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Characterisation and Petrogenesis of Enclaves in Punugodu Granite Pluton, Prakasam District, Andhra Pradesh, India

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Abstract*: Punugodu Granite Pluton (PGP) is one among the many granitic plutons hosted by Nellore Schist Belt (NSB) and considered as post collisional A-type Granite. It consists a variety of enclaves; they are seen as Xenoliths, Mafic magmatic enclaves (MME), Felsic magmatic enclaves (FME) and Basic Microgranular Enclaves (BME) which are having a distinct field, petrographic, and geochemical characteristics. They are subalkaline tholitic to alkaline and magnesian to ferroan in nature. Chondrite normalized REE patterns of MME, FME and xenoliths show fractionation, relative LREE enrichment and HREE depletion with negative-Eu anomalies. When compared among these enclaves, BME show slightly less fractionated REE patterns without Eu-anomalies, which is transitional between tholitic-alkaline basalts, and akin to oceanic - continental tectonic settings. BME of OIB signatures which are early formed and assimilated into granitic melts or late stage chemical exchange/equilibration of coeval melts at high temperatures. Enclaves could have derived from a single magma source more likely to be a high Ti-basaltic parentage with an involvement of magma chamber process in connection with mixing-mingling process at the coeval generation of magmas and assimilation process by the late stage granitic plutonism.*

Keywords: *granitoid, enclaves, Nellore schist belt, petrogenesis*

1. Introduction

Enclaves [1] are lower crustal rock fragments enclosed in another homogeneous, intrusive igneous rock, commonly occurs in many granitoids. They represent a wide variety of rock fragments firmly of igneous and metamorphic origin. They occur in host rock because of different magmatic possesses and provide vital evidences on the origin and evolution of granitic magma. The study of enclaves in granitoids has a long history [2, 3, 4, 5]. Several workers have classified these enclaves into various types: Xenolith and Xenocryst [6], Schlieren [7], Surmicaceous Enclaves [8], Microgranular Enclaves [9], Mafic Magmatic Enclave [10], Composite Enclaves [11], Microgranitoid Enclave [12, 13]. Didier and Barbarin [14] proposed an abbreviation MME that may stand for either mafic microgranular enclave, mafic microgranitoid enclave or mafic magmatic enclave. Generally, the abbreviation FME used for felsic microgranular enclave and felsic magmatic enclave. These mainly occur in the upper parts of high-level intrusions [15]. Enclaves of diverse origin quit rare in many granitoids, however different types of enclaves do occur in some A-type granitoids, and provide vital clues on not only their genesis but also pertaining to the process involved. Further, magmatic enclaves and its distribution in felsic plutons may provide insights into magma chamber processes and dynamics [16]. Although MMEs may have originated in many different ways and from different sources, there has been a general consensus that textural criteria allow recognition of a class of enclaves that formed by mingling of an externally derived magma with granitic magma while it was still mobile [17, 18] these can appropriately be termed magmatic enclaves [19]. Detailed studies on MME have provided significant information on the nature of source rocks, the mechanism of production of granitic melt [20], existence of mixing of magmas of different compositions [21, 22] rheology of host magmas and tectonic settings of granites as well as interaction between continental crust and mantle [23, 24].

Granites can be generated and emplaced in many different geodynamic contexts. Granites are not exclusively continental, according to estimations by [25, 26] that the granitic component may represent from 1 to 5% of the oceanic crust. A-type granites commonly occur in post-orogenic or intraplate tectonic settings [27, 28] provide significant information on post-collisional/intraplate extensional magmatic processes within the continental lithosphere and their contribution to the build-up of the upper continental crust [29, 30]. Anorogenic or A-type granites do occur either in oceanic areas or in continents, have recently received much attention [31, 32] because of their economic potential and tectonic significance [33]. However, they are rare in the lower crust, fairly common at shallower depths, especially at the subvolcanic level where they form ring complexes rooting caldera volcanoes [34]. The presence of enclaves in alkaline anorogenic granitoids is an indicative of processes that have acted at different levels during the magma mixing history. Studies on

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enclaves provide significant information on the nature of the source rocks and the mechanism of production of granitic melts and their mixing mingling process. The present paper deals with a detailed field observation, petrographic and geochemical characterization of different types of enclaves identified in the Punugodu granite pluton with an aim to solve certain problems involved in the genesis of various types of enclaves in the felsic igneous system.

