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Petrological and Geochemical Characterisation of the Punugodu Granite Pluton Nellore Schist Belt; Implications for Proterozoic Anorogenic Granite Magmatism in the Eastern Dharwar Craton, Southern India

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ABSTRACT

In this paper we present the in-situ field observations along with petrographic and geochemical results of the Punugodu granite pluton of Nellore schist belt, Eastern Dharwar Craton, South India. Located to the South of Podili alkali granite, the Punugodu granite pluton occupies an area of 7 sq. km. Field studies indicate that the Punugodu granite is deformed along the margins. Enclaves of metavolcanics and quartzite of the Nellore schist belt are observed in the pluton indicating its intrusive nature. Petrographically the rock is mainly composed of K-feldspar, with sub ordinate quartz, amphibole, biotite, pyroxene and hypersolvus in nature. Zircon, titanite, fluorite, apatite and opaques are the accessory phases. Geochemical studies reveal that the Punugodu granite indicates the metaluminous nature and exhibits calc-alkaline trend. Punugodu granite is charecterised by high SiO_2 contents ranging from 69.62 % to 72.7 %, high $Na_2O + K_2O$, relatively low MgO contents ranging from 0.13 % to 0.76 %. The $CaO-Na_2O-K_2O$ contents range from 10.15 % to11.14 %. Chondrite normalised Rare Earth Elements diagram shows relative enrichment of Light Rare Earth Elements and negative europium anomaly for the Punugodu granite. It is relatively enriched in High Field Strength Elements (HFSE); Zr (85.54 to 311.83 ppm), Y (108.07 to 156.60 ppm), Nb (131.59 to 216.61 ppm) and the (36.38 to 51.62 ppm). In the Y+Nb vs Rb trace element tectonic discrimination diagram Punugodu granite falls in the within plate granite field (WPG). The high SiO_2 and $Na_2O + K_2O$, relatively low MgO contents along with enriched HFSE and within plate character indicates the anorogenic nature of the fluorite bearing Punugodu granite.

Key words: Punugodu granite, Nellore schist belt, EDC, India

INTRODUCTION

A-type magmatic provinces are widespread in the Earth's crust and have been formed since Archean times as a result of geodynamic processes associated with extensional tectonic environments. The diversity of rock types, with contrasting petrographic and geochemical signatures is a particular feature of A-type magmatism (Whalen et al., 1987; Eby, 1990; Poitrasson et al., 1995; Litvinovsky et al., 2002; Vilalva and Vlach, 2014). Proterozoic A-type granite magmatism was reported along the eastern margin of the Cuddapah basin (Reddy, 1989; 1991). Moeen, (1998), carried out mineralogical studies and P-T estimates of the Nellore schist belt (NSB) litho units. Close to the eastern margin of the Cuddapah basin (Nagaraja Rao et al., 1987; Tripathy and Saha, 2015), a regional curvilinear shear zone defined as Terrain boundary shear zone (TBSZ) was demarcated along the western margin of the Nellore schist belt (Chetty and Murthy, 1994; Chetty, 1999). The TBSZ has been interpreted as a crustal scale shear zone and a major tectonic feature to the west of the Eastern Ghat Granulite belt (EGMB) of South India (Chetty, 2017). Significant zone of Proterozoic granite magmatism was demarcated in the NSB; close to the eastern margin of the Proterozoic Nallamalai Fold Belt (Sesha Sai, 2013a; Sesha Sai, 2016). Presence of calc silicate bands close to the vicinity of Kanigiri granite and Podili granite is recorded (Prasada Rao and Ahluwalia, 1974). Presence of pyroclastic volcanism in the form of agglomerate was reported by Srinivasan and Roop Kumar (2007). Rare metal mineralisation in the granite around Kanigiri area is reported by Banerjee et al., (1983), while Dharma Rao and Reddy (2007) carried out trace element and geochronological studies on the Kanigiri granite. The Mesoproterozoic Kanigiri granite (Gupta et al., 1984; Sain et al., 2017) is located to the west of Punugodu pluton. Punugodu granite pluton was initially noticed by Reddy and Sesha Sai (2003). Saha et al., (2015), studied the tectono stratigraphic evolution of the Nellore schist belt. We present the in-situ field observations in addition to petrographic

