

Proterozoic Magnesian Feldspathic Magmatism in the Nallamalai Fold Belt, Southern India – Petrogenesis of Vellaturu-Ipuru-Nakerikallu (VIN) Arc Magmatic Granites, Eastern Dharwar Craton

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ABSTRACT

Through extensive field studies substantiated by detailed petrographic, geochemical and mineral chemistry studies, a significant event of “Proterozoic magnesian feldspathic magmatism” is reported from the SE part of the Indian sub-continent. Three major granitoids i.e. Vellaturu, Ipuru and Nakerikallu (VIN) are emplaced along an NNE-SSW axis in the Proterozoic Nallamalai fold belt (NFB) in the Eastern Dharwar craton (EDC). The axis of emplacement of VIN granites represents a tectonic contact that is juxtaposed along the NE fringes of NFB and adjoining Precambrian accretionary terrain comprising of gneisses and amphibolites with intrusive granites in the northern part of the Nellore schist belt (NSB). Petrographically the VIN granitoids are biotite $\pm$ hornblende bearing with apatite and zircon as accessory phases. Exsolution texture is observed in the form of microcline microperthite intergrowth. In IUGS, QAP diagram the VIN granitoids essentially fall in granite - granodiorite field. Presence of mafic rich microgranitoid enclaves (MMEs) are prominently noticed in the VIN granitoids indicating magma mingling. These granitoids are deformed along their margins. Enclaves of quartzite of NFB and older amphibolites indicate the intrusive nature of VIN granitoids. Major oxide analyses indicate that the Mg# ranges from 43 to 56. Rare earth element studies reveal a general enrichment of LREE relative to HREE. Incompatible HFSE element studies indicate a significant Nb and Ti negative anomaly; characteristic of subduction zone magmatism. In Y + Nb vs Rb trace element tectonic discrimination diagram the granitic rocks of Nakerikallu, Ipuru and Vellaturu essentially fall in post-collisional granites (post-COLG) field. Based on the remarkable magnesian feldspathic character coupled with their emplacement in an arc magmatic tectonic setting, it is concluded that the VIN granitoids in the Proterozoic NFB, SE India; mark a significant event of “Proterozoic magnesian feldspathic magmatism” in the EDC.

INTRODUCTION

The magnesian feldspathic rocks; products of arc magmatic processes, are characteristically emplaced in magmatic arcs and ‘post-collisional’ tectonic environments (eg. Frost & O’Nions, 1985, Frost et. al., 2006). Granite batholiths along the Andean magmatic arc provide critical insights into the crustal growth and accretion along active continental margins (eg. Cobbing, 1999; Schellart, 2017). The magnesian rocks, which are exemplified by Caledonian and Cordilleran batholiths, are characterized by their differentiation under oxidizing and relatively hydrous conditions (eg. Osbourn, 1959; Frost and Frost, 2008). The Fe-index distinguishes between melts that have undergone

extensive iron enrichment during differentiation from those that have not (Frost et.al. 2001). The shift from tonalite-trondjemite-granodiorite (TTG) dominated to granodiorite-granite (GG) dominated continental crust was a gradual transition that took place over several hundred million years and the GG suite is characterized by higher alkali contents relative to CaO (eg. Frost et.al. 2006). Precambrian magnesian, high-K alkali-calcic granites and granodiorites from amphibolitic continental crust is reported from the Damara orogen in Namibia (Bergemann et.al. 2014). Paleoproterozoic synkinematic magnesian high-K magmatism has been recorded from the Tamkoro-Bossangoa massif, along the Bossangoa-Bossebele shear zone in north-western part of central African craton (Danguene, et.al. 2014). Skjerlie and Johnston (1993) undertook dehydration melting experiments on magnesian tonalite gneiss containing <+20% biotite and <+2% hornblende. At 10 kbar biotite dehydration melting produces strongly ferroan melts by incongruent melting reactions that also produce orthopyroxene. However, with greater degrees of melting, the melt composition crosses the ferroan–magnesian boundary into the magnesian field. Magmas that are derived due to the partial melting of continental crust may inherit the magnesian character (eg. Frost and Frost, 2008). The present work deals with extensive, field, petrographic, mineral chemistry and geochemical studies and that results in documenting a significant event of the “Proterozoic magnesian feldspathic arc magmatism” from the northeastern fringes of the Nallamalai fold belt (NFB) in Eastern Dharwar craton (EDC), SE India.

GEOLOGICAL SETTING

The Proterozoic Cuddapah basin of the eastern Dharwar craton (EDC) is one of the few intra-cratonic sedimentary basins in the world that preserves a thick sequence of clastic and non-clastic rocks with associated magmatic rocks (Nagaraja Rao et al. 1987). During its evolution the basin witnessed Paleoproterozoic ultramafic-mafic-felsic magmatism contemporaneous with the sedimentation of Cuddapah Supergroup (Chatterjee and Bhattacharji, 2001; Anand, et al., 2003, Sessa Sai, 2014; Sheppard et al., 2017; Sessa Sai et al., 2017). Intrusive magmatism has been recorded in the NFB; the deformed eastern part of the Proterozoic Cuddapah basin (Crawford and Compston, 1973; Chalapathi Rao et al, 1999; 2012). The stratigraphy of the Cuddapah basin was initially established by (King, 1981), while (Rajurkar & Ramalingaswamy, 1978; Nagaraja Rao, et al. 1987) refined various aspects pertaining to the stratigraphy of the basin. The structural and tectonic aspects of the Cuddapah basin were studied by Narayanaswami (1966), Nagaraja Rao et al. (1987), Chetty (2011), Saha and Tripathy (2012) and Tripathy et al., (2018). Close to the vicinity of the eastern margin of NFB, a crustal-scale shear zone