2. Field and Geological Setting

The Nellore Schist Belt (NSB) largely consists of metavolcanics, extends for about 370 km length in NS direction, from Sirasanambedu in the south to Vinukonda in the north. Structurally, the entire belt is thrust stacked terrane and is extensively deformed and metamorphosed under green schist to amphibolite facies conditions. It hosts for many small granitic plutons at close vicinity to the eastern margin of Cuddapah Basin (CB). These plutons are considered as Proterozoic, post orogenic A-type granites. Most of them are undeformed, generally less than 10 sq. km., tor shaped and emplaced in a narrow tact. The granitic activity in this belt began at Vinukonda around 1600 ma and possibly ended at Kanigiri around 1000 ma [35].

The area around Kanigiri-Punugodu lies at the contact between Ongole domain and Udayagiri domain forms as an important segment in the NSB [36], which has characterized by the presence of both subsolvus and hypersolvus granite types

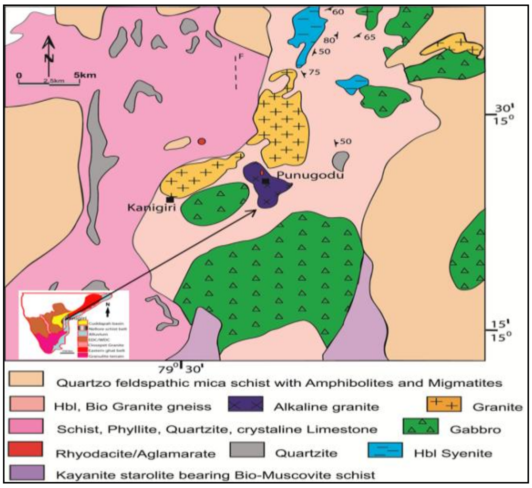

***Figure 1**. Geological map of the Punugodu granite pluton and adjoining rocks, Prakasam District, Andhra Pradesh*

The Punugodu granite pluton which has been identified as hypersolvus, traced at Punugodu village, near Kanigiri town [37], hosts for the presently studied enclaves. It covers an area of about 7 sq. km, trending N-S direction, occurs to the east of rare metal bearing Kanigiri granite and south of Podili granite (Figure 1). It has close contact relationship with a rhyodacitic volcanic plug that has almost bounded by hornfelsic rocks. The granite has a spatial association with gabbro, hornfels, epidotised calc-silicate chert and acid volcanic rocks. However, the calc silicate chert is a discontinued band with an average width of 50 meters, traced on the granite body as a roof pendent. Ophiolite mélange [38] and agglomerates [39] have also been reported from this area.

3. Petrography

The host Punugodu granite is a massive equigranular, homogeneous and coarse grained, consists of quartz and perthitic feldspar as essential minerals. Biotite, hornblende, arfvedsonite, aegirine, apatite, fluorite, zircon, sphene, and opaques identified as accessory phases.