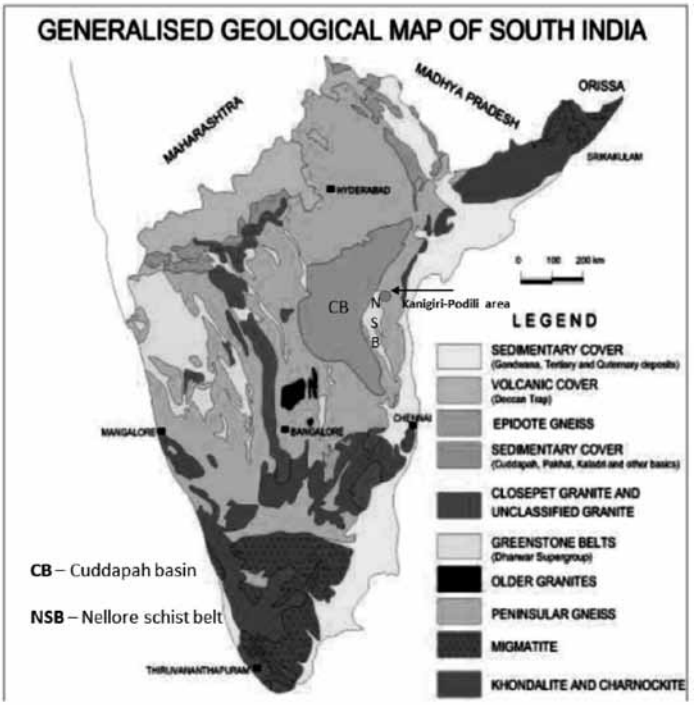

Figure 1. Geological Map of South India showing the location of the Kanigiri-Podili area to the east of Cuddapah basin, Eastern Dharwar Craton, SE India (modified after GSI, 2013).

and geochemical details of the Punugodu granite pluton of Nellore schist belt and explain the spatial relationship of the pluton with adjoining NSB litho units.

GEOLOGY OF PUNUGODU AREA

The Punugodu granite pluton is located in the Northern part of the NSB in Eastern Dharwar Craton (EDC), SE India (Figure 1). The Punugodu pluton is an N-S trending oval body that occupies an area of about 7 sq. km. Field studies indicated two sets of fractures (i) N-S trending vertical fractures and (ii) NNW-SSE trending sub-vertical fractures with steep easterly dips. Geologically the area around Punugodu comprises metavolcanic and metasedimentary sequences of the Neoarchean NSB (Ravikant, 2010). The rocks the NSB are intruded by granites (Figure 2) of Proterozoic age (Gupta et al., 1984; Dharma Rao and Reddy, 2007; Sesha Sai, 2013a; Sain et al., 2017) and mafic dykes of dolerite and gabbro composition (Srinivasan and Roop Kumar, 1995). Quartzo-feldspathic veins traverse the granites in N-S and WNW-ESE directions (Sesha Sai, 2006). The Podili alkali granite (Prasad Rao and Ahluwalia, 1974; Sesha Sai, 2004; 2013a) lies to the north of Punugodu pluton, while the Kanigiri granite lies to its west (Figure 2).

To the northeast of the Punugodu granite, highly deformed biotite granite is reported at Andhra Konda (Sesha Sai, 2004). Detailed field, petrographic and petrochemical characterisation of the granitic rocks around Kanigiri – Podili area is carried out and the comparative studies on field, petrography, mineral chemistry and geochemistry are provided in a tabular form (for details see Sesha Sai, 2013a). Astrophyllite bearing alkali granite was reported along the western margin of the Podili pluton (Sesha Sai, 2013b). An olivine gabbro is noticed in the form of an intrusive dyke to the South of Kanigiri granite and South west of Punugodu pluton (Srinivasan and Roop Kumar, 1995).

Contact thermal effect resulted in the formation of hornfels rocks that are noticed mainly along the margins of the Punugodu pluton with the host NSB lithounits (Figure 2a). Remnants of schistose rocks and quartzites of NSB are noticed in the upper parts the pluton (Narshimha et al., 2016). However, the presence of NSB volcanic enclaves in the pluton indicates its intrusive nature.

Field and Petrography

The Punugodu granite is mesocratic, phaneritic, massive equigranular and coarse grained. It is exposed as a low-lying hillock (Figure 3a) to the south of Podili pluton in northern part of the NSB. Enclaves of metavolcanics and calc-silicate rock of NSB are also found in the Punugodu pluton (Figure 3b). At places clusters of mafic minerals and deep blue fluorite crystals are noticed in the Punugodu granite, when examined with hand lens. Petrographic studies indicate that the rock is hypersolvus in nature.