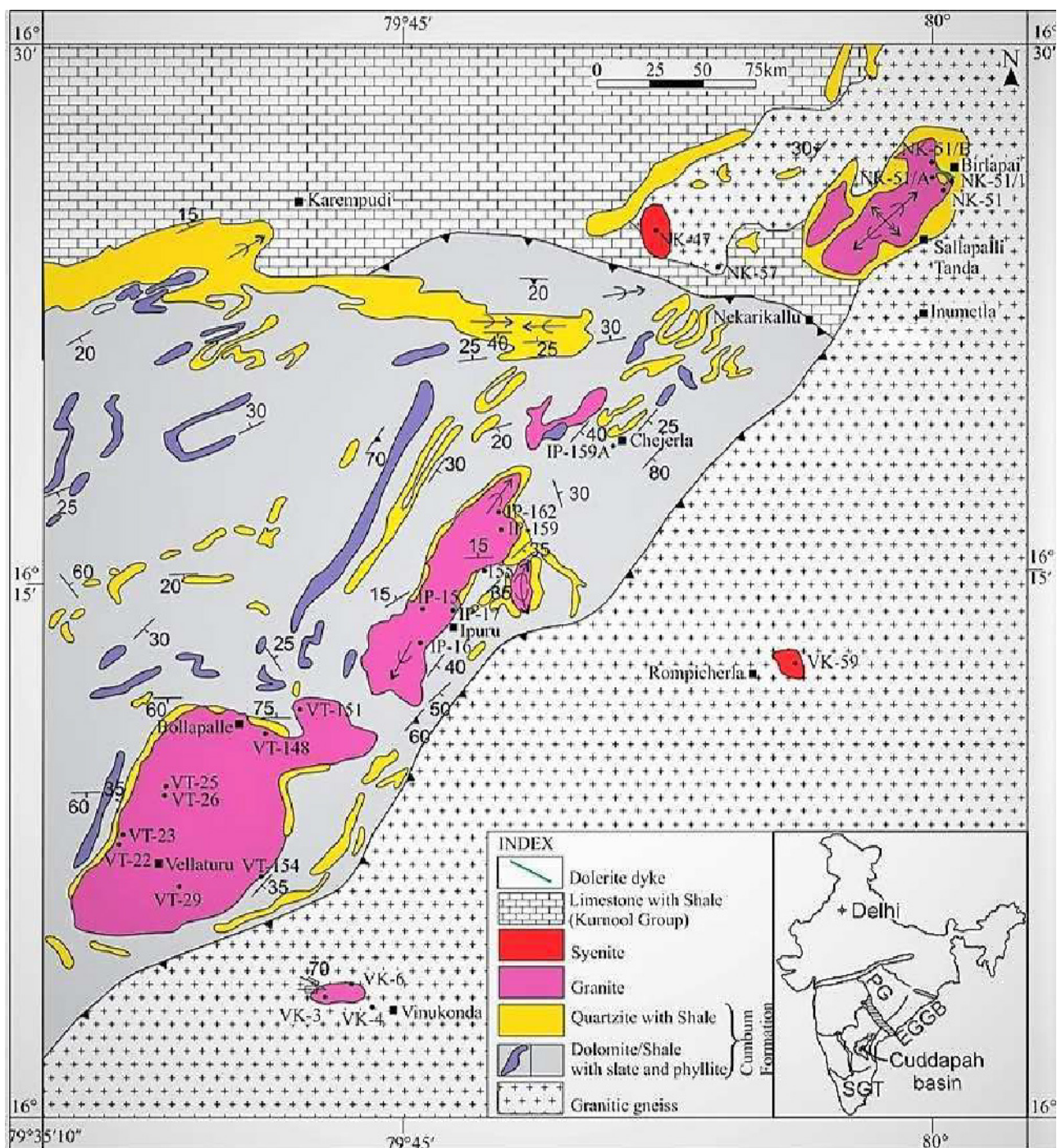


Fig.1. Geological Map on Northeastern fringes of the Nallamalai Fold Belt, SE India showing the VIN granites disposed along a NE-SW axis (modified after GSI, 1981). Inset Map of India showing Cuddapah basin in SE India

defined as terrane boundary shear zone (TBSZ) was demarcated (Chetty and Murthy, 1994). TBSZ is as a major tectonic feature to the west of the Eastern Ghats Mobile belt (EGMB) of south India (eg. Chetty, 1999; Chetty, 2017). After the stabilization of the Archaean nuclei in Peninsular India, a series of Proterozoic to early Paleozoic sedimentary basins were developed (Meert and Pandit, 2015). The present study deals with the field, petrographic, mineral chemistry and geochemical studies to ascertain the petrogenetic aspects of three major granitoids i.e. Vellaturu, Ipuru and Nakerikallu (VIN) that fall in the Northeastern fringes of the Proterozoic Nallamalai fold belt (NFB) of eastern Dharwar craton (EDC) in SE India. The VIN granitoids occur as isolated oval shaped plutons over a stretch of about 70 km from Vellaturu in southwest to Nakerikallu in north-east (Fig.1). The VIN granitoids (Fig.2) are deformed along their margins and are

emplaced along a NNE-SSW axis in contiguity with the NE fringes of the Proterozoic NFB.

SAMPLING AND ANALYTICAL TECHNIQUES

Systematic sampling was carried out in the study area in the NE fringes of NFB in EDC representing the three plutons. In all cases, efforts had been made to collect fresh samples free from any secondary minerals for the purpose of chemical analyses. A total of 42 nos. of thin sections were studied for petrographic analyses and the areas of interest were selected for mineral chemistry studies. Major oxide, trace element and Rare Earth Element was carried out by XRF and ICP-MS methods at the Geological Survey of India, Chemical Laboratory, Southern Region, Hyderabad. The results of XRF and ICPMS analyses of VIN granites are given in Table 1.

EPMA analyses were carried out at GSI, Southern Region, Hyderabad, by CAMECA Sx 100. Analytical conditions: Accelerating voltage: 15kV, current: 12nA. Beam size: 1 μ . All natural standards have been used except for Mn and Ti for which synthetic standards have been used. The results of EPMA analyses of feldspar and biotite from VIN granites are furnished in Table 2 and Table 3.

Monazite mineral analyses were performed using a CAMECA SX-100 electron microprobe analyzer at the Petrology Division, SR, Geological Survey of India, Hyderabad. The EMP is equipped with five wavelength dispersive spectrometers (WDS), e.g., WDS 1 (TAP crystal), 2 (PET crystal) and 4 (LIF crystal) fitted with low-pressure detectors, and WDS 3 (LPET crystal) and WDS 5 (LIF) fitted with high pressure detectors (all detectors use P-10 gas). Poly-propylene separation windows were used with WDS 1, 2 and 4 and Mylar windows are used with WDS 3 and 5. Calibration, overlap correction,

quantification and age calculations were performed with the CAMECA SX-100 Peak Sight-Geo and Age Quanta software package. Pulse-height analyzers (PHAs) were adjusted by selecting the differential auto mode for all the elements. Matrix effects were eliminated by using the X-PHI correction method proposed by Merlet (1992; 1994). Monazites were analysed using 20 kV acceleration voltage and 200 nA beam current with beam 1 μ m size. The signals used are Si Ka, P Ka, K Ka, Ca Ka, La La, Ce La, Pr La, Nd La, Sm La, Gd La, Pb Ma, U Mb, Th Ma, Y La for calibration of elements using natural standards for Si, K, Ca, P, Fe, Pb and synthetic standards for Al, REE, Y, U, Th. Standards used are wollastonite for Si, Ca, orthoclase for K, apatite for P, corundum for Al, hematite for Fe, synthetic glass standards for REE, U, Th and Pb on crocoite. The counting time for peak measurement 10s for Si, K, Ca, Al, Fe, 30s for P, 60s for REE and 240s for U, Th, Pb and with half of the peak measurement time allotted for background measurement

Table 1. Major oxide and trace element analyses of VIN granitoids, Nallamalai Fold Belt, SE India