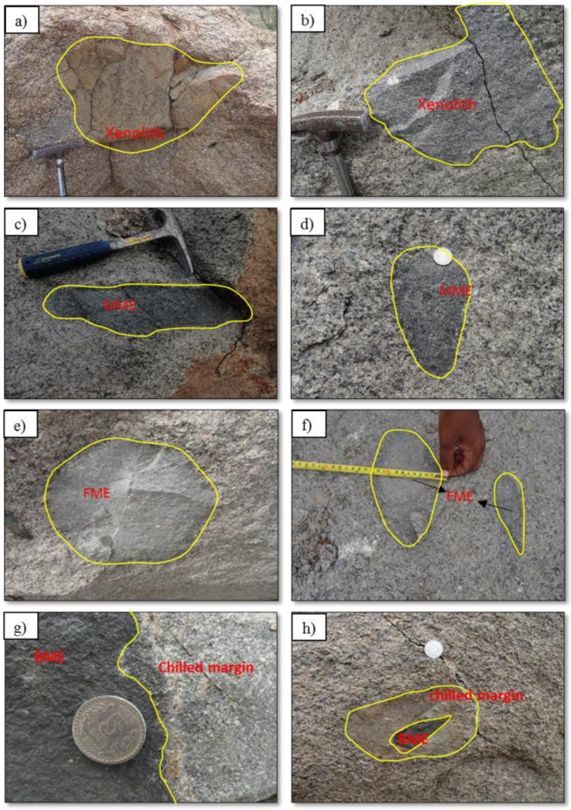

***Figure 2**. Field photographs: (a) & (b) xenoliths fine grained, having irregular shapes and sharp contact with host rock. (c) & (d) MME melanocratic, elongated, ellipsoidal, fine-grained, having phenocrysts of Quartz and Perthite. (e) & (f) FME leucocratic, rounded ellipsoidal, fine grained also consists Quartz and Perthite phenocrysts. (g) & (h) BME having chilled margins with crenulated to cuspate contact*

The unique feature of this granite is the presence of single feldspar (microcline perthite) expressing its hypersolvus nature. Several enclaves of acidic and basic are noticed to the extent of nearly 1% of the volume of the pluton; however, they show diverse mineralogical, textural and structural characteristics. These enclaves have been identified as xenoliths, mafic magmatic enclaves (MME), felsic magmatic enclaves (FME) and basic microgranular enclaves (BME).

Most xenoliths (Figure 2a&b) are felsic, angular and show sharp contacts with host granite present in varied dimensions (few centimeters to 1.5 meter). They are mostly rhyodacitic consist of quartz, feldspars, and perthite as essential minerals, and hornblende, zircon, biotite and other opaques as accessories. Broadly, they are less deformed exhibiting recrystallized quartz, plagioclase with bent lamellae, coronas and granophyric textures (Figure 3a). Mafic xenoliths, however less in abundance, are coarse grained composed of altered plagioclase and clinopyroxene as major constituents with fluorite, calcite, sphene, epidote, and chlorite as accessories (Figure 3b&c). Fractures and frequently developed rusty halos, sharp edges, and development of cracks are the characteristic feature of these xenoliths.

MME types (Figure 2c&d) exhibit ellipsoid, spherical, lenticular, linear shapes. However, few of them are showing angular sides that may have resulting from late shear effecting. They are essentially composed of hornblende, alkali amphibole, augite, plagioclase and quartz, with subordinate fluorite, sphene, apatite and opaques (Figure 3e,f&g). The sizes of MME are widely variable. The rounded ones vary from 2cm to 10cm diameter, lenticular types with up to 60cm length - 8cm width, and ellipsoid shaped extend up to 8cm width - 25cm length. MME are darker and fine grained exhibiting igneous texture. Occasionally, clusters of darker minerals are found within these enclaves mimicking composite type enclaves. More than one composite enclaves are enclosed in MME and they have sharp contact with the host (Figure 3a).. Fine grained margins formed as shells around the MME. MME host mantled xenocrysts (mafic-rimed) of quartz and perthite often rimmed by hornblende, they present at the core and also lay across the contact clearly indicating that they crystalized and brought into the enclave. Bluish green alkali amphibole occurs as rims and blebs replace augite at places.

FME (Figure 2e&f) are rounded, ellipsoidal and spherical in shape. They exhibit igneous textures with similar mineralogical composition of perthite, quartz, K-feldspar (microcline) and pleochroic biotite like in host rock (Figure 4a). The most conspicuous feature of FME is the presence of quartz and perthite (mafic-rimed) mantled xenocrysts similar to crystals present in the host and also in MME. Wavy extinct quartz phenocrysts and opaques rimed with biotite flakes are very common in FME (Figure 4b&c). Few felsic bands, moderately coarse grained crystals with similar mineralogy, believed to be formed early as chilled margins. In contrast with MME, these are dominated type of enclaves. The monogenic felsic swarms and roundness of the enclaves indicate that the portion of child margins remobilized by the granitic melts during its emplacement. These acid magmatic enclaves might have been resulted from the disruption of felsic margins of plutons [40].