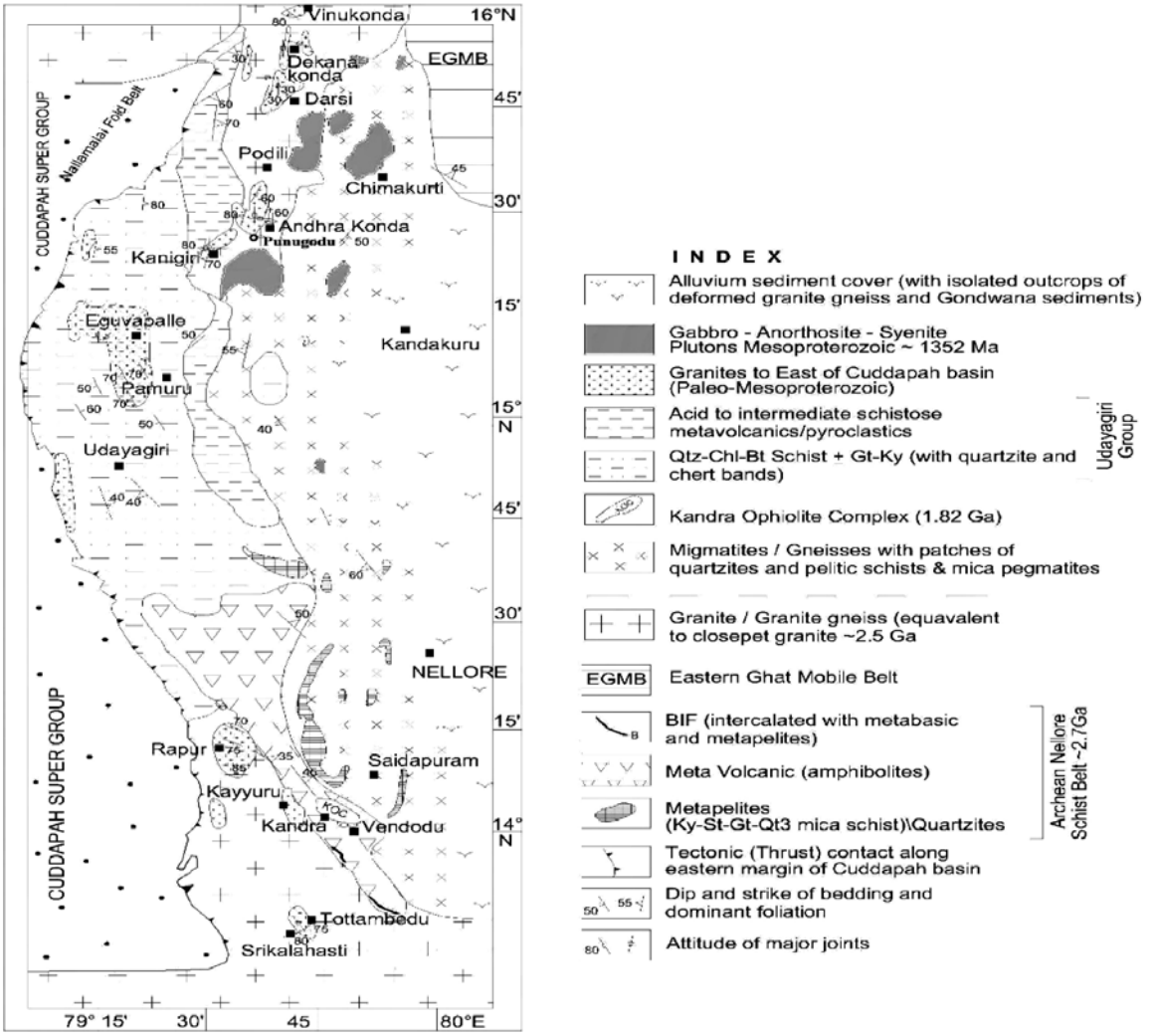

Figure 2. Geological Map of Nellore Schist Belt and adjoining areas, Andhra Pradesh, India showing the location of Proterozoic Granite Plutons.

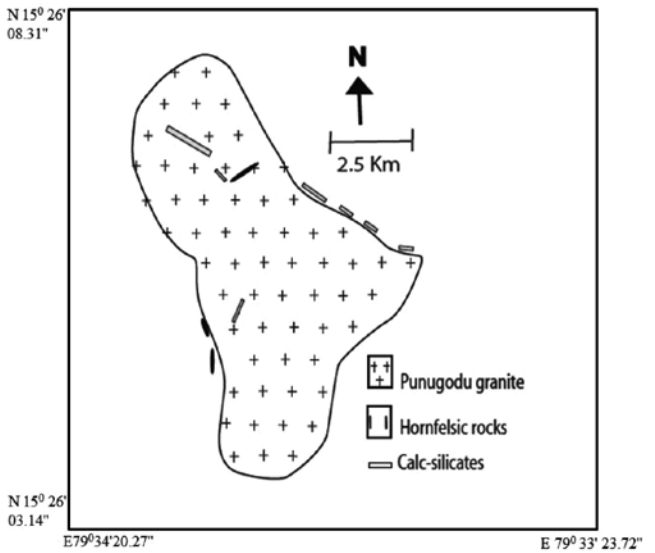

Figure 2a. Geological Map of the Punugodu Granite Pluton, Northern part of the Nellore schist belt, EDC, India.