Sample	Vellaturu granite				Ipuru granite				Nakerikallu granite			
	VT 22	VT 22A	VT 30A	VT 32 A	IPB 37 A	IP 43	IP 44	IP 45	NK 57	NK 59	NK 60	NK 61
SiO ₂	66.03	65.36	68.19	64.28	71.44	71.85	71.17	71.012	71.69	70.36	68.75	70.44
TiO ₂	0.57	0.52	0.48	0.62	0.35	0.27	0.28	0.34	0.28	0.42	0.35	0.23
Al ₂ O ₃	15.04	14.90	15.04	14.59	14.01	14.18	14.42	14.22	14.26	14.43	15.08	14.67
Fe ₂ O ₃	5.39	5.92	4.57	5.72	3	2.68	2.73	2.16	2.90	4.11	4.02	3.09
MnO	0.05	0.06	0.03	0.06	0.03	0.04	0.03	0.04	0.01	0.01	0.02	0.02
MgO	3.23	3.78	1.77	3.43	1.39	1.26	1.30	1.48	1.21	1.81	1.87	1.84
CaO	2.68	2.73	2.45	4.32	2	1.80	1.97	1.72	2.19	1.39	2.07	2.14
Na ₂ O	2.59	2.09	2.19	3.39	2.53	2.63	2.83	2.64	2.72	2.39	2.65	2.35
K ₂ O	4.28	4.43	5.09	3.33	5.04	5.11	5.17	5.06	4.58	4.91	5.03	5.16
P ₂ O ₅	0.13	0.22	0.20	0.26	0.21	0.18	0.19	0.22	0.15	0.16	0.15	0.16
Mg#	54	56	43	54	48	48	49	48	45	47	48	53
Cr	51	49	25	59	25	24	22	24	29	28	25	29
Co	14	17	8	12	6	5	5	8	7	8	8	8
Ni	20	21	10	15	9	8	8	10	10	9	11	11
Rb	96	100	125	55	199	185	198	189	123	117	132	142
Sr	307	284	232	264	265	268	260	263	324	271	381	345
Cs	0.67	0.65	1.10	0.54	1.47	1.32	1.47	1.45	0.5	0.48	0.43	0.54
Ba	1089	1269	1186	340	910	986	965	1053	757	898	1097	1268
Sc	10	11	6	12	5	5	5	6	5	6	7	6
V	68	68	69	76	38	34	34	39	32	70	44	34
Nb	10	9	11	9	9	8	7	12	11	13	12	9
Zr	407	389	254	145	518	391	441	441	381	498	396	346
Th	19	14	26	22	79	46	61	55	43	83	57	37
U	1.2	1.5	2.5	1.5	18.7	16.6	14.2	13.1	1.8	2.5	2.3	1.7
Y	10	15	12	15	12	11	11	15	18	23	22	16
La	42.80	39	45.86	32.57	110.51	77.09	93.88	74.34	81.27	114.99	96.43	67.80
Ce	83.76	76.20	84.87	67.96	187.01	128.08	162.41	130.61	145.42	211.35	173.07	115.49
Pr	10.26	10.4	10.43	8.94	21.18	14.52	18.02	15.35	17.16	25.34	20.51	14.49
Nd	32.14	33.23	33.35	30.86	62.37	43.28	52.76	47.50	51.98	77.53	62.69	44.70
Sm	5.23	6.38	6.02	6.48	9.43	6.90	8.01	8.73	8.85	13.76	11.46	8.06
Eu	1.53	1.56	1.34	1.69	1.51	1.34	1.51	1.61	1.23	1.40	1.48	1.41
Gd	3.34	4.21	3.94	4.47	5.66	4.18	4.71	5.25	5.83	8.60	7.47	5.35
Tb	0.42	0.62	0.55	0.66	0.67	0.55	0.56	0.71	0.86	1.26	1.13	0.82
Dy	1.66	2.56	2.12	2.69	2.36	2.01	2.01	2.67	3.38	4.74	4.40	3.25
Ho	0.25	0.40	0.30	0.40	0.32	0.28	0.28	0.37	0.48	0.65	0.60	0.46
Er	0.69	1.10	0.74	1.05	0.80	0.71	0.74	0.99	1.19	1.56	1.48	1.15
Tm	0.10	0.16	0.09	0.15	0.10	0.09	0.10	0.14	0.15	0.19	0.18	0.14
Yb	0.72	1.06	0.52	0.96	0.58	0.51	0.60	0.84	0.95	1.18	1.04	0.88
Lu	0.12	0.17	0.07	0.15	0.09	0.08	0.09	0.12	0.15	0.19	0.16	0.1
ΣREE	182	177	190	159	403	280	346	289	390	463	482	264
(La/Yb) _N	41	26	61	24	132	106	109	61	60	68	64	54
(Gd/Yb) _N	4	3	6	4	8	7	7	5	5	6	6	5
(Yb) _N	4	7	3	6	4	3	4	5	6	7	6	5
Eu/Eu*	1.05	0.86	0.79	0.91	0.58	0.71	0.69	0.67	0.49	0.37	0.46	0.62
Nb/Nb*	0.76	0.67	1.02	1.55	0.47	0.50	0.40	0.95	0.56	0.63	0.59	0.55
Zr/Zr*	2.17	1.85	1.24	0.71	1.48	1.57	1.49	1.50	1.23	1.05	1.02	1.26
Ti/Ti*	0.32	0.24	0.23	0.27	0.11	0.12	0.11	0.12	0.09	0.09	0.09	0.08

Table 2 EPMA analyses of feldspars from VIN granitoids, Nallamalai Fold Belt, SE India

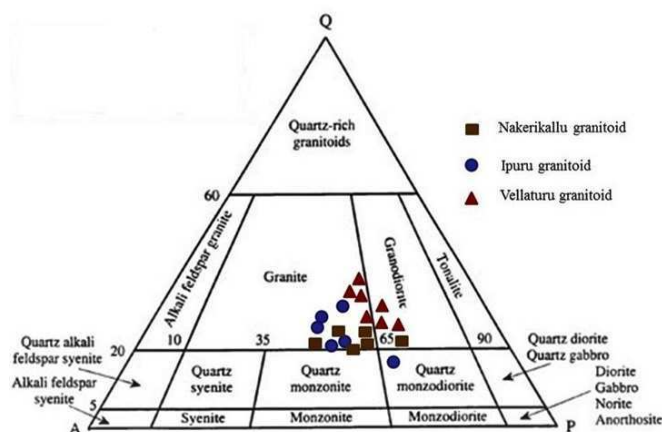
Sample	Vellaturu Granite				Ipiru Granite				Nakerikallu Granite				K-feldspar	Exsolved plagioclase	Plagioclase (rim)(core)	K-feldspar	Exsolved plagioclase	Plagioclase
	VT-22	VT-22	VT-22	VT-22	VT-22	VT-22	VT-22	VT-22	IP-35	IP-35	IP-35	IP-35						
SiO ₂	61.05	59.49	59.40	58.60	67.75	67.68	62.88	62.82	64.00	66.46	65.70	66.79	62.42	63.42	67.49	64.30	61.02	
Al ₂ O ₃	24.33	24.76	24.55	24.32	19.51	19.61	18.48	18.62	18.06	20.57	21.05	20.01	18.34	17.92	19.72	21.48	23.77	
FeO	0.02	0.05	0.01	0.07	0.04	0.05	0.03	0.04	0.00	0.01	0.09	0.09	0.19	0.06	0.12	0.32	0.05	
CaO	6.17	6.13	6.27	6.48	0.17	0.21	0.00	0.00	0.00	1.07	1.95	0.49	0.10	0.10	0.52	2.28	5.78	
Na ₂ O	7.92	8.01	7.87	7.72	10.91	10.96	0.30	0.50	0.32	10.55	10.37	11.45	0.30	0.53	11.79	11.00	8.98	
K ₂ O	0.08	0.08	0.08	0.06	0.08	0.12	16.63	16.71	15.53	0.32	0.08	0.07	16.97	17.00	0.20	0.09	0.16	
MgO	0.01	0.03	0.01	0.01	0.02	0.03	0.02	0.01	0.01	0.02	0.00	0.04	0.01	0.01	0.12	0.06	0.00	
Total	99.86	98.73	98.36	98.36	98.57	98.80	98.38	98.73	98.32	99.07	99.37	99.04	98.38	99.07	99.98	99.57	99.82	
Si	10.88	10.74	10.76	10.73	11.99	11.96	11.88	11.84	12.04	11.76	11.62	11.82	11.84	11.93	11.85	11.43	10.90	
Al	5.11	5.27	5.24	5.25	4.07	4.08	4.11	4.14	4.00	4.29	4.39	4.17	4.10	3.97	4.08	4.50	5.01	
Fe(ii)	0.00	0.01	0.00	0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.01	0.01	0.03	0.01	0.02	0.05	0.01	
Ca	1.18	1.19	1.22	1.27	0.03	0.04	0.00	0.00	0.00	0.20	0.37	0.09	0.02	0.02	0.10	0.43	1.11	
Na	2.74	2.80	2.76	2.74	3.74	3.76	0.11	0.18	0.12	3.62	3.56	3.93	0.11	0.19	4.01	3.79	3.11	
K	0.02	0.02	0.02	0.01	0.02	0.03	4.01	4.02	3.73	0.07	0.02	0.02	4.11	4.08	0.04	0.02	0.04	
Mg	0.00	0.01	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.03	0.02	0.00	
Total	19.94	20.03	20.01	20.02	19.86	19.89	20.12	20.19	19.88	19.94	19.97	20.06	20.21	20.22	20.14	20.23	20.17	
An	29.96	29.58	30.43	31.58	0.85	1.04	0.00	0.00	0.00	5.21	9.37	2.30	0.48	0.47	2.35	10.23	26.01	
Ab	69.58	69.96	69.11	68.08	98.67	98.25	2.67	4.35	3.04	92.94	90.17	97.31	2.60	4.50	96.57	89.29	73.13	
Or	0.46	0.46	0.46	0.35	0.48	0.71	97.33	95.65	96.96	1.85	0.46	0.39	96.92	95.03	1.08	0.48	0.86	