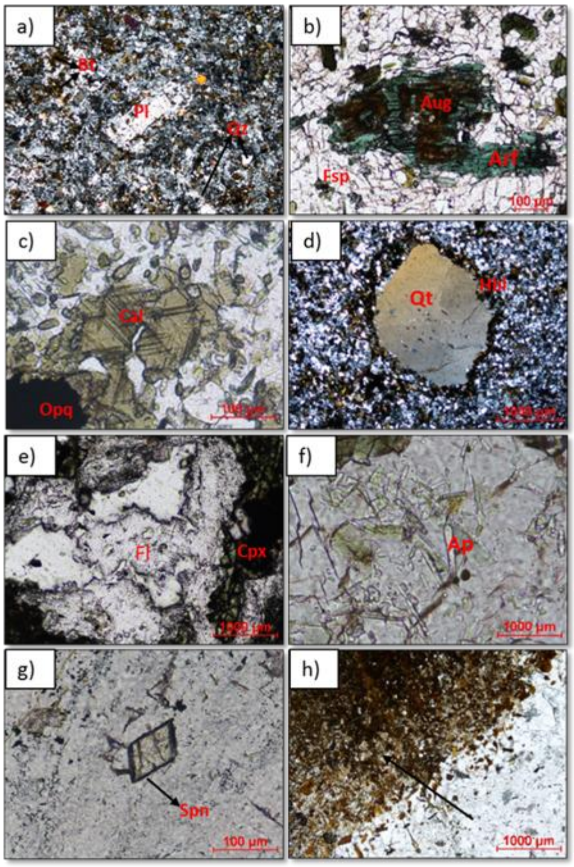

***Figure 3**. Microphotographs: (a) Xenolith containing euhedral phenocryst of Plagioclase with corona surrounded by a fine grained matrix of quartz, feldspar and biotite (b) Replacement of Clinopyroxene by alkali amphibole around its margin in xenolith. (c) Calcite and opaques in a meta-xenolith. (d) Mantled xenocryst (ocellus) of quartz in the mafic magmatic enclave, groundmass consists quartz and plagioclase. Hornblende occurred as a mantle on the quartz xenocryst. (e) Fluorite and Cpx in MME. (f) Apatite needles in MME. (g) Euhedral sphene in MME. (h) Contact between the composite enclave and host rock*

BME (Figure 2g&h) are basaltic, fairly dark, consist of fine grained crystals of plagioclase and pyroxene dispersed in glassy matrix exhibits sub optic texture. Secondary minerals developed from clinopyroxene are amphibole, chlorite and opaques. The occurrence of long needle like phenocrystic laths of plagioclase in the glassy ground mass an indicative of magma chamber process (Figure 4d&e) prior to emplacement. Plagioclase microphenocrysts intersect at places and they show desiccation cracks and sericitization. Highly pleochroic hornblende surrounded by chlorite at places. Most BME are with recrystallized light coloured child margins (Figure 2h) composed of fine grained quartz, perthite and biotite with sharp, crenulated to cuspate contact (Figure 4f). This type of contacts mainly appears in some special cases where there are large volumes of mafic magma or where mafic magmas are dominate over felsic magma [41].