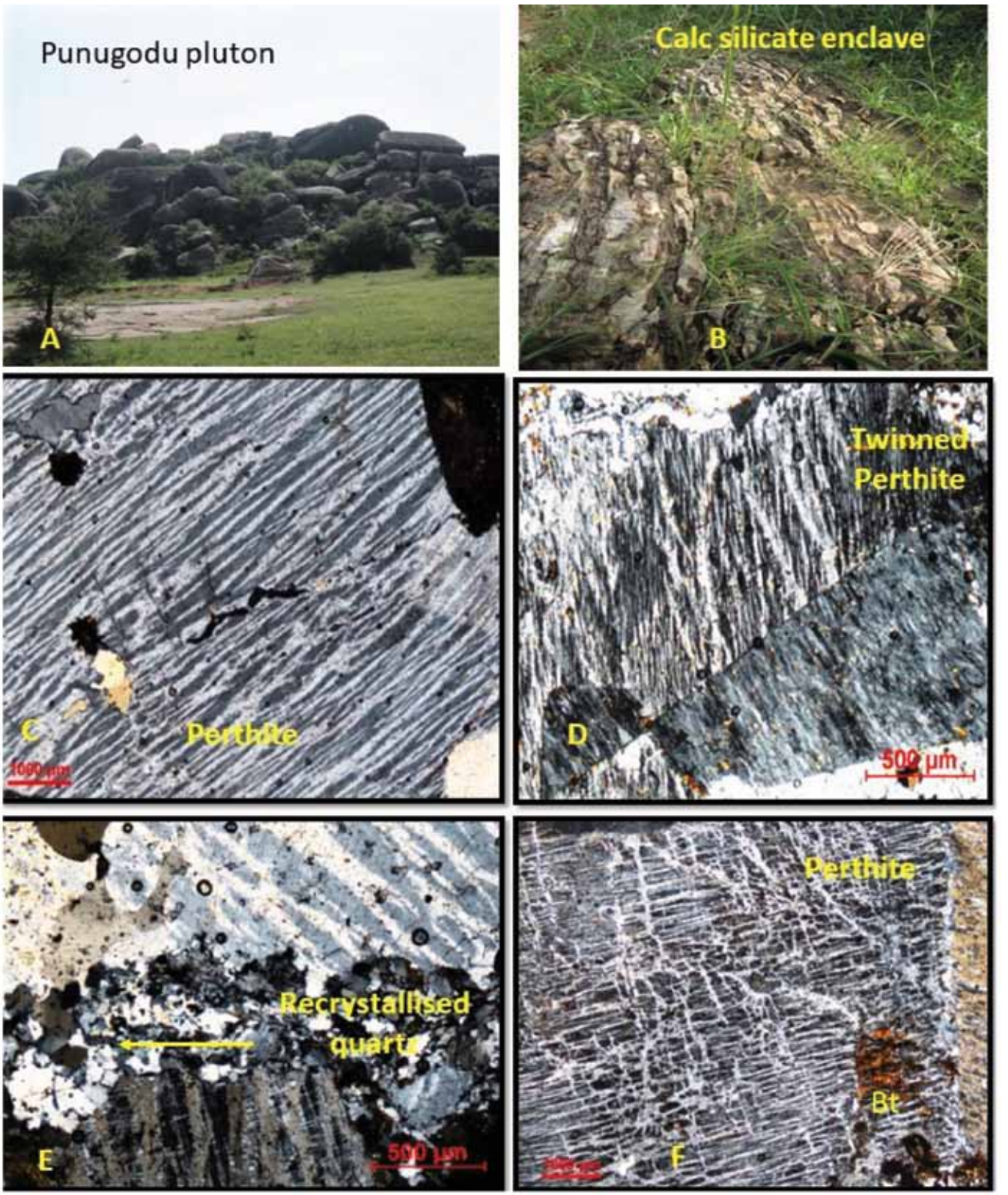

Figure 3. A. Field photograph showing the Punugodu pluton. **B.** Field photograph showing the calc silicate enclave in Punugodu pluton **C.** Photomicrograph in cross nicols showing the perthite intergrowth in Punugodu granite **D.** Photomicrograph in cross nicols showing the twinned perthite in Punugodu granite **E.** Photomicrograph in cross nicols showing recrystallized quartz within the perthitic K-feldspar **F.** Photomicrograph in cross nicols showing the string type microperthite with inclusions of biotite

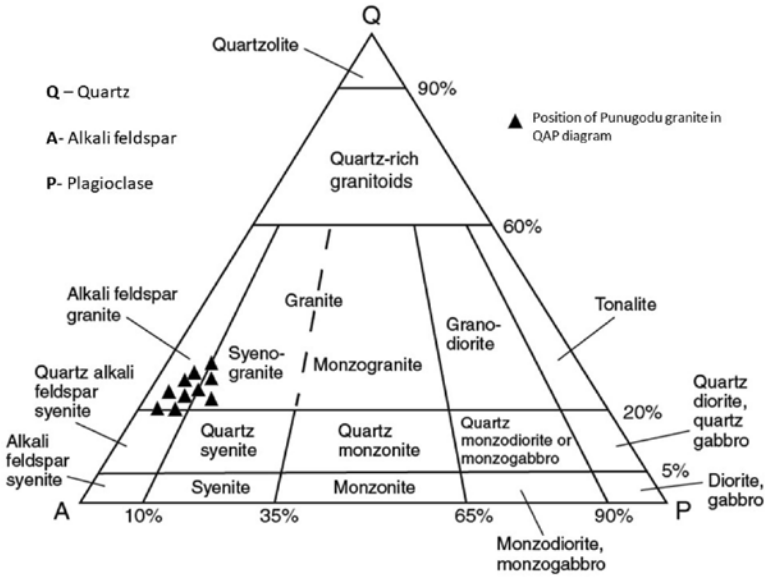

Figure 4. Position of Punugodu granite in QAP diagram (after Streckeisen, 1974).