Table 3. Biotite analyses for the Ipiru and Nakerikallu granites, NFB, SE India

Oxides	Ipiru granite				Nakerikallu granite		
	IP-35	IP-35	IP-35	IP-35	NK-51	NK-51	NK-51
SiO ₂	36.52	36.01	35.77	36.59	37.34	37.37	37.32
TiO ₂	1.20	1.02	2.25	2.18	3.12	3.02	3.10
Al ₂ O ₃	14.57	15.23	14.55	14.72	14.79	14.57	14.56
FeO ^T	20.47	19.58	20.70	20.62	17.74	17.66	17.62
MnO	0.12	0.11	0.10	0.10	0.29	0.35	0.38
MgO	11.56	11.28	10.50	10.48	11.24	12.55	12.82
CaO	0.00	0.00	0.04	0.04	0.05	0.05	0.04
Na ₂ O	0.04	0.02	0.06	0.07	0.07	0.07	0.07
K ₂ O	10.09	10.15	9.85	9.92	10.51	10.42	10.46
BaO	0.00	0.00	0.00	0.00	0.00	0.00	0.000
Cr ₂ O ₃	0.120	0.00	0.030	0.030	0.00	0.00	0.00
NiO	0.00	0.06	0.00	0.00	0.06	0.06	0.07
H ₂ O*	3.86	3.82	3.82	3.86	3.93	3.97	3.98
Total	98.55	97.28	97.66	98.61	99.14	100.08	100.42
No. of oxygens 22							
Si	5.671	5.646	5.616	5.672	5.696	5.645	5.622
Al iv	2.329	2.354	2.384	2.328	2.304	2.355	2.378
Al vi	0.338	0.461	0.309	0.362	0.355	0.240	0.207
Ti	0.140	0.120	0.266	0.254	0.358	0.343	0.351
Cr	0.015	0.000	0.004	0.004	0.000	0.000	0.000
Fe	2.658	2.568	2.718	2.673	2.263	2.231	2.220
Mn	0.016	0.015	0.013	0.013	0.037	0.045	0.048
Mg	2.676	2.637	2.458	2.422	2.556	2.826	2.879
Ni	0.000	0.008	0.000	0.000	0.007	0.007	0.008
Ca	0.000	0.000	0.007	0.007	0.008	0.008	0.006
Na	0.012	0.006	0.018	0.021	0.021	0.021	0.020
K	1.999	2.030	1.973	1.962	2.045	2.008	2.010
Ba	0.000	0.000	0.000	0.000	0.000	0.000	0.000
OH*	4.000	4.000	4.000	4.000	4.000	4.000	4.000
Total	19.853	19.844	19.765	19.718	19.650	19.729	19.750
Y total	5.843	5.808	5.768	5.729	5.576	5.692	5.713
X total	2.011	2.036	1.998	1.989	2.074	2.036	2.037
Al total	2.667	2.815	2.693	2.690	2.659	2.594	2.585
Fe/Fe+Mg	0.498	0.493	0.525	0.525	0.470	0.441	0.435

FIELD, PETROGRAPHY AND MINERAL CHEMISTRY**Vellaturu Granite**

Vellaturu granitoid is at the SW part of the axis of emplacement. It is coarse grained, porphyritic at places, mesocratic and massive, exhibiting sharp contact with the N10°E-S10°W striking and westerly (30 to 35°) dipping quartzite-phyllite of NFB. Presence of enclaves of quartzite and phyllite of NFB are noticed indicating its intrusive nature. Specks of pyrite, chalcopyrite and covellite are noticed within the mafic rich portions of the granodiorite. Petrographic studies reveal that the rock exhibits hypidiomorphic texture and essentially composed of plagioclase, microcline, quartz, biotite and chlorite, while zircon, titanite, epidote and opaques are the accessory minerals. Zircon is the conspicuous accessory mineral and it is noticed as discrete euhedral grains at places in Vellaturu granite (Fig. 3a). At places patches of sericitised plagioclase are noticed in fresh microcline micropertthite grains. Vellaturu granitoid is porphyritic in nature in its NE part (Fig. 3b). Porphyritic variants are characterised by the presence of euhedral K-feldspar phenocrysts. The euhedral nature coupled with the

**Fig.2** Position of VIN granitoids in IUGS QAP diagram (Streckeisen, 1976)

preservation of the terminal ends in the K-feldspar phenocrysts indicates the undeformed nature. However along the margins the Vellaturu body shows evidences of deformation in the form of wavy extinction and recrystallization of quartz. EPMA analyses of K-feldspar indicated SiO_2 - 62.82 to 62.88 %, Al_2O_3 - 18.48 to 18.62 % and K_2O - 16.63 to 16.71 %, while exsolved plagioclase in perthite analysed SiO_2 - 67.68 to 67.75 %, Al_2O_3 - 19.51 to 19.61 %, Na_2O - 10.91 to 10.96 % and CaO - 0.17 to 0.21 % (Table-2). EPMA analyses of discrete plagioclase grain from Vellaturu granite indicated SiO_2 - 58.60 to 61.05 %, Al_2O_3 - 24.32 to 24.76 %, Na_2O - 7.72 to 8.01 % and CaO - 6.13 to 6.48 %. The host K-feldspar and exsolved plagioclase in perthite fall near the Or and Ab end members respectively on the Or-Ab-An feldspar ternary diagram, while the discrete grains of plagioclase show andesine composition. In QAP diagram (Streckeisen, 1976) the rock falls in granite-granodiorite field. Along its margins the Vellaturu granitoid is intensely deformed and exhibits characters of ductile shearing. Deformational textures in the form of distorted twin lamellae of plagioclase and recrystallisation and progressive extinction in quartz are observed during the petrographic studies. Presence of MMEs showing diffusive contact with the granitoid is conspicuously noticed in the Vellaturu granitoid in its central part (Fig. 3c). Also, presence of deformed amphibolite xenoliths is noticed (Fig. 3d).