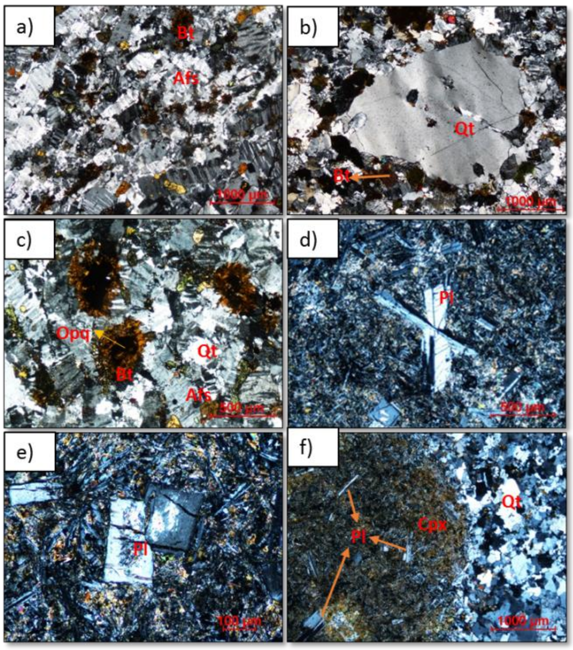

***Figure 4**. Microphotographs: (a) Perthites in FME are twinned, fragmented consist interstitial biotite clusters. (b) Quartz xenocryst in FME surrounded by biotite, perthite and quartz. (c) Opaque rimed with biotite clusters in FME. (d) Intersect of elongated, twinned plagioclase crystals in BME surrounded by a glassy matrix of clinopyroxene and plagioclase. (e) Microphenocrysts of Plagioclase surrounded by needle like elongated plagioclase crystals. (f) Sharp contact between BME and FME where they show distinct mineralogy*

4. Geochemistry

Table 1 presents the whole rock major, trace and rare earth element (REE) data of representative samples of enclaves. The host granite rock shows normal levels of silica which range from 68 to 71 wt. %, and high total alkalis ($K_2O + Na_2O$) ranging from 7.72 to 10.22 wt. %. It is ferroan- magnesian, alkali to alkali-calcic and metaluminous. The average SiO_2 content in Xenolith, MME, FME and BME are 62.5%, 55.5%, 66.5%, 46.5% (all in wt. %) respectively. These are magnesian to ferroan in nature. When plotted on AFM triangular discrimination diagram magma [42], enclaves occupy tholitic calc-alkaline to the alkaline fields with a distinct trend (Figure 5). The BME show tholitic to calc-alkali character. MME and xenolith are calc-alkaline to alkaline, and the FME with alkaline nature. Figure 6 shows nomenclature of enclaves on the total alkalis-silica diagram.

The BME and xenoliths are more enriched in compatible elements like CaO, MgO, Fe_2O_3 and Co. Whereas MME and FME relatively poor in CaO, MgO and Co. However, all four enclaves form a relatively continuous suite in the Harkar variation diagram (Figure 7), and show linear trends with decreasing Fe_2O_3, CaO, MgO, P_2O_5, TiO_2, Sr and Ni and increasing Na_2O, K_2O, Al_2O_3, Zr, and Ce. The TiO_2 content is high in BME (1.48-1.83 wt. %) in contrast to other enclaves. They are tholeiitic to alkaline with enriched Nb in the range of 20-79 ppm and low total alkali contents of 3.7-5.2 wt.%. When compared to MME, FME and xenoliths show high total alkalis (7.3-9.4 wt.%), Zr (144-466 ppm) and Ti/Y, Nb/Y and Zr/Y ratios 9.0-16.3, 0.7-0.9 and 3.6-4.3 respectively.

Chondrite normalized REE distribution patterns of MME, BME and mafic xenolith (Figure 8) show LREE enrichment and HREE depletion with pronounced Eu¬- negative anomalies. ∑REE are in the range of 143 - 990 ppm. Eu/Eu* amounts to 0.62-0.99. Whereas La/Yb_N 24.0-6.2. Ni and Cr contents range between 39-70 and 176-283 respectively. BME patterns show slightly less fractionated without Eu-anomaly, which are transitional to tholitic-alkaline basalts, and akin to oceanic - continental tectonic settings. The low Zr/Nb ratios (4.4-5.2) and high Nb/Yb (7.6-12.1) and Zr/Y (3.6-4.3) ratios relative to N-MORB are indicative of partial melting of enriched mantle source. Hence, we speculate BME of OIB signatures which are early formed and assimilated into granitic melts or late stage chemical exchange/equilibration of coeval melts at high temperature might have given such BME. The FME show similar REE distribution patterns with very low Eu/Eu* values 0.09-0.69 and ∑REE in the range of 184-2665. Ni, Cr contents of felsic xenoliths are in the range of 8-10 and 74-113 ppm respectively. Multi elements spider diagrams indicate Nb-Ta coupled negative anomalies for mafic xenolith/enclaves whereas for felsic enclaves/xenoliths they are flat or enriched. Variable ∑REE contents in case of MME, FME and xenoliths indicate different degrees of partial melting in a subduction zone tectonic setting.

