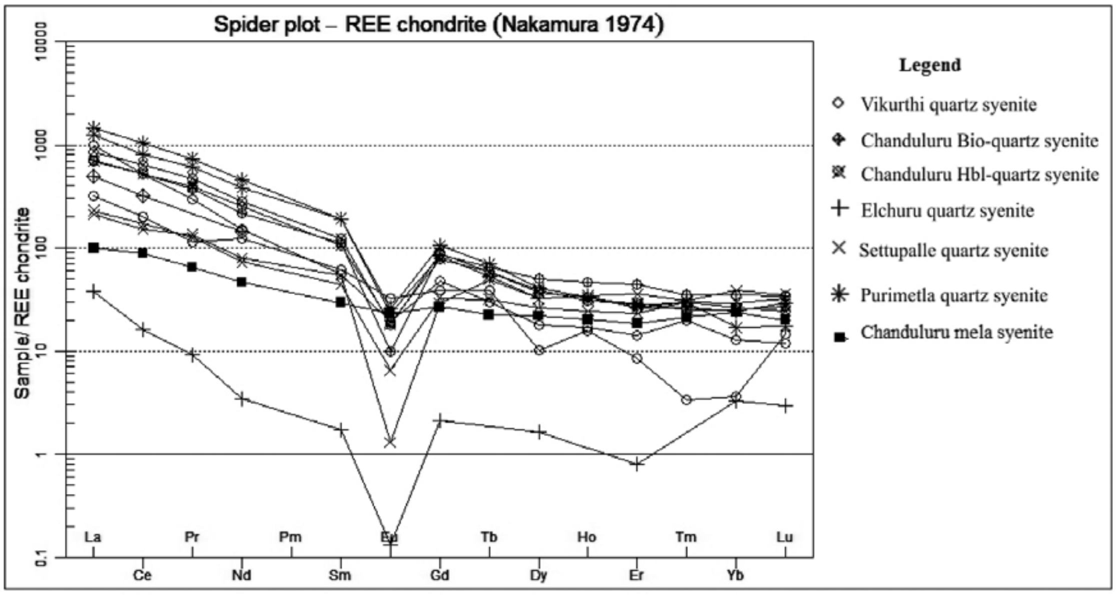

Figure 4. Chondrite normalised REE patterns of PAP Quartz syenites.

Table 5. REE concentrations in ppm of quartz syenites of PAP. S.No, 2,3: Vikurthi; 4: Elchuru; 5,6: Settupalle (authors unpublished data); 7,8:Purimetla (Present study); 9: Uppalapadu; 1,10,11,12: Chanduluru. The references are given at the Table no.4.

S. No	1	2	3	4	5	6	7	8	9	10	11	12
Sp.No	D125I	IS42	IS11	J15/93b	S1	S20	P7	P11	U11	D26	D49	D30
Pluton	Cha	Vik	Vik	El	Stp	Stp	Pu	Pu	Up	Cha	Cha	Cha
Rock	M.Sy	Q.Sye	Q.Sye	Q.Sye	Q.Sye	Q.Sye	Q.Sye	Q.Sye	Q.Sye.G	H.Qsy	H.Qsy	B.Qsy
La	32.87	104.7	328.2	12.42	76	70	482	417	165	228.44	284.17	232.5
Ce	76.19	172.6	455.7	13.86	148	132	904	692	275	450.13	549.83	450.42
Pr	7.28	12.9	33.5	1.03	14	15	82	69	NA	43.99	53	42.07
Nd	29.15	77.9	94.6	2.18	46	50	288	243	91	158.16	178.27	137.21
Sm	6	12.6	11.4	0.35	9	11	39	39	NA	21.43	24.86	22.74
Eu	1.8	2.5	1.5	0.01	0.5	0.1	2	1.8	NA	1.47	1.38	0.76
Gd	7.39	10.8	13.1	0.58	9	8	29	23	NA	21.5	24.6	23.83
Tb	1.05	1.8	1.4		1.5	2.3	3.3	2.5	NA	2.78	2.73	3.06
Dy	7.52	3.5	6.2	0.56	9	11	14	11	NA	13.17	12.7	17.31
Ho	1.41	1.1	1.2		1.7	2.4	2.3	2.4	NA	2.17	2.32	3.25
Er	4.18	1.9	3.2	0.18	5.2	8	5.9	6	NA	6.6	6.27	9.99
Tm	0.64	0.1	0.6		0.9	0.92	0.8	0.89	NA	0.76	0.89	1.06
Yb	5.24	0.8	2.8	0.72	6.5	8.5	5.4	3.7	NA	5.54	5.75	7.64
Lu	0.68	0.5	0.4	0.1	1.1	1.2	1	0.6	NA	0.92	0.83	1.15
Total	181.4	403.7	953.8	31.99	328.4	320.42	1858.7	1511.89	531	957.06	1147.6	952.99
LREE	151.49	394	938	30.43	302.5	286.1	1826	1484.8	531	925.12	1116.11	909.53
HREE	29.91	9.7	15.8	1.56	25.9	34.32	32.7	27.09	NA	31.94	31.49	43.46
LREE/HREE	5.0649	40.62	59.37	19.506	11.68	8.3362	55.841	54.8099	NA	28.964	35.4433	20.928