Ipuru Granite

Ipuru granitoid occupies the central part of the axis of emplacement. It is coarse grained, leucocratic to mesocratic and massive in nature. It occurs as low-lying outcrops around Ipuru and Bhadrupalem areas in the north eastern fringes of the NFB. Enclaves of quartzite and phyllite of NFB are noticed along the eastern part of the Ipuru granite. Two generations of quartzo-feldspathic vein emplacement are noticed. The

ENE-WSW trending veins displace the NNW-SSE trending veins. In the SE part the Ipuru granitoid is porphyritic in nature. Petrographic studies reveal that the granite mainly consists of plagioclase, microcline, quartz, amphibole and chlorite while zircon, epidote, titanite, muscovite and opaques are the accessory minerals. K-feldspar is microcline that exhibits characteristic cross hatched twinning. Fine exsolved lamellae of Na-plagioclase is often noticed in such microcline perthite grains (Fig. 3e). At places it is noticed that relatively sub-oval zircon haloes along the margin, indicating a magmatic overprint perhaps due to remobilization and emplacement (Fig. 3f). Along its margins the Ipuru granitoid is deformed. In QAP diagram (Streckeisen, 1976) the samples from Ipuru body mainly fall in granite – granodiorite field. However, a few samples from the western part of the Ipuru granite fall in the field of quartz monzodiorite.

EPMA analyses of K-feldspar of Ipuru granite indicates SiO_2 - 64 %, Al_2O_3 - 18.06 % and K_2O - 15.53 %, while exsolved plagioclase in perthite analysed SiO_2 - 66.46 %, Al_2O_3 - 20.57 %, Na_2O - 10.55 % and CaO - 1.07 %. EPMA analyses of the core and rim of the plagioclase from Ipuru granite indicated SiO_2 - 66.79 % and 65.7 %, Al_2O_3 - 20.01 and 20.05 %, Na_2O - 11.45 and 10.37 % and CaO - 0.49 and 1.95 %, indicating reverse chemical zoning phenomenon. Biotite in Ipuru granite analysed SiO_2 upto 36.59 %, Al_2O_3 up to 14.72 %, K_2O - 10.15 %, FeO - 20.70 and MgO - 11.56 % indicating composition of an Mg enriched annite, characteristic of magnesian granites. Field observations indicate the presence of oval to sub-oval shaped mafic rich microgranular enclaves (MMEs) are widely noticed. The oval shaped MMEs show an ENE-WSW trend. At places the MME occur as elongated melanocratic patches with the granite. Conspicuous diffusive contact between the granite and the MMEs is evident by the presence of K-feldspar grains within the MME (Fig. 3g), suggesting magma mingling process during crystallization.

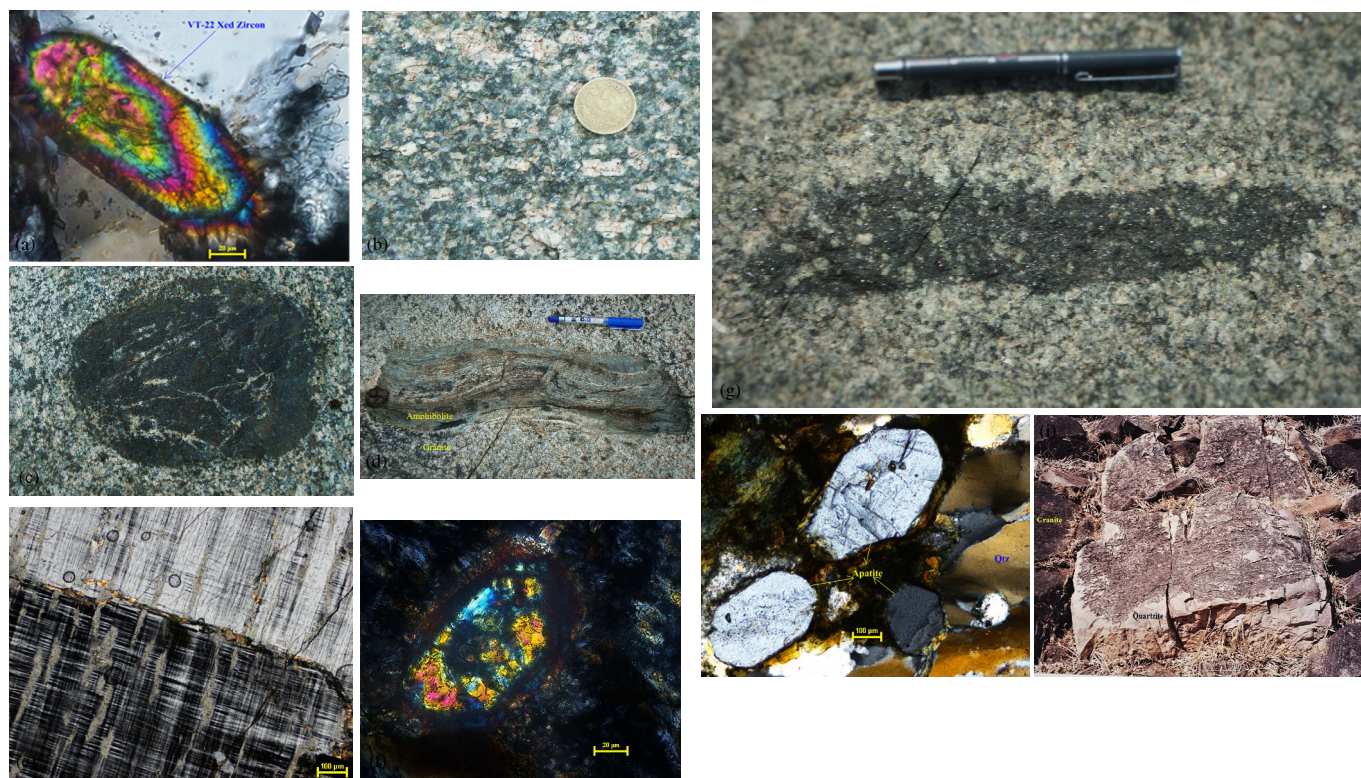


Fig.3. (a) Photomicrograph of zircon grain in Vellaturu granite. (b) Field photograph showing euhedral K-feldspar in Vellaturu granite (c) Field photograph showing MME within the Vellaturu granite. (d) Field photograph of amphibolite xenoliths in Vellaturu granite. (e) Photomicrograph showing exsolved Na-plagioclase in microcline, Ipuru granite. (f) Photomicrograph of zircon with haloes along margin, Ipuru granite. (g) Field photograph showing the diffusive contact between granite and MME in Ipuru granite. Note the presence of subhedral K-feldspar with MME. (h) Photomicrograph of apatite, Nakerikallu granite. (i) Quartzite enclave in Nakerikallu granite, NFB.

NAKERIKALLU GRANITE

Well exposed around Birlapai area in the north eastern fringes of the NFB, the Nakerikallu granite is disposed at the NE part of (VIN) granite axis of emplacement. It intrudes the tightly folded quartzite / phyllitic quartzite intercalated units of Cumbum Formation. Nakerikallu granite is coarse grained, mesocratic and massive. However along its margins the granitoid is deformed. Two sets of prominent fractures (i) The N35°E - S35°W vertical fractures and (ii) N50°W - S50°E fractures dipping southerly. A NE-SW trending basic dyke traverses the granite. Minor quartz veins are noticed traversing the granite along NE-SW direction.