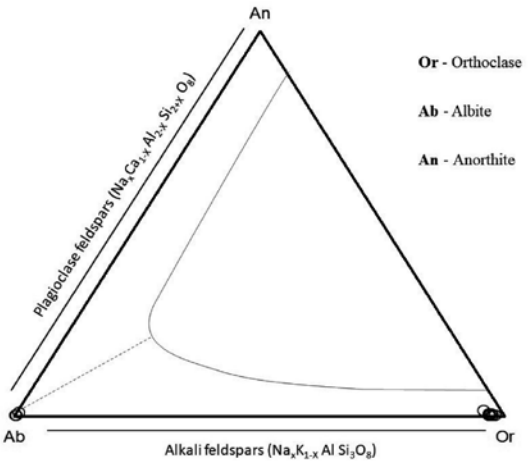

Figure 4a. Position of alkali feldspar host and plagioclase exsolved lamellae of Punugodu granite in the Or-Ab-An feldspar mineral chemistry diagram

Perthitic alkali feldspar (Figure 3c) is the dominant mineral phase in the rock followed by quartz, biotite and amphibole. Zircon, titanite, fluorite, apatite and opaques are the accessory minerals. Relict clinopyroxene is noticed at places. Quartz is anhedral and often shows wavy extinction and occurs amidst the larger perthite grains. Biotite is interstitial and pleochroic in shades of brown. Hornblende is pleochroic in shades of green to brown. At places clusters of biotite and amphibole are noticed in Punugodu granite. Alkali feldspar is mainly represented by microcline. Perthite intergrowth texture is prominently noticed in the rock. At places coarse grained perthite exhibits twinning (Figure 3d). Recrystallised quartz is noticed amidst large perthite grains. An admixture of relatively small size quartz grains along with minor amounts of biotite is noticed at places giving rise to development of mortar texture indicating deformed state of the rock (Figure 3e). String type of perthite is dominant among the intergrowth alkali feldspar (Figure 3f). Inclusions of biotite are often noticed in the perthite grains (Figure 3f). Fluorite is interstitial in nature. Apatite is euhedral and occurs as both discrete grains as well as inclusion in mafic phases. Zircon and titanite are noticed as euhedral grains and are often associated with the mafic minerals. Zircon is also seen as minute euhedral inclusions in perthite grains. In the IUGS QAP diagram (Streckeisen, 1974), the Punugodu granite mainly falls in the field of alkali feldspar granite (Figure 4). However, a few samples also fall at the boundary of granite-alkali feldspar granite and at the boundary of alkali feldspar quartz syenite and alkali feldspar granite.

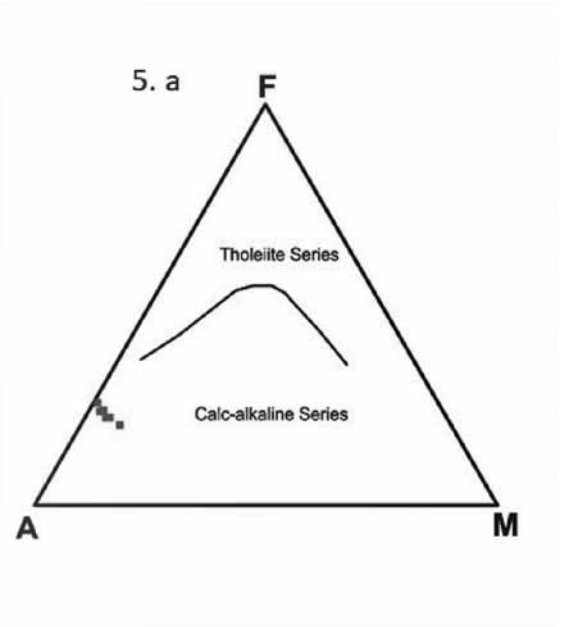

Figure 5a. Punugodu granite exhibition calc alkaline nature in AFM diagrams (Irvine and Barager, 1971).

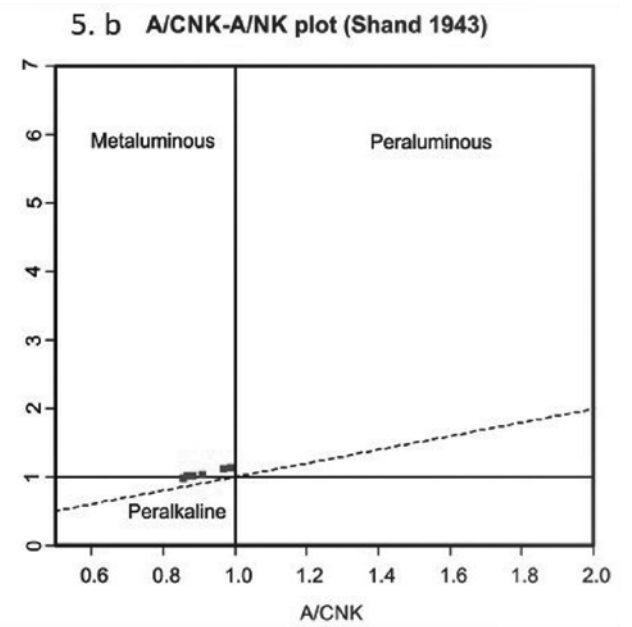

Figure 5b. Metaluminous nature of Punugodu granite on A/NK-A/CNK diagram (Shand, 1943).