Note: abbreviations are same as mentioned in table 3, NA- Not available.

magma that produced melasyenite, which upon fractional crystallization has given rise to the quartz syenites in the PAP (Figure 3). A cause and consequence modal (originally envisaged by (Huppert and Sparks, 1988) was adopted for Chanduluru complex to explain the genesis of the sequence which consists of gabbro-diorite-syenite-granite (Sharma and Ratnakar, 2000). In this present study the similar model is considered as the driving mechanism for the formation of quartz syenites in various syenite plutons of the PAP including Purimetla.

Tectonic setting

The emplacement tectonics of various igneous suits are demonstrated by different bivariant and triangular diagrams with the help of major oxides and trace elements (eg. Floyd and Winchester, 1975; Pearce and Cann 1973; Pearce et al., 1977, 1984; Pearce, 2008; Wood et al., 1979). In the global context the syenitic magmatism corresponding to Archean age is quite rare compared to Proterozoic whereas the later is commonly associated with the continental rift/ extensional tectonic settings (eg. Gardar Province, (Upton et al., 2003); Klokken intrusion, (Parsons, 1979, 1981); Ntem Complex, (Tchameni et al., 2001). In PAP the tectonic setting for the Proterozoic magmatism corresponding to alkaline syenitic composition is often found in rift/ extensional settings (e.g. Upadhyay et al., 2006; Upadhyay, 2008; Chalapathi Rao et al., 2012; Hari et al., 2014; Vijaya Kumar et al., 2015). Whereas the tholeitic magmatism is mainly confined to the subduction settings (e.g. Vijaya Kumar et al., 2015; Subramanyam et al., 2016). This Proterozoic bimodal magmatic association confined to PAP tholeitic (IAB type) and alkaline (OIB type) show difference in their geochemical signatures, which imply that they were derived from divergent magmatic sources that contributed to the growth of Eastern Ghats continental crust. The emplacement of quartz syenites along with the other syenites within the various syenite plutons of the PAP are mainly confined to the within plate or extensional rift settings (e.g. see Sharma and Ratnakar, 2000).

CONCLUSION

The suture between the EDC and EGB paved way to the emplacement of several alkaline and subalkaline complexes, which have the quartz syenite as an integral part. Geochemical signatures of the present study indicate their evolved compositions. Presence of normative quartz and hypersthene in the quartz syenites indicates their sub alkaline nature, however few quartz syenites show alkaline affinity. Among the quartz syenites taken up for this study Purimetla and Chanduluru are high in their LREE contents, whereas Uppalapadu and Vikurthi are moderate and Settupalle and Elchuru are low. The high LREE contents are mainly attributed to the presence of zircon, apatite, allanite and monazite. Significant negative Eu anomalies in the quartz syenites portray the removal of plagioclase by the fractional crystalisation from the melasyenite, which is devoid of negative Eu anomaly. Quartz syenites of the PAP are evolved from a melasyenite, which is formed by the partial melting of LREE enriched amphibole crust, triggered by the heat generated during the induction of the gabbroic magma in to the continental crust.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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