Petrographic studies indicated that the Nakerikallu granite exhibits hypidiomorphic texture and essentially composed of microcline, plagioclase and quartz, with subordinate mafics consisting of amphibole and biotite. Epidote, zircon, carbonates and opaques are noticed as accessory minerals. Biotite is chloritized. Apatite is the conspicuous accessory mineral; in the rock and at places euhedral to subhedral apatite grains are noticed as clusters (Fig. 3h). Field observation indicate the presence of a light grayish white coloured quartzite enclave (5m length in N20°E- S20°W direction and width 2m), indicating its intrusive nature of Nakerikallu granite into the NFB sequence (Fig. 3i). In QAP diagram (Streckeisen, 1976) the samples from Nakerikallu body mainly fall in granite-granodiorite field. EPMA analyses of K-feldspar from Nakerikallu granite has SiO₂ up to 63.42 %, Al₂O₃ upto 18.34 %, and K₂O upto 17.0 %, while the exsolved plagioclase in host K-feldspar analysed SiO₂ - 67.49, Al₂O₃ - 19.72 %, Na₂O - 11.79 % and CaO - 0.52 %, indicating predominantly albite composition. Discrete grains of plagioclase analysed SiO₂ ranging from 61.02 to 64.30 %, Al₂O₃ ranging from 21.48 to 23.77 %, K₂O ranging from 0.09 to 0.16 %, Na₂O ranging from 8.98 to 11.0 % and CaO ranging from 2.28 to 5.78 %, indicating the variation from oligoclase to andesine (Fig.4). Biotite mineral composition in Nakerikallu granite indicate SiO₂ upto 37.37 %, Al₂O₃ - 14.79 %, K₂O - 10.51 %, FeO - 17.74 and MgO - 12.82 % indicating relatively Mg enriched annite. Close to the vicinity of the Nakerikallu granite, the folded quartzite-phyllite sequence of the NFB is well exposed on Birlapai-Nakerikallu section. Field studies indicate that the granitoids

at Ipuru and Nakerikallu area in NFB are traversed by dolerite dykes (Sesha Sai, 2004).

GEOCHEMISTRY

MAJOR OXIDE GEOCHEMISTRY

The VIN granitoids exhibit remarkable magnesian feldspathic character; FeO / FeO + MgO varies from 0.61 to 0.72 (Fig.5 a). Magnesian granites in contrast to ferroan granites do not exhibit strong iron enrichment (Frost and Frost, 2008). The Mg # ranges from 43 to 56. In AFM diagram (Irvine and Barager, 1971), the VIN granitoids exhibit profound calc-alkaline trend (Fig.5 b). The VIN suite is characterized by higher alkali contents relative to CaO. The average Na₂O / K₂O ratio is 0.55. The SiO₂ varies from 64.28 to 71.69 with the average being 69.22 %. Most of the rocks of granitoid affinity that have < 70 % SiO₂ are magnesian (Frost et.al. 2001).

Remarkable consistency in the Al₂O₃ contents is noticed; Al₂O₃ varies from 14.01 to 15.08 % with the average Al₂O₃ being 14.57 %. In A/NK vs A/CNK plot the most of the VIN granites fall in peraluminous field, while a few exhibit metaluminous character (Fig.5 c). In Cordilleran magnesian granites both peraluminous and metaluminous are present (Frost and Frost, 2008). Constant increase in both Na₂O and K₂O content is noticed with increase in SiO₂ in the VIN granitoids, while remarkable negative correlation is noticed between SiO₂ vs TiO₂ wherein the Ti is sharply decreased with increase in SiO₂ with crystallisation of the granitic magma. In the modified alkali lime index (MALI) diagram the VIN granites show alkalic to alkali calcic nature. Magnesian granitoids with peraluminous character are alkali-calcic and calcic granitoids (Shimura et al., 1992; Johnson et al., 1997). Average Al₂O₃ of 14.57 % and average Na₂O + K₂O + CaO of 9.7 % along with presence of apatite corroborates with the peraluminous nature of VIN granitoids.

TECTONIC DISCRIMINATION

Emplaced along an NE-SW axis in the NE fringes of the NFB in the eastern half of the Proterozoic Cuddapah basin, the VIN granites show intense deformation along their peripheral parts. In the Y+Nb

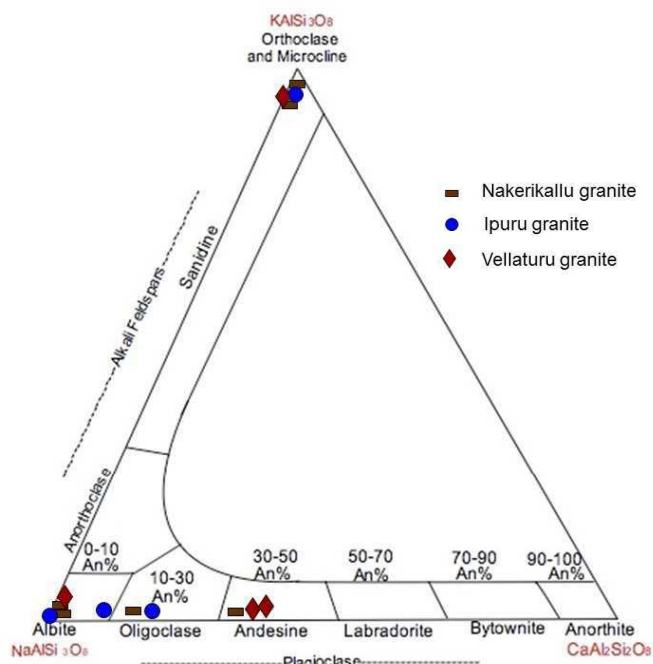


Fig.4 Orthoclase-Albite-Anorthosite triangulate plot depicting the position of feldspars from the VIN granites, Nallamalai Fold belt, SE India

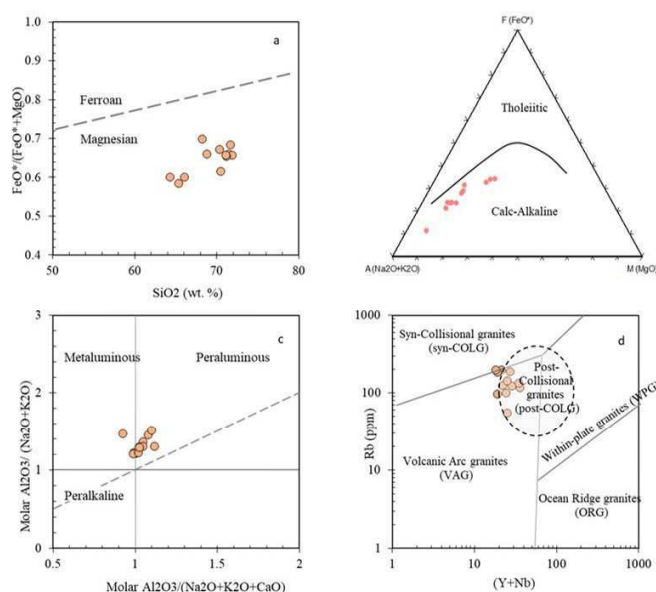


Fig. 5a. SiO₂ vs FeO* / (FeO*+MgO) diagram (Frost et al., 2006); **Fig.5b** AFM diagram (Irvine and Barager, 1971); **A/CNK vs A/NK** diagram (Shand, 1943) and **Y+Nb vs Rb** (Pearce, 1996)

vs Rb binary trace element tectonic discrimination plot for the granitic rocks (Pearce, et.al. 1984), the VIN granites mostly fall in the field of volcanic arc granites (VAG). However, it is noticed that a few samples of VIN granites (Fig.5d) are disposed close to the boundary of VAG and syn collisional granites (syn- COLG). Volcanic arc granites are exposed in the present day eroded sections i.e. the deeper plutonic parts of the magmatic arcs and these granitoids are recognized as distinct geochemical type (eg. Pearce et al.1984; Frost, et al.2001). The calc-alkaline nature of VIN granites, presence of biotite $\pm$ amphibole and their occupying the fields of granodiorite-monzodiorite-tonalite-granite in QAP plot corroborates with the granitoids emplaced in VAG setting. Mesoproterozoic calc alkaline granites emplaced in volcanic arc tectonic setting have been reported in south western margin of Baltic shield (Andersen, et al. 2004). In major oxide discrimination diagram these granitoids are termed as island arc and continental arc granites (Maniar and Piccoli, 1989). The Paleoproterozoic Msusule tonalites of SW Tanzania exhibit VAG characters (Manya and Maboko, 2016).