Feldspar mineral chemistry

To ascertain the mineral chemistry of the perthitic feldspar from the Punugodu granite Electron Probe Micro Analyses (EPMA) was carried out. Analytical results indicate that the host alkali feldspar is close to the orthoclase end member composition with $Or_{95.10 \text{ to } 97.51}$ and the exsolved plagioclase in the perthite is near albite end member composition with $An_{98.78 \text{ to } 99.63}$ (Figure 4a). Exsolved lamellae of albite analysed Na_2O – 11.40 % to 11.73 %, K_2O – 0.07 % to 0.12 %, CaO – 0.11 %, SiO_2 – 68.21% to 68.31 %, Al_2O_3 – 19.52 % to 19.76 %, while the host K-feldspar analyses K_2O – 15.53 % to 16.14 %, Na_2O – 0.34 % to 0.39 %, SiO2– 63.49% to 64.53 %, Al_2O_3 – 17.91 % to 18.93 %. EPMA analyses were carried out at Southern Region Petrological Laboratory, GSI, and Hyderabad with the aid of CAMECASx100.Analyses conditions: Accelerating voltage: 15kV, current: 12nAand Beam size: 1 μ. All natural standards have been used except for Mn and Ti, for which synthetic standards have been used. Major oxide analyses were carried out by XRF method at the Geological Survey of India, Chemical Laboratory, Southern Region and Hyderabad.

Geochemistry

The Punugodu granite is characterised by high SiO_2 contents ranging from 69.62 % to 72.7 %, high Na_2O + K_2O, relatively low MgO contents ranging from 0.13 % to 0.76 %. The Al_2O_3 content ranges from 11.74 % to 13.44 % and the TiO_2 content ranges from 0.30 % to 0.37 %. The K_2O contents (5.65 to 6.44 %) are more than the Na_2O contents (3.31 to 3.73%) in the alkali feldspar dominated Punugodu granite. The CaO content is relatively low and ranges from 0.93 % to 1.18 %, characteristic in metaluminous syenites. The CaO-Na_2O-K_2O contents range from 10.15 to % 11.14 % and less than the Al_2O_3 content in the Punugodu granite, indicating the metaluminous nature. In the A/NK – A/CNK diagram (Shand, 1943), some samples from the Punugodu granite fall close to the boundary of metaluminous – peralkaline field (Figure 5b). Geochemical studies indicate that the Punugodu granite is metaluminous in nature and exhibits calc alkaline trend (Figure 5a and Figure 5b).

Trace element geochemistry indicates incompatible element enrichment in the Punugodu granite. Relatively higher values of high field strength elements (HFSE) are analysed; Zr values range from 85.54 to 311.83 ppm, Y values range from 108.07 to 156.60 ppm and Nb values range from 131.59 to 216.61 ppm. Th values range from 36.38 to 51.62 ppm and Ta values range from 4.65 to 11.25 ppm. Among the Large ion lithophile elements (LILE), relatively higher values of rubidium range from 179.08 to 251.74 ppm in the Punugodu granite. In the Y+Nb vs Rb trace element tectonic discrimination diagram (Pearce et al., 1984), the Punugodu granite falls in the Within plate granite field (WPG). Chondrite normalised Rare Earth Element (REE) diagram shows relative enrichment of Rare Earth Element Elements (LREE) and negative europium (Eu) anomaly for the Punugodu granite and the Eu / Eu* values range from 0.04 to 0.07. The $\sum$ REE contents in Punugodu granite range from 648.29 to 1829.45 ppm indicating an overall REE enriched nature of Punugodu pluton.

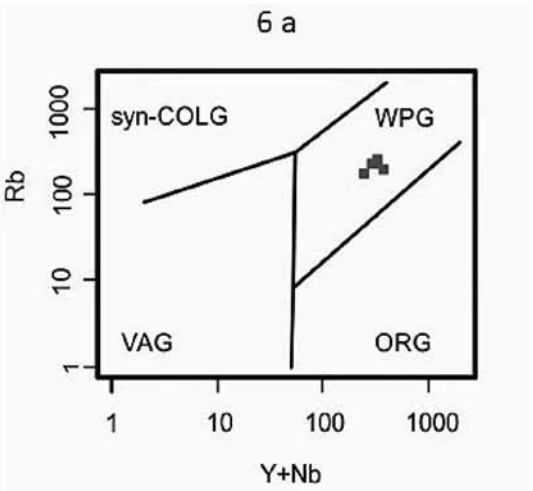

Figure 6a. Y+Nb vs Rb trace element tectonic discrimination diagram (Pearce et al., 1984), showing the WPG nature of Punugodu granite.