5. Conclusions

Field and petrography combined with whole-rock geochemistry, described in this paper, facilitated to identify four types of enclaves in the host Punugodu granite pluton. These enclaves show high Zr/Ti ratios indicate that they could have been derived from single magma source more likely to be a high Ti-basaltic parentage with an involvement of magma chamber process (phenocrystic BME). Mineral replacement phenomenon observed in the MME and FME, indicates mixing and mingling processes due to their coeval generation. Rhyodacitic xenoliths are the obvious products of assimilation process by the late stage granitic plutonism. The presence of fluorite in host granite as well as in enclaves clearly reflects low degree of partial melting of the mantle at a high temperature which subsequently intruded into crustal country rock.

***Abbreviations**: Bt: Biotite, Qt: Quartz, Aug: Augite, Pl: Plagioclase, Cal: Calcite, Hbl: Hornblende, Fl: Fluorite, Cpx: Clinopyroxene, Ap: Apatite, Opq: Opaque* [43] *xpl: cross polarized light, ppl: plane polarized light.*

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***Table 1**. Major oxide, Trace and Rare Earth Element concentrations of enclaves enclosed in Punugodu Granite Pluton*

Sample	PG-8X	PG-12X	PG-19	PG-E-5	PG-E-9	PG-E-11	PG-E-14	PG-4X	PG-E-6	PG-E-7	PG-E-3	PG-E-4	PG-21	PG-22
		MME			**FME**				**BME**			**Xenoliths**		
SiO_2	53.31	49.43	62.88	66.46	67.41	66.92	66.88	45.2	48.73	48.99	64.92	64.22	61.54	61.22
Al_2O_3	14.47	11.03	13.81	13.66	13.62	13.97	13.88	13.94	13.11	13.18	13.23	13.51	13.22	13.11
Fe_2O_3	8.24	10.71	6.67	6.76	6.05	4.31	5.31	10.95	12.01	11.48	6.42	6.06	7.32	7.94
MnO	0.09	0.2	0.11	0.11	0.09	0.07	0.09	0.14	0.16	0.14	0.1	0.1	0.13	0.13
MgO	2.86	9.91	0.88	0.35	0.17	0.49	0.52	12.27	7.61	8.21	0.76	1.29	2.88	3.49
CaO	1.55	6.69	3.99	2.01	1.74	2.68	2.01	9.56	9.71	10.82	3.11	3.51	3.62	3.53
Na_2O	5.11	4	5.82	4.09	4.14	4.75	5.89	2.6	3.66	2.31	5.97	5.39	6.11	5.12
K_2O	3.23	4.93	3.43	4.18	4.26	4.27	3.61	2.15	1.58	1.43	3.51	3.66	3.37	3.46
TiO_2	0.5	1.02	0.71	0.67	0.65	0.49	0.52	1.54	1.48	1.83	0.79	0.65	0.87	0.95
P_2O_5	0.07	0.16	0.1	0.05	0.05	0.08	0.06	0.23	0.18	0.29	0.13	0.08	0.1	0.12
La	422.3	121.1	160.0	591.6	598.7	220.0	212.2	71.7	30.3	26.5	135.4	172.8	149.8	122.3
Ce	821.6	230.6	295.0	1220.8	1222.7	386.8	455.9	140.6	63.2	61.4	287.6	316.4	266.4	249.1
Pr	105.5	30.1	40.8	100.5	101.3	53.7	38.2	18.7	8.9	5.3	24.5	42.2	29.4	20.9
Nd	409.6	121.2	129.2	426.6	426.9	168.5	166.2	79.0	31.7	26.3	109.2	132.7	135.2	90.4
Sm	77.93	26.3	26.6	67.76	67.41	31.81	31.02	15.5	7.28	5.42	21.8	25.8	27.8	18.0
Eu	0.68	0.84	0.60	1.22	1.16	1.00	0.69	1.58	1.46	1.73	0.81	0.65	1.15	0.82
Gd	76.36	28.81	21.62	66.41	68.14	27.43	31.57	15.24	5.76	5.29	21.43	20.12	27.03	18.13
Tb	12.70	5.18	3.94	7.77	7.43	4.72	4.28	2.54	1.12	0.81	3.33	3.57	3.95	2.76
Dy	54.98	24.27	20.29	35.10	32.20	24.23	21.54	11.31	5.84	4.39	18.00	18.04	19.89	14.73
Ho	10.40	4.94	3.55	5.08	4.57	4.35	3.26	2.18	1.01	0.69	2.84	3.18	2.97	2.30
Er	34.99	16.75	10.47	14.41	12.89	13.17	9.40	7.63	3.05	2.06	8.49	9.60	8.39	6.84