TRACE AND RARE EARTH ELEMENT GEOCHEMISTRY

The trace element character of the VIN granitoids show profound negative niobium (Nb) and titanium (Ti) anomaly, characteristic of arc magmas (Fig.6d to 6f). In contrast to the granites that are produced in intracontinental settings (e.g. Manya and Maboko, 2016), the VIN granites are characterized by relatively high Zr/Sm ratios ranging from 22 -78, and display positive Zr anomalies on a primitive mantle normalized trace element variation diagram relative to the neighboring REE (Fig. 6d, e, f). These rocks are further characterized by high $(La/Yb)_N$ coupled with low $(Yb)_N$ ratios that are typically observed in the Na-rich granitoids (e.g. Manya et al., 2007) and adakites (e.g. Khanna et al., 2015) generated in subduction-related tectonic environment. Depletion of niobium is observed in some of the arc related magmas and the continental crust (eg. Kelemen et al, 1993). large ion lithophile elements (LILEs) analyses indicate lower Rb and relatively higher Sr and Ba contents in the VIN granitoids. The Rb content varies from 55 to 199 ppm, Sr varies from 232 to 381 ppm and the Ba content of VIN granites range from 340 to 1269 ppm. The relatively higher Ba contents (> 750 ppm Ba) in the Victorian granites

from the southern Lalchan Fold Belt has been ascribed to melting of Ba rich sediments (eg. Rositter and Grey, 2008). Amongst the High Field Strength Elements (HFSE), the Nb varies from 7 to 13 ppm, Y varies from 11 to 23 ppm and Zr from 145 to 518 ppm. Enriched Sr and Ba, depleted Rb, and highly depleted Y, Nb, and Zr in the Trondhjemites of Nubian Shield indicate volcanic arc granite characters (eg. Abdel Fattah 1990). The VIN granites show a relative enrichment of LREE. The + REE content vary from 1594 to 482 ppm. Chondrite normalised REE plot of Vellaturu granitoid do not show negative Eu (Fig. 6 a), while, low europium anomaly is noticed in Ipuru and Nakerikallu granites (Fig. 6 b & 6 c).

MAGMA MINGLING

Presence of abundant mafic rich microgranular enclaves (MMEs) is conspicuously noticed in the VIN granitoids indicating magma mingling process. Oval to sub oval shaped MMEs are widely noticed, particularly in the Vellaturu and Ipuru bodies. Studies indicate that in VIN granitoids the MMEs are medium grained, dark grey and composed of quartz, plagioclase, K-feldspar and biotite as the main constituents with accessory titanite, zircon and opaques. Chemical analyses indicate SiO_2 - 48.40%, Al_2O_3 - 15.39 %, $Fe_2O_3^T$ - 10.95 %, MgO - 6.04 %, CaO -3.05 %, Na_2O - 2.39 %, K_2O - 5.12 % in the MME indicating a low silica and high Fe-Mg contents. MMEs in the granitoid, indicate a magmatic origin for these enclaves (Vernon 1984). At places, it is noticed that relatively large euhedral K-feldspar crystals in the granitoid swerve around the contact with the MME and also remarkable diffusive contact can be noticed between the host granite and the MME suggesting the magma mingling phenomenon preserved in the relatively undeformed central part of VIN granitoids. Close to the vicinity of the MMEs it is noticed that the relatively large K-feldspar grains show alignment. The presence of MMEs in the granitoids may indicate the process of magma mingling (eg. Hibbard 1991; Pitcher 1993). Mingling of felsic and mafic magma is a widely recorded phenomenon in granites of syn collisional origin (eg. Chen et al., 2015; Chen et al., 2018). The Sarhan volcanic-arc granitoids in NE Turkey show the presence of MME (Zafar Aslan, 2005).

AGE OF VIN GRANITES

Proterozoic NFB, an arcuate fold thrust belt is poised along a major terrane boundary in SE India, i.e. the eastern part of the Cuddapah basin and western margin of the Neoproterozoic NSB in EDC (eg. Saha, 2002; Chetty, 2011; 2017). In this context, understanding the age of the VIN granites is key to ascertain the timing of the major deformational event that resulted in the formation of NFB. During the present studies, an attempt has been made to ascertain the age of Ipuru granite by monazite dating. Results indicate a presumable prolioth age ranging from 2071 ± 56 Ma to 2253 ± 61 Ma and an age range of 1509 ± 50 Ma to 1573 ± 59 Ma for remobilization and emplacement of the Ipuru granite. Studies indicate that the monazite is rimmed by apatite and allanite (Fig.7). To authenticate the emplacement age of $\sim 1573 \pm 59$ Ma for Ipuru granite by monazite dating in the present studies and the $\sim 1575 \pm 20$ Ma Rb-Sr age for Vellaturu granite by Crawford and Compston (1973), the following three aspects have been considered (i) Field observations (Hazra et al., 2004; Sessa Sai, 2004), indicate the presence of xenoliths of NFB confirming the intrusive nature of these granitoids into the deformed NFB (ii) based on dating of detrital zircons, Collins et al., (2014), suggested that the sediments of the Nallamalai Group were deposited between 1659 ± 22 Ma and ~ 1590 Ma and (iii) A U-Pb age of 1550 Ma was constrained for the youngest detrital zircons from the Bairenkonda Quartzite of NFB (Joy et al., 2015).

In light of above observations, the Rb-Sr model age of the $\sim 1575 \pm 20$ Ma age for NFB granite (Crawford and Compston, 1973) is interestingly poised very close to 1550 Ma, and hence remains a

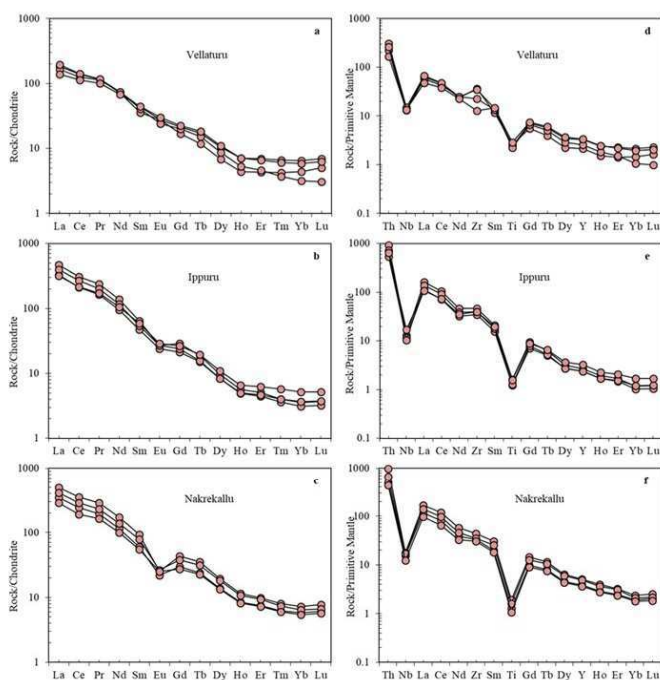


Fig. 6 Chondrite normalized REE (a, b, c) and primitive mantle normalized trace element variation diagram (d, e, f) for the VIN granites