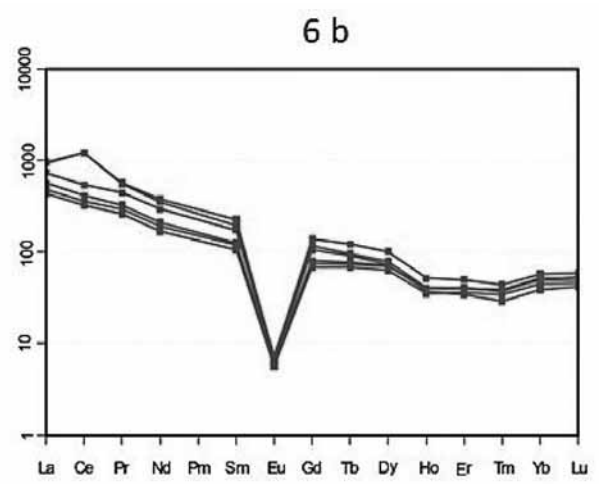

Figure 6b. Chondrite normalised REE diagram showing LREE enrichment and negative Eu anomaly for the Punugodu granite.

Table 1. Major oxide analyses of Punugodu granite, Nellore schist belt, EDC, India

Sample	**PG-3**	**PG-5**	**PG-6**	**PG-8**	**PG-9**	**PG-10**
SiO_2	71.17	71.18	69.77	71.39	69.62	72.7
$Al2O_3$	13.3	12.45	13.23	13.44	13.34	11.74
$Fe2O_3$	3.6	2.93	3.58	3.2	3.36	3.02
MnO	0.07	0.06	0.07	0.05	0.06	0.05
MgO	0.13	1.1	0.45	0.32	0.76	0.58
CaO	0.99	1.18	1.15	0.96	0.93	0.97
Na_2O	3.31	3.54	3.73	3.39	3.67	3.55
K_2O	6.02	5.91	6.26	5.8	6.44	5.65
TiO_2	0.37	0.3	0.35	0.3	0.3	0.27
P_2O5	0.02	0.05	0.03	0.02	0.03	0.03
LOI	0.64	0.68	0.82	0.54	0.68	0.52
SUM	99.62	99.38	99.44	99.41	99.19	99.08
CIPW Norm						
Q	26.87	25.00	22.07	27.07	21.35	28.82
C	0	0	0	0	0	0
Or	35.57	34.92	36.99	34.27	38.05	33.39
Ab	28.00	29.95	31.56	28.68	31.05	28.92
An	3.652	0.625	0.867	4.325	0.905	0
Ne	0	0	0	0	0	0
Ac	0	0	0	0	0	0.978
Di	0.089	3.186	2.418	0	2.104	3.014
Wo	0	0	0.247	0	0	0
Hy	0.283	1.263	0	0.797	0.918	0.048
Ol	0	0	0	0	0	0
Il	0.15	0.15	0.128	0.15	0.107	0.128
Hm	3.6	4.62	2.93	3.58	3.2	3.36
Tn	0.715	1.034	0.571	0.666	0.217	0.571
Pf	0	0	0	0	0	0
Ru	0	0	0	0	0.156	0
Ap	0.047	0.284	0.118	0.071	0.047	0.071
Sum	98.99	98.64	98.71	98.63	98.88	98.52

Table 2. Trace and rare earth element analyses of Punugodu granite, NSB, EDC, India

Sample	PG-3	PG-5	PG-6	PG-8	PG-9	PG-10
Sc	1.849	1.779	1.905	1.924	1.923	1.852
V	2.001	1.426	1.557	1.283	1.256	1.229
Cr	7.864	7.92	8.06	8.175	8.081	8.308
Co	0.401	0.373	0.406	0.541	0.481	0.57
Ni	1.513	1.407	1.276	1.196	1.169	1.358
Cu	0.481	0.497	0.496	0.471	0.472	0.444
Zn	42.31	37.552	48.865	45.125	52.406	38.759
Ga	37.556	37.025	38.915	36.924	40.41	35.427
Rb	197.34	179.08	224.74	241.15	251.47	225.28
Sr	9.589	10.82	10.401	11.414	9.872	8.391
Y	156.60	108.07	129.48	137.87	137.49	123.57
Zr	128.39	85.54	153.56	278.95	311.83	275.63
Nb	216.61	131.59	194.90	183.02	188.05	167.13
Cs	1.589	1.527	1.95	1.936	2.011	1.646
Ba	32.67	39.95	37.364	58.361	56.391	69.456
Hf	4.861	3.238	6.121	10.238	12.918	10.056
Ta	8.188	4.657	8.178	8.065	11.259	8.52
Pb	17.396	16.942	17.287	21.497	19.788	14.544
Th	51.627	36.388	47.13	42.974	45.006	39.198
U	5.953	3.755	5.182	6.428	6.423	8.369
La	312.75	242.53	320.03	187.86	161.25	144.13
Ce	1056.6	469.78	1047.8	359.97	314.77	280.37
Pr	64.947	49.94	62.215	36.84	32.94	29.15
Nd	238.74	184.5	224.23	133.2	119.4	105.7
Sm	46.258	35.48	39.358	25.72	24.04	21.57
Eu	0.542	0.487	0.572	0.475	0.468	0.431
Gd	38.263	29.15	32.084	22.14	20.69	18.84
Tb	5.72	4.258	4.562	3.644	3.488	3.193
Dy	34.824	25.22	27.388	24.42	23.86	21.70
Ho	3.629	2.585	2.849	2.787	2.757	2.472
Er	11.218	7.711	9.213	9.042	8.975	8.191
Tm	1.318	0.863	1.104	1.13	1.156	1.034
Yb	12.636	8.536	11.076	10.84	11.33	9.978
Lu	2.011	1.413	1.815	1.656	1.786	1.537
Eu/Eu*	0.04	0.05	0.05	0.06	0.06	0.07
∑REE	1829.5	1062.	1784.3	819.8	726.9	648.4