Tm	4.25	2.11	1.53	2.56	2.29	1.90	1.75	0.93	0.46	0.40	1.68	1.41	1.53	1.33
Yb	27.11	13.23	10.57	17.98	16.79	13.13	12.39	5.89	3.25	2.85	12.05	9.92	10.34	9.45
Lu	4.12	1.95	1.63	2.70	2.58	2.08	1.80	0.89	0.51	0.39	1.76	1.54	1.43	1.34
Sc	10.39	36.35	7.59	4.27	4.48	6.87	4.74	46.18	31.58	30.21	9.45	7.275	12.72	14.25
V	41.31	605.1	37.39	5.89	4.90	19.78	25.51	721.8	260.33	215.44	25.11	39.04	81.90	82.78
Cr	53.25	61.70	113.44	195.87	165.73	99.50	248.94	63.04	74.37	283.77	164.08	97.32	252.86	176.71
Co	3.60	69.55	5.26	3.19	2.39	4.45	4.67	115.9	37.85	45.44	5.19	6.15	17.22	18.72
Ni	7.21	44.55	9.54	49.69	43.08	10.41	50.10	88.00	10.64	70.35	39.78	8.96	51.87	45.81
Cu	62.88	96.42	1.217	21.01	22.29	2.33	39.45	251.5	5.26	42.67	23.88	3.023	23.90	29.52
Zn	328.60	975.53	95.44	136.35	128.28	116.68	212.05	190.4	73.404	111.82	173.55	103.58	186.86	196.65
Ga	39.3	26.33	48.06	79.71	79.54	50.05	48.78	22.4	24.97	19.48	39.82	50.849	42.001	38.312
Rb	290.7	1014.	320.05	313.03	269.99	198.69	139.75	111.3	68.416	58.73	300.0	319.02	182.93	454.39
Sr	13.0	33.99	33.32	34.23	36.84	45.70	56.79	262.1	241.29	385.40	28.88	28.55	57.40	51.49
Y	366.0	196.3	132.95	187.8	172.4	164.3	133.9	79.87	38.40	28.81	125.5	127.2	112.1	102.1
Zr	998.4	408.4	606.10	443.85	621.53	722.08	359.42	466.7	263.80	144.39	596.1	862.3	413.2	397.0
Nb	490.2	128.3	147.69	180.30	173.63	159.54	119.47	79.04	35.166	20.433	106.17	149.28	78.765	88.729
Cs	0.82	3.86	1.029	0.98	0.923	1.06	0.94	0.72	0.88	0.942	0.98	0.96	1.02	1.25
Ba	60.50	206.8	6.52	3.36	1.34	0.79	1.40	675.6	1.45	1.65	6.46	5.53	1.49	6.654
Hf	18.8	9.84	69.25	47.29	57.07	171.90	49.65	9.83	331.7	541.1	102.0	67.02	73.19	150.24
Ta	12.21	3.95	6.55	2.67	2.61	6.58	1.95	2.87	2.04	0.54	1.750	7.06	1.86	1.98
Pb	4.269	10.07	22.57	20.65	15.42	39.29	41.37	2.67	18.71	11.74	24.21	31.11	24.63	28.8
Th	83.47	40.82	25.01	57.14	58.06	31.19	30.29	15.0	4.716	3.682	21.051	30.71	19.75	26.00
U	8.52	8.29	5.25	6.08	5.74	4.32	5.81	2.32	1.18	1.45	5.91	5.34	4.029	5.373