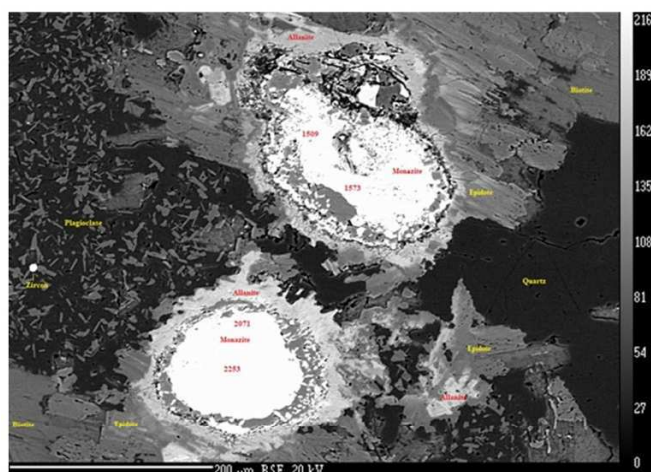


Fig.7. BSE image showing the monazite rimmed by allanite in the Ipuru granite. Note the presence of epidote close to the vicinity of monazite

significant contribution. However, radiogenic isotope studies involving modern techniques like U-Pb zircon dating will help to precisely date the VIN granites.

DISCUSSION

Understanding the tectono-magmatic implications of granite magmatism is key to unravel the evolutionary history of the continental crust in Dharwar craton (Jayananda et al., 2000; Jayananda et al., 2018). Understanding the geological domain comprising the eastern margin of Proterozoic NFB, the Proterozoic accretionary events in the Neoproterozoic NSB to the west of EGMB, is essential to unravel the critical events of break up and assembly of Proterozoic continents (Zhao et al., 2003; Ravikant, 2010; Santosh, 2012; Chetty, 2017). In this context, tectonically distinct events of Proterozoic granite magmatism in the north eastern fringes of the NFB (VIN granites of present study) and the granites along the western margin of the NSB (Vinukonda in north to Sri Kalahasthi in south), provide critical insights to understand the Proterozoic tectonic evolution along the eastern margin of EDC (eg. Chetty, 2017; Sesha Sai, 2013; Saha and Sain, 2018). The deformed nature of the Vellaturu, Ipuru and Nakerikallu granites along their margins indicate syn to post tectonic nature for the emplacement for the VIN granites of NFB. Mineral chemistry of the discrete grains of plagioclase from the VIN granites indicate composition ranging from oligoclase to andesine (Fig.4), while the exsolved plagioclase within the perthitic K-feldspar is albite in composition. Granitic rocks along the continental margin magmatic are predominantly calc alkaline in nature and mineralogically vary from granite-granodiorite in composition with plagioclase (oligoclase to andesine), K-feldspar (perthitic with exsolved Na-plagioclase), biotite (relatively Mg rich annite) and amphibole as essential phases, while apatite is a conspicuous accessory phase (eg. Frost and Frost, 2014).

The present study indicates that the emplacement of the Proterozoic VIN volcanic arc granites of magnesian nature postdate the major deformational event that resulted in formation of the NFB (Nagaraja Rao et al, 1987), a curvilinear fold thrust belt that form eastern part of the Proterozoic Cuddapah basin of EDC in SE India. Granites can attain VAG characters due to the interaction of crustal and mantle-derived melts (Pearce, 1996). However, intrusion of VIN granites into the deformed NFB and their disposition close to a major terrane boundary i.e. the Proterozoic NFB and the Archaean NSB indicate the presence of a continental margin tectonic setting. Further, the 1575 ± 20 Ma Vellaturu granite (Crawford and Compston, 1973) is spatially juxtaposed close to the 1588 Ma Vinukonda granite (Dobmeier

et. al., 2008). Study of the Mesoproterozoic arc granites in south western margin of Baltic shield indicated their formation in a magmatic arc along the continental margin (Andersen, et.al. 2004). Mesoproterozoic magmatic arc granites of Cachoeirinha are reported from SW Amazonian craton and compositionally these granites are tonalites, granodiorites and granites ascribed to the represent juvenile magmatic activity that occurred between 1590 and 1520 Ma (Amarildo et.al.2004). Precambrian volcanic arc granites have also been identified in Phelps Lake Region of the Hearne Province in the Canadian Shield (Harper, 2004). Instances of Proterozoic arc magmatism has also been recorded in North American Craton (eg Bally and Palmer, 1989; Sims et.al.1993) and from the Wadi Dabr complex, Egypt (Abu El-El; 1997).

Presence of mafic rich microgranitoid patches (MMEs) within the VIN granitoids suggest their magmatic origin with involvement of mingling phenomenon. The granite and granodiorite rocks of arc magmatic origin Southeast Anatolian orogen contain mafic microgranular enclaves (Fatih Karaoglan et al., 2013). Alignment of the K-feldspar along the margins of the MME and remarkable diffusive contact between the host granite and the MME suggest magma mingling phenomenon preserved in the undeformed part of Vellaturu granite. The VIN granitoids are however deformed particularly along their margins. An age of 1588.4 ± 7.1 has been ascribed to the emplacement of Vinukonda granite (Dobmeier et al., 2008), that is disposed close to the eastern margin of Vellaturu granite, at the southern part of the VIN granite axis of emplacement. The arc magmatic tectonic setting of the VIN granites along with their calc alkaline nature and granodioritic compositions is akin to the Paleoproterozoic granodiorites of Saza area in SW Tanzania (Manya, 2014). Nagaraju and Chetty (2014), observed that geological domain along the eastern margin of Dharwar craton and the adjoining EGMB demarcated by the TBSZ is geologically a complex terrane.

The present work dealing with the magnesian feldspathic magmatic nature of VIN granites, highlights the existence of a Mesoproterozoic magmatic arc in the NE fringes of NFB, along the continental margin of EDC. The axis of emplacement of VIN granites represents a linear tectonic contact that is juxtaposed along the north eastern margin of the Proterozoic NFB and adjoining Precambrian accretionary terrain comprising of the gneisses and amphibolites with intrusive granites in the northern part Nellore schist belt (NSB).

CONCLUSION

- The paper presents the field and laboratory studies dealing with classification, petrogenesis and tectonic setting of the VIN granites in the northeastern fringes of the Proterozoic NFB from the SE part of Indian sub-continent.
- Petrographically VIN granites are apatite, zircon, titanite bearing biotite $\pm$ amphibole granites and fall in granite-granodiorite field in the IUGS-QAP plot.
- Presence of enclaves of NSB lithounits and older amphibolite confirm their intrusive nature, while occurrence of mafic rich patches (MMEs) suggest their magmatic origin.
- VIN granitoids are deformed particularly along their eastern margins indicating syn to post tectonic nature of emplacement.
- Geochemical variables; $\text{FeO} / (\text{FeO} + \text{MgO})$ ratio indicate the magnesian nature of the VIN calc alkaline granitoids.
- The negative Nb and Ti anomalies, in combination with the incompatible element ratios in the VIN granites, which are typically observed in adakitic rocks, provide compelling evidence of their origin in a subduction-related tectonic setting.
- Based on the remarkable magnesian feldspathic character coupled with their emplacement in an arc magmatic setting, it is concluded that the VIN granitoids in the Proterozoic NFB; mark a significant

event of “Proterozoic magnesian feldspathic magmatism” in SE India.

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