DISCUSSION

Anorogenic granites are emplaced in extensional setting and are charecterised by their distinct mineralogy and geochemistry (Loiselle and Wones, 1979; Whalen et al., 1987; Eby, 1990). Presence of fluorite and interstitial biotite, high SiO_2, $Na_2O + K_2O$ contents, low CaO, Sr contents along with enriched Zr, Y, Rb, high REE contents in Punugodu hypersolvus granite and LREE enrichment indicate anorogenic character for the Punugodu granite. Thorium values range from 36.38 ppm to 51.62 ppm. Pronounced negative Eu anomaly coupled with significant enrichment of the Light rare earth elements (LREE) ranging from 580.92 to 1719.29 ppm indicates an enriched crustal source. Hypersolvus anorogenic granites of Proterozoic age have been reported from the Labrador (eg Collerson, 1982). Punugodu pluton is located to the south of Podili pluton and falls within the Proterozoic granite magmatism zone, close to the eastern margin of the Cuddapah basin (Sesha Sai, 2013a) in EDC. Both the hypersolvus Podili alkali granite and the sub solvus Kanigiri biotite are fluorite bearing and are geochemically charecterised by high SiO_2, $Na_2O + K_2O$ contents, low CaO, Sr contents and enriched HFSE contents (Sesha Sai, 2013a).

Table 3. EPMA analyses of the feldspar from the Punugodu granite, NSB, EDC, India.

SiO_2	63.48	68.30	64.89	69.30	64.39	64.63	64.56	68.21	64.53	68.35	63.79	63.72
$Al2O_3$	17.91	19.51	18.25	19.49	18.22	18.20	18.25	19.76	18.13	19.60	17.42	17.73
FeO	0.17	0.04	0.11	0.08	0.04	0.17	0.15	0.13	0.02	0.04	0.46	0.61
CaO	0.24	0.11	0.00	0.01	0.00	0.00	0.00	0.00	0.07	0.00	0.05	0.00
Na_2O	0.39	11.40	0.34	11.63	0.38	0.27	0.36	11.73	0.34	11.49	0.29	0.23
K_2O	15.53	0.12	15.97	0.10	16.01	15.96	15.69	0.07	16.14	0.09	16.37	16.48
MgO	0.02	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.08
Cations on the basis of 32 oxygen												
Si	12.00	11.98	12.03	12.02	12.01	12.02	12.02	11.94	12.02	11.98	12.04	11.98
Al	3.99	4.03	3.99	3.98	4.00	3.99	4.01	4.07	3.98	4.05	3.87	3.93
Fe(ii)	0.03	0.01	0.02	0.01	0.01	0.03	0.02	0.02	0.00	0.01	0.07	0.10
Ca	0.05	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00
Na	0.14	3.88	0.12	3.91	0.14	0.10	0.13	3.98	0.12	3.90	0.11	0.08
K	3.74	0.03	3.77	0.02	3.81	3.79	3.73	0.01	3.83	0.02	3.94	3.95
Mg	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
TOTAL	19.95	19.95	19.93	19.95	19.96	19.92	19.91	20.02	19.97	19.96	20.05	20.07
End members												
An	1.23	0.54	0.00	0.05	0.00	0.00	0.02	0.00	0.33	0.00	0.26	0.00
Ab	3.67	98.78	3.09	99.41	3.45	2.49	3.39	99.63	3.05	99.52	2.61	2.09
Or	95.10	0.68	96.91	0.53	96.55	97.51	96.59	0.37	96.62	0.48	97.13	97.91

Anorogenic granites are characteristically emplaced in extension tectonic setting and are charecterised by their distinct mineralogy, whole rock and trace element composition (Loiselle and Wones, 1979; Collins et al., 1982; Whalen et al., 1987; Eby, 1990).

In the Y+Nb vs Rb trace element tectonic discrimination diagram, the Punugodu granite falls in the within plate granite field (WPG).

CONCLUSION

The paper presents the field, petrographic and geochemistry of the Punugodu granite pluton of Nellore schist belt, Eastern Dharwar Craton, South India. The deformed nature along the margins and presence of enclaves of metavolcanics of the Nellore schist belt indicate the intrusive nature. The alkali feldspar enriched Punugodu granite falls to the south of the Podili alkali granite pluton. Presence of fluorite, apatite and interstitial biotite, high $SiO_2$and Na_2O + K_2O, relatively low MgO and relatively enriched in HFSE contents along with the within plate character in the trace element tectonic discrimination plot indicates its anorogenic nature.

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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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