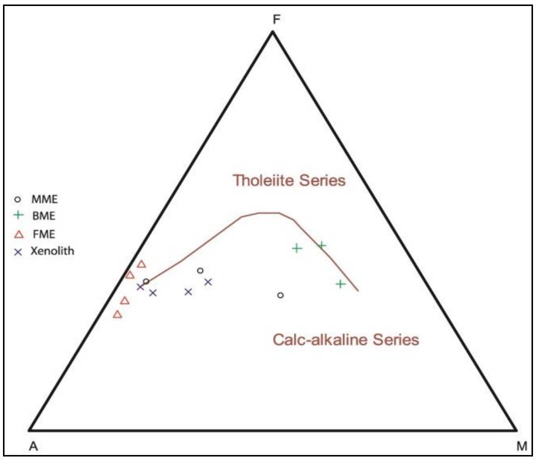

Figure 5. *A-F-M plots for the representative enclaves*

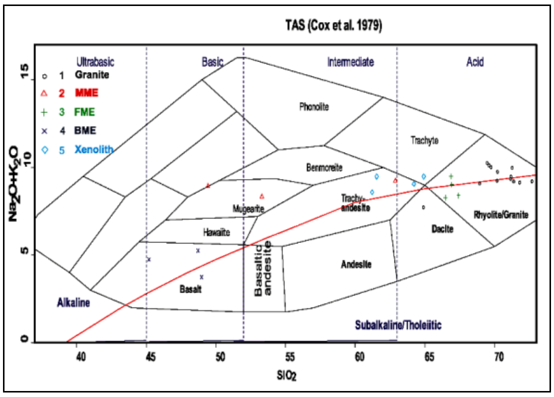

Figure 6. *SiO_2vs Na_2O+K_2O, binary diagram for the host Punugodu granite and its enclaves (after Cox et al., 1979)*

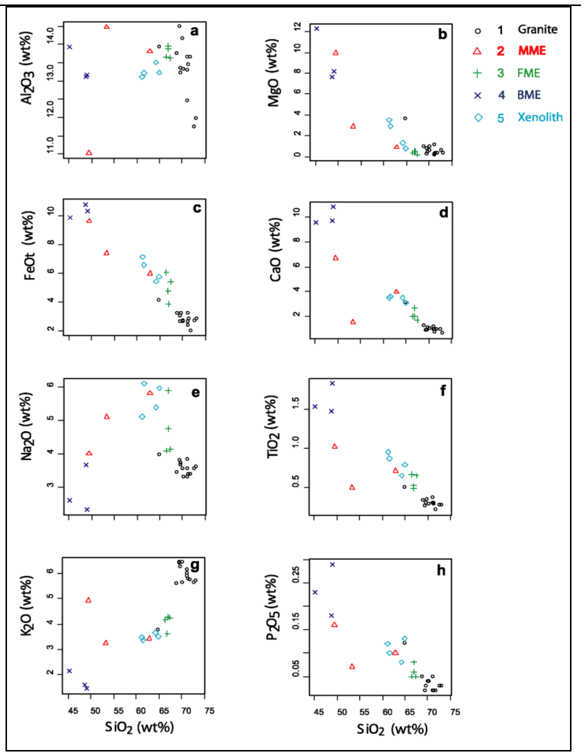

Figure 7*. Harkar variation diagram for the Punugodu granite and its enclaves*

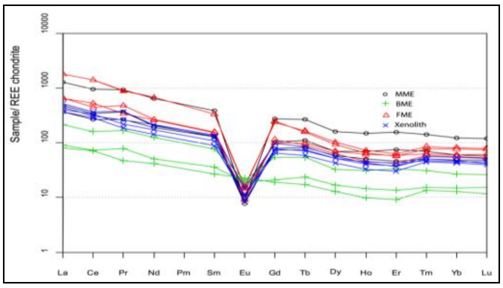

Figure 8*. Chondrite normalized REE abundances of enclaves in Punugodu